Evaluation of Graph Drawings as Embeddings for Routing in Distributed Systems

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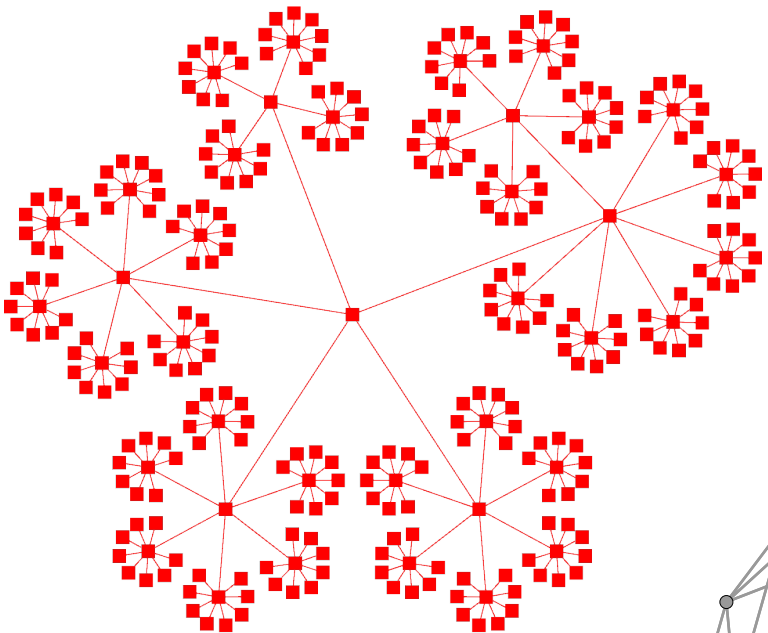

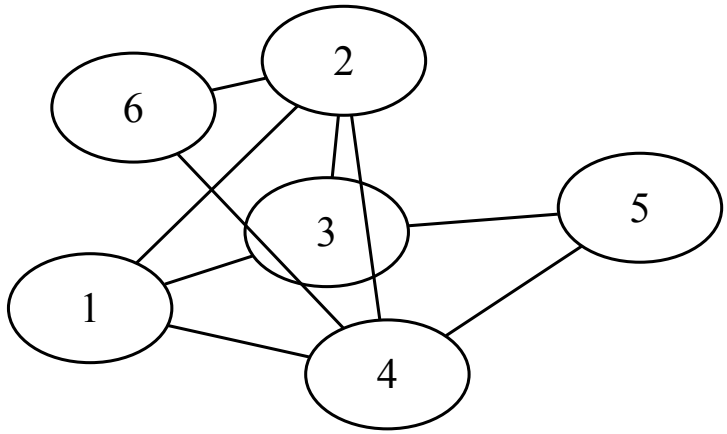

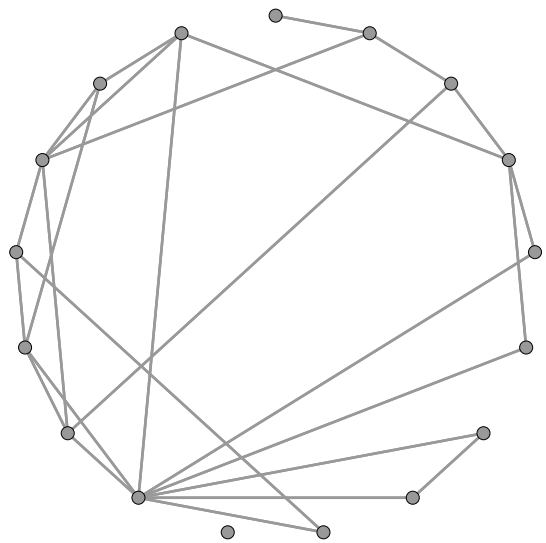

Outline

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- Introduction
- Graph drawing algorithms
  - Circular drawing algorithms
  - Hierarchical drawing algorithms
  - Force-driven drawing algorithms
- Routing algorithms
- Evaluation
  - Graph types
  - Root vertex choice
  - Routing in Barabási-Albert graphs
  - Runtimes and routing success
- Conclusion and future work

Outline

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Routing in distributed systems
Introduction

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- Routing in a distributed system requires an identifier space

Routing in distributed systems
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TECHNISCHE UNIVERSITÄT DARMSTADT

- Routing in a distributed system requires an identifier space
  - Assignment of coordinates to each node in the system

Routing in distributed systems
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- Routing is done with local knowledge only

Routing in distributed systems
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  - Coordinates of sender and destination node are known

Routing in distributed systems
Introduction

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- Routing in a distributed system requires an identifier space
  - Assignment of coordinates to each node in the system
- Routing is done with local knowledge only
  - Coordinates of sender and destination node are known
  - Each node knows its neighbors coordinates

Routing in distributed systems
Existing algorithms: CAN

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- **C**ontent-**A**ddressable **N**etwork

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TECHNISCHE UNIVERSITÄT DARMSTADT

- **C**ontent-**A**ddressable **N**etwork
- Each node is responsible for a partition of data, accessible through hashes
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- Greedy routing is enabled by design and always successful

Routing in distributed systems
Existing algorithms: CAN

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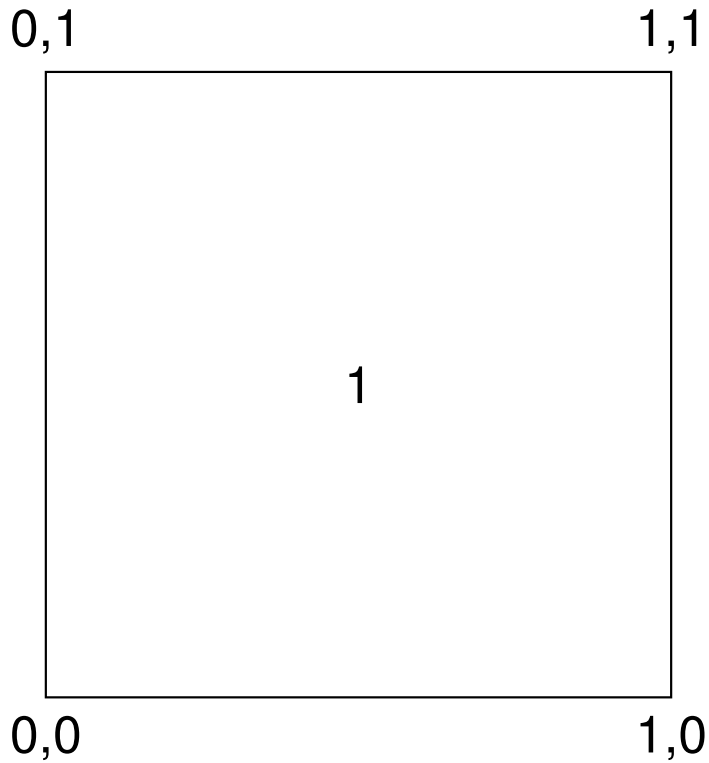

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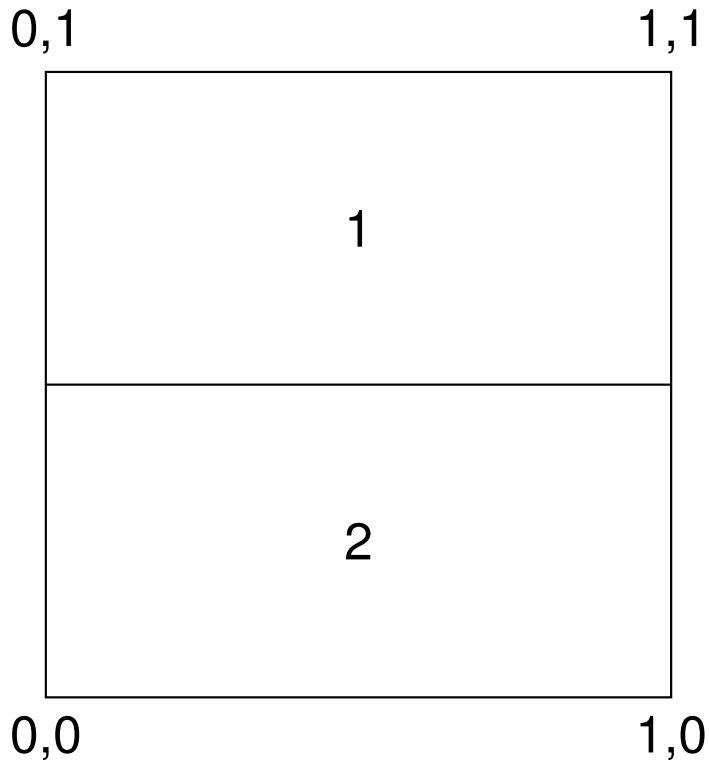

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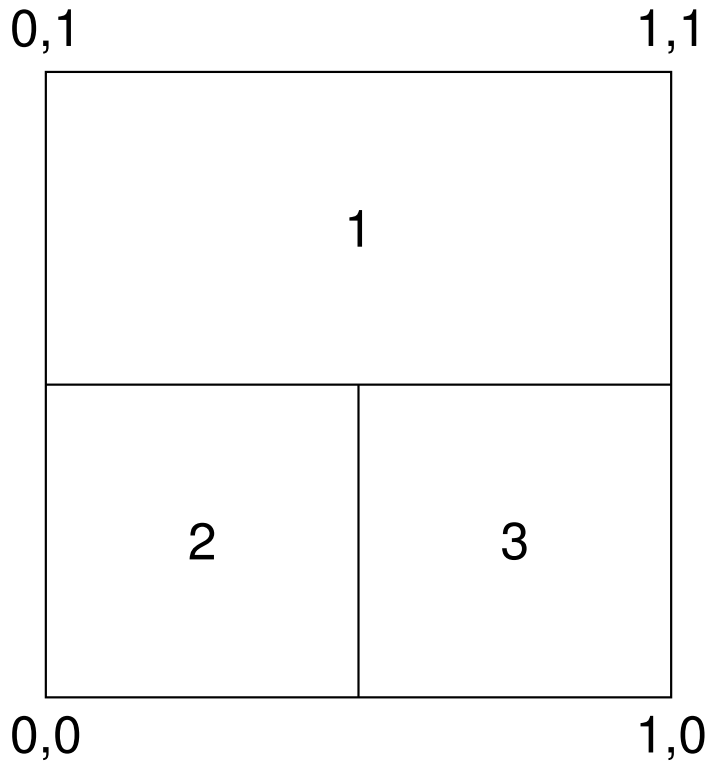

Scenario: routing in distributed systems
Preconditions for our work

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- A network is given, with all vertices and edges

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- A network is given, with all vertices and edges
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- Routing should be made possible

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TECHNISCHE UNIVERSITÄT DARMSTADT

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- No vertices or edges must be left out or added

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- Routing should be made possible
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  - Contrast to DHTs: assume the graph structure to be strictly fixed

Scenario: routing in distributed systems
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```
1:8252;18292;19951;21024;17656
2:8655;12237;12497;14863
3:2370;2483;4111;5781;16632;23896
4:7739;10140;10342;12794;14266
5:4010;5545;13193;17423
6:216;1411;1932;5579;9383;17652;23365;23694;21794;23789
7:8959;14519;15263
8:5274;22783;24542
9:8941
10:3075;5375;6384;11320;22738;23896
11:4882;8823;11770;12225;14109;20649;1235;2237;3142;10330;24037
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Scenario: routing in distributed systems
Our approach

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- Use graph drawing algorithms as an embedding to assign a coordinate space

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Our approach

TECHNISCHE UNIVERSITÄT DARMSTADT

- Use graph drawing algorithms as an embedding to assign a coordinate space
- Distributed greedy routing algorithms can be used now
  - No need to construct large routing tables
  - Each vertex only knows its neighbors and their coordinates

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

Graph drawing algorithms
Classification

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- Fixed-vertex drawing algorithms

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- Hierarchical drawing algorithms

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  - Tree-like layout

Graph drawing algorithms
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  - Either vertically arranged (root vertex at the top)...

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  - Simulate a physical model

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  - Result: two-dimensional identifier space
- Force-driven drawing algorithms
  - Simulate a physical model
  - Result: n-dimensional identifier space

Outline

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Algorithm by Six and Tollis

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- Return a circular arrangement of vertices

Algorithm by Six and Tollis

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- Minimize the number of edge crossings

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- Minimize the number of edge crossings
- Resolving edge crossings in a brute-force manner is very inefficient
- Split up the work into two phases
  - First phase: use a complex algorithm to get a layout with (relatively) little crossings
    - Place as much edges as possible on the circumference
  - Second phase: swap neighbors to further reduce crossings

Algorithm by Six and Tollis
Example drawings

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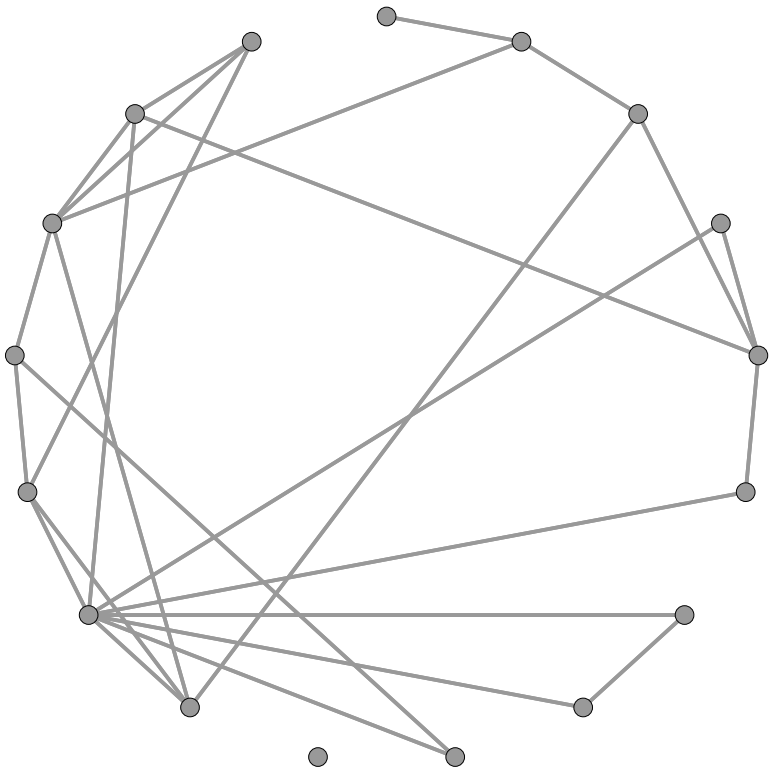
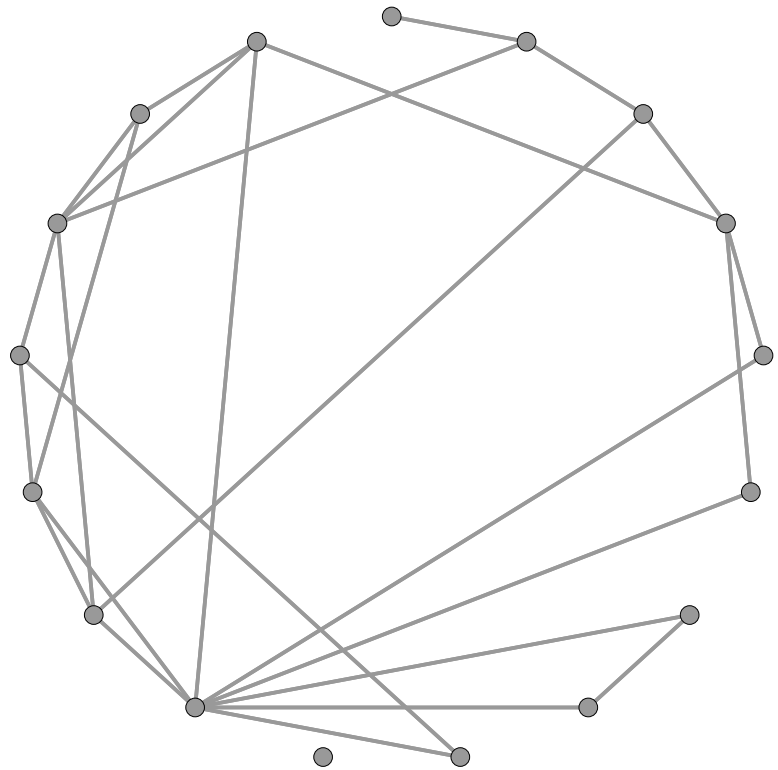


After first phase



Final layout

Algorithm by Six and Tollis
Summary

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- Algorithm returns aesthetically pleasing results on low-degree graphs

Algorithm by Six and Tollis
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- Algorithm returns aesthetically pleasing results on low-degree graphs
- Very sophisticated and complex algorithm

Algorithm by Six and Tollis
Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

- Algorithm returns aesthetically pleasing results on low-degree graphs
- Very sophisticated and complex algorithm
- But: as the average degree and the number of vertices grows, the algorithm gets horribly slow

Outline

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Algorithm by Wetherell and Shannon

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- Return a tree-like arrangement of vertices with a root vertex at the top

Algorithm by Wetherell and Shannon

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return a tree-like arrangement of vertices with a root vertex at the top
- Initially: choose any vertex as the root

Algorithm by Wetherell and Shannon

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return a tree-like arrangement of vertices with a root vertex at the top
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- Transform the graph to a spanning tree

Algorithm by Wetherell and Shannon

TECHNISCHE UNIVERSITÄT DARMSTADT

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- Algorithm traverses the spanning tree twice

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  - First time for relative positioning of each vertex to its parent vertex in the tree

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  - Second time for absolute positioning

Algorithm by Wetherell and Shannon
Example drawing

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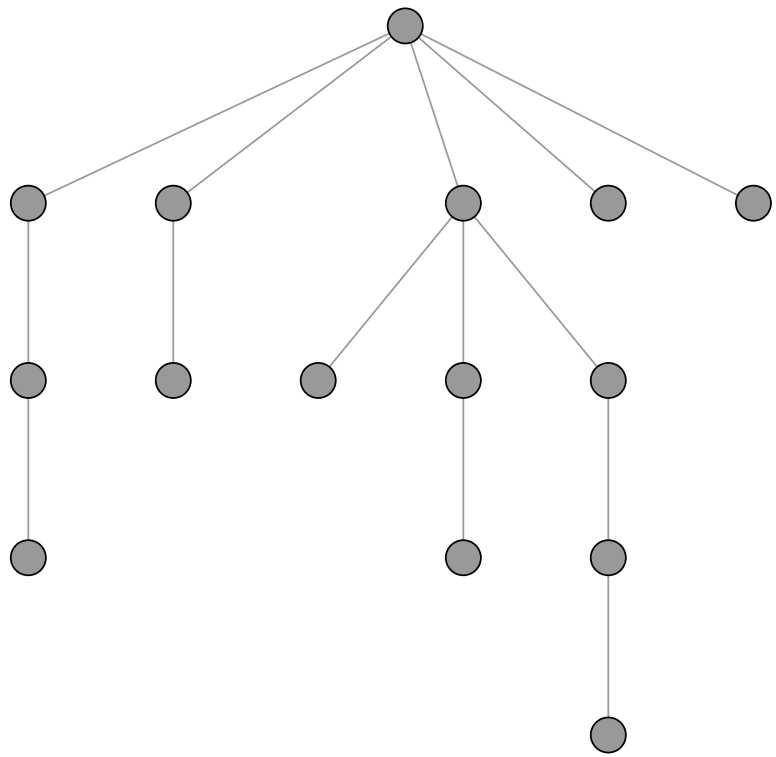

Algorithm by Melançon and Herman

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- Return a hierarchical arrangement of vertices with a root vertex at the center

Algorithm by Melançon and Herman

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return a hierarchical arrangement of vertices with a root vertex at the center
- Initially: create a spanning tree

Algorithm by Melançon and Herman

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return a hierarchical arrangement of vertices with a root vertex at the center
- Initially: create a spanning tree
- Child vertices are arranged on a circle around their common parent vertex

Algorithm by Melançon and Herman

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return a hierarchical arrangement of vertices with a root vertex at the center
- Initially: create a spanning tree
- Child vertices are arranged on a circle around their common parent vertex
- Radii are decreased exponentially to avoid overlapping

Algorithm by Melançon and Herman
Example drawing

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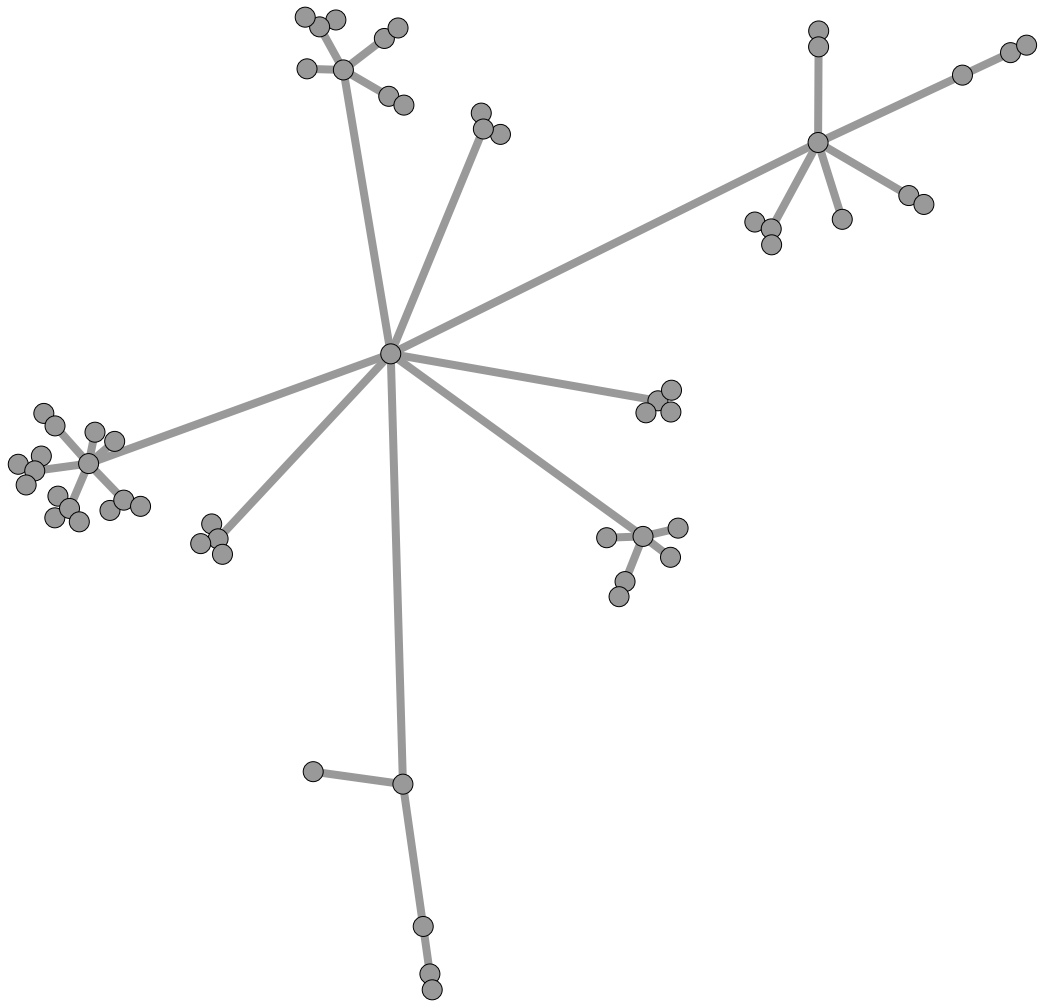

Algorithm by Melançon and Herman
Example drawing - spanning tree

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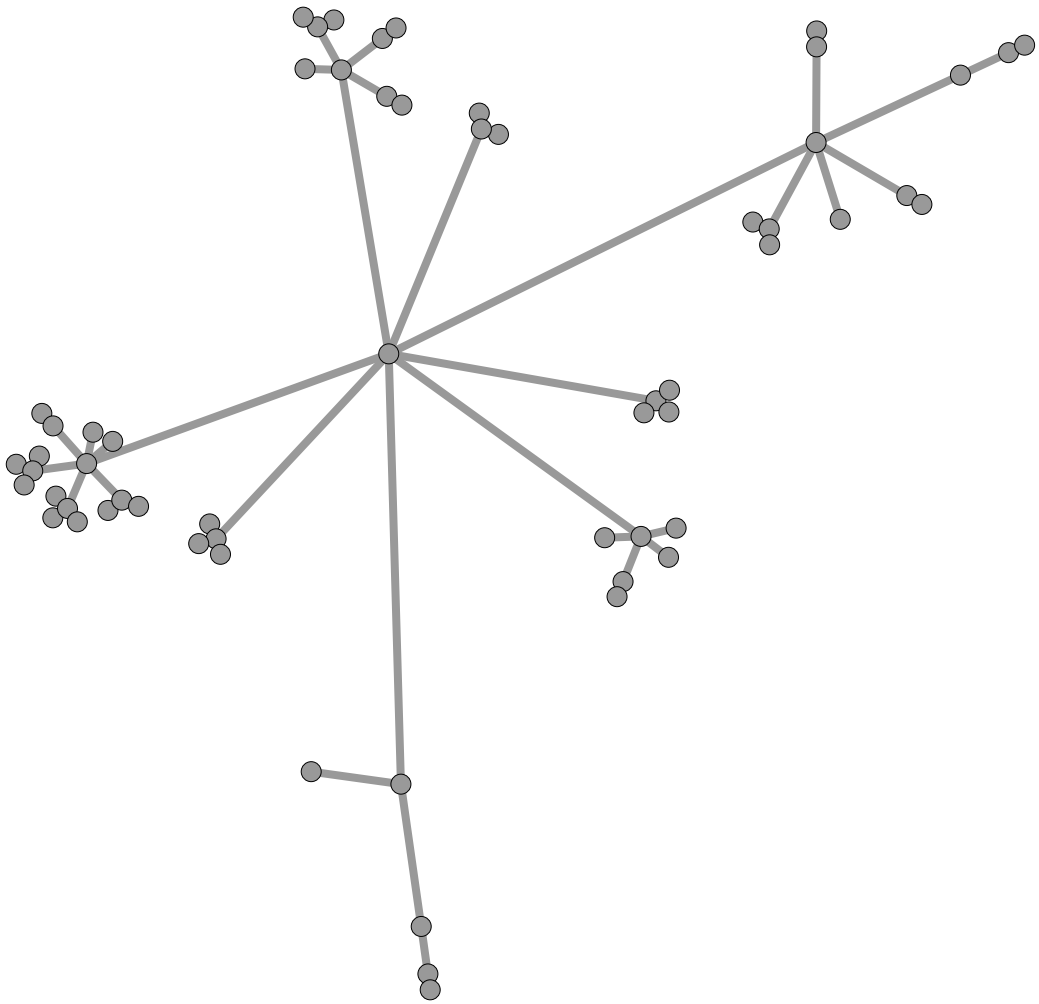

Algorithm by Melançon and Herman
Example drawing - complete graph

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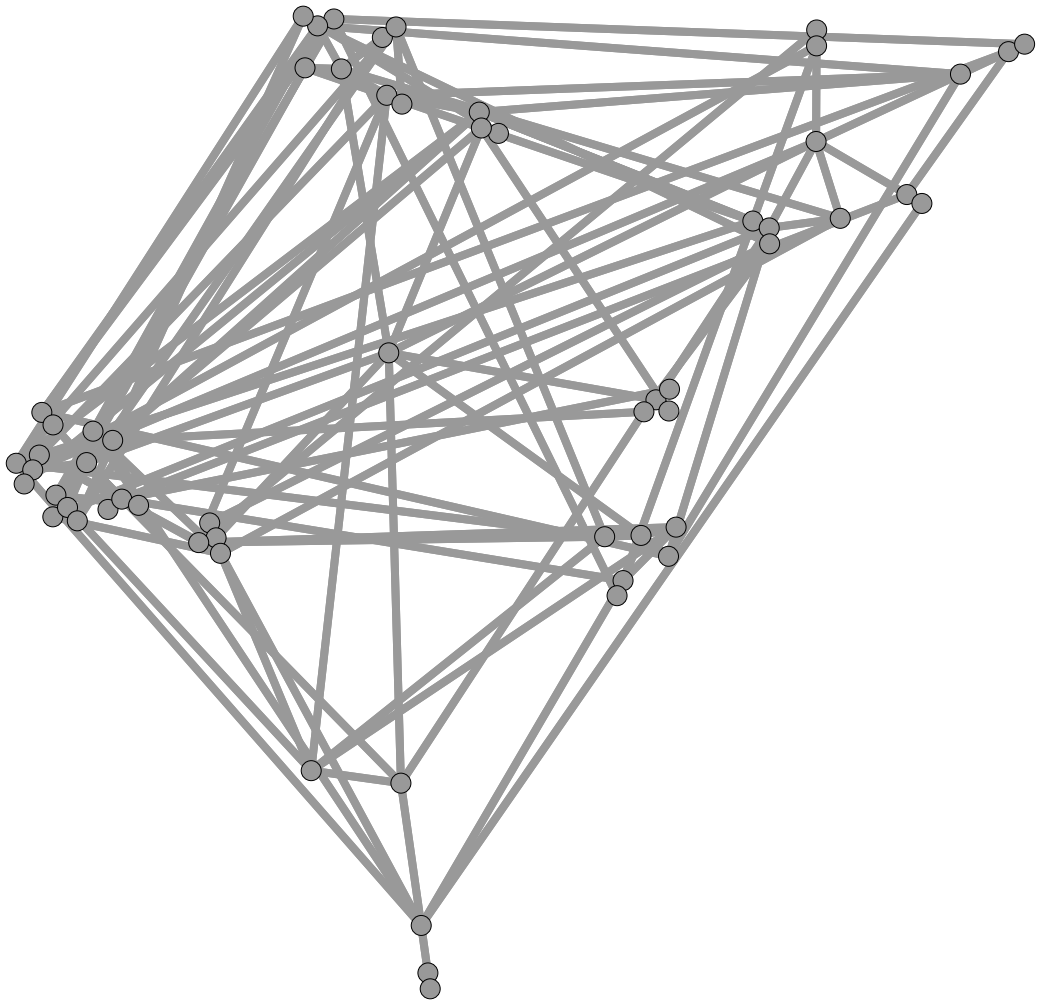

Hierarchical drawing algorithms
Summary

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- Huge advantage of these algorithms: fast results

Hierarchical drawing algorithms
Summary

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- Huge advantage of these algorithms: fast results
- Drawings cannot visualize the structure of cyclic graphs

Outline

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Force-driven drawing algorithm by Fruchterman and Reingold

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return an arrangement of evenly distributed vertices

Force-driven drawing algorithm by Fruchterman and Reingold

TECHNISCHE UNIVERSITÄT DARMSTADT

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Force-driven drawing algorithm by Fruchterman and Reingold

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return an arrangement of evenly distributed vertices
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- Represent vertices by steel rings and edges by springs

Force-driven drawing algorithm by Fruchterman and Reingold

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return an arrangement of evenly distributed vertices
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- Take any random initial position for the vertices

Force-driven drawing algorithm by Fruchterman and Reingold

TECHNISCHE UNIVERSITÄT DARMSTADT

- Return an arrangement of evenly distributed vertices
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- Represent vertices by steel rings and edges by springs
- Take any random initial position for the vertices
- Release the rings and let them swing into an optimal state

Force-driven drawing algorithm by Fruchterman and Reingold

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Force-driven drawing algorithm by Fruchterman and Reingold

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Force-driven drawing algorithm by Fruchterman and Reingold

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  - Adjacent vertices should appeal each other
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- Iterative algorithm
  - May take ten or thousand iterations until a “stable” position is reached

Force-driven drawing algorithm by Fruchterman and Reingold
Example drawing: initial positioning

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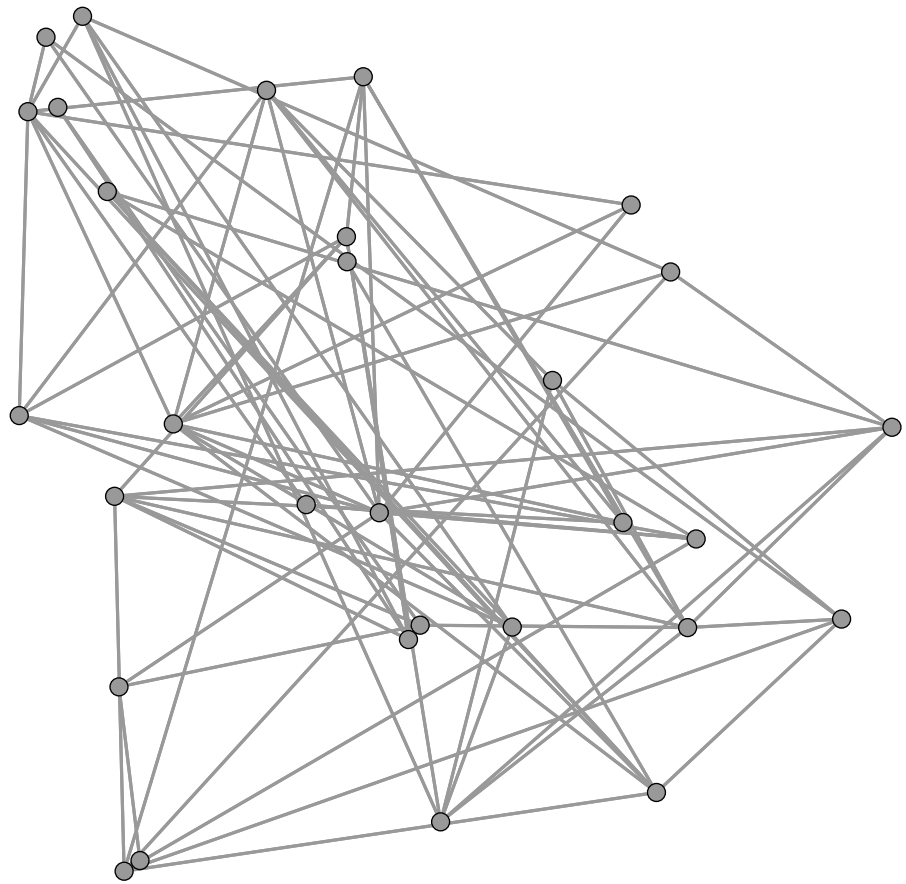

Force-driven drawing algorithm by Fruchterman and Reingold
Example drawing: after 50 iterations

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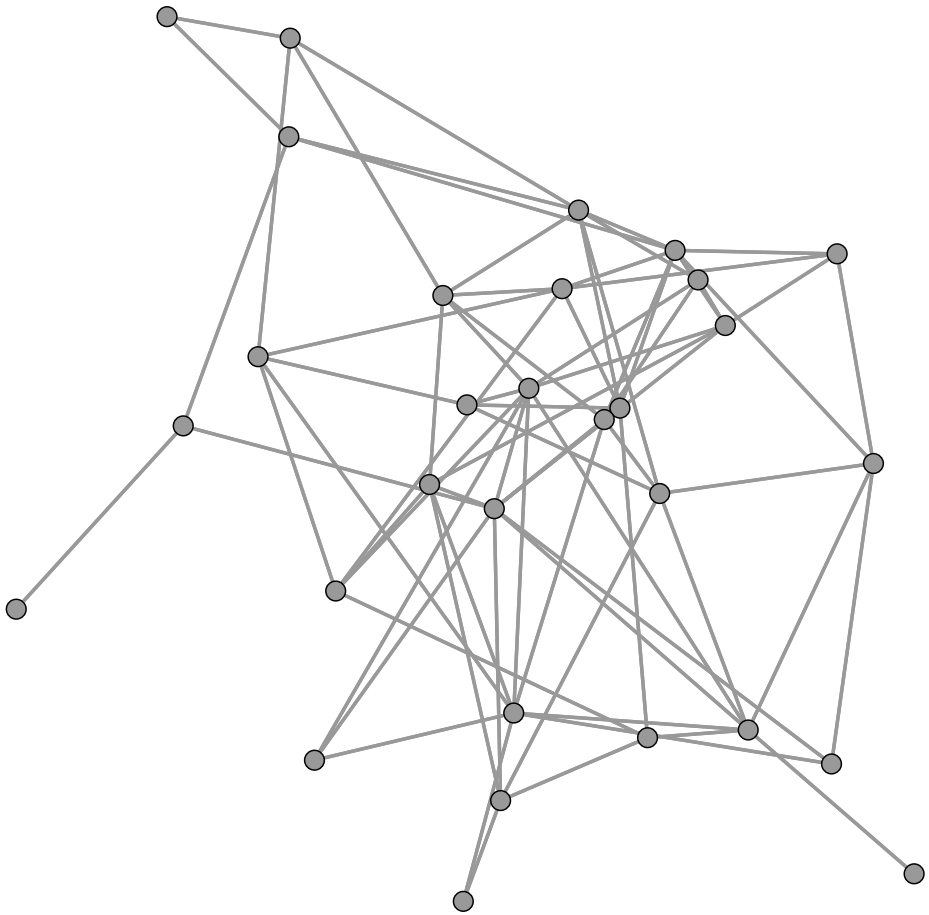

Force-driven drawing algorithm by Fruchterman and Reingold
Example drawing: after 150 iterations

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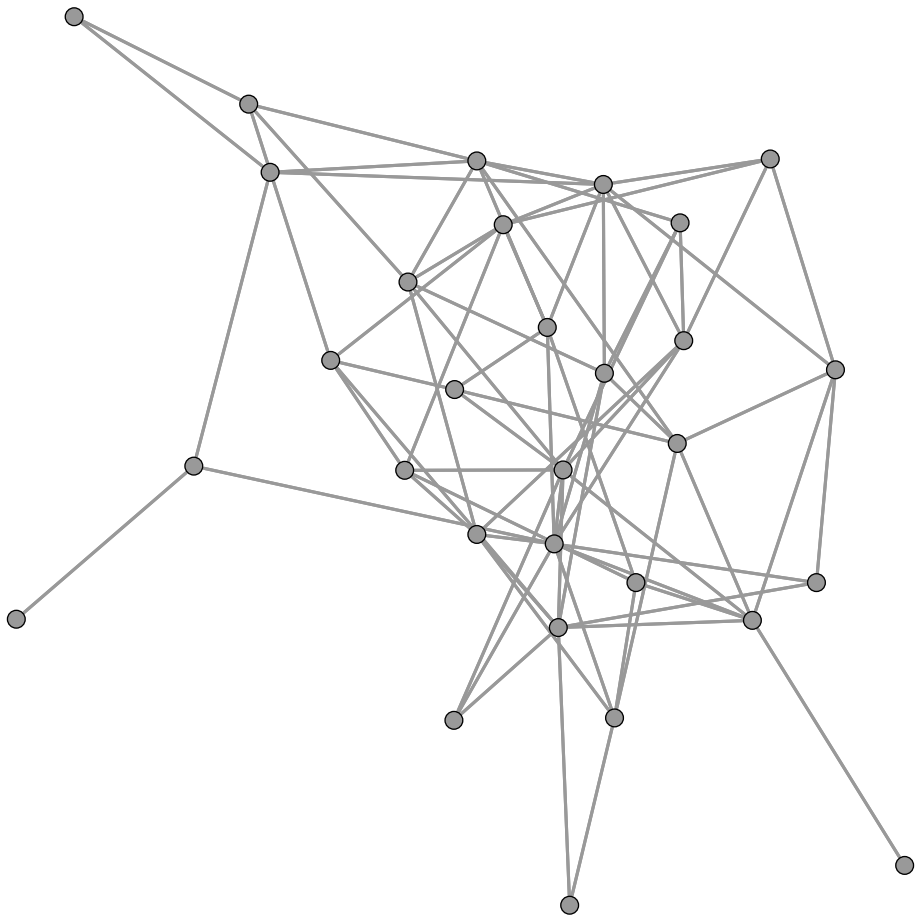

Force-driven drawing algorithm by Fruchterman and Reingold
Summary

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- Versatile algorithm for all kinds of graphs

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Summary

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- Versatile algorithm for all kinds of graphs
- Problem: missing termination check
  - Stable state reached after ten or a hundred iterations?
- Common runtime for each iteration step roughly $\Theta(|V| + |E|^2)$

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

Greedy routing

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- In each routing step:

Greedy routing

TECHNISCHE UNIVERSITÄT DARMSTADT

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  - Calculate the distances from each neighbor vertex of the current vertex to the destination

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  - Much longer routes (average $<$ 40 hops, maximum up to ttl)

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Lookahead routing

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- Characteristics in the usage
  - Relatively slow computation ($<$ 40ms per route)
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  - Medium average success rate (up to 10% in random graphs, up to 60% in real-world scale-free networks)

Outline

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Graph types used for the evaluation

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  - The OpenPGP Web of Trust, another social network

Graph types used for the evaluation
Degree distribution

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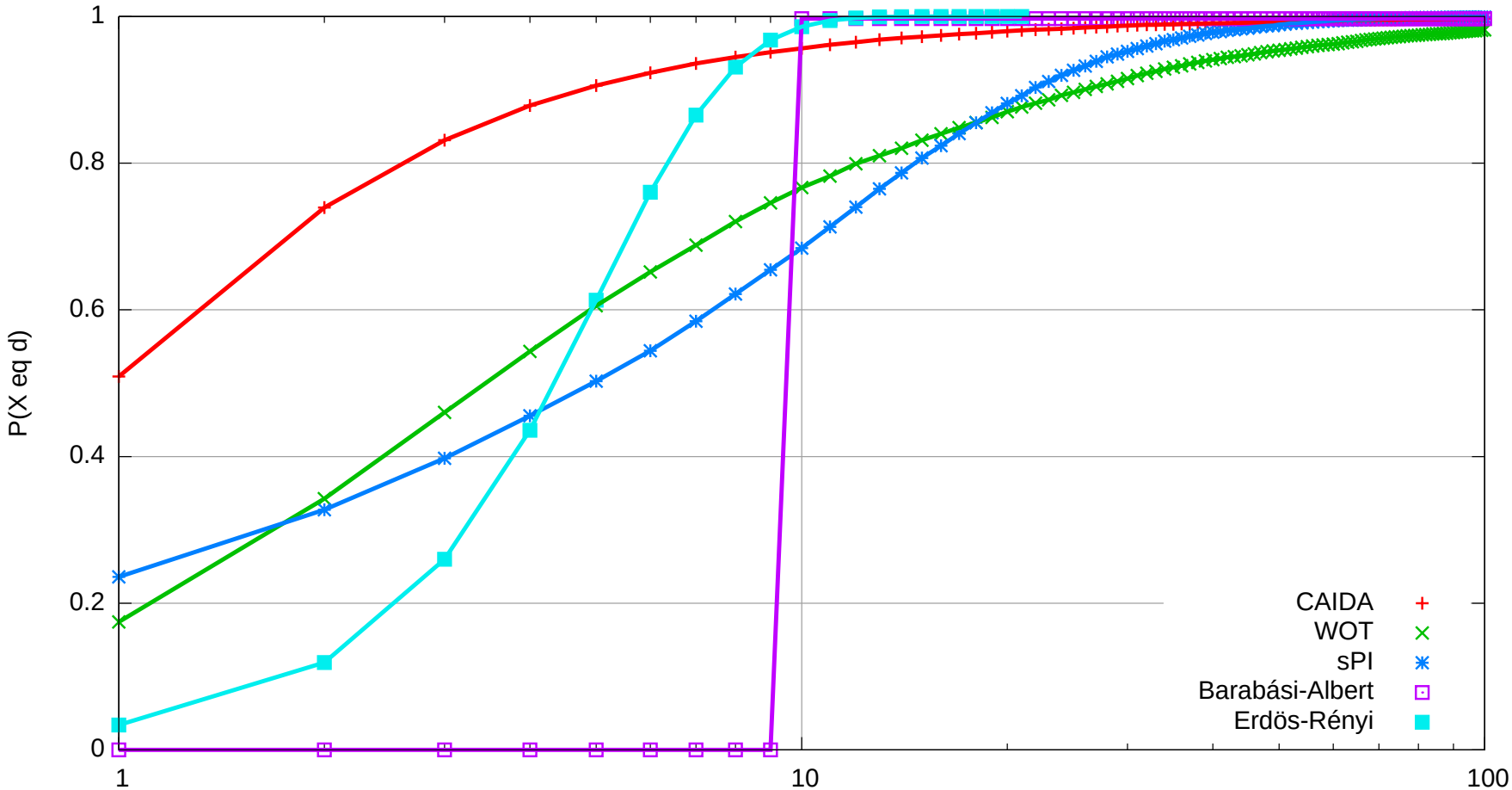

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

Influence of the root vertex choice in hierarchical drawing algorithms

TECHNISCHE UNIVERSITÄT DARMSTADT

- Hierarchical drawing algorithms work on a spanning tree

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  - Random vertex?

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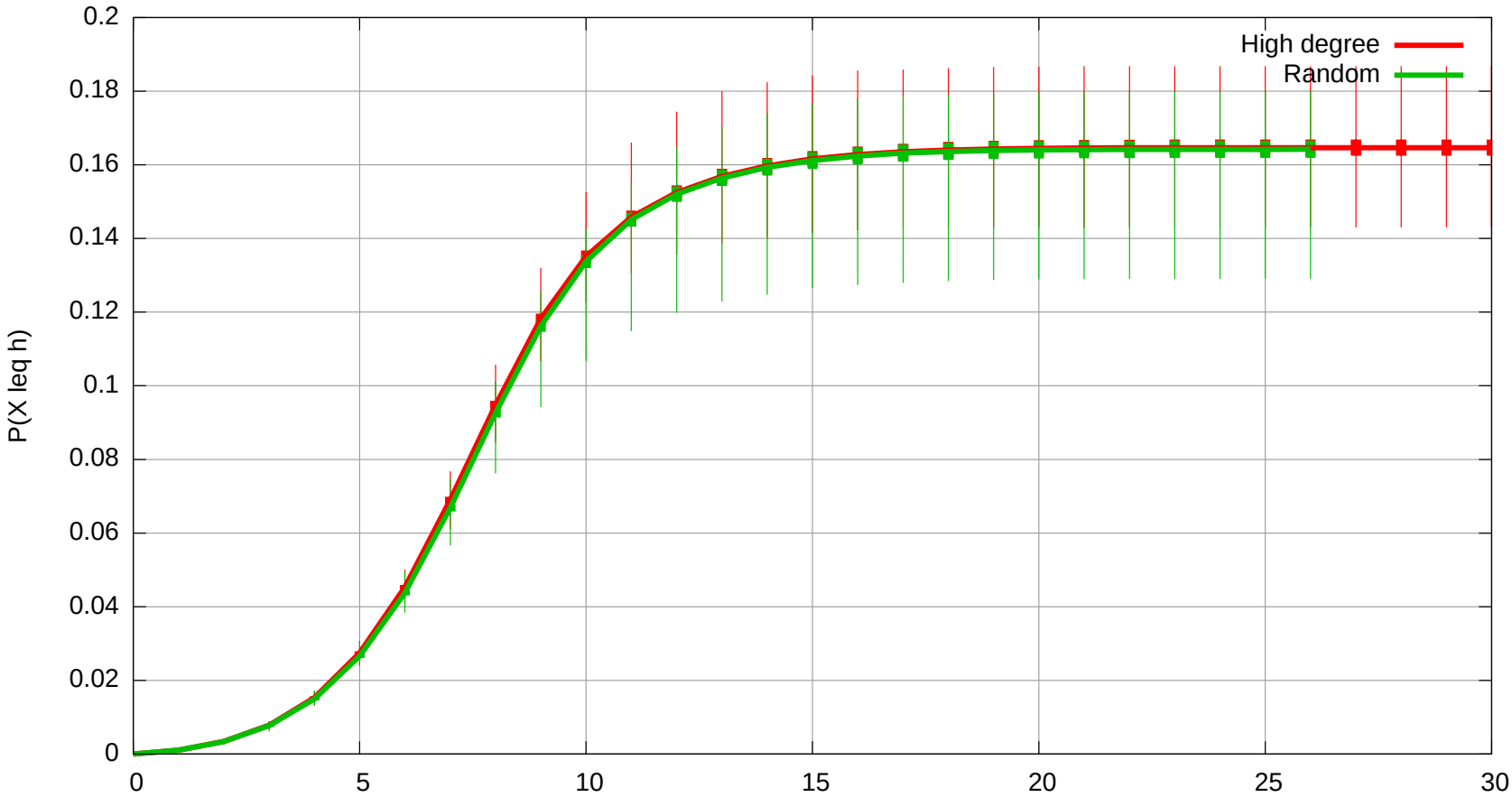

Erdös-Rényi graph with 5,000 vertices, embedded using Melançon/Herman

Influence of the root vertex choice in hierarchical drawing algorithms

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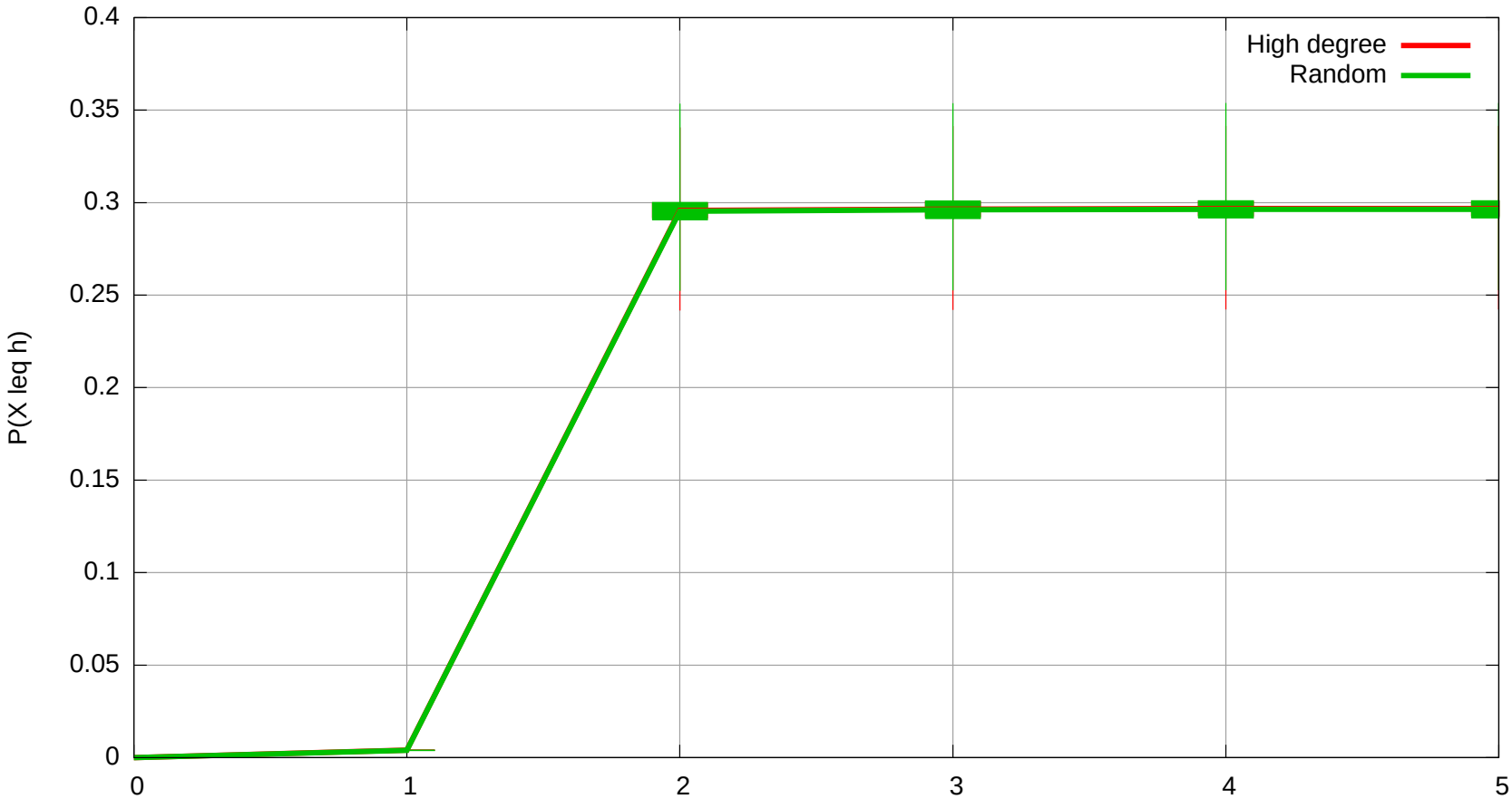

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- Root vertex choice does not influence the routing results

Outline

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Routing in Barabási-Albert graphs

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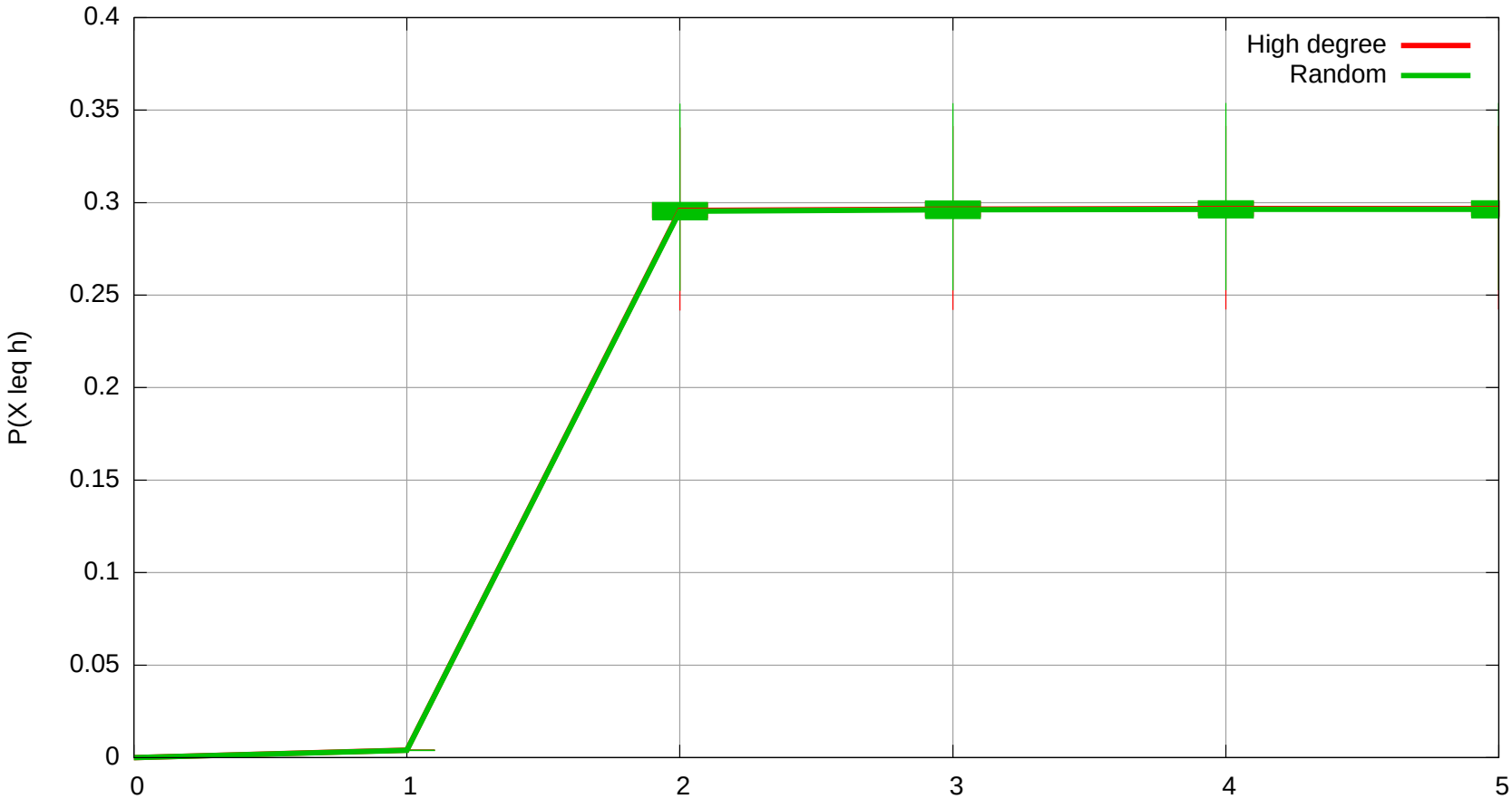

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DARMSTADT

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TECHNISCHE UNIVERSITÄT DARMSTADT

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TECHNISCHE UNIVERSITÄT DARMSTADT

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Routing in Barabási-Albert graphs

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- Little number of routes succeed after one hop
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- Little number of routes takes more than two hops

- Hypothesis: Routing on Barabási-Albert graphs either succeeds after two hops or fails

Routing in Barabási-Albert graphs

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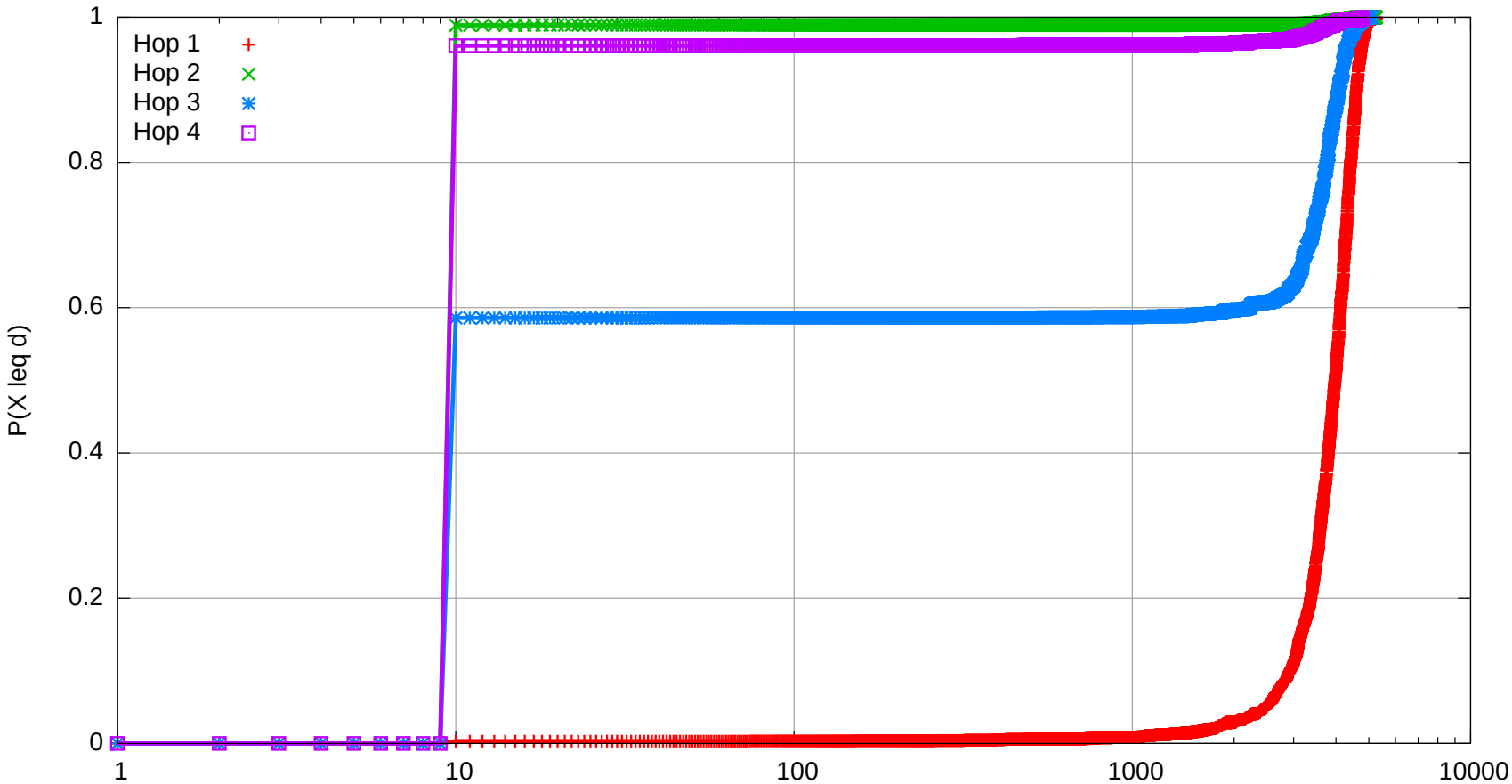

Hop degree distribution in greedy routing on Barabási-Albert graphs

Routing in Barabási-Albert graphs

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- First hop: any high degree vertex

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Routing in Barabási-Albert graphs

TECHNISCHE UNIVERSITÄT DARMSTADT

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  - High probability that destination is reached
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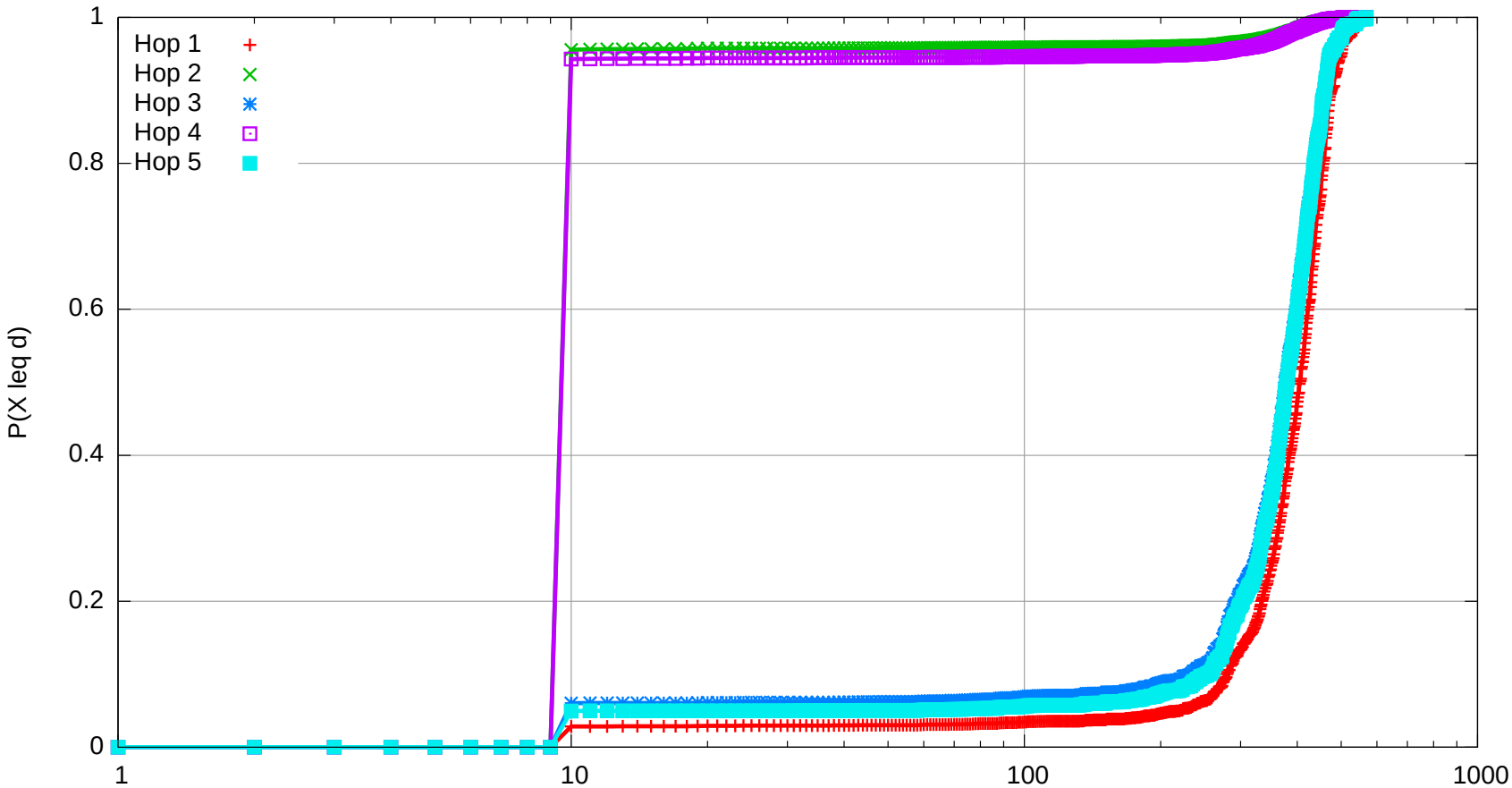

Hop degree distribution in greedy routing with backtracking

Routing in Barabási-Albert graphs
Summary

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Routing in Barabási-Albert graphs
Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

- Routing on Barabási-Albert graphs either succeeds after two hops or fails
- Choosing “wrong” first hop cannot be recovered!

Routing in Barabási-Albert graphs

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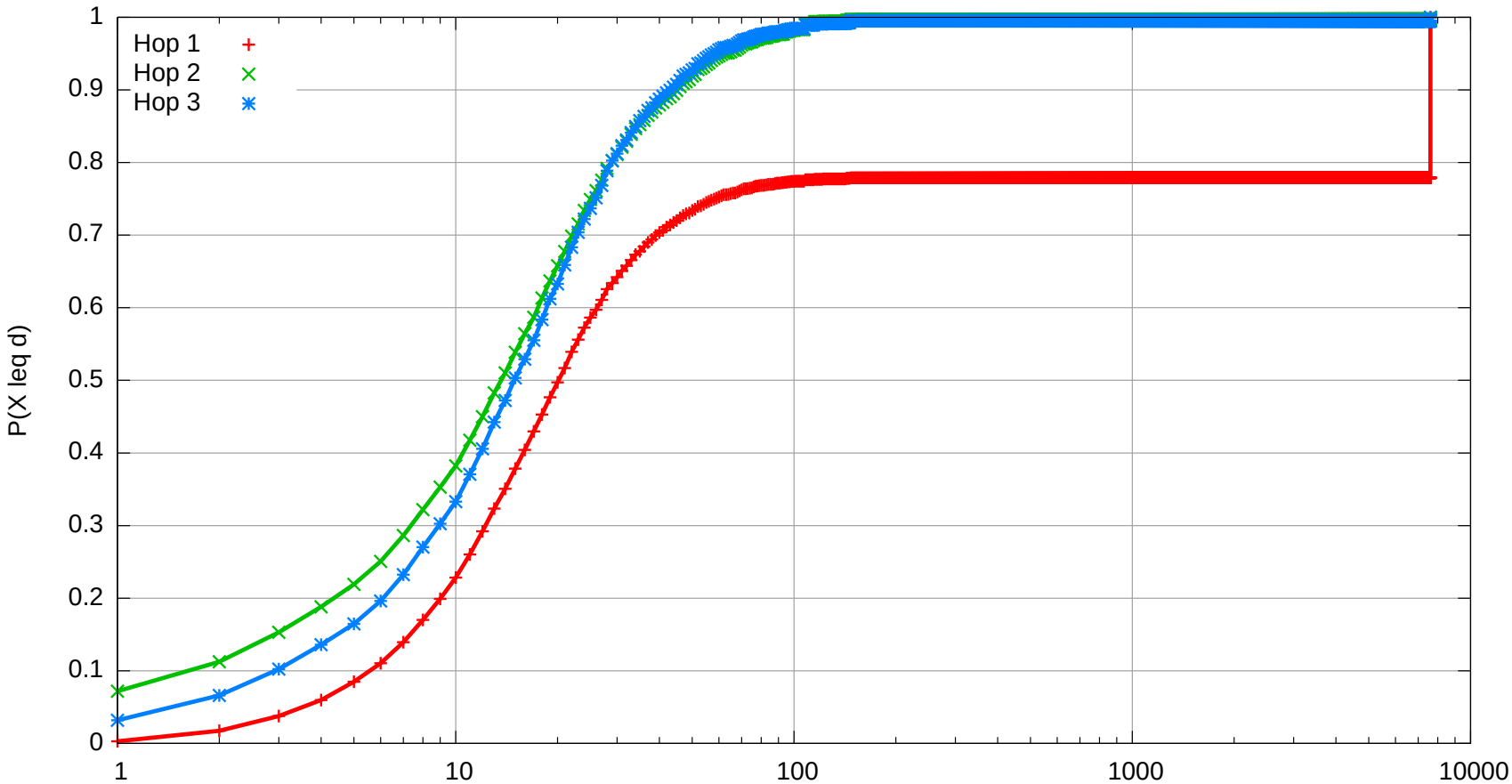

Hop degree distribution in greedy routing on the sPI network

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

Runtimes of the evaluated graph drawing algorithms

TECHNISCHE UNIVERSITÄT DARMSTADT

- Six/Tollis

Runtimes of the evaluated graph drawing algorithms

TECHNISCHE UNIVERSITÄT DARMSTADT

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  - 5sec on an Erdös-Rényi graph with 1,000 vertices and 5,000 edges

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  - 277.5min on a Barabási-Albert graph with 5,000 vertices and 100,000 edges

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TECHNISCHE UNIVERSITÄT DARMSTADT

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  - 5sec on an Erdös-Rényi graph with 1,000 vertices and 5,000 edges
  - 277.5min on a Barabási-Albert graph with 5,000 vertices and 100,000 edges
  - $>$ 50h on a scale-free graph with 25,000 vertices and 300,000 edges, extracted from the *Web of trust*
- Wetherell/Shannon and Melançon/Herman
  - $<$ 4msec on an Erdös-Rényi graph with given size
  - $<$ 4msec on an Barabási-Albert with given size
  - $<$ 25msec on the scale-free graph extracted from the *Web of trust*

Runtimes of the evaluated graph drawing algorithms

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  - 36sec on an Erdös-Rényi graph with given size

Runtimes of the evaluated graph drawing algorithms

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  - $<$ 25msec on the scale-free graph extracted from the *Web of trust*
- Fruchterman/Reingold
  - 36sec on an Erdös-Rényi graph with given size
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Runtimes of the evaluated graph drawing algorithms

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  - $<$ 25msec on the scale-free graph extracted from the *Web of trust*
- Fruchterman/Reingold
  - 36sec on an Erdös-Rényi graph with given size
  - 17min on an Barabási-Albert graph with given size
  - $>$ 13h on the scale-free graph extracted from the *Web of trust*

Routing success of the evaluated graph drawing algorithms

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TECHNISCHE UNIVERSITÄT DARMSTADT

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  - Up to 16% routing success using greedy routing

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  - More than 50% routing success using greedy routing with backtracking (ttl 100 hops)

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  - WS: less than 2% using greedy routing, MH: up to 13%

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  - Less than 0.4% (sic!) using greedy routing

Routing success of the evaluated graph drawing algorithms

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  - WS: less than 8% using lookahead routing, MH: about 65%
- Fruchterman/Reingold
  - Less than 0.4% (sic!) using greedy routing
  - About 4% using greedy routing with backtracking

Routing success of the evaluated graph drawing algorithms

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  - Less than 0.4% (sic!) using greedy routing
  - About 4% using greedy routing with backtracking
  - Less than 20% using lookahead routing

Routing success of the evaluated graph drawing algorithms

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- Six/Tollis: Long-running algorithm in larger graphs

Routing success of the evaluated graph drawing algorithms

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- Six/Tollis: Long-running algorithm in larger graphs
- Melançon/Herman: Very fast algorithm

Routing success of the evaluated graph drawing algorithms

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- Six/Tollis: Long-running algorithm in larger graphs
- Melançon/Herman: Very fast algorithm
- Routing results comparable

Routing success of the evaluated graph drawing algorithms

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- Six/Tollis: Long-running algorithm in larger graphs
- Melançon/Herman: Very fast algorithm
- Routing results comparable
- No obvious recommendation possible

Outline

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Conclusion

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- Evaluation of graph drawings as embeddings for routing in distributed systems

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- Literature research about graph drawing algorithms and selection

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- Evaluation of graph drawings as embeddings for routing in distributed systems
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- Implementation of graph drawing algorithms
- Simulation and evaluation of routing success

Conclusion

TECHNISCHE UNIVERSITÄT DARMSTADT

- Evaluation of graph drawings as embeddings for routing in distributed systems
- Literature research about graph drawing algorithms and selection
- Implementation of graph drawing algorithms
- Simulation and evaluation of routing success
- Graph drawing algorithms **can** be used as embeddings

Future work

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- Other spanning tree choices for hierarchical drawing algorithms

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- Other spanning tree choices for hierarchical drawing algorithms
- Improved termination conditions for Six/Tollis or Fruchterman/Reingold

Future work

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- Improved termination conditions for Six/Tollis or Fruchterman/Reingold
- High-dimensional embeddings using Fruchterman/Reingold

Future work

TECHNISCHE UNIVERSITÄT DARMSTADT

- Other spanning tree choices for hierarchical drawing algorithms
- Improved termination conditions for Six/Tollis or Fruchterman/Reingold
- High-dimensional embeddings using Fruchterman/Reingold
- Distributed embeddings

Thanks for your attention!