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Praktikum Mobile und Verteilte Systeme

Indoor Navigation & AR and AG in Street Networks & Quality Metrics in Constrained Free Space

Prof. Dr. Claudia Linnhoff-Popien
André Ebert, Sebastian Feld
http://www.mobile.ifi.lmu.de

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Praktikum Mobile und Verteilte Systeme

→ Lessons Learned

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LOCATION-BASED SERVICES

CONCLUSION

Navigation and route planning as an important part of LBS

Spatial information as part of context-aware computing

Approaches and ideas to be discussed are more of **tools** rather than **applications**

Topics
- Trajectory Computing
- (Big) Data Analysis for Geospatial Trajectories
- Somewhat Information Retrieval

ROUTE PLANNING

FINAL REMARKS

Successful approaches **exploit different properties** of the road networks that make them easier to deal with

Geometry-based algorithms are consistently dominated by established techniques

Careful engineering is essential to unleash the full computational power of modern computer architectures (exploit locality of reference and parallelism)

The ultimate goal

- A worldwide multimodal journey planner, that takes into account real-time traffic and transit information, historic patterns, schedule constraints, and monetary costs
- Moreover, all the elements should be combined in a personalized manner

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Praktikum Mobile und Verteilte Systeme

→ Indoor Navigation

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INDOOR NAVIGATION

USE CASES

Pedestrian Navigation

- Maintenance jobs in complex industrial buildings
- Assistance for visitors in unknown buildings (hospitals, airports, fairs, …)
- Action forces

Mobile robots in storehouses

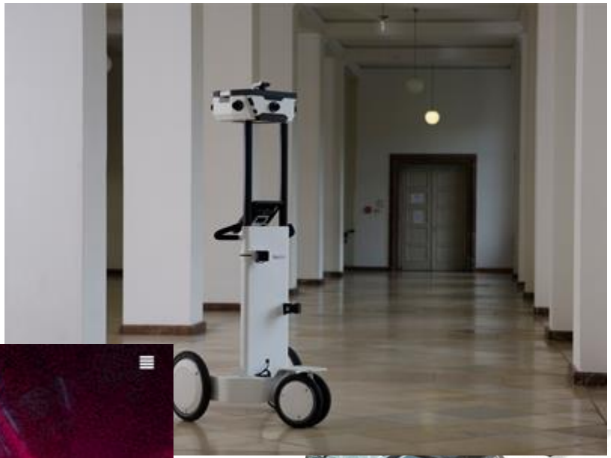
- Smart City
- Ambient Assistant Living

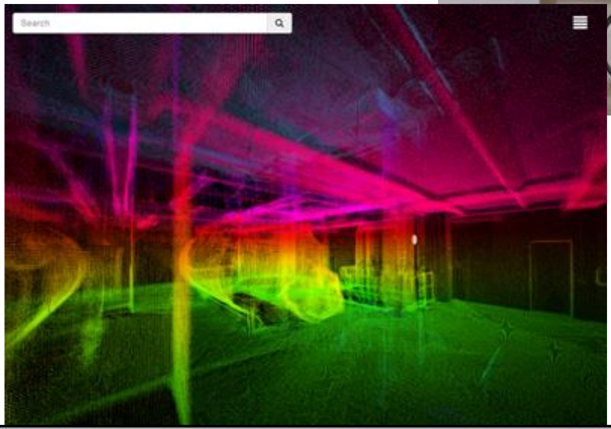
Non-player character in **computer games**

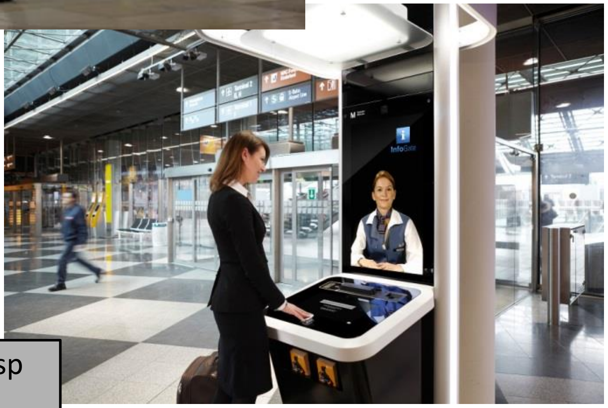
- AI for NPCs

Novel services

- NavVis…







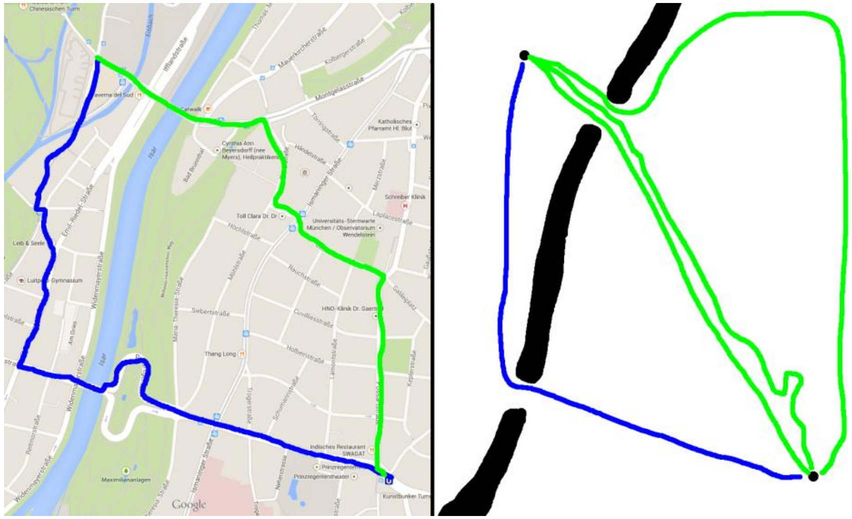
http://munich-airport.com/de/micro/infogate/30_produkte/20_counter/30_bsp/index.jsp
http://www.navvis.com/company/media-resources/

INDOOR NAVIGATION

INDOOR VS. OUTDOOR

Main differences
- Higher degree of **freedom of movement**
- Several possibilities of **map representations**
- Multiple levels inside a building
- No such concepts of highways, country ways, …

Many concepts/algorithms/measures not directly transferable
- Transfer map representation from indoor to outdoor?
- Redefine concepts?



http://ieeexplore.ieee.org/abstract/document/7275488/

INDOOR NAVIGATION

MAP REPRESENTATIONS

Street networks form a **quite natural graph structure**

- Streets are modelled as sequences of linear segments
- Crossings and turning points become a vertex of the graph
- The graph gets embedded
- → High-quality abstraction of the real abilities of movement

Different situation for **constrained free space**

- Movements in all directions are possible
- Potential constraints regarding the movements, e.g. mobile robot with steering creates smooth trajectories with bounded curvature
- Such complicated objects are computationally demanding
- Trajectories may be modelled as polylines, i.e. points connected by linear segments

INDOOR NAVIGATION

MAP REPRESENTATIONS

Map representations effectively **reduce the space of possible movements** for more **efficient planning**

Tradeoff

- Map representation’s ability to describe any given path in the building
- Computational complexity of algorithms performing choices in the environmental model

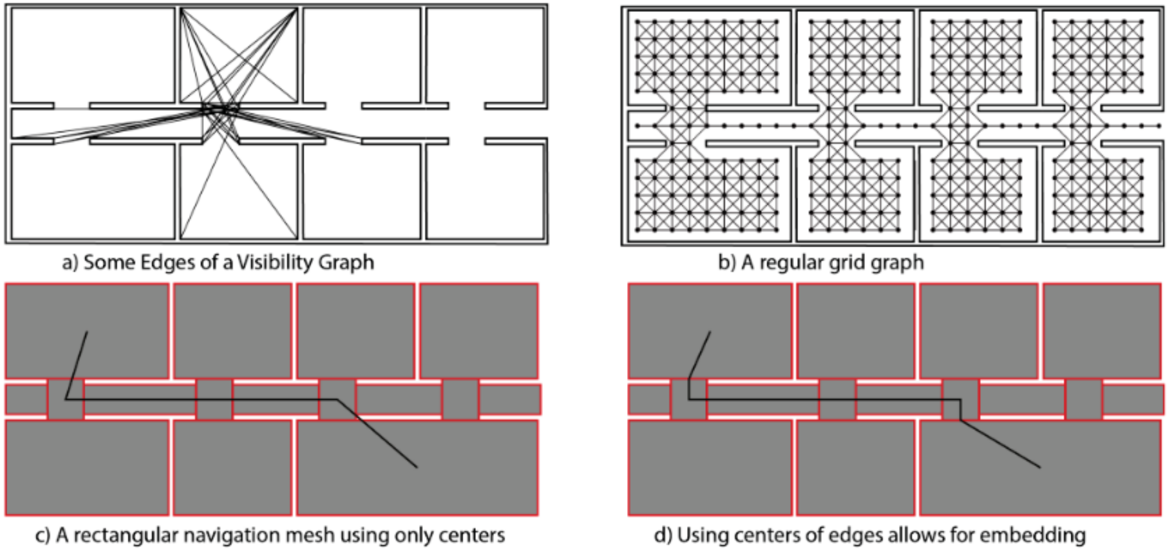


Figure 1. Examples of map representations, adapted from (Werner, 2014).

http://lbs2016.lbsconference.org/wp-content/uploads/2016/11/1_4.pdf

INDOOR NAVIGATION

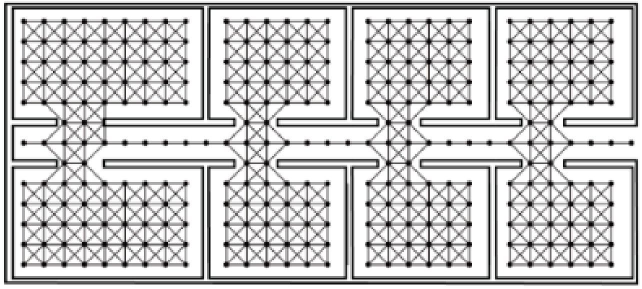
CONSTRAINED GRIDS

Choose arbitrary length for **regular grid** to put over the map

Points of the grid represent vertices and two adjacent points are connected if they are connected by free space

Occupancy grids

- Use a **two-dimensional bitmap** to represent walkable space in one color (white) and obstacles in another color (black)
- Thus, each pixel creates a vertex and two pixels are connected if they are both white and direct neighbors



b) A regular grid graph

Pros/Cons

- (-) Grids are large and inefficient
- (+) Computers are able to manipulate large bitmaps efficiently
- (+) Graphs have bounded degree of 4 when connecting vertical and horizontal neighbors, or 8 including diagonals
- (+) Algorithms' performance depends only on the amount of free space and not on the complexity of involved geometry

http://lbs2016.lbsconference.org/wp-content/uploads/2016/11/1_4.pdf

INDOOR NAVIGATION

POLYGONAL MAPS

Constraints are modelled as polygons and a graph is created using vertices and edges of the polygons

Several constructions, e.g. **visibility graph**

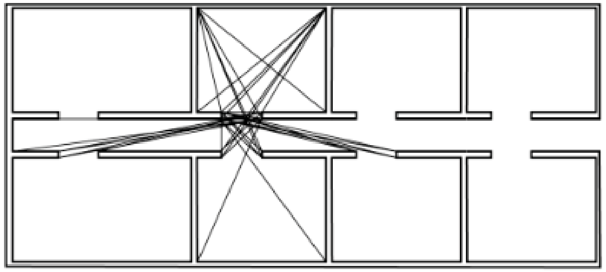
- All vertices of these polygons are connected as long as the direct line between them does only cross free space

Some good properties

- Relatively small for few and simple polygons
- It contains all shortest paths between vertices of the involved polygons

However

- It is not obvious, how this graph can be used for motion planning starting in arbitrary locations in free space
- Shortest paths in this graph tend to scrape along walls or walk in diagonals



a) Some Edges of a Visibility Graph

http://lbs2016.lbsconference.org/wp-content/uploads/2016/11/1_4.pdf

INDOOR NAVIGATION

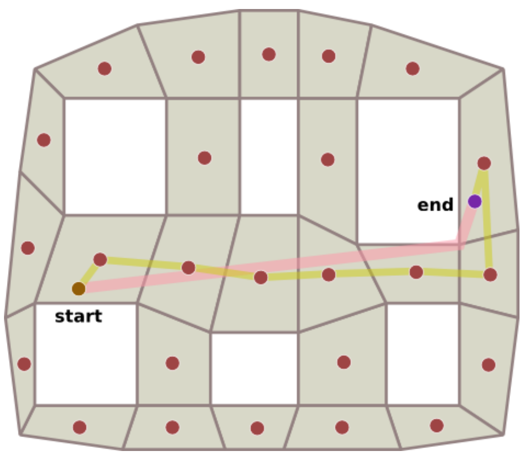
NAVIGATION MESH

Tessellation of free space and adding edges to a graph for each edge shared by two polygons meaning that one could go from one polygon to the other

Each polygon represents some space and simple polygons have the advantage of having low degree in the resulting graph

Navigation meshes are often built from very simple polygons such as triangles or rectangles

In a sense, the grid-based approach is also a navigation mesh in which small and regular squares are being used for the polygons



http://theory.stanford.edu/~amitp/GameProgramming/polygon-navmesh-faces.png

INDOOR NAVIGATION

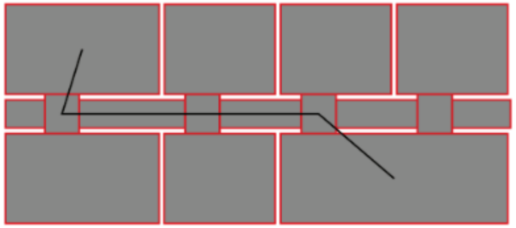
NAVIGATION MESH

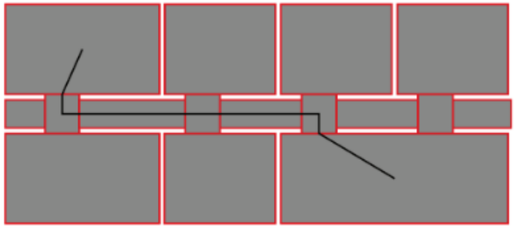
Multiple choices for building a graph representation from a navigation mesh

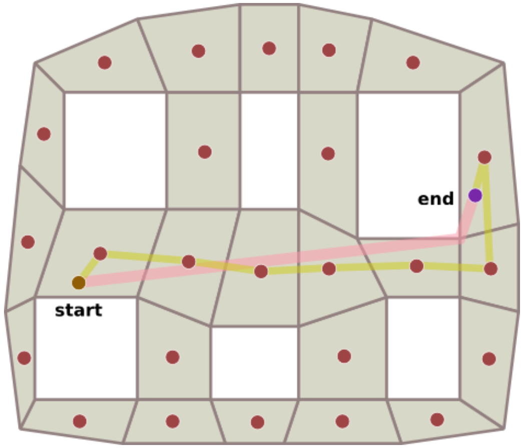
Represent each **polygon as a vertex** and connect neighboring vertices

When polygons are convex, use **centers of the polygons' edges** as navigation points leading to slightly better paths

Traversing edges of the involved polygons → wall-scraping behavior
- Positive: knowing which obstacles are being passed
- Negative: not being able to directly visualize the path


c) A rectangular navigation mesh using only centers


d) Using centers of edges allows for embedding



http://lbs2016.lbsconference.org/wp-content/uploads/2016/11/1_4.pdf
http://theory.stanford.edu/~amitp/GameProgramming/polygon-navmesh-faces.png

INDOOR NAVIGATION

MAP REPRESENTATIONS

Visibility graph (a)

- Amount of edges and average degree of vertices may be high
- Effect gets worse when GIS systems are used in which round objects are tessellated into many line segments (e.g. circular pillar)

Regular grid graph (b)

- Low-degree vertices, but many of them

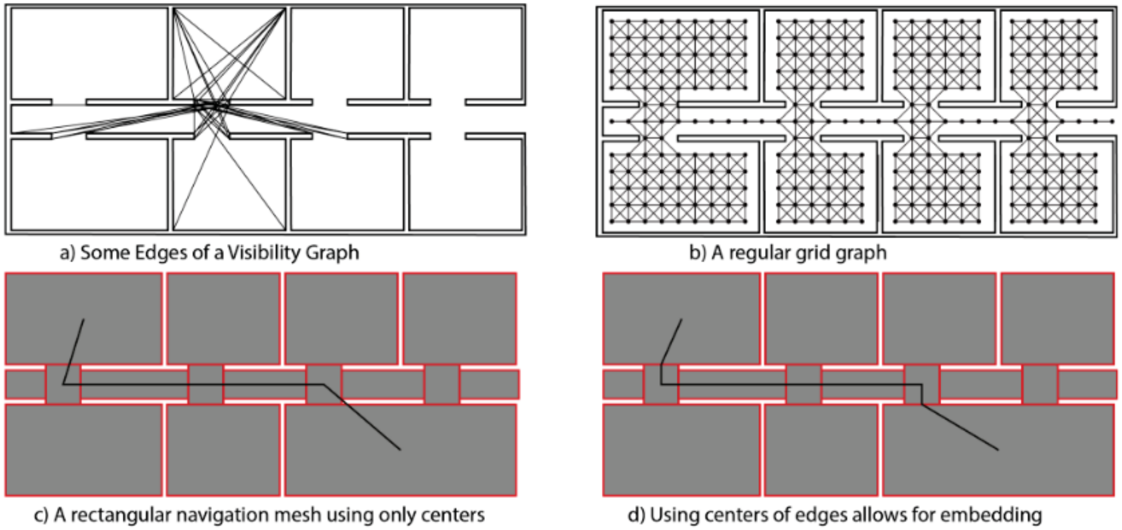


Figure 1. Examples of map representations, adapted from (Werner, 2014).

http://lbs2016.lbsconference.org/wp-content/uploads/2016/11/1_4.pdf

INDOOR NAVIGATION

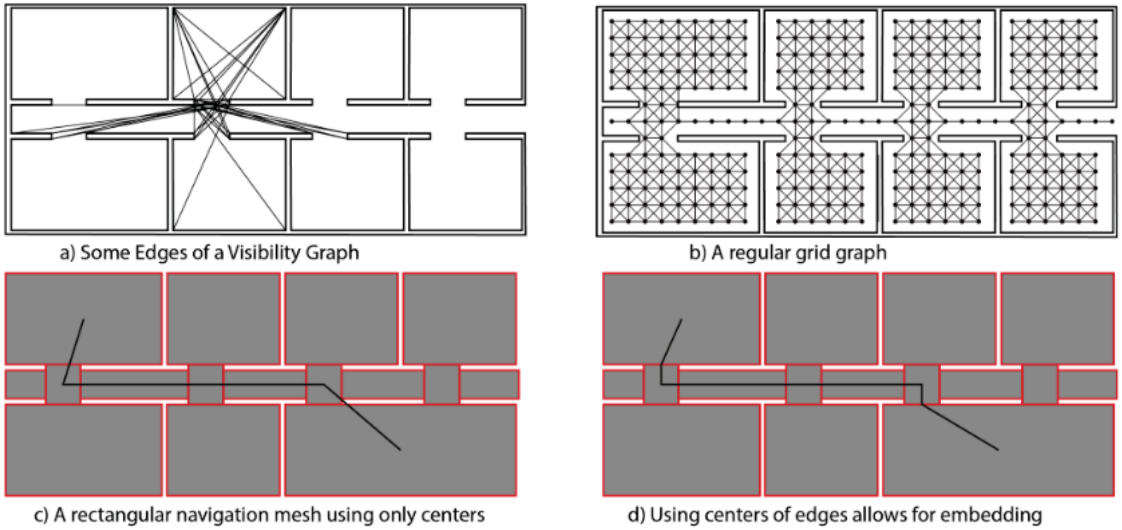
MAP REPRESENTATIONS

Rectangular navigation mesh (c)

- Shortest path is calculated only on rectangles' center points leading to situations where line segments are not fully inside free space

Rectangular navigation mesh (d)

- Shortest path remains in free space due to the use of middle points of the rectangles' edges and also the rectangles' convexity



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AR/AG IN STREET NETWORKS

EXAMPLES

Personalized routing based on preference

- CO_2-consumption
- toll pricing
- fuel consumption

… or based on experience

- scenic value
- risk of traffic jams

https://dl.acm.org/citation.cfm?id=2444019

AR/AG IN STREET NETWORKS

MOTIVATION

State-of-the-art

- Gather and sort existing work regarding **quality metrics** of **alternative routes** and **alternative graphs** in road networks

Constrained free space

- Clarify what **challenges** need to be tackled in order to create such metrics for constrained free space scenarios
- **Discussion** of possible courses of action, opportunities, and limitations

Examples

- Pedestrian navigation
- Even maritime or aviation scenarios

ALTERNATIVE ROUTES IN STREET NETWORKS

QUALITY METRICS – OVERVIEW

Central reference

- (Abraham et al., 2013) with predecessor (Abraham et al., 2010)
- Finding good alternatives by defining an "**admissible path**" using three measures

Approach

- Three measures as hard constraints for a target function
- Sort candidates and return first admissible path

Further improvements

- (Luxen, Schieferdecker, 2012)
- (Kobitzsch, 2013)

Alternative Routes in Road Networks

ITTAI ABRAHAM, DANIEL DELLING, ANDREW V. GOLDBERG
and RENATO F. WERNECK
Microsoft Research Silicon Valley

We study the problem of finding good alternative routes in road networks. We look for routes that are substantially different from the shortest path, have small stretch, and are locally optimal. We formally define the problem of finding alternative routes with a single via vertex, develop efficient algorithms for it, and evaluate them experimentally. Our algorithms are efficient enough for practical use and compare favorably with previous methods in both speed and solution quality.

Categories and Subject Descriptors: G.2.2 [**Graph Theory**]: Graph algorithms

General Terms: Algorithms, Experimentation, Measurement, Performance

Additional Key Words and Phrases: shortest paths, route planning, alternative paths, speedup techniques

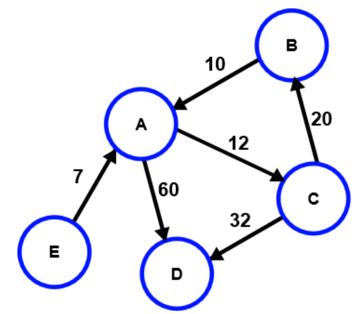
https://dl.acm.org/citation.cfm?id=2444019

ALTERNATIVE ROUTES IN STREET NETWORKS

PRELIMINARIES

Based on prosaic definitions, Abraham et al. formally define the class of paths to be found as “**admissible alternative paths**”

$G = (V, E)$	**directed graph** with nonnegative edge weights
$\|V\| = n$	number of **nodes**
$\|E\| = m$	number of **edges**
P	**path** in G
$\|P\|$	number of the path’s edges
$l(P)$	sum of the edge weights
$l(P \cap Q)$	sum of edge weights **shared** by P and Q
$l(P \setminus Q)$	sum of edge weights **<u>not</u> shared** by P and Q
$Opt(s, t)$	point-to-point **shortest path** problem between s and t



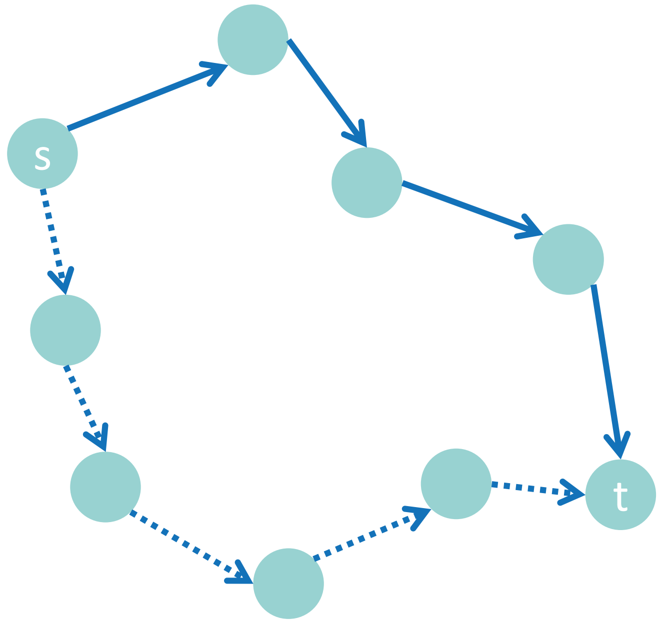
https://de.wikipedia.org/wiki/Graph_(Graphentheorie)#/media/File:CPT-Graphs-directed-weighted-ex1.svg

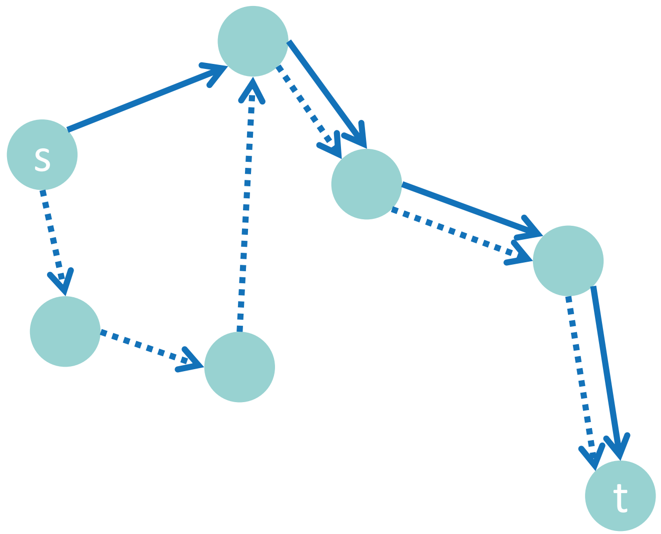
ALTERNATIVE ROUTES IN STREET NETWORKS

LIMITED SHARING

Limited Sharing

- The alternative path has to be **significantly different** to the reference path
- I.e., the total length of edges shared must be a small fraction of the reference route's length





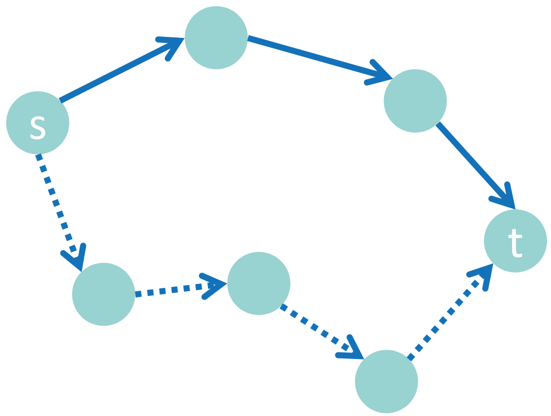
$$l(Opt \cap P) \leq \gamma \cdot l(Opt)$$

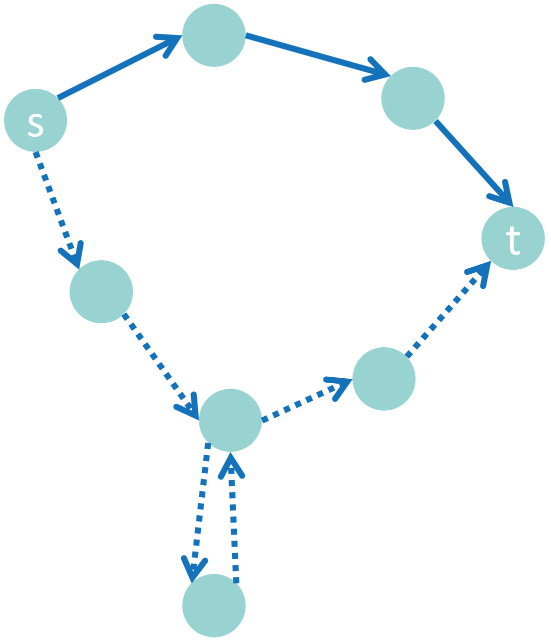
ALTERNATIVE ROUTES IN STREET NETWORKS

LOCAL OPTIMALITY

Local Optimality

- The alternative path must be **reasonable**
- I.e., no unnecessary detours are allowed
- Every local decision must make sense, so every subpath up to a certain length is a shortest path





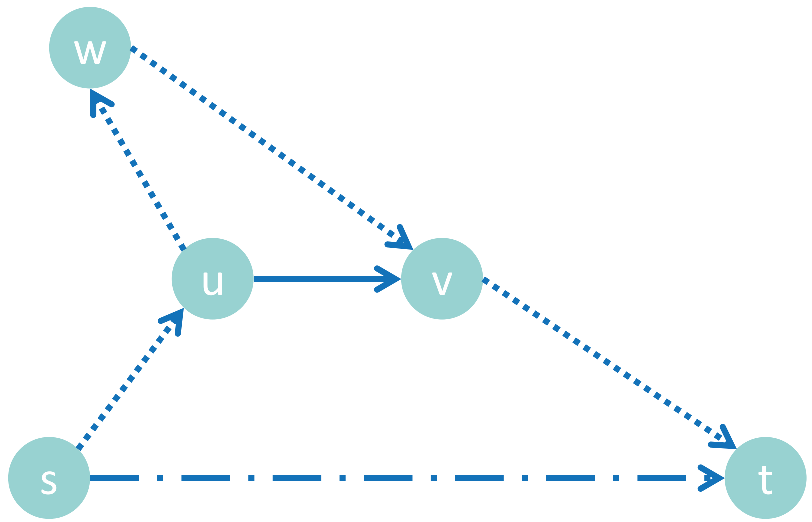
P is T-locally optimal for $T = \alpha \cdot l(Opt)$.
A path P is T-locally optimal if every subpath P' of P with $l(P') \leq T$ is a shortest path

ALTERNATIVE ROUTES IN STREET NETWORKS

UNIFORMLY BOUNDED STRETCH (UBS)

Uniformly Bounded Stretch (UBS)

- The alternative path must **not be much longer** than the reference path
- I.e., every subpath needs to have a good stretch
- This enhances local optimality: a path with high optimality may be shortened with a shortcut



P is $(1+\varepsilon)$-UBS.
A path P has $(1+\varepsilon)$-UBS if for every subpath P' of P with end points s', t', the inequality $l(P') \leq (1+\varepsilon) \cdot l\big(Opt(s',t')\big)$ holds

Rationale: the alternative through w is a concatenation of two shortest paths, s-w and w-t.

Although it has high local optimality, it looks unnatural because there is a much shorter path between u and v.

ALTERNATIVE GRAPHS IN STREET NETWORKS

QUALITY METRICS – OVERVIEW

Central reference
- (Bader et al., 2011), based on Dees' master's thesis (Dees, 2010)
- Preliminary aspects published before in (Dees et al., 2010)
- Definition of an **alternative graph** (AG) as the union of several paths having the same start and goal as a **compact representation** of multiple alternative routes

Approach
- Calculate shortest path
- Insert into AG
- Gradually calculate further alternative paths
- Insert greedily into AG optimizing a target function

Further work
- Efficient implementations: (Radermacher, 2012), (Kobitzsch et al., 2013)
- Higher quality: (Paraskevopolous, Zaroliagis, 2013)

https://link.springer.com/chapter/10.1007/978-3-642-19754-3_5

Alternative Route Graphs in Road Networks*

Roland Bader[1], Jonathan Dees[1,2], Robert Geisberger[2], and Peter Sanders[2]

[1] BMW Group Research and Technology, 80992 Munich, Germany.
[2] Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany.

Abstract. Every human likes choices. But today's fast route planning algorithms usually compute just a single route between source and target. There are beginnings to compute *alternative routes*, but there is a gap between the intuition of humans what makes a good alternative and mathematical definitions needed for grasping these concepts algorithmically. In this paper we make several steps towards closing this gap: Based on the concept of an *alternative graph* that can compactly encode many alternatives, we define and motivate several attributes quantifying the quality of the alternative graph. We show that it is already NP-hard to optimize a simple objective function combining two of these attributes and therefore turn to heuristics. The combination of the refined penalty based iterative shortest path routine and the previously proposed Plateau heuristics yields best results. A user study confirms these results.

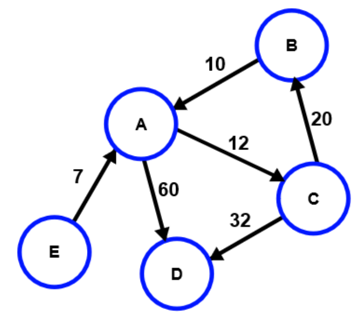
ALTERNATIVE GRAPHS IN STREET NETWORKS

PRELIMINARIES

After depicting the measures prosaically, Bader et al. turn to the **formal definitions**

$G = (V, E)$ — **graph** with edge weight function $w: E \to \mathbb{R}_+$
s, t — **source** node and **target** node

$H = (V', E')$ — **alternative graph** with $V' \subseteq V$ such that for every edge $e \in E'$ there exists a simple s-t-path in H containing e



For every edge (u, v) in E' there must be a path from u to v in G and the edge weights $w(u, v)$ must be equal to the path's weight

$d_G(u, v)$ — shortest path distance from u to v in G
$d_H(u, v)$ — shortest path distance from u to v in H

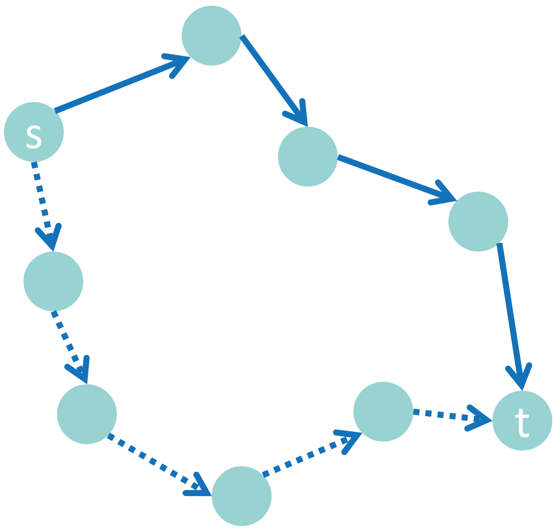
https://de.wikipedia.org/wiki/Graph_(Graphentheorie)#/media/File:CPT-Graphs-directed-weighted-ex1.svg

ALTERNATIVE GRAPHS IN STREET NETWORKS

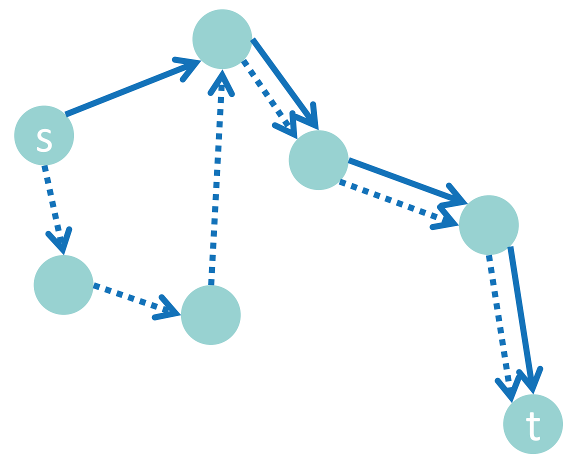
TOTAL DISTANCE

Total Distance

- Describing the extent to which the routes defined by the AG are **non-overlapping**
- Maximum value when the AG consists of disjoint paths only



$td = 9$



$td = 7$

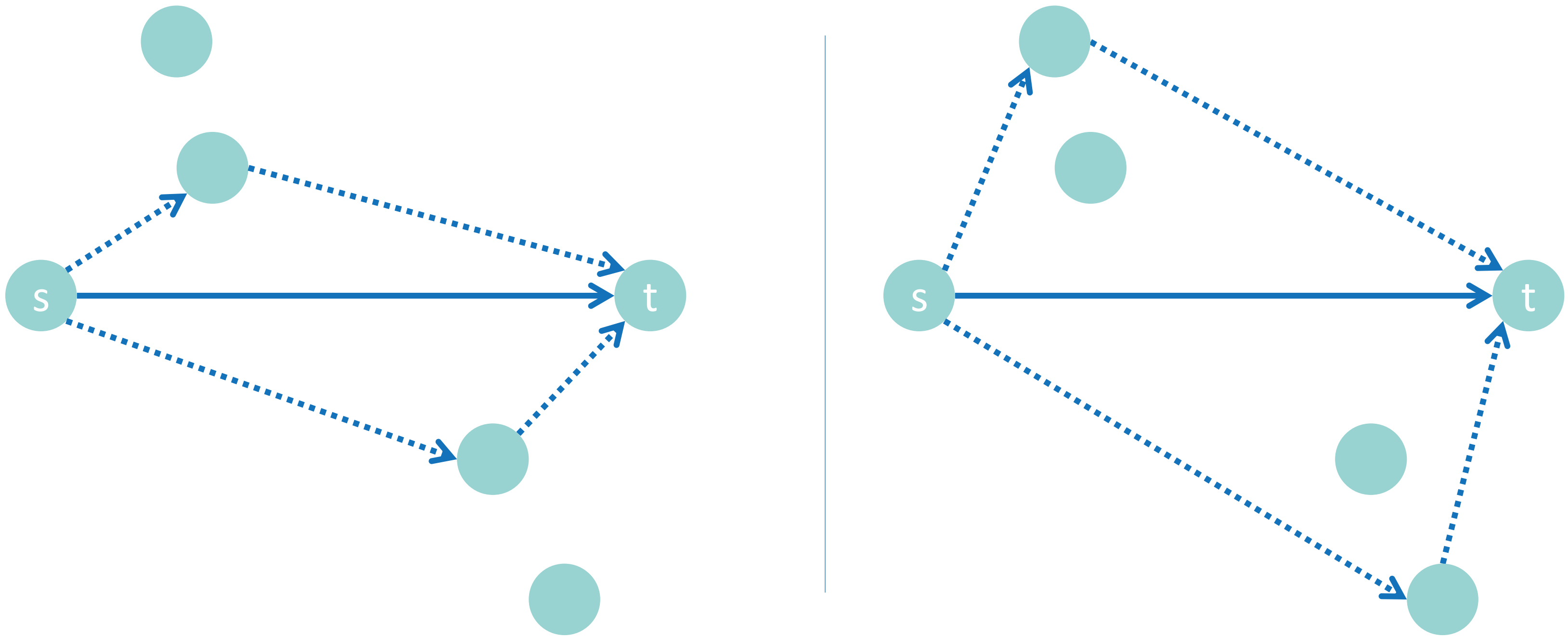
$$\sum_{e=(u,v)\in E'} \frac{w(e)}{d_H(s,u) + w(e) + d_H(v,t)}$$

ALTERNATIVE GRAPHS IN STREET NETWORKS

AVERAGE DISTANCE

Average Distance

- Describing the quality as the **average stretch** of an alternative path



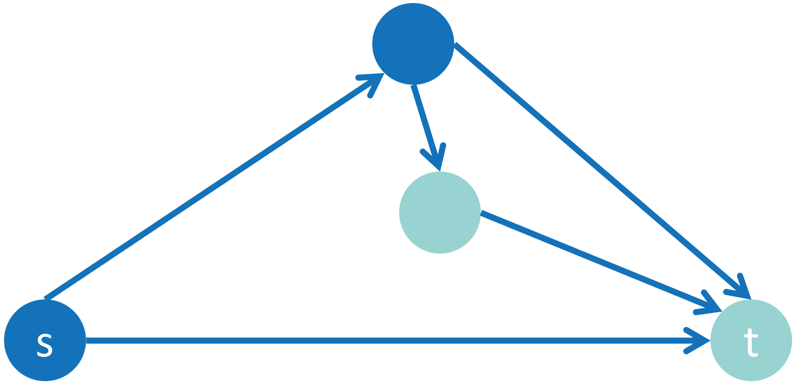
$$\frac{\sum_{e \in E'} w(e)}{d_G(s,t) \cdot totalDistance}$$

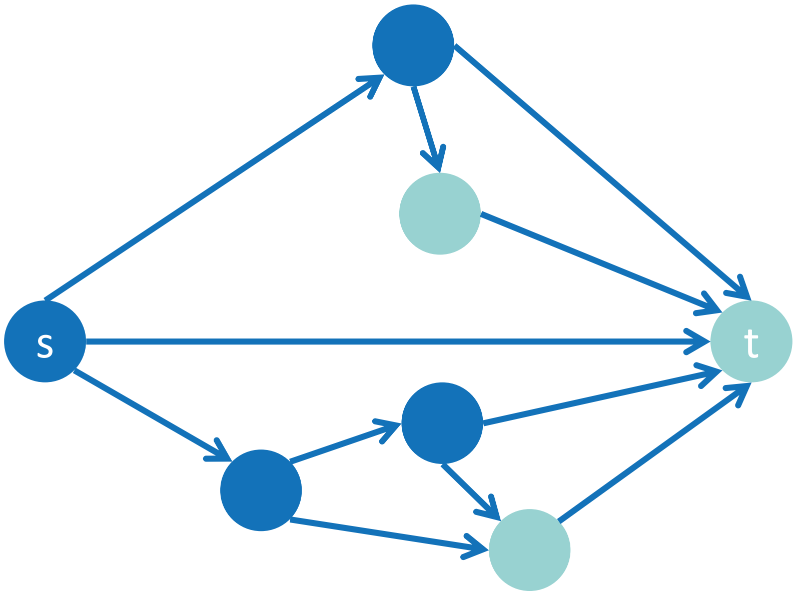
ALTERNATIVE GRAPHS IN STREET NETWORKS

DECISION EDGES

Decision Edges

- Describing the **complexity** of the AG
- Used to retain the representation easily understandable for human users





$$\sum_{v \in V' \setminus \{t\}} outdegree(v) - 1$$

AR/AG IN STREET NETWORKS

SUMMARY

Abraham et al. state that a proper **alternative route** should

- be substantially different from a reference path (“limited sharing”)
- not have unnecessary detours (“local optimality”)
- not be much longer than the shortest path (“uniformly bounded stretch”)

Bader et al. proposed that a good **alternative graph** should have

- low overlap of the included routes (high “total distance”)
- low stretch of included alternatives (low “average distance”)
- low complexity (few “decision edges”)

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AR/AG IN CONSTRAINED FREE SPACES

EXAMPLES

Personalized and **context-based** navigation
- Remaining time, gender, preferences, …
- Shops “line of sight” to choose by themselves

Regulation of **person flows**
- Avoid crowded areas (also for mobile robots)
- Proactive avoidance of bottlenecks

Rescue squads
- Avoid blocked areas
- Prepared route card

Game-based AI
- Tactical maneuvering of bots

http://munich-airport.com/de/micro/infogate/30_produkte/20_counter/30_bsp/index.jsp

QUALITY METRICS IN CONSTRAINED FREE SPACE

MOTIVATION

Quality measures of alternatives

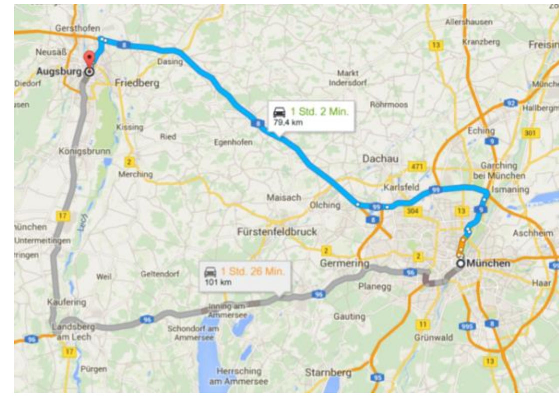
- Somehow subjective or philosophical
- Used to create alternative graph

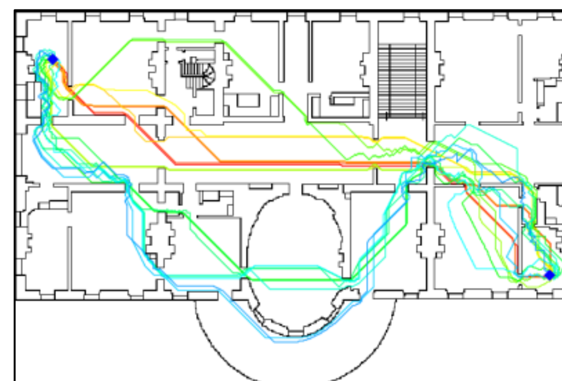
“Outdoor” vs. “Indoor”

- Works fine in street networks, seems solved
- Outdoor measures not readily applicable in indoor scenarios

(Feld et al., 2016)

- Discuss reasons why measures cannot be directly transferred
- 1st thought: **Transfer** map representation from indoor to outdoor
- 2nd thought: **Redefine** measures





http://lbs2016.lbsconference.org/wp-content/uploads/2016/11/1_4.pdf
http://ieeexplore.ieee.org/abstract/document/7275488/

QUALITY METRICS IN CONSTRAINED FREE SPACE

OVERVIEW

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Bader et al. proposed that a good **alternative graph** should have

- low overlap of the included routes (high “total distance”)
- low stretch of included alternatives (low “average distance”)
- low complexity (few “decision edges”)

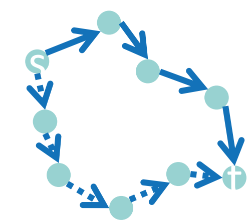
We **discuss the transferability** of the measures from road networks to constrained free space scenarios

1. “limited sharing” and “total distance” both limit the amount of edges that alternatives have in common
2. “uniformly bounded stretch” and “average distance” both rely on the idea that alternatives should not be excessive in length
3. “local optimality” means even subpaths should be short
4. “decision edges” refers to some kind of complexity

QUALITY METRICS IN CONSTRAINED FREE SPACE

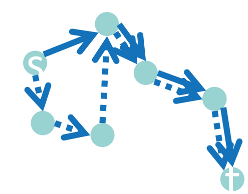
LIMITED SHARING & TOTAL DISTANCE

Limit the length of edges that alternatives have in common



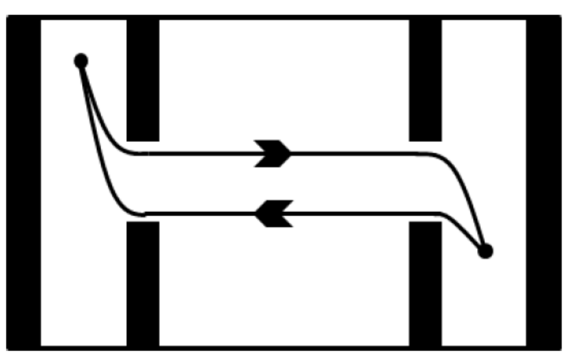
Most important question: How to define **overlap** or **sharing** in an unambiguous way

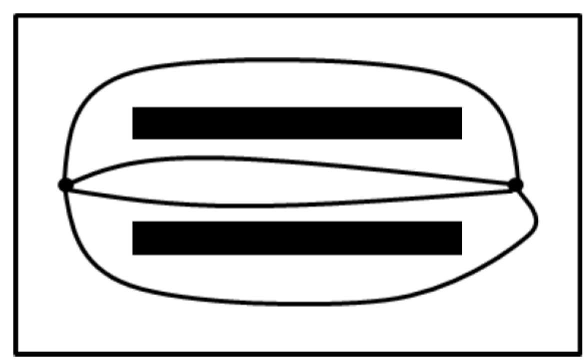
Even decisions in **implementation** design may have impact (“left-handed Dijkstra”)



High ambiguity of equivalent routes having equivalent meanings

- Continental scale, no interaction, e.g. airplane navigation
- Pedestrians seeing and talking to each other





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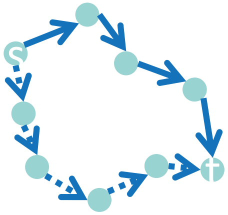
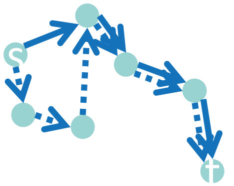
QUALITY METRICS IN CONSTRAINED FREE SPACE

LIMITED SHARING & TOTAL DISTANCE



General strategies

- Decide which points actually “overlap” in an **application-dependent** and **map-dependent** way
- Three possible general strategies



Strategy 1: **Map representation**

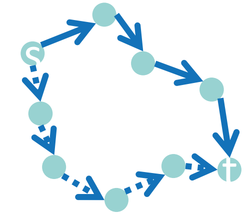
- Definition of **original measures** for paths in graphs
- Consistently map all free space paths to a graph such that **different edges** mean semantically **different movements**
- Problem: **Tradeoff** between map complexity and expressiveness, see existing map representations
- Also: Number of edges and quality of overlap depends on **complexity of involved geometry**

QUALITY METRICS IN CONSTRAINED FREE SPACE

LIMITED SHARING & TOTAL DISTANCE

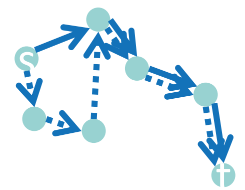
Strategy 2: **Connected space**

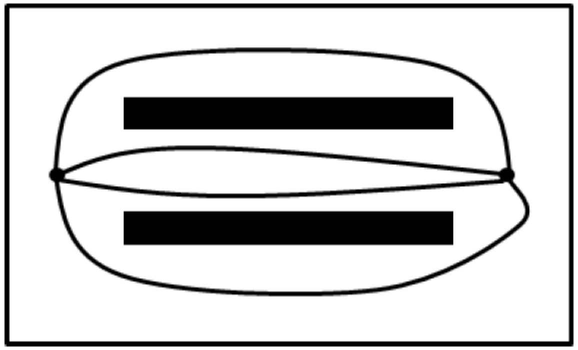
- Define overlap from the **space** that two routes have in common
- Some kind of **map topology**
- **Homotopy**? Has some drawbacks…



Strategy 3: **Distance**

- Replace **binary and counting** nature of overlap by **continuous framework** in which distances of routes are used
- **Threshold** for overlap





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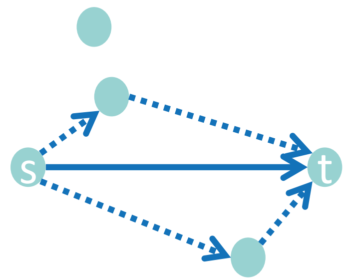
QUALITY METRICS IN CONSTRAINED FREE SPACE

UNIFORMLY BOUNDED STRETCH & AVERAGE DISTANCE

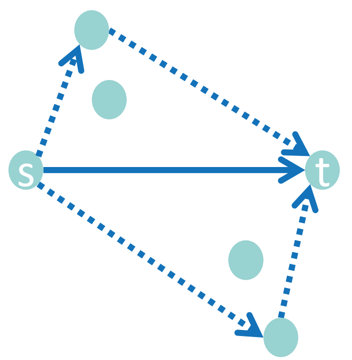
Bounding the stretch

- Stretch that is **too small** prevents some alternatives
- Ideal amount of stretch is **application-dependent** (airport vs. manufacturing)



Route's length

- Length in map representation can be **highly different** than in reality
- For example: Navigation mesh with central points vs. corner graphs

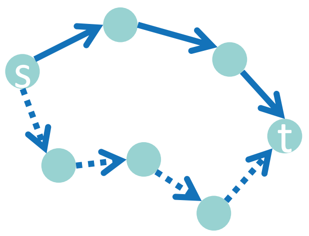


QUALITY METRICS IN CONSTRAINED FREE SPACE

LOCAL OPTIMALITY

Handle it in **post-processing** anyways?

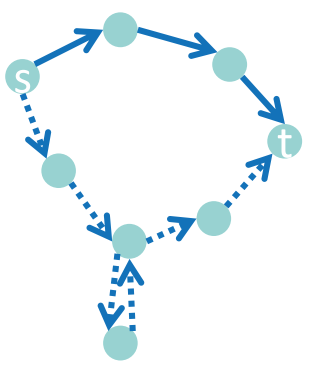
How to treat detours due to inaccuracies in **map-to-graph-translations**?



Do we want the shortest? Or the simplest? (wall scraping etc.)

In a nutshell

- What is an “**optimal**” path and what is a “**locally optimal**” path?
- Perhaps: Considering local optimization as an **application-dependent post-processing** step

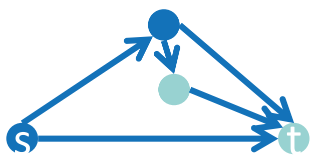


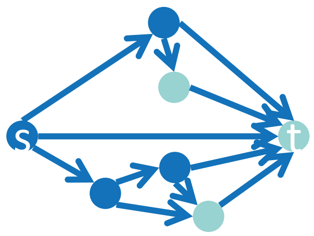
QUALITY METRICS IN CONSTRAINED FREE SPACE

DECISION EDGES

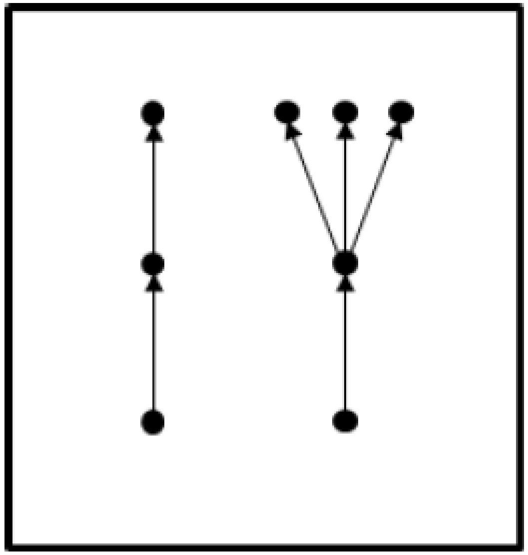
Similarity to overlap

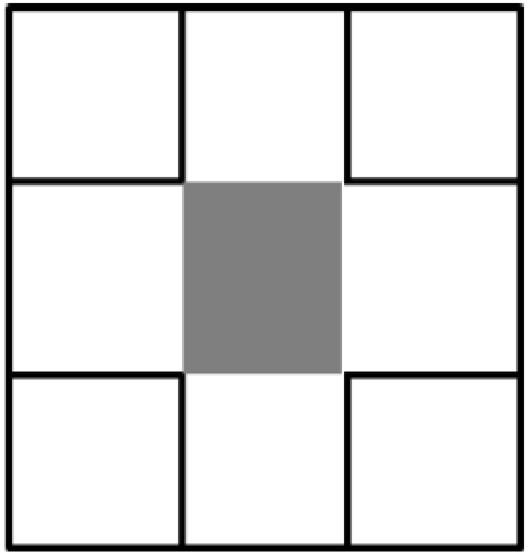
- Use overlap as a definition for decision
- A decision is taken place where overlap changes
- In some sense: we extend overlap from edges to vertices





Integration into **map creation** process?





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QUALITY METRICS IN CONSTRAINED FREE SPACE

INTERACTIVE DISCUSSION

Abraham et al. state that a proper **alternative route** should

- be substantially different from a reference path (“limited sharing”)
- not have unnecessary detours (“local optimality”)
- not be much longer than the shortest path (“uniformly bounded stretch”)

Bader et al. proposed that a good **alternative graph** should have

- low overlap of the included routes (high “total distance”)
- low stretch of included alternatives (low “average distance”)
- low complexity (few “decision edges”)

Interactive Discussion