COGA
Combinatorial Optimization & Graph Algorithms

DFG Research Center MATHEON
mathematics for key technologies

Möhring, Rolf

Online Scheduling of Bidirectional Traffic

默里・罗尔夫

We are hiring!

BISEC
BEIJING INSTITUTE FOR
SCIENTIFIC AND ENGINEERING COMPUTING
北京科学与工程计算研究院

UNIVERSITY OF TECHNOLOGY BEIJING
北京工業大學
1960

Some of my applied projects

- Adaptive Traffic Control

  PTV GROUP the mind of movement

  Bundesministerium für Bildung und Forschung

- Routing of AGVs in the Hamburg harbor

  HHLA

  Bundesministerium für Bildung und Forschung

- Constructing periodic timetables in public transport

  PTV GROUP the mind of movement DB BVG S Bahn Berlin DB

- Coordinated traffic light control in networks

  PTV GROUP the mind of movement

  Bundesministerium für Bildung und Forschung

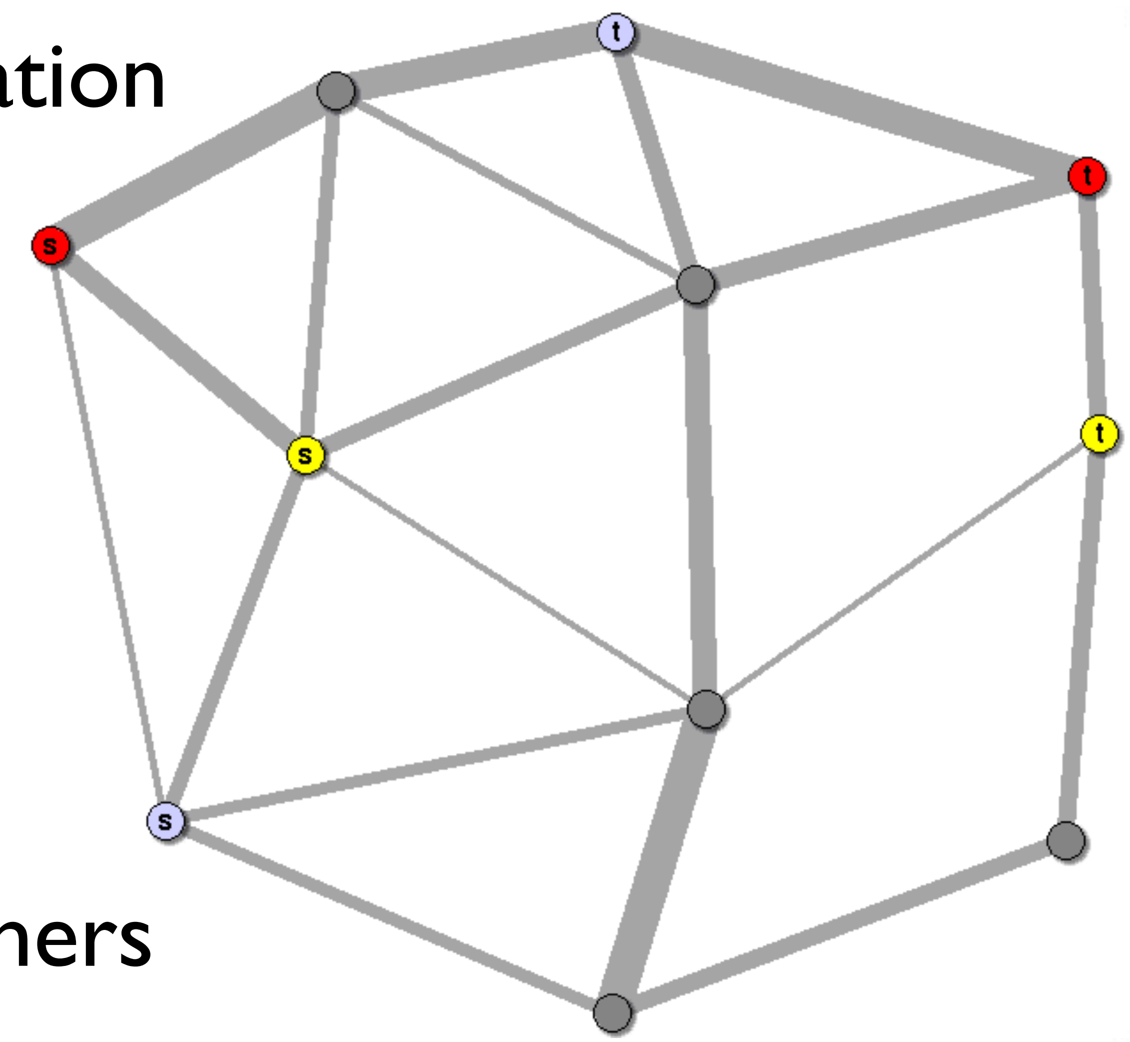
- Ship Traffic Optimization for the Kiel Canal

  WSV.de Wasser- und Schifffahrtsverwaltung des Bundes

Common characteristics

Network flows (in many variations) and scheduling

- techniques from discrete optimization and operations research
  - network and graph algorithms, optimization, heuristics …
  - integer linear programming
- modeling
- implementation skills
- speaking the language of practitioners



Theory ⟺ Applications

Bidirectional Traffic

train networks

road networks

ship traffic

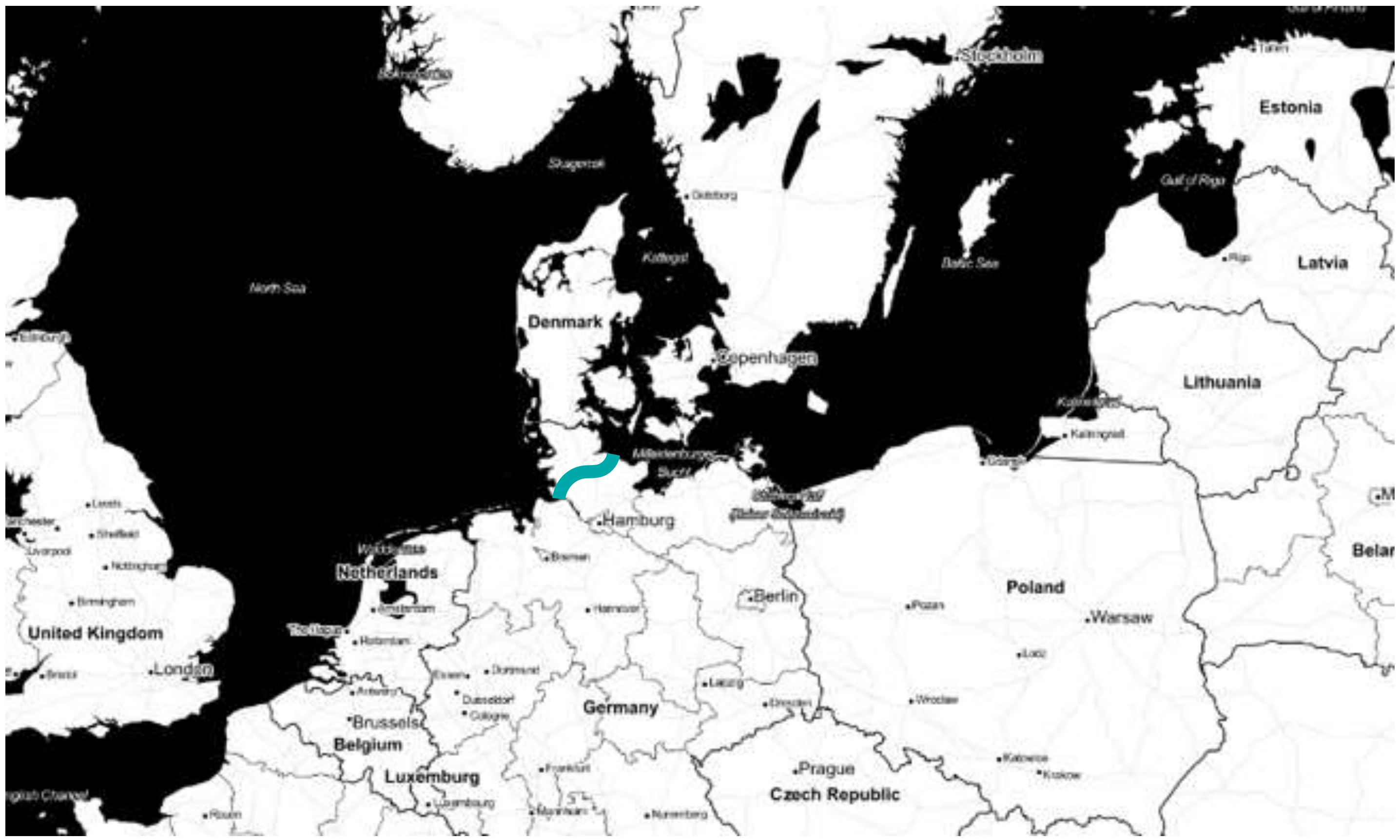
communication networks

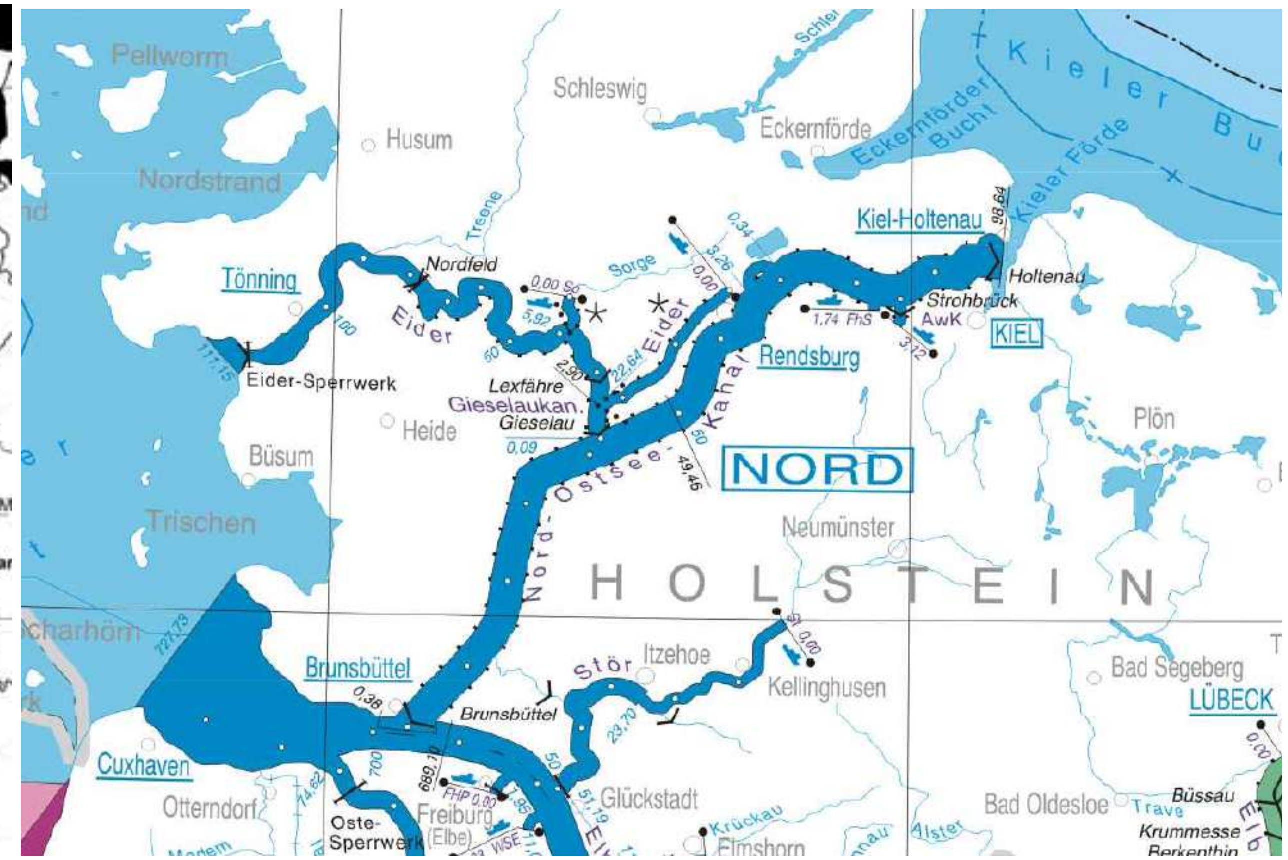
Optimizing the Kiel Canal

Elisabeth Lübbecke
Marco Lübbecke
Rolf Möhring

WSV.de
Wasser- und
Schifffahrtsverwaltung
des Bundes

The Kiel Canal (Nord-Ostsee-Kanal)



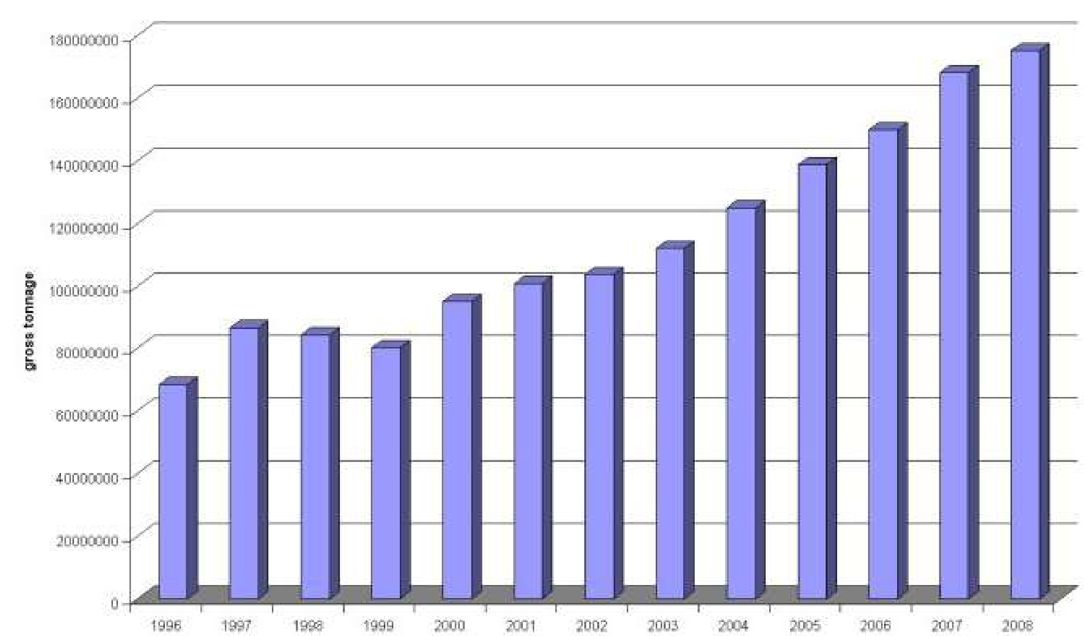


- Connects North Sea and Baltic Sea
- 280 nautical miles saved compared to the way around Skaw
- Canal with highest traffic in the World

Some traffic details

- Passage lasts 8–10 hours
- 40-50 vessels at the same time

- It's too tight in the canal
- traffic guidance is needed

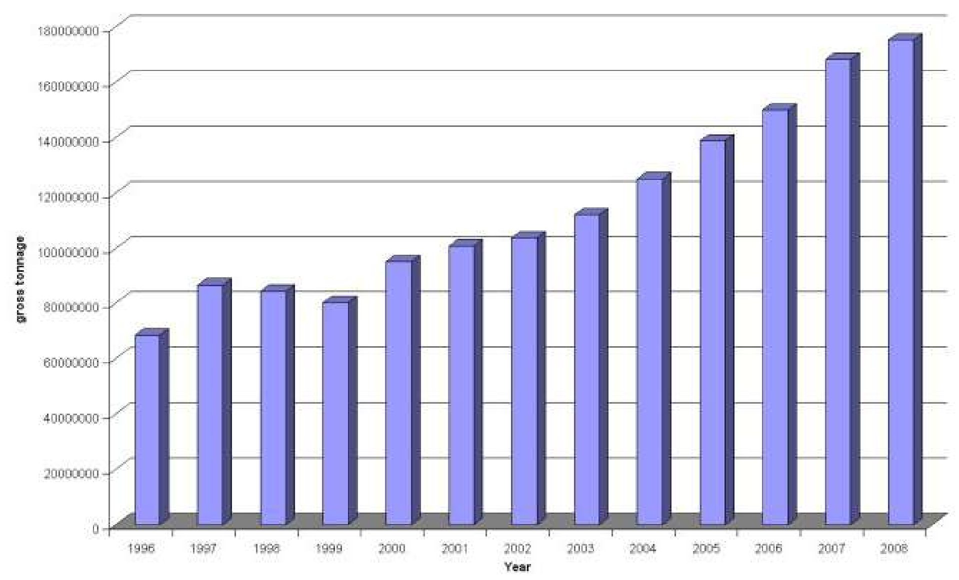


- Increasing gross tonnage
- 1996 – 2008

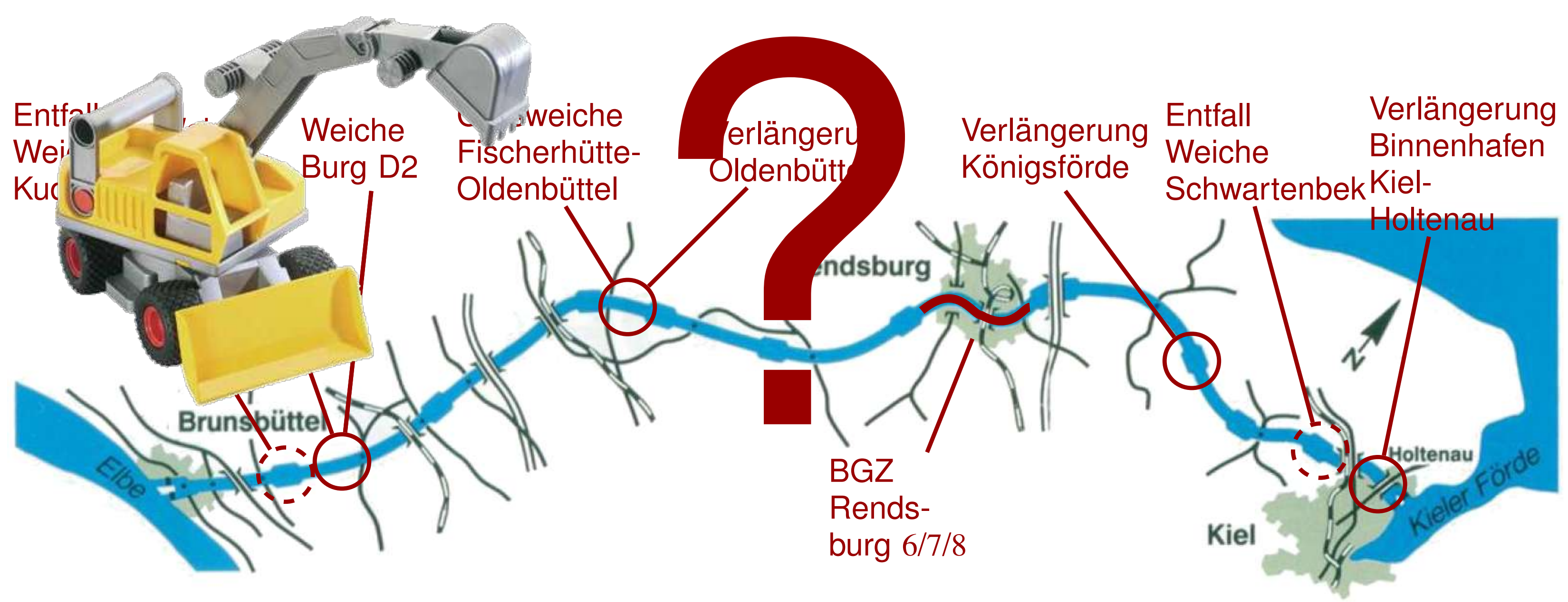
Why optimization?

We are not prepared for future traffic, need better routing

Increasing gross tonnage
1996 – 2008



Canal needs enlargement



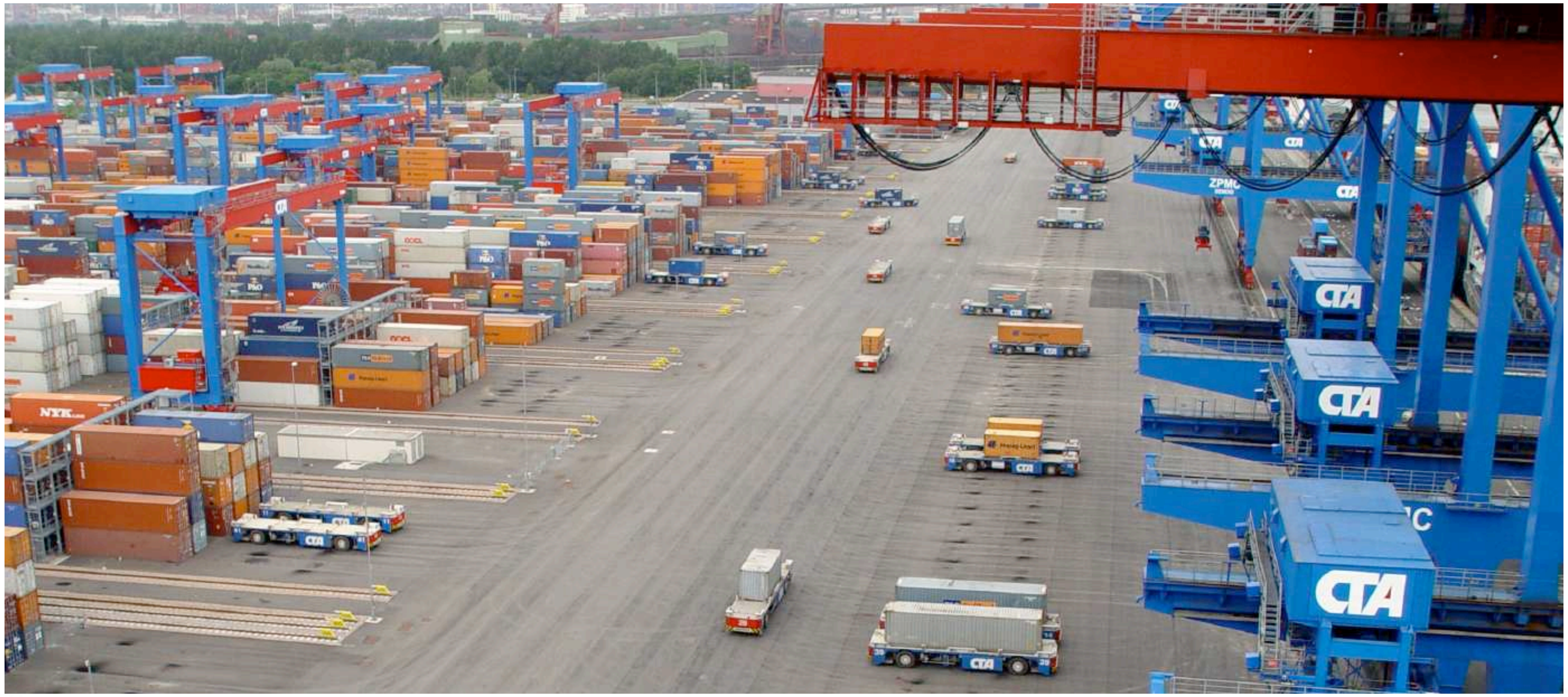
Why we (the COGA group)?

They new about this application …

Routing of AGVs in the Hamburg harbor

HHLA

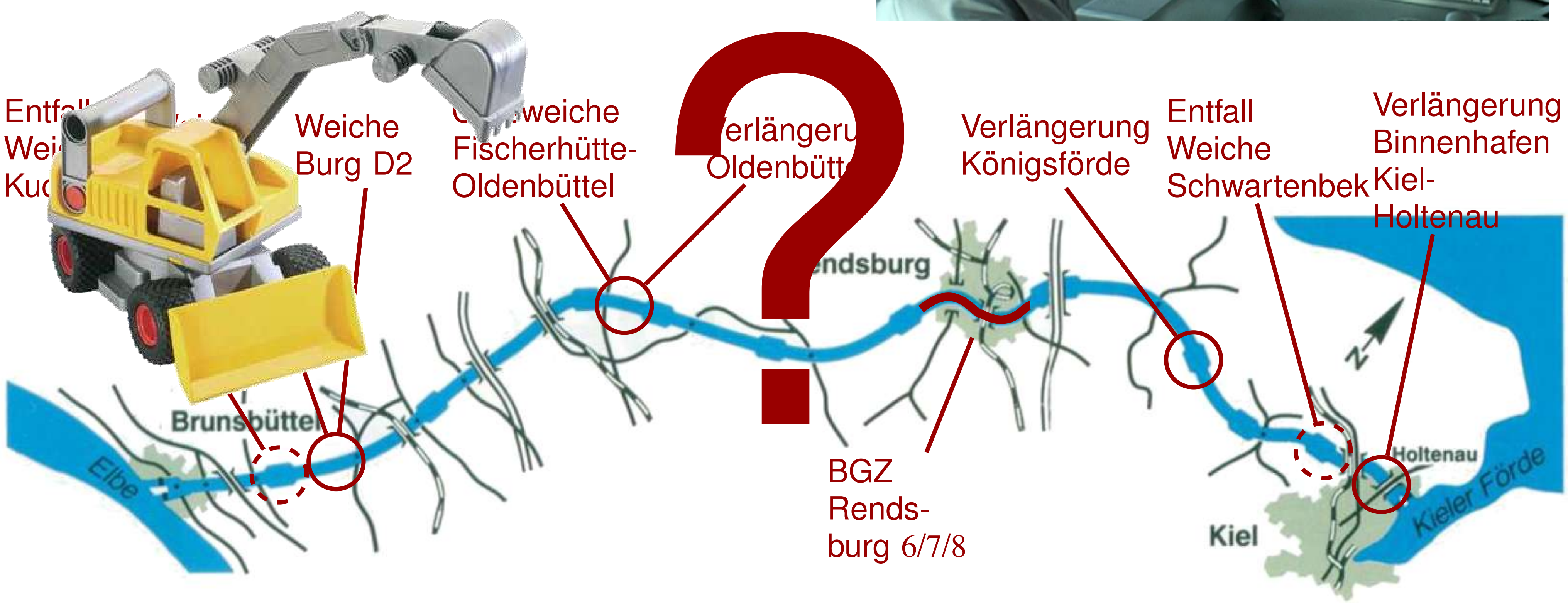
Bundesministerium für Bildung und Forschung



… and thought theirs was similar

What do you expect from us?

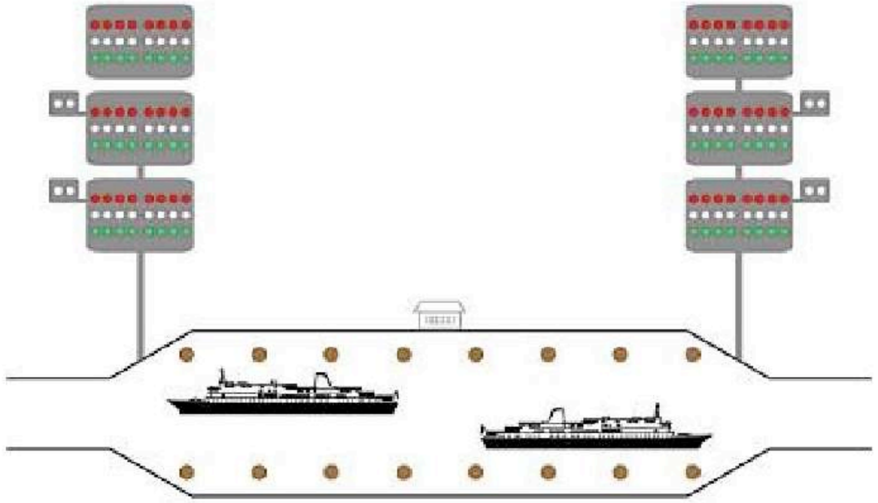
- Improve manual planning



- Recommendations for canal enlargement (widening, new sidings …) for future traffic
- Automated guidance during construction phase

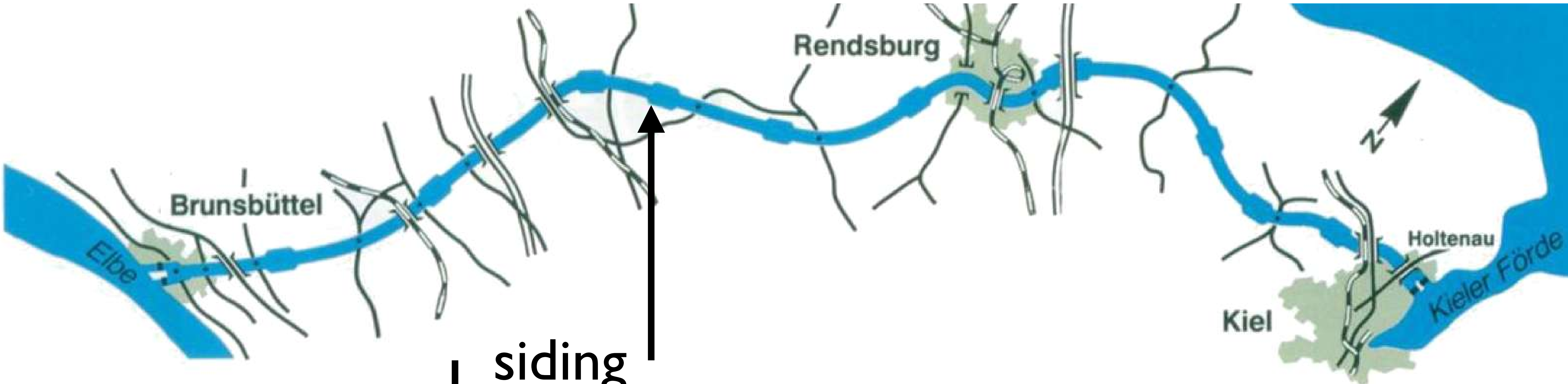
What is the main problem?

Opposing traffic creates the main problems …

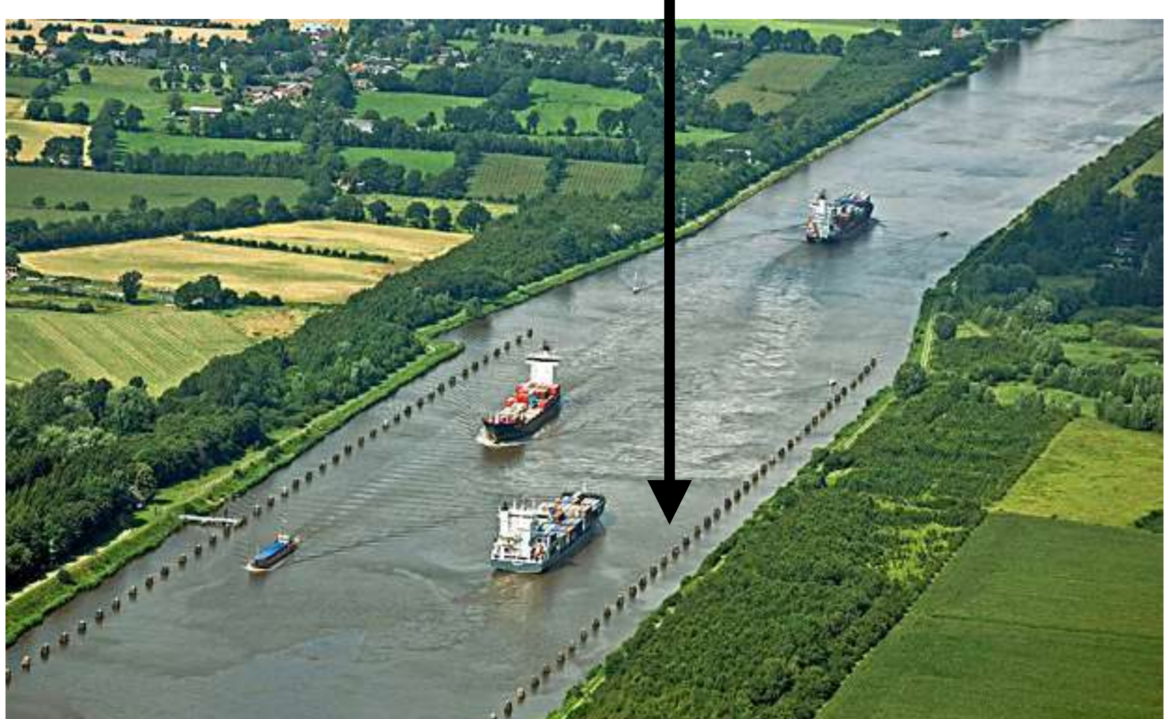




- Ships must be scheduled to wait in sidings (turnouts)
- Waiting can‘t be too long
- New ships arrive online

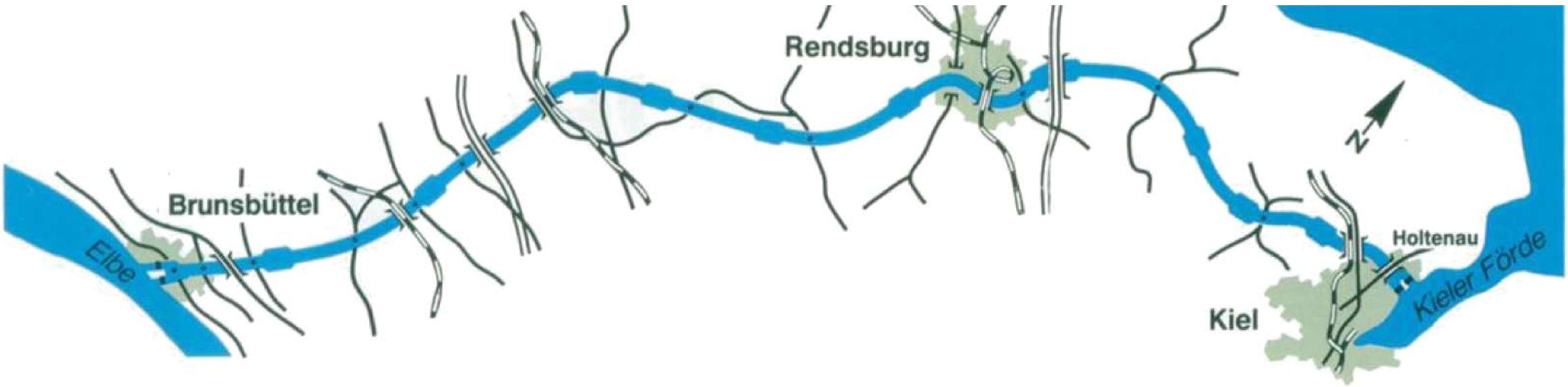
Detailed view at a siding

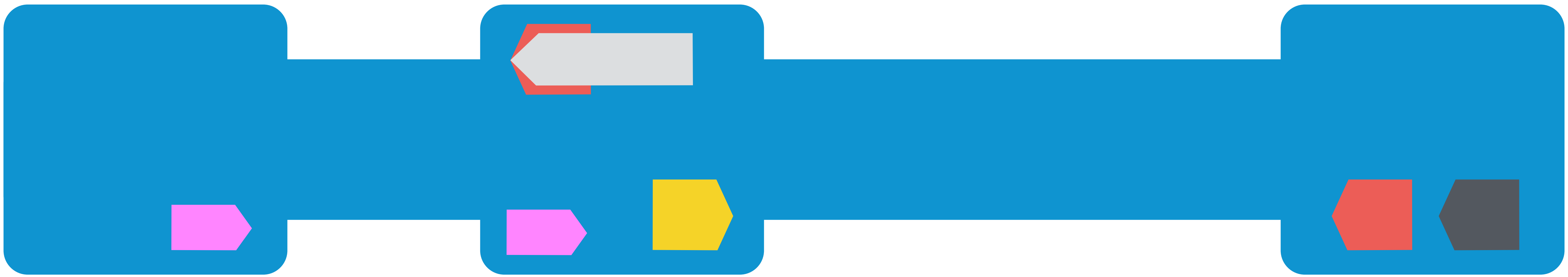


siding



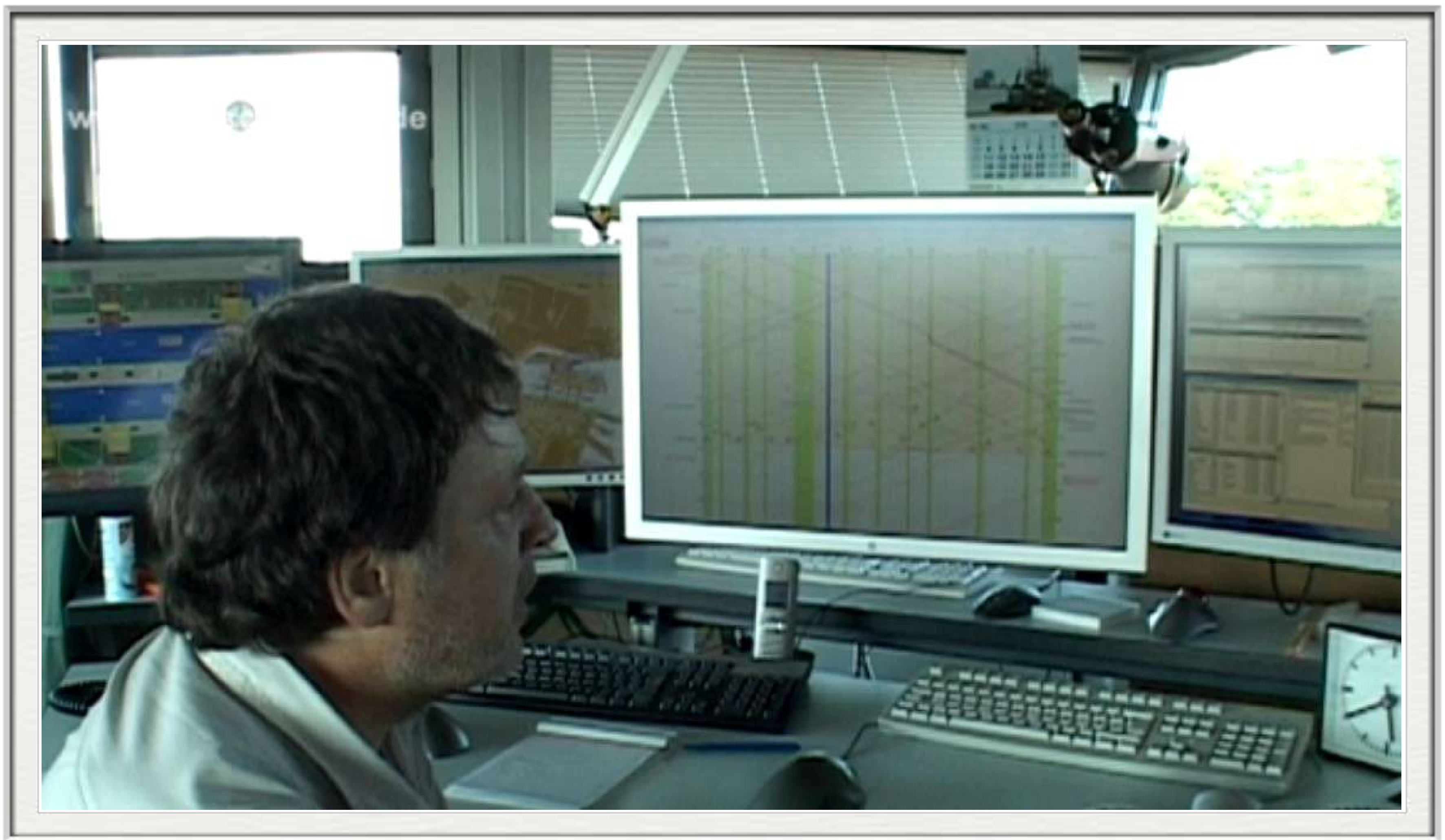
A glimpse at traffic details





Combines routing and scheduling

What is the current practice?

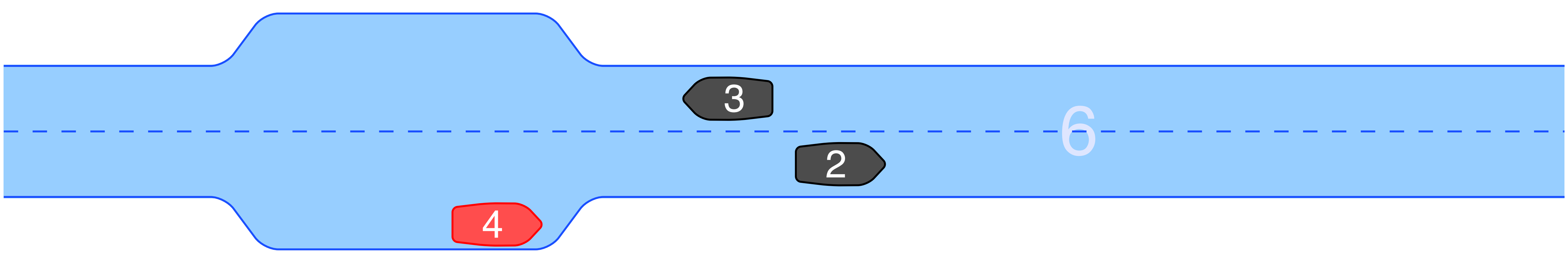


Manual traffic guidance by experienced planners with a nautical background

Optimization model

- The canal
  - segments and sidings
  - passing limits per segment
  - capacities per siding
- The ships
  - dimensions, type
  - origin, destination
  - release date, velocity

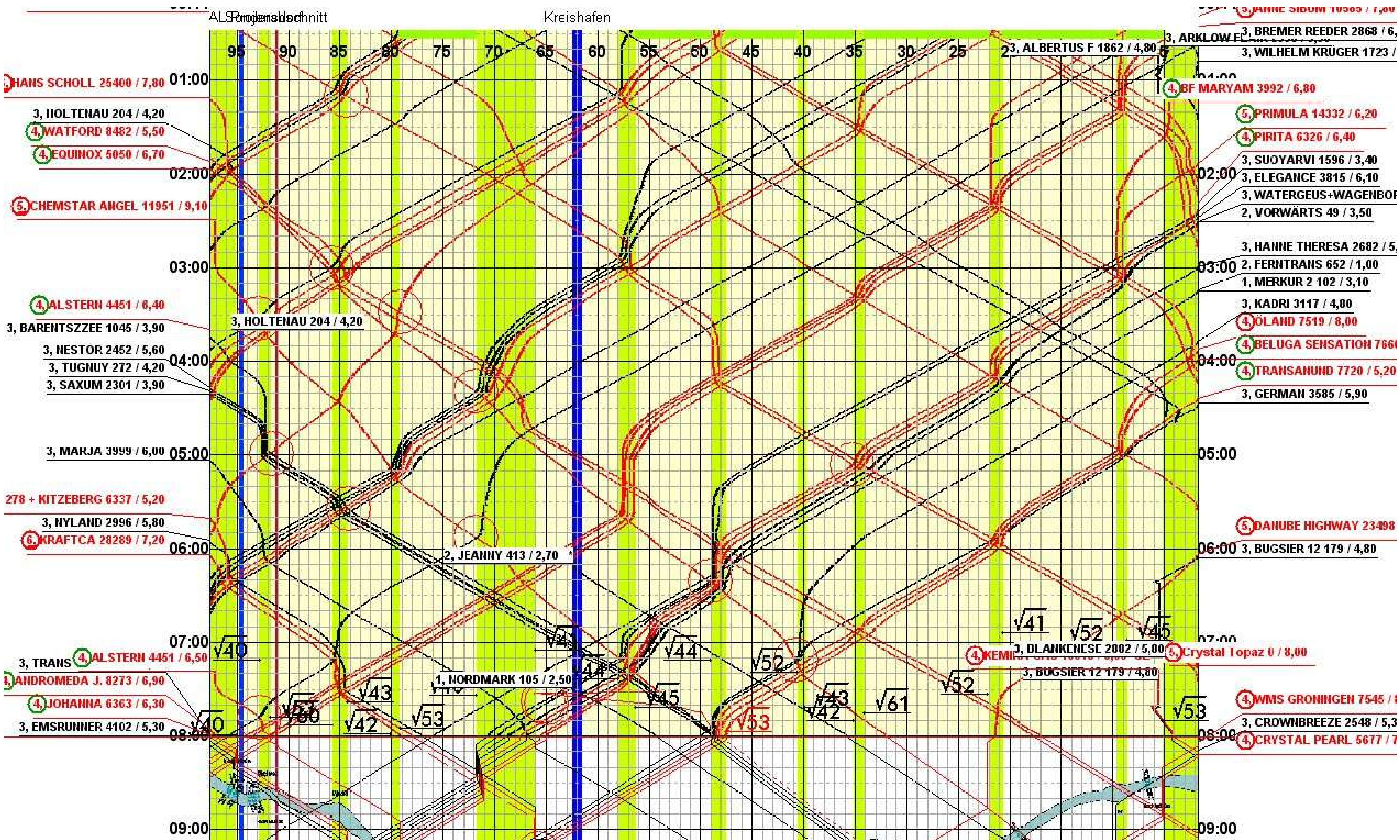
sum of ship types ≤ passing limit of segment



Goal: Find collision-free dynamic routes minimizing total waiting time $\sum_{\text{ship } s} w_s$

Is data available?

Yes, we have a space time diagram of every day



Can we get data?

Yes, we have everything on our computers …

- The canal
  - topography
  - capacities per siding
  - passing model

- The ships and their manually planned routes
  - plus traffic group, waiting times etc.

We agreed on a side contract to get the data out of their database

Routing AGVs in the Hamburg Harbour

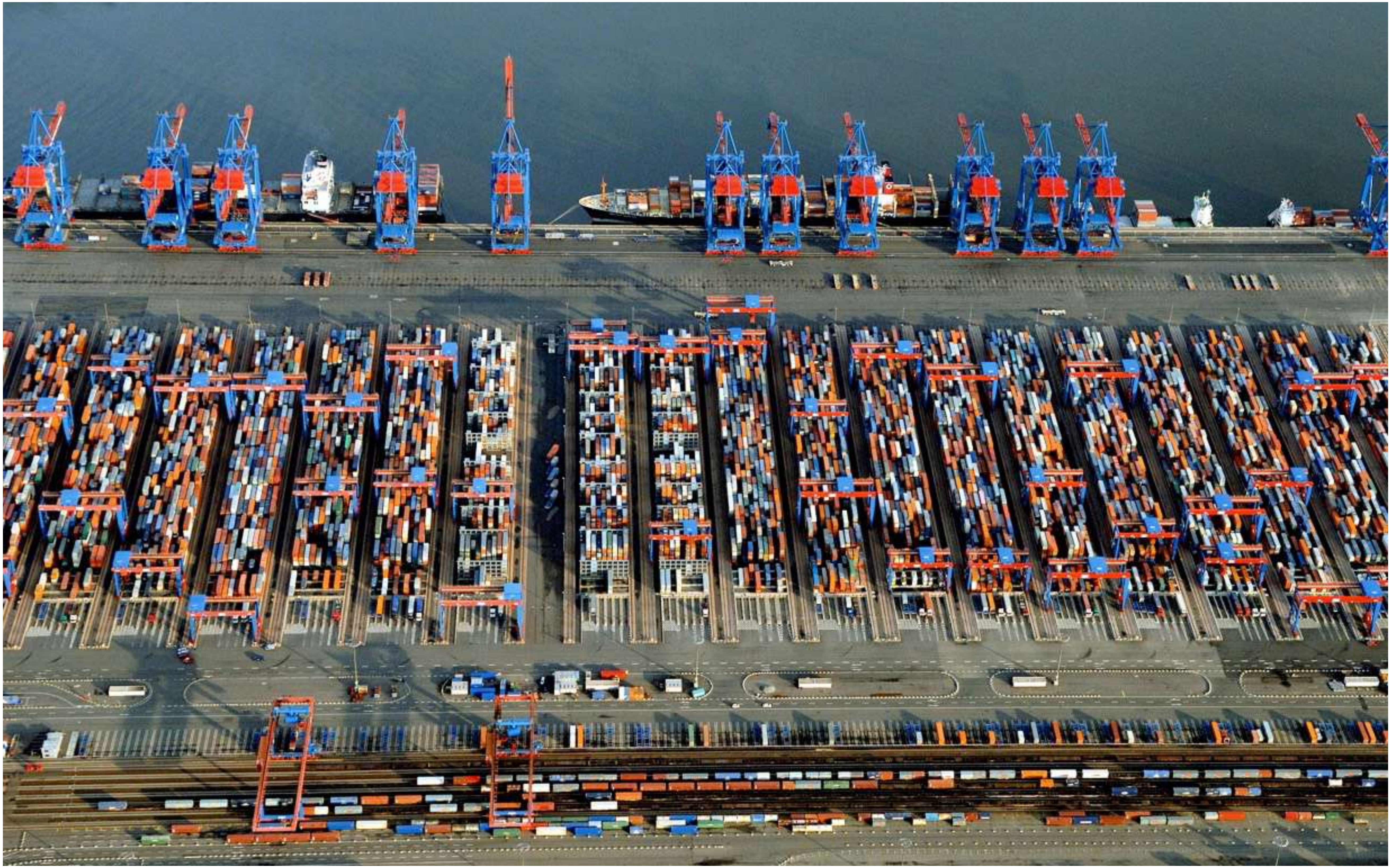
Ewgenij Gawrilow, Elisabeth Günther,
Ekkehard Köhler, Rolf Möhring, Björn Stenzel

Container Terminal Altenwerder (CTA)

- most modern container terminal
- far reaching automatization of the logistic processes
- expanding at high rates
- here: Transport of containers between waterside and storage area
  - with 70 Automated Guided Vehicles (AGVs)

Overview of the harbor layout

Overview of the harbor layout

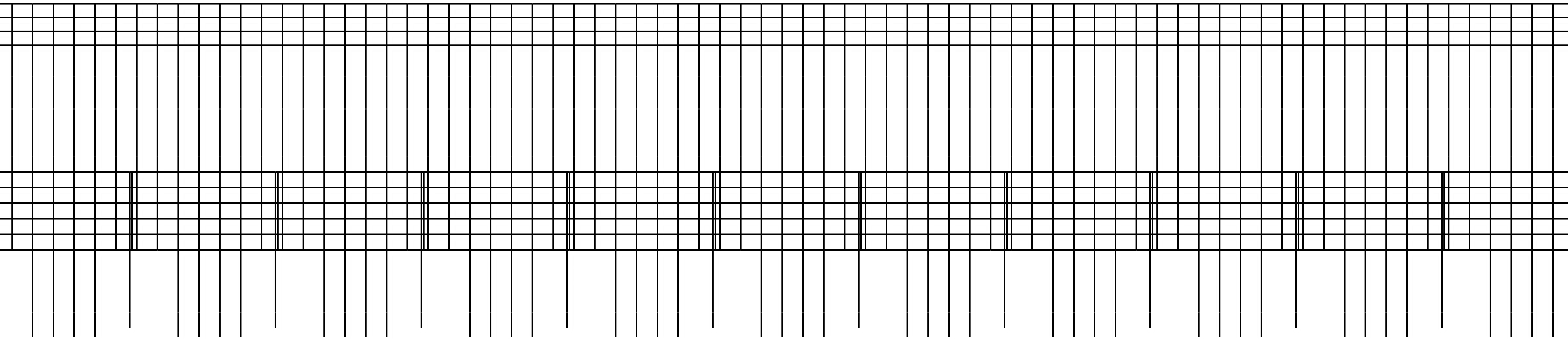


Routing area with AGVs

Optimization model

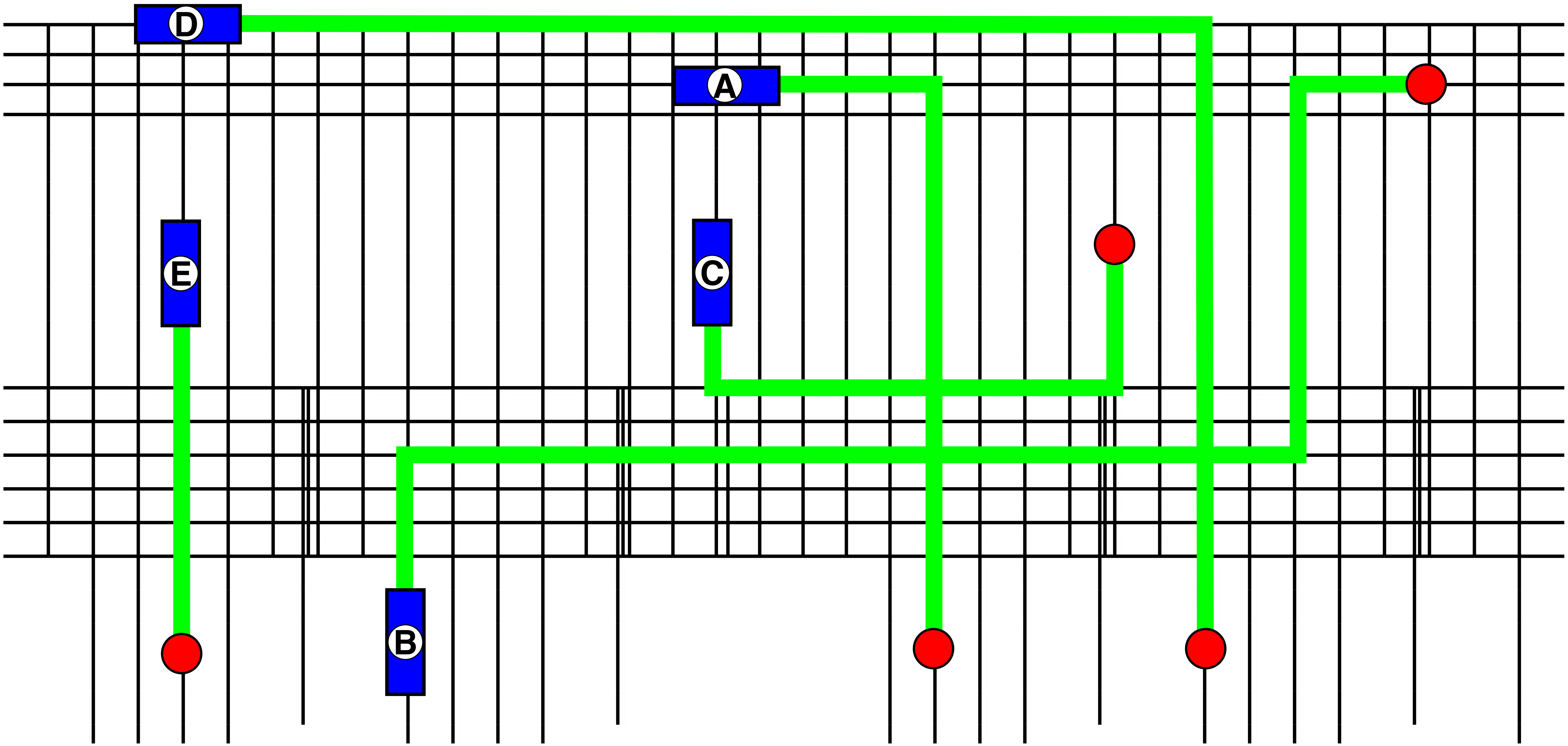
- Graph with 15,647 arcs and 5,445 vertices
- Travel times τ_a on arc a
- Sequence of routing requests with
  - start, destination, departure time
- Wanted: – collision-free routes
  – garanteed arrival times
  – high throughput at the bridges (= cranes)

water side

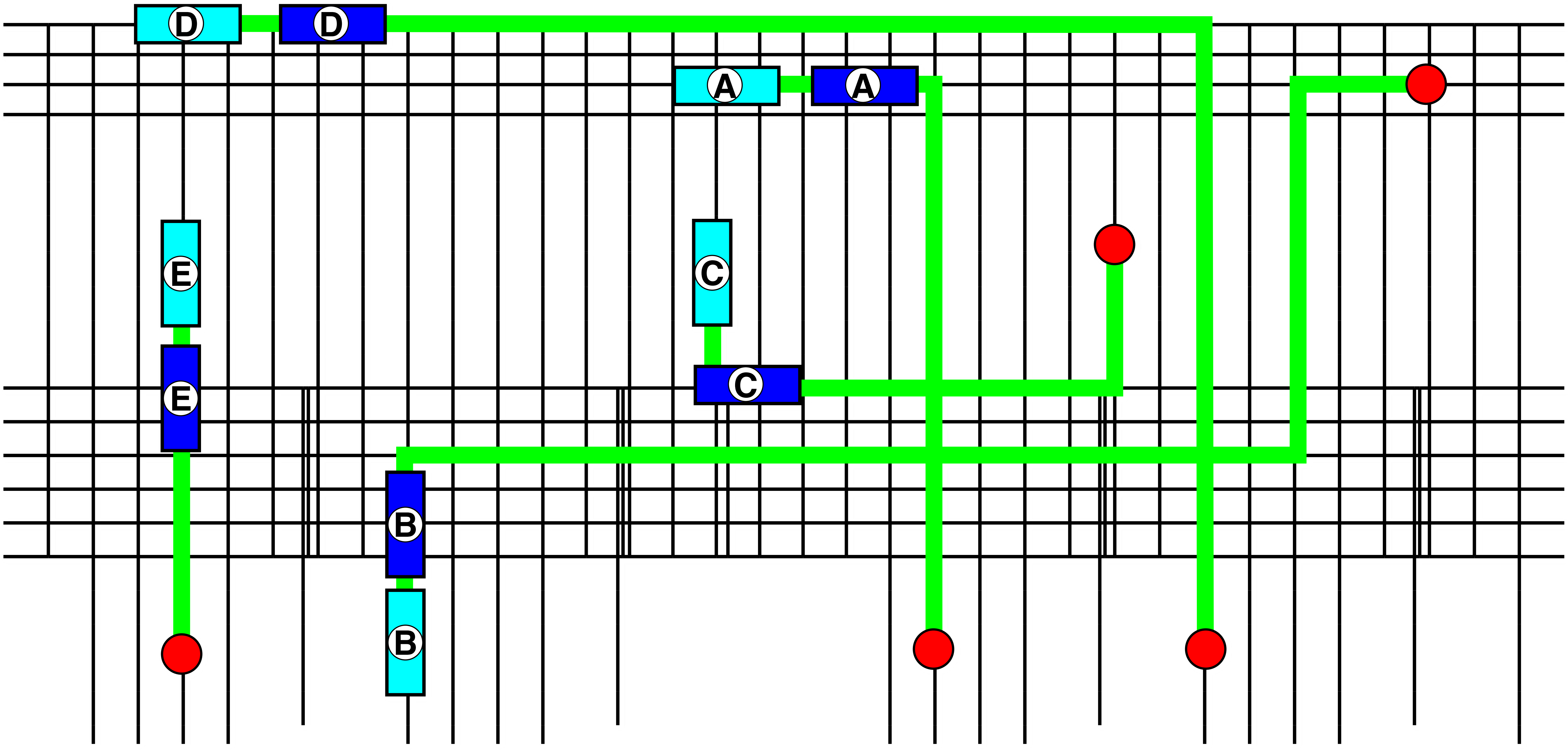


storage area

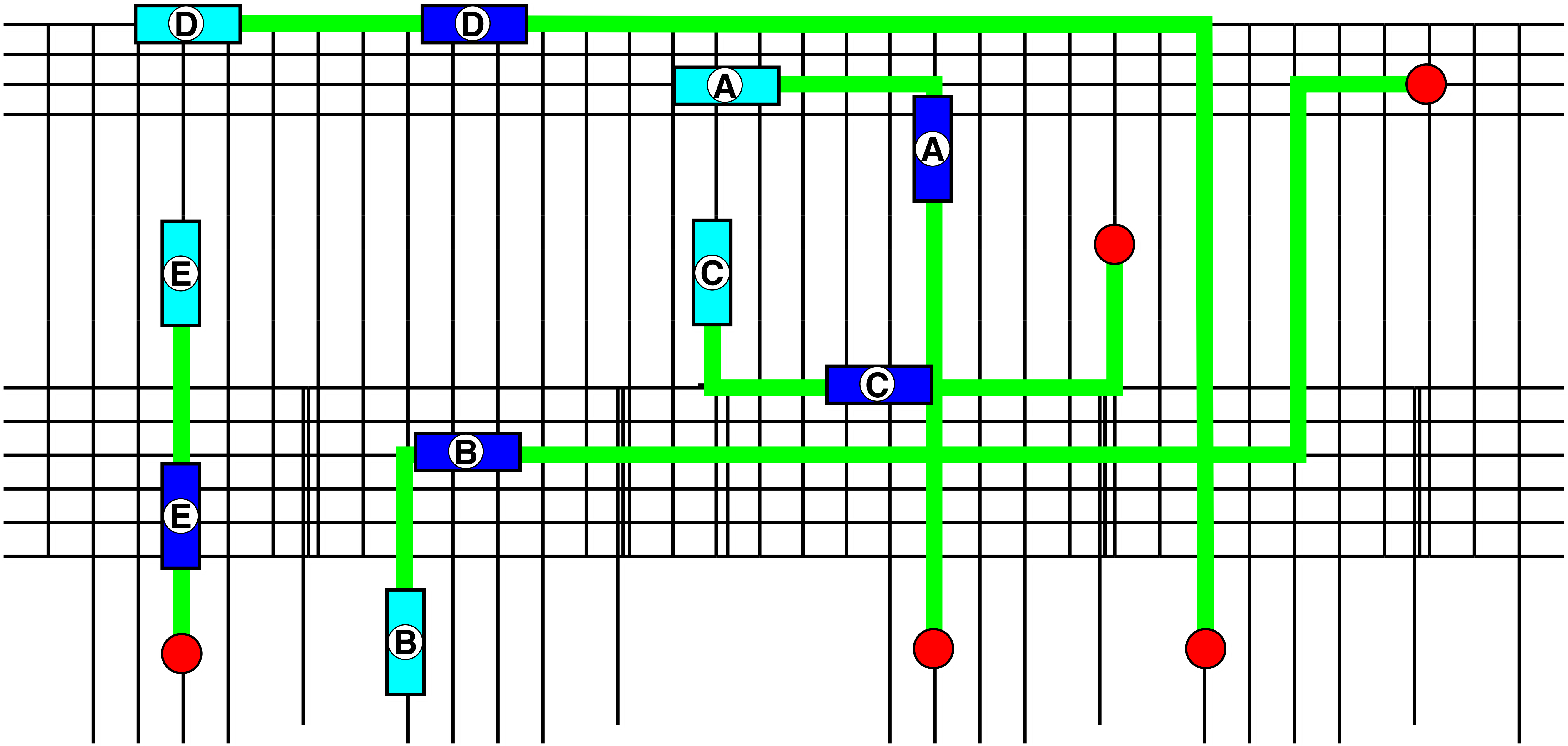
Example of a routing



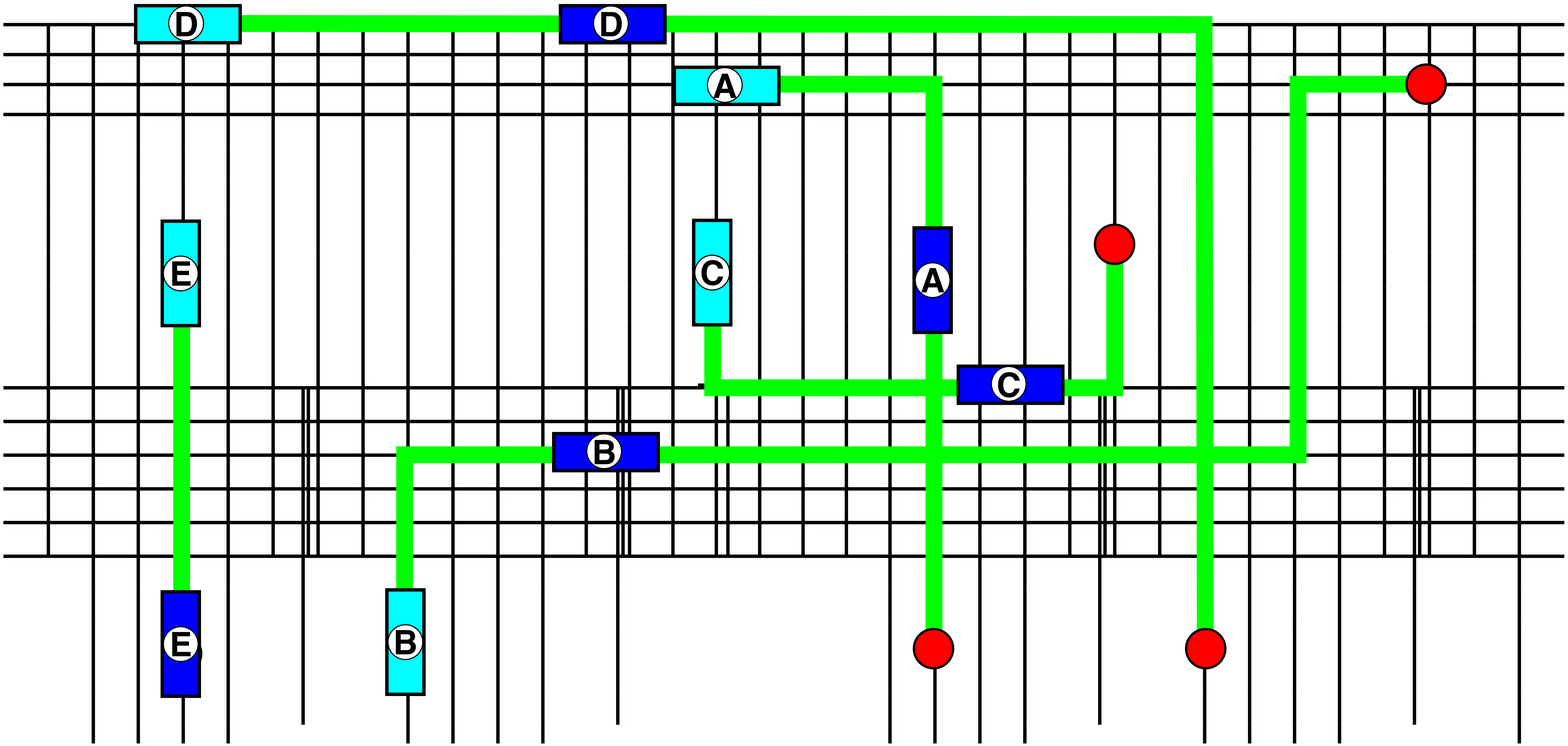
Example of a routing



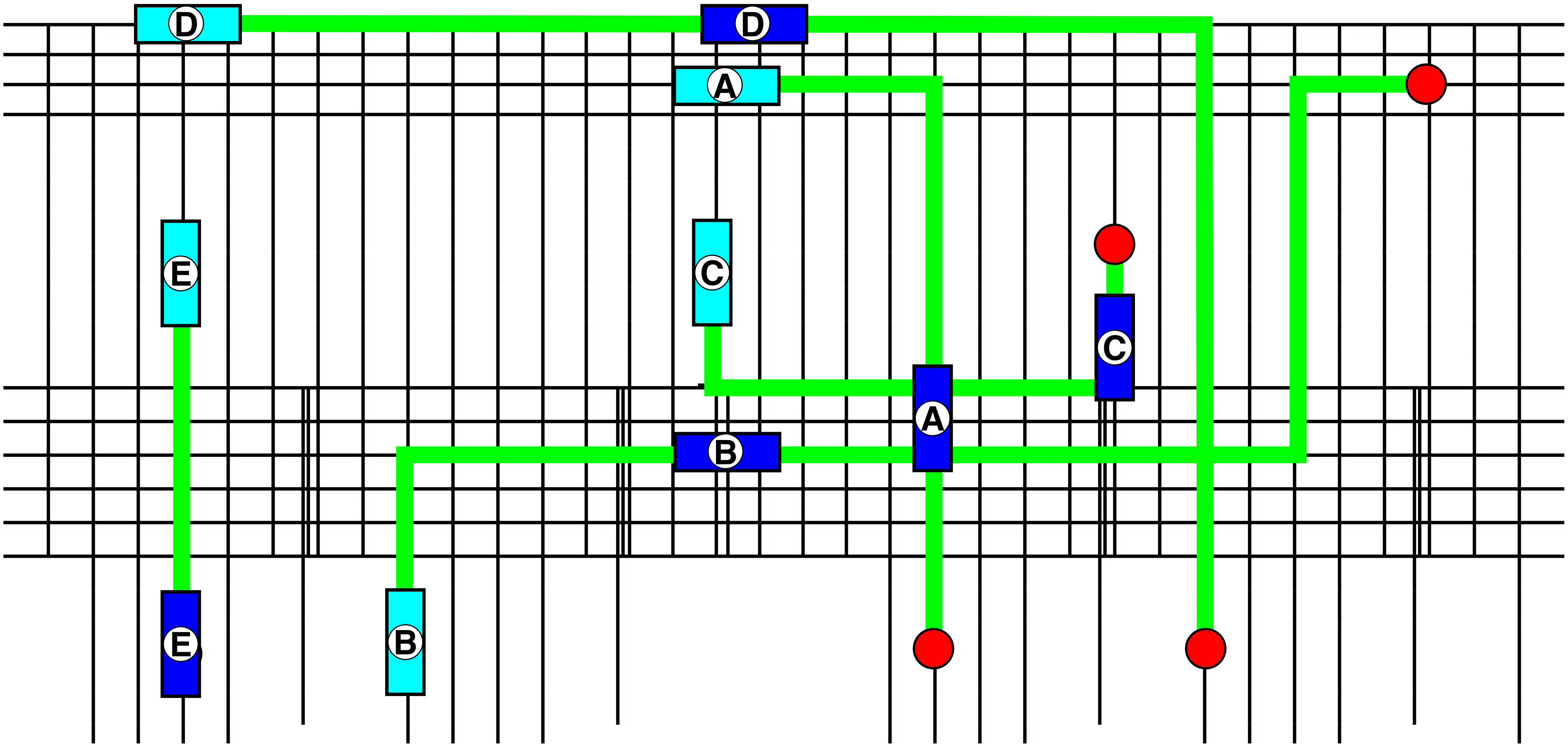
Example of a routing



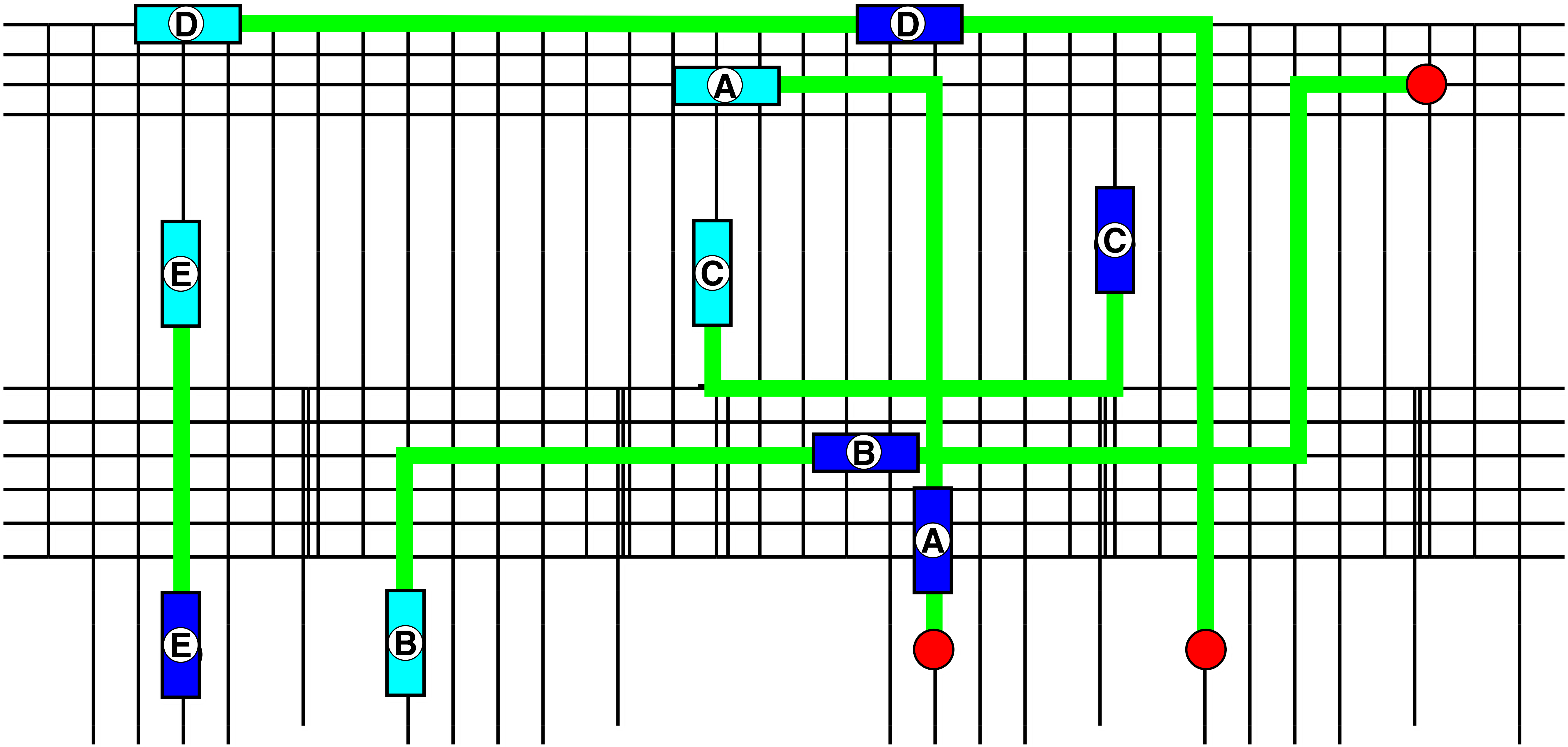
Example of a routing



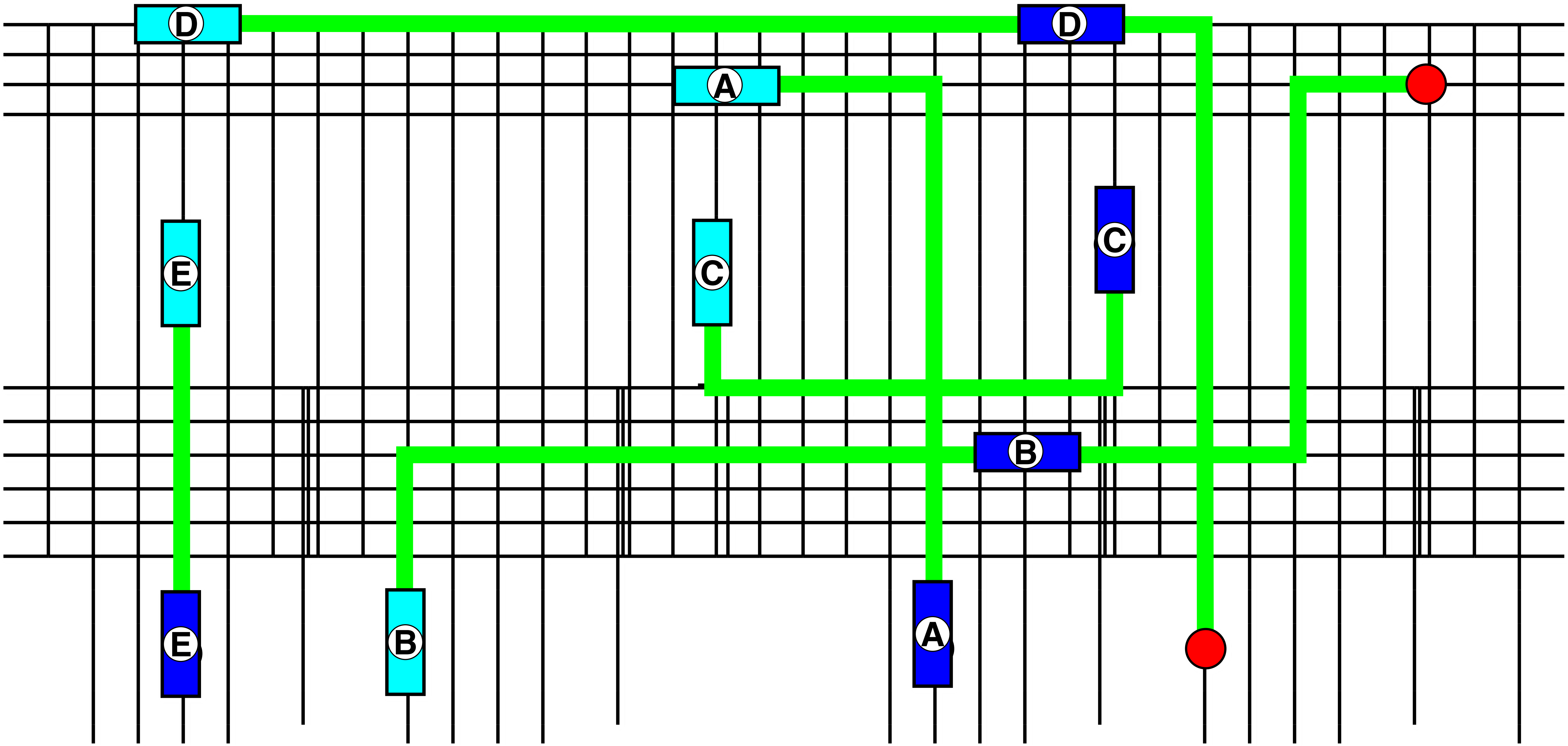
Example of a routing



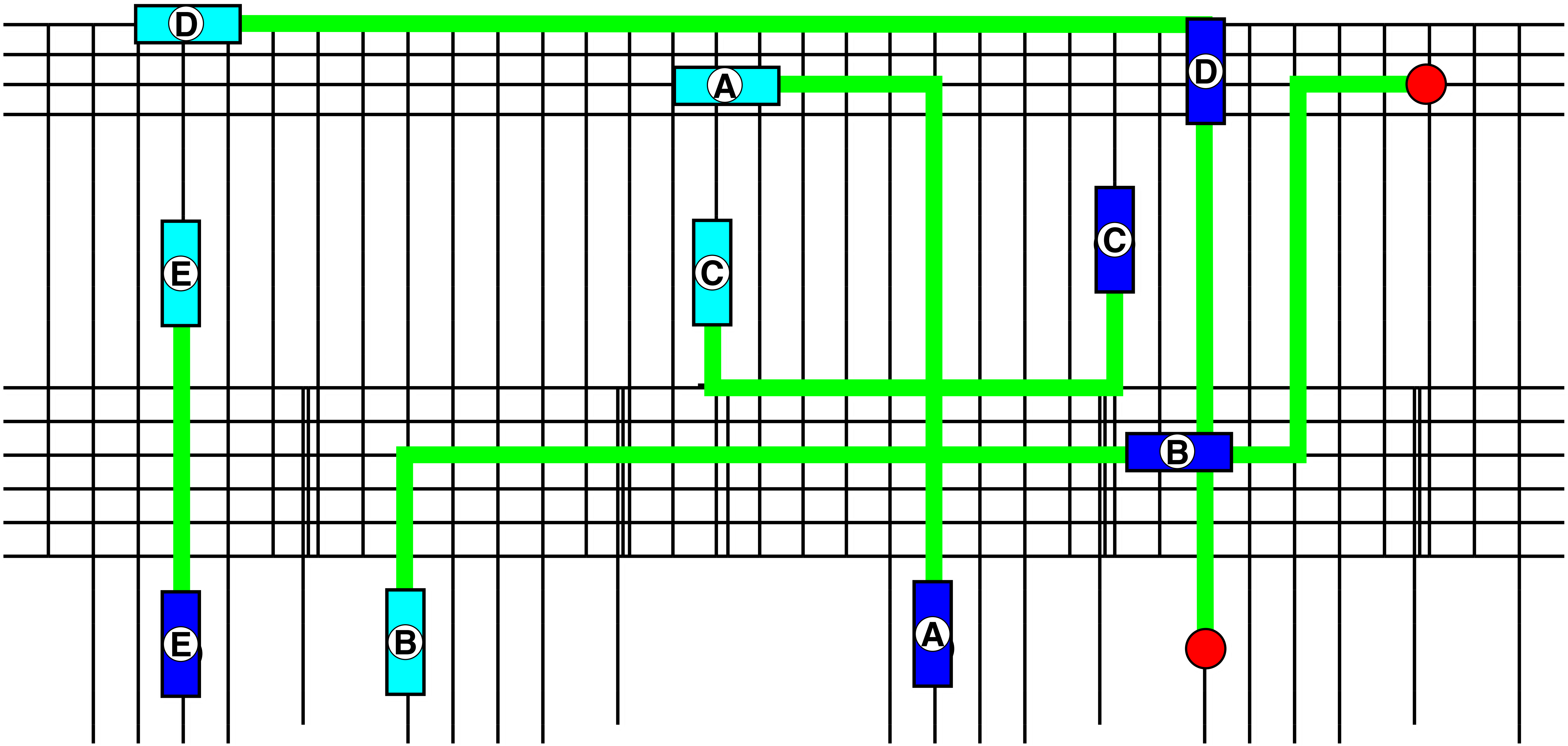
Example of a routing



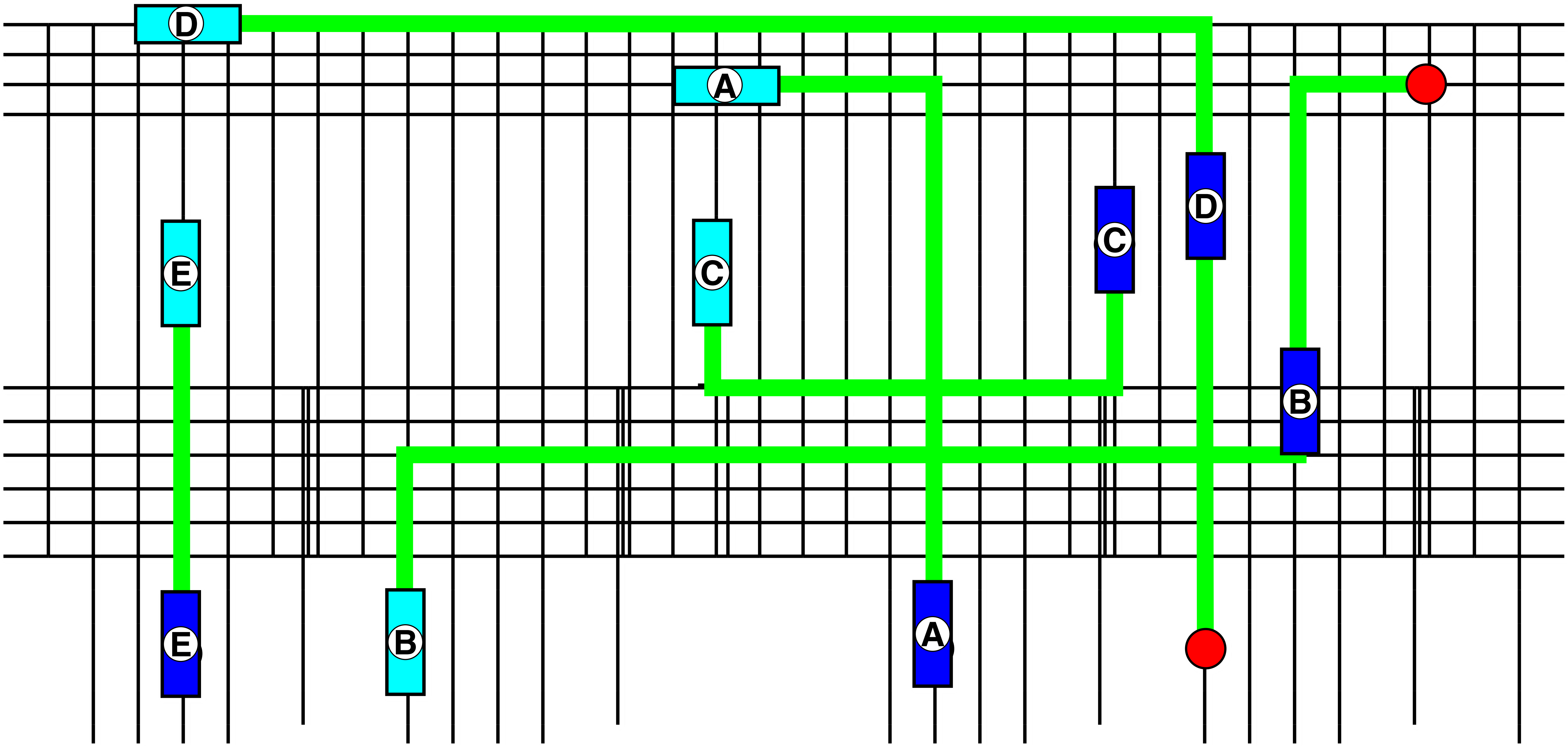
Example of a routing



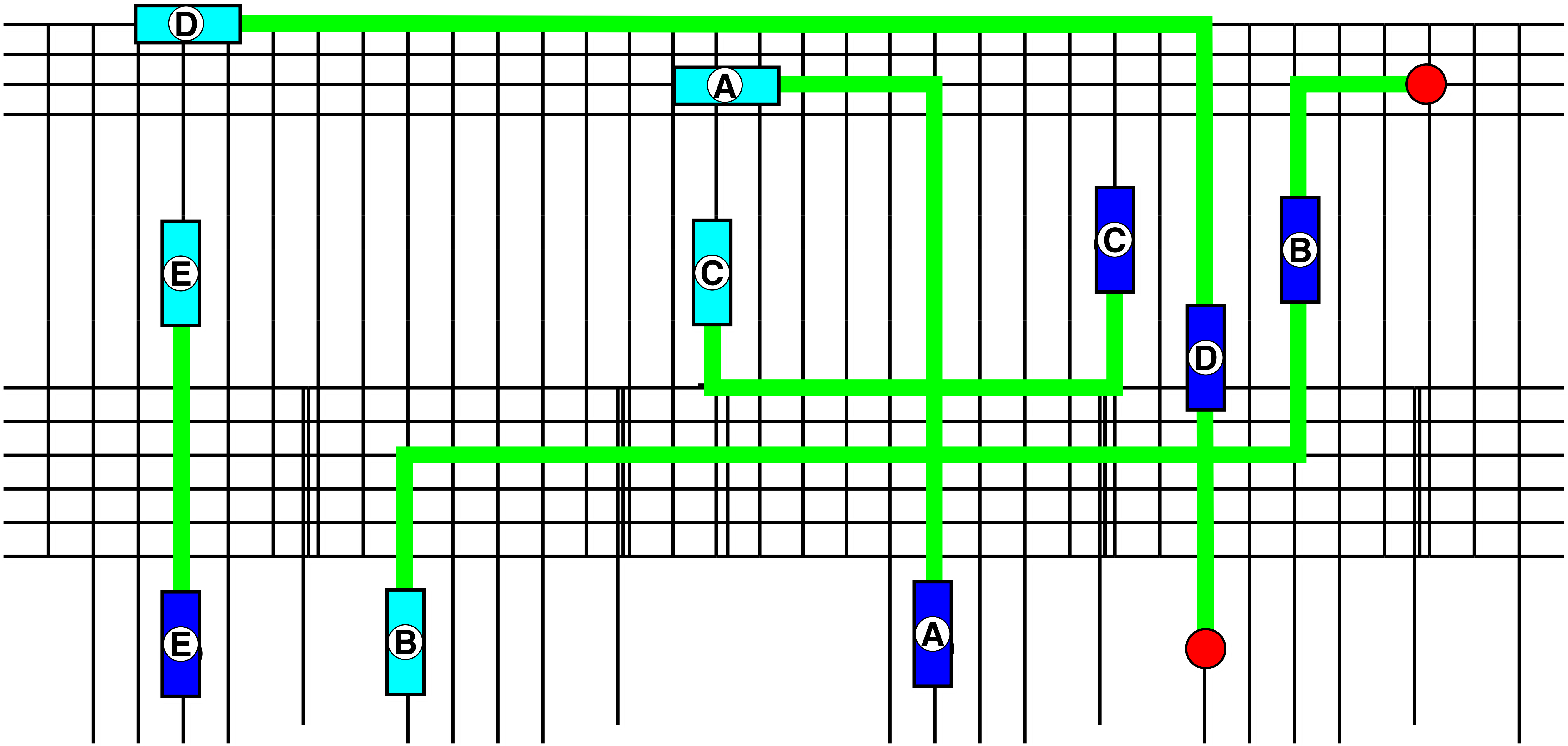
Example of a routing



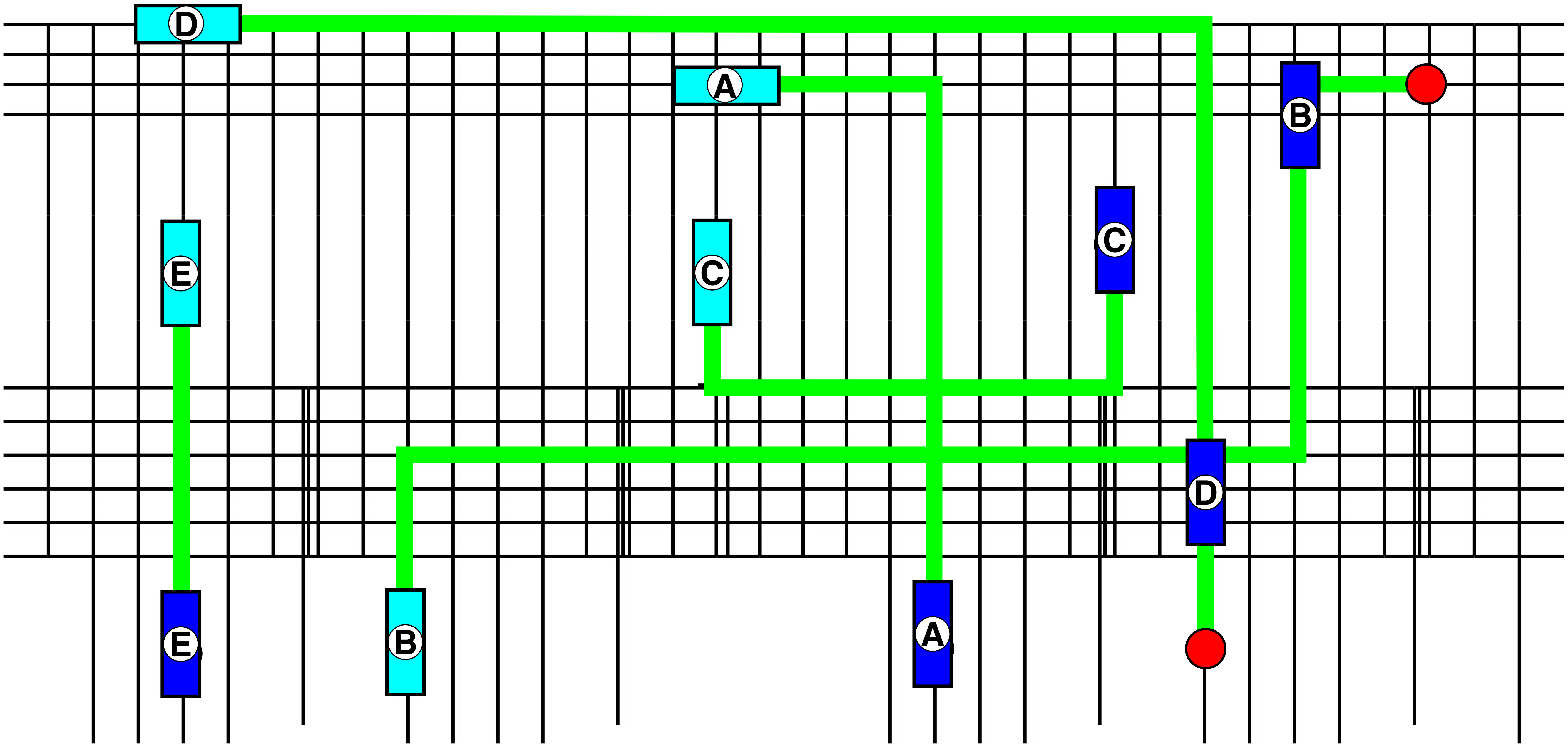
Example of a routing



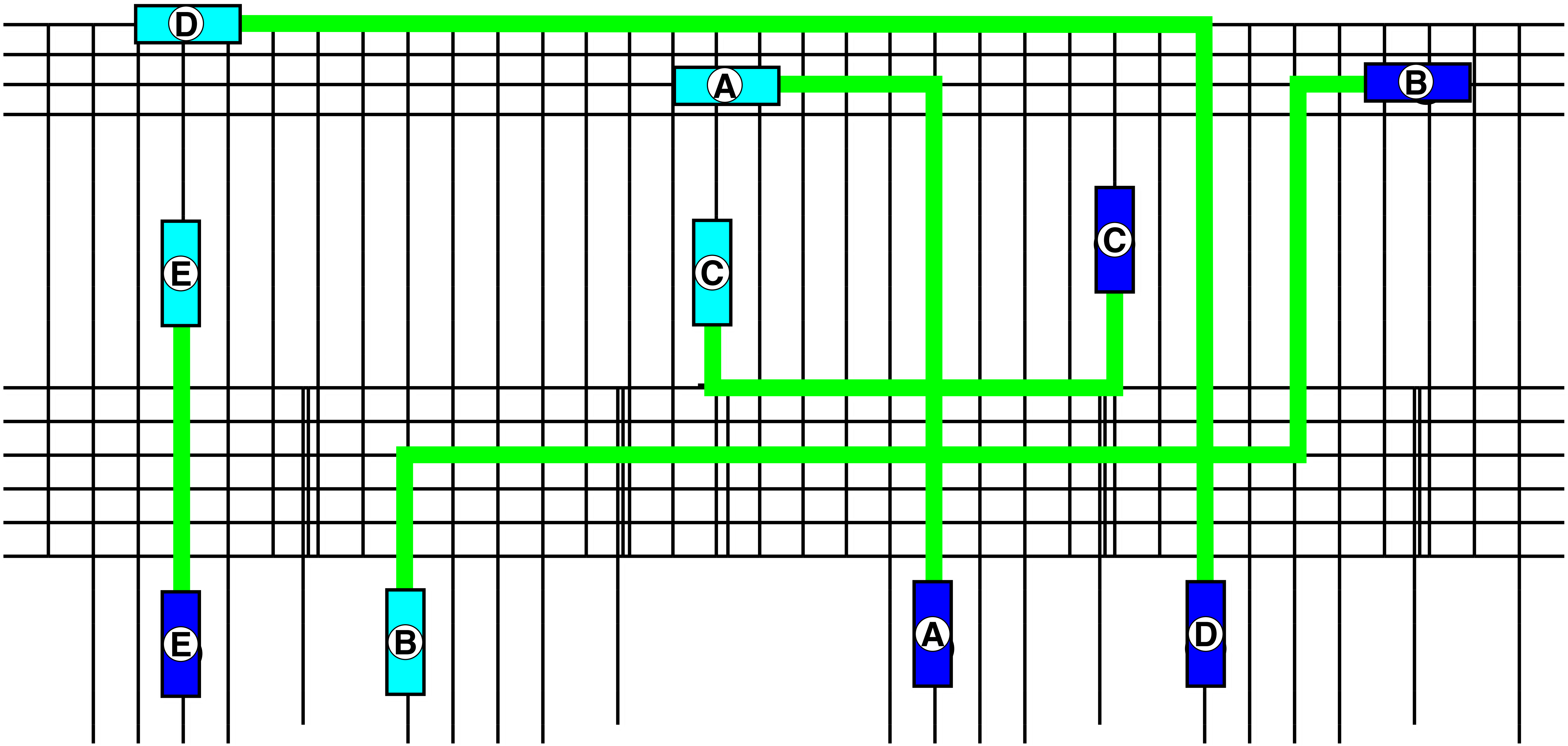
Example of a routing



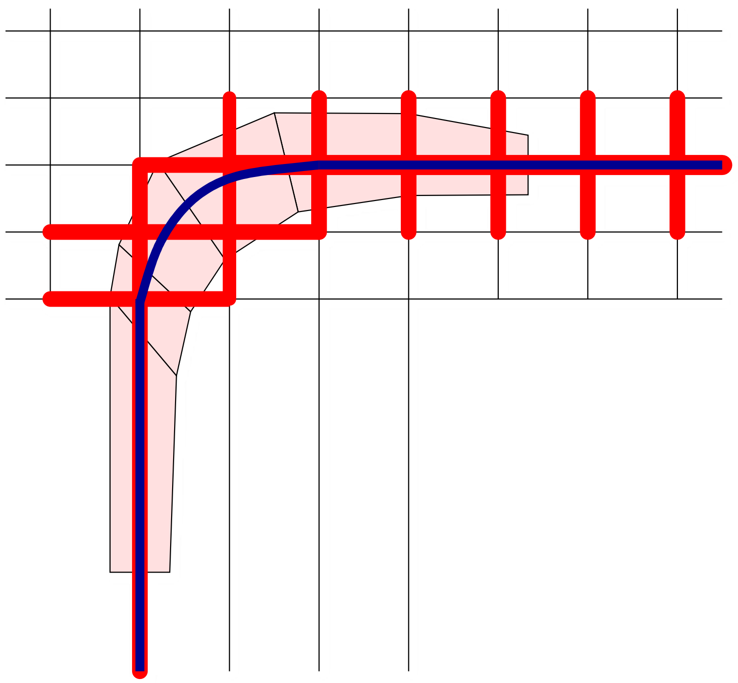
Example of a routing



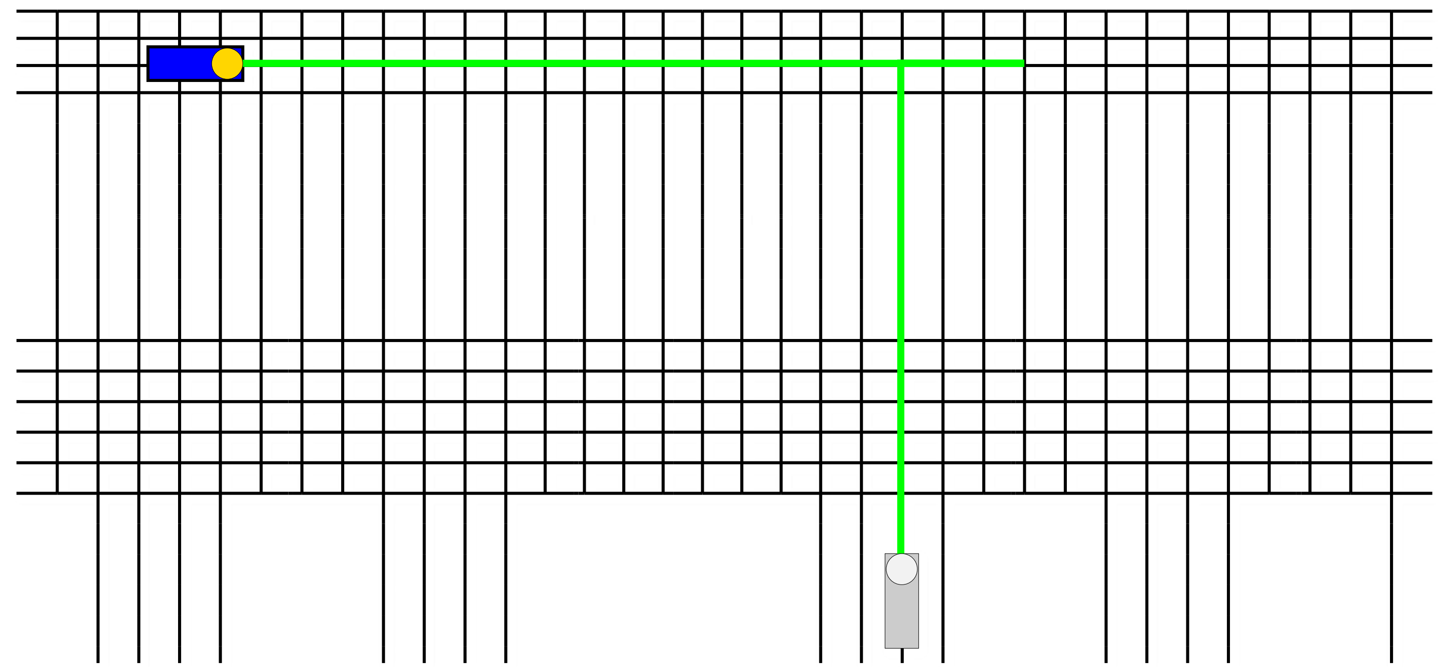
Example of a routing



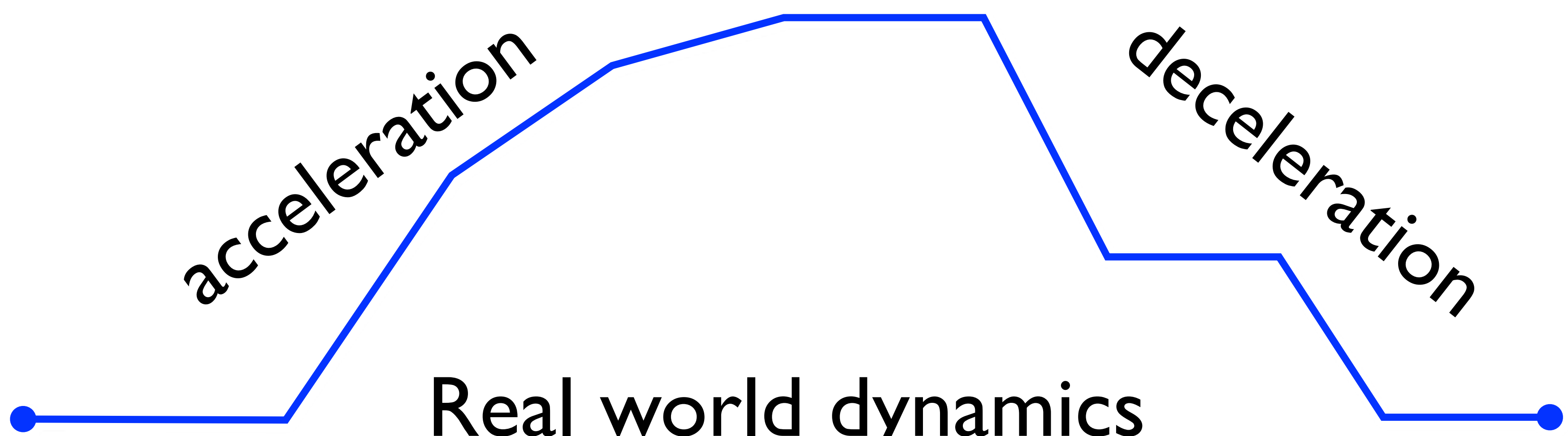
Complicating conditions



Turning behavior

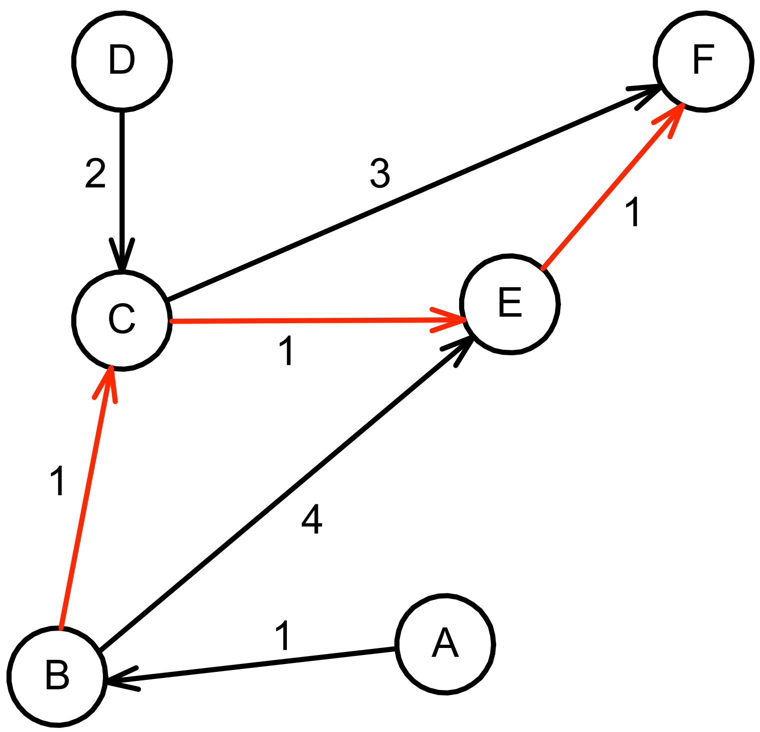


Orientation at the destination

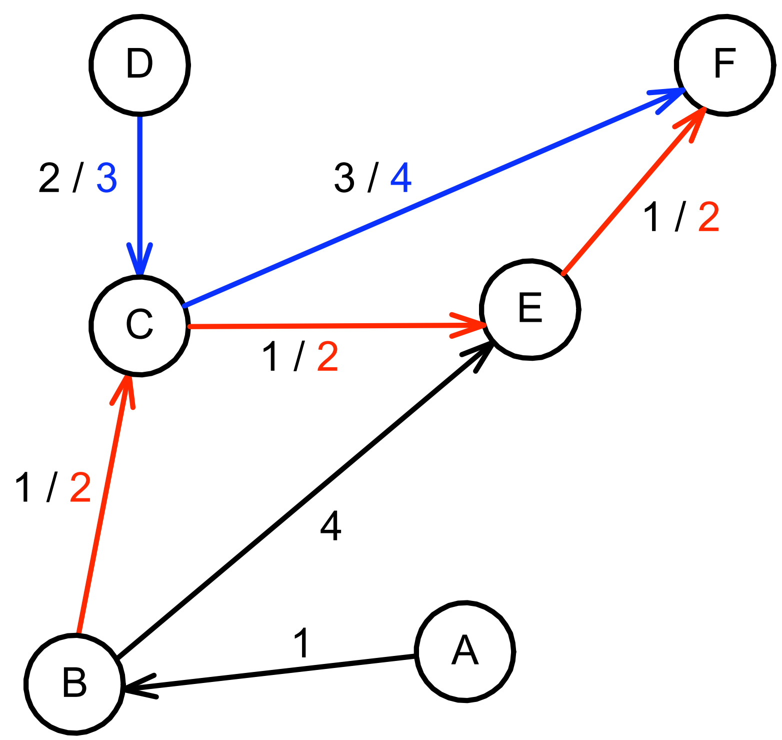


Real world dynamics

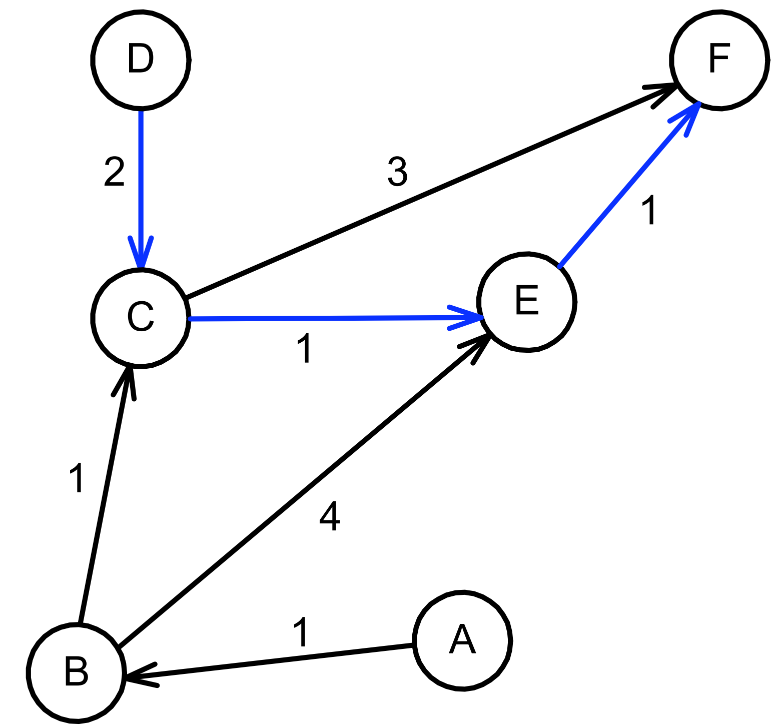
Used: static routing methods



compute shortest path in graph



penalize used arcs, compute new path

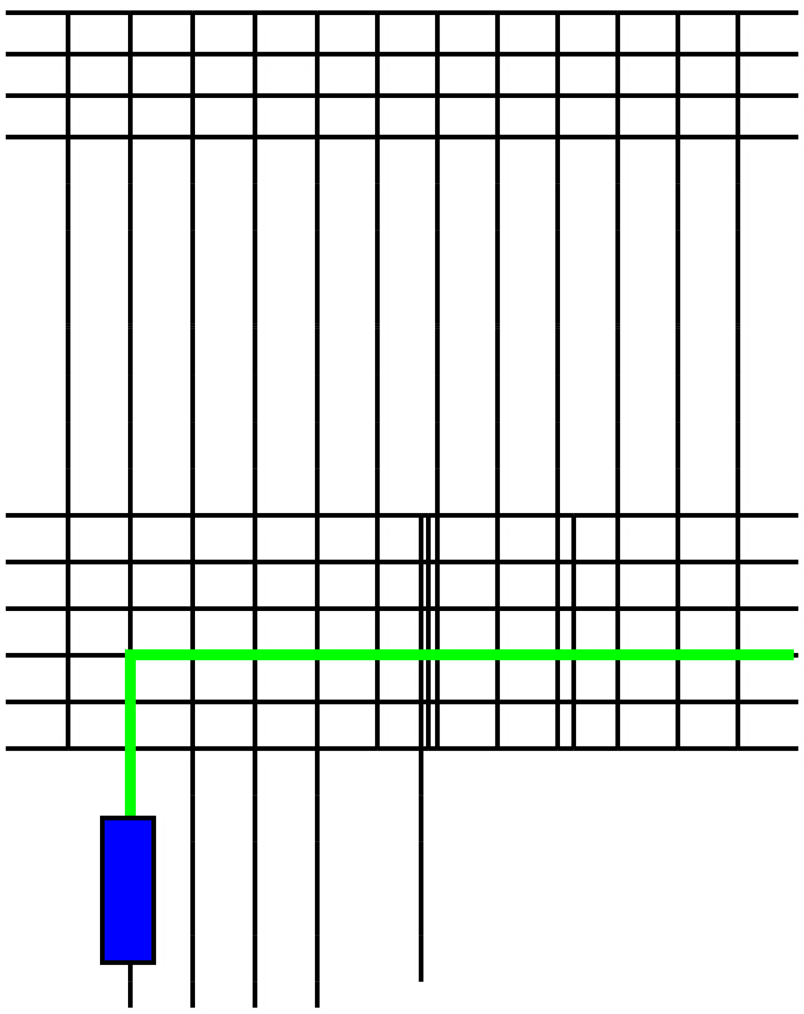


computed paths need not be shortest paths

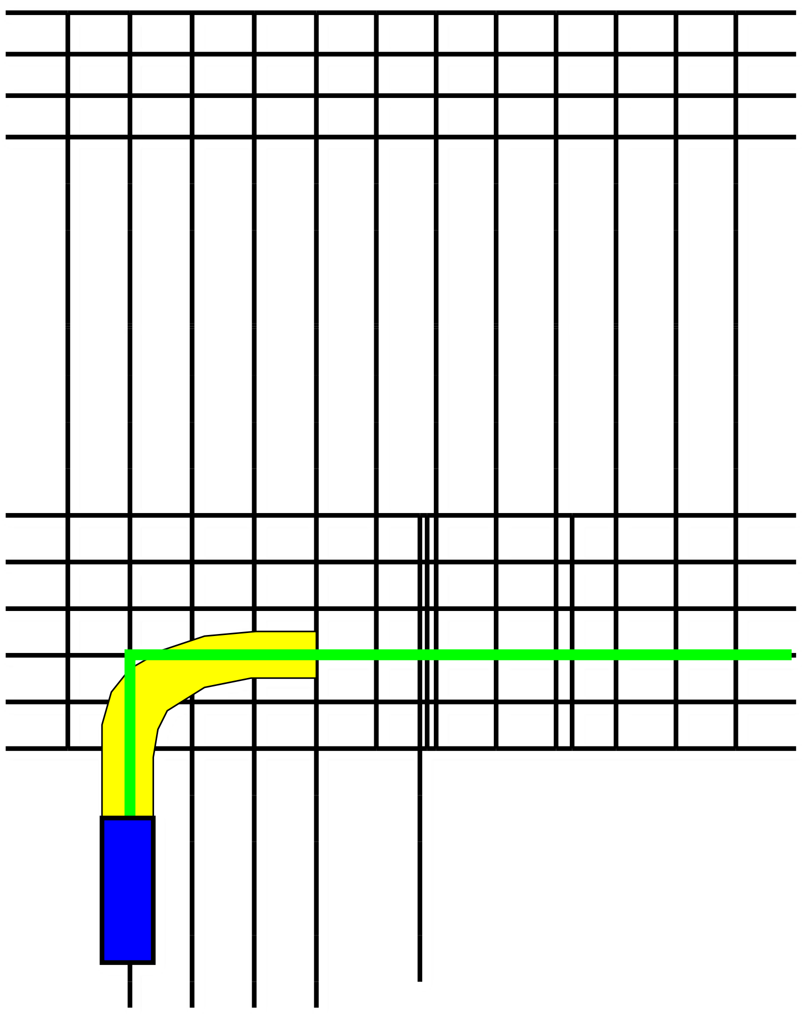
Hope that this avoids collisions at run time

Needs collision control at run-time

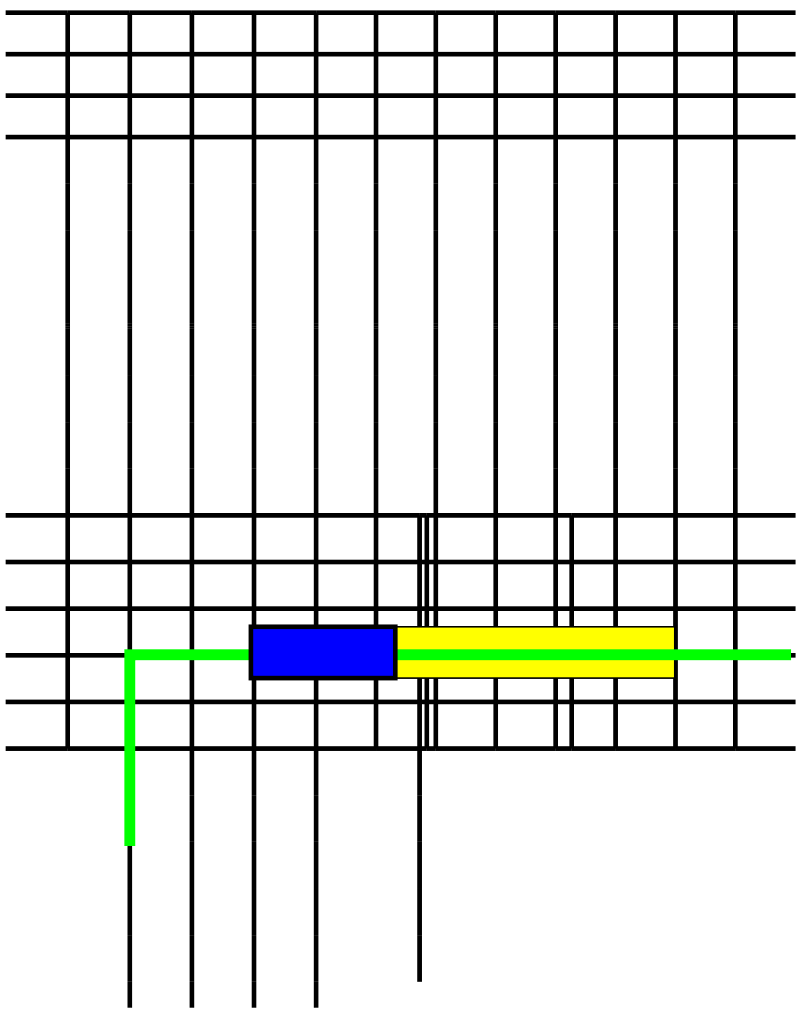
Reserve parts of a route exclusively for one AGV (Claiming)



Compute route



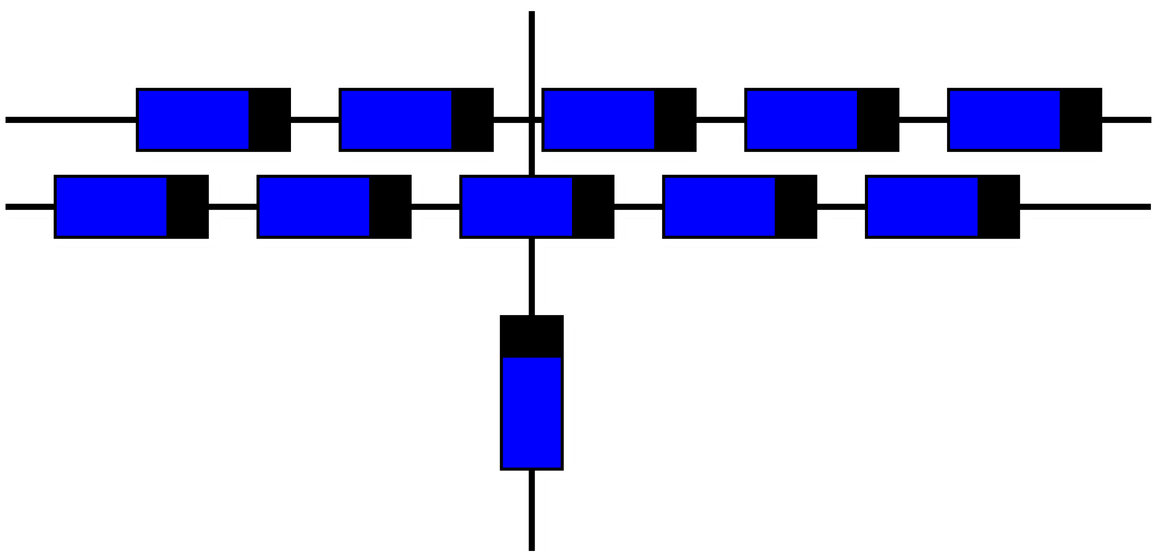
Claim 1



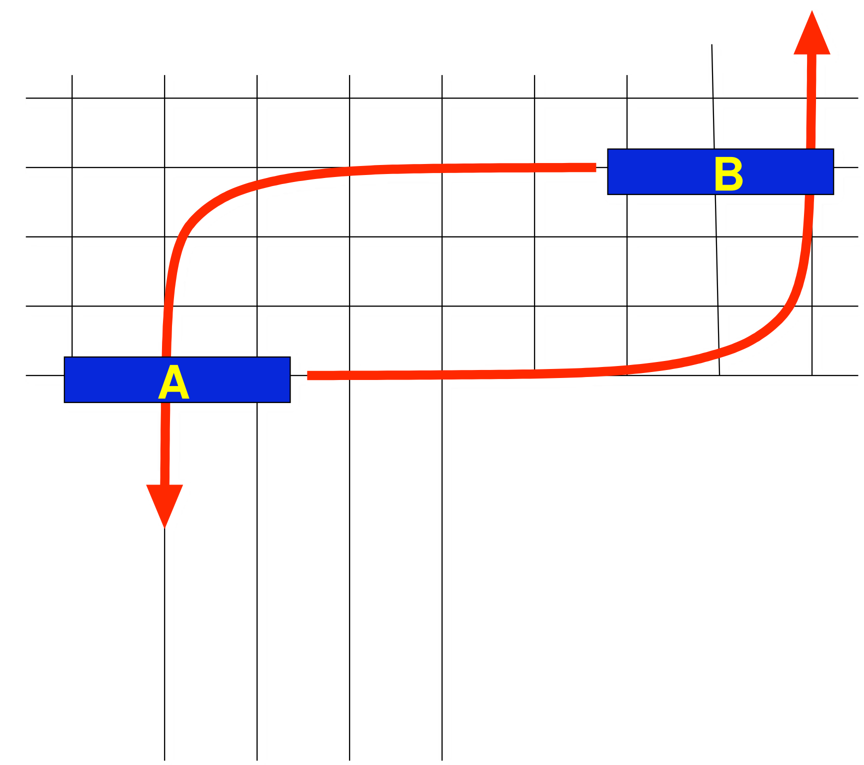
Claim 2

Disadvantages of claiming

1. no guaranteed arrival times

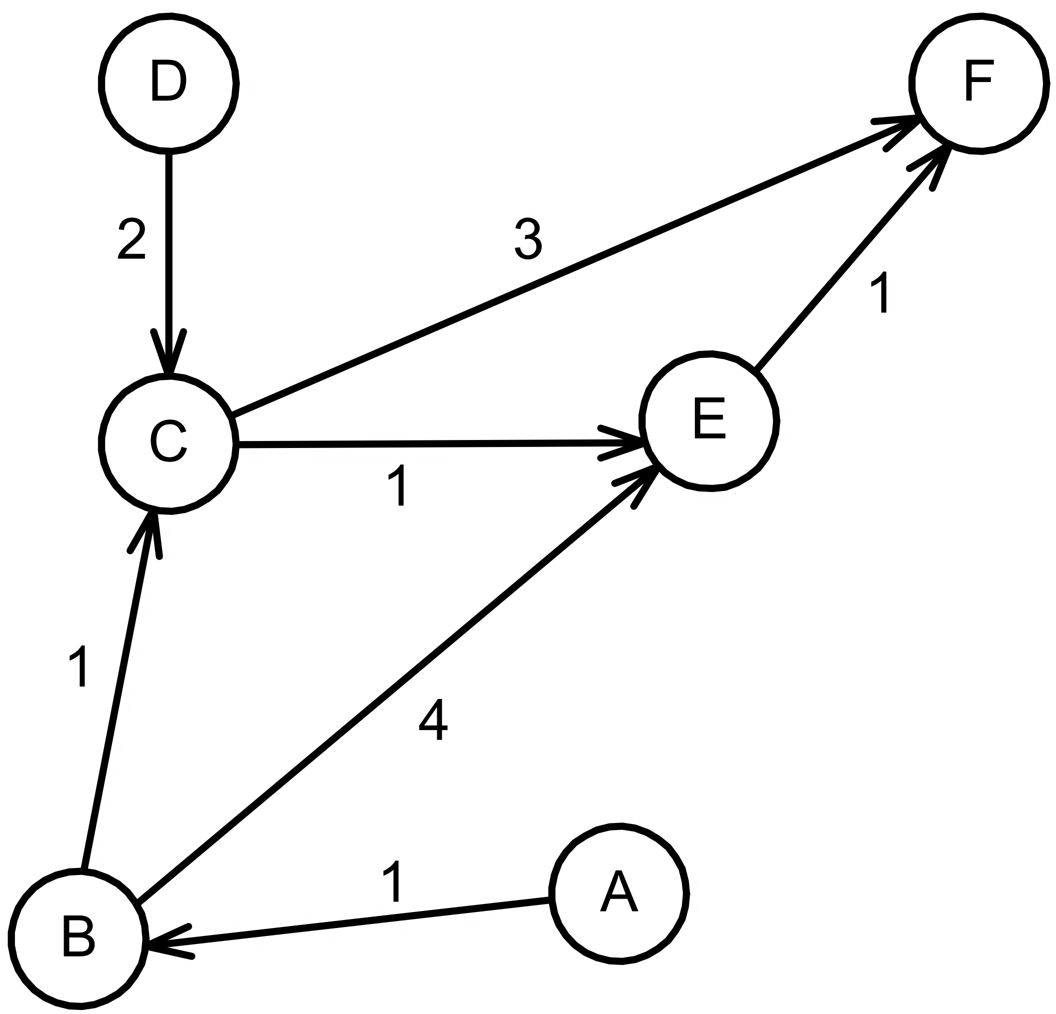


2. livelocks

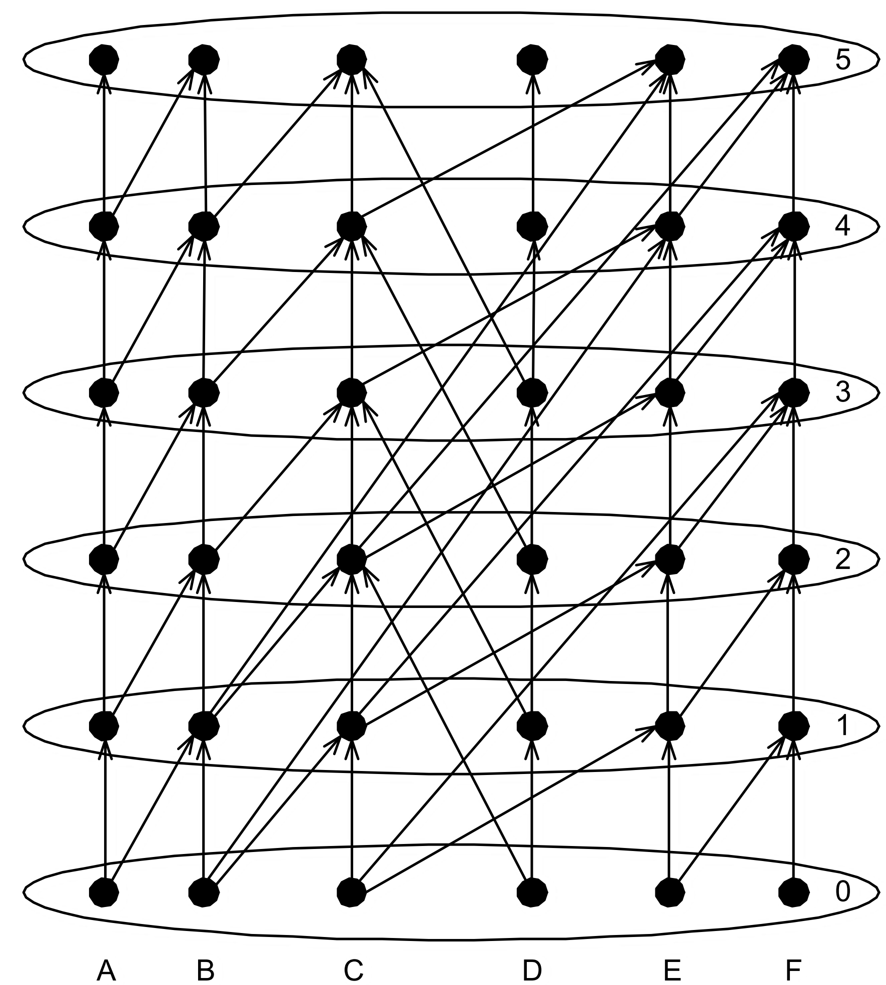


3. deadlocks

Our approach: dynamic flows

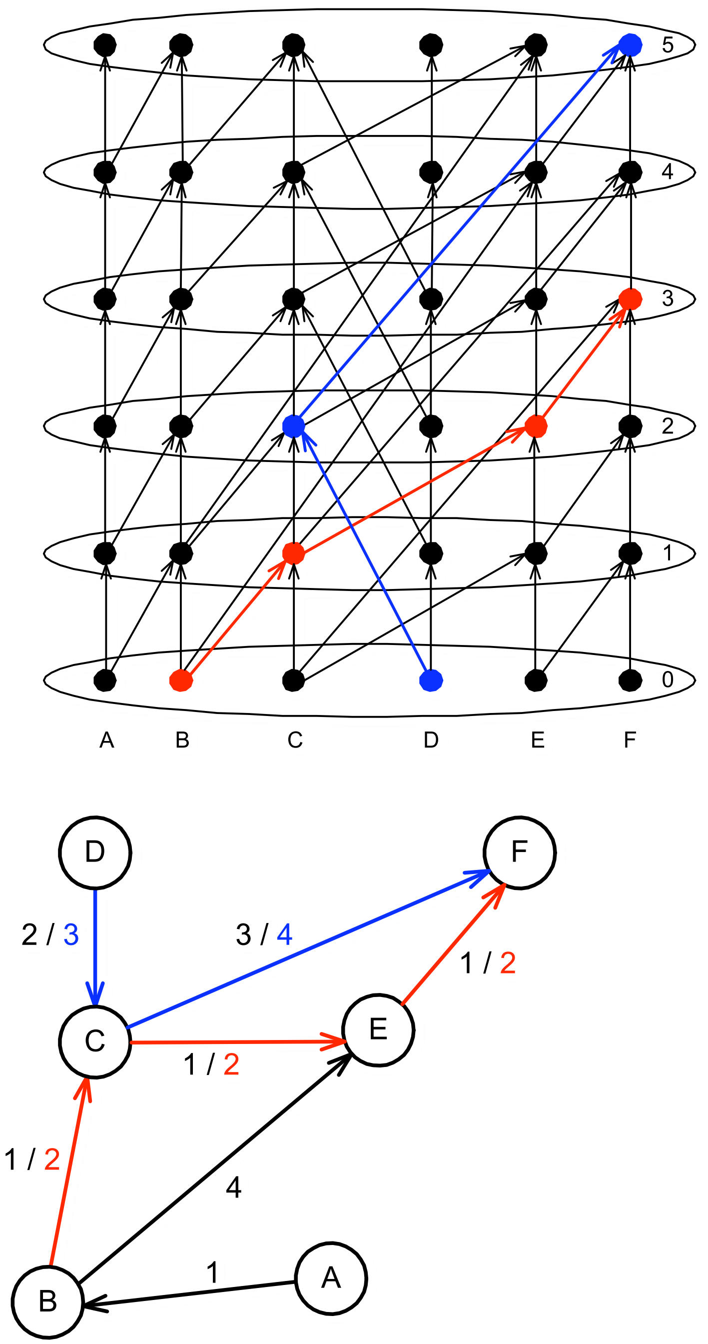


Graph

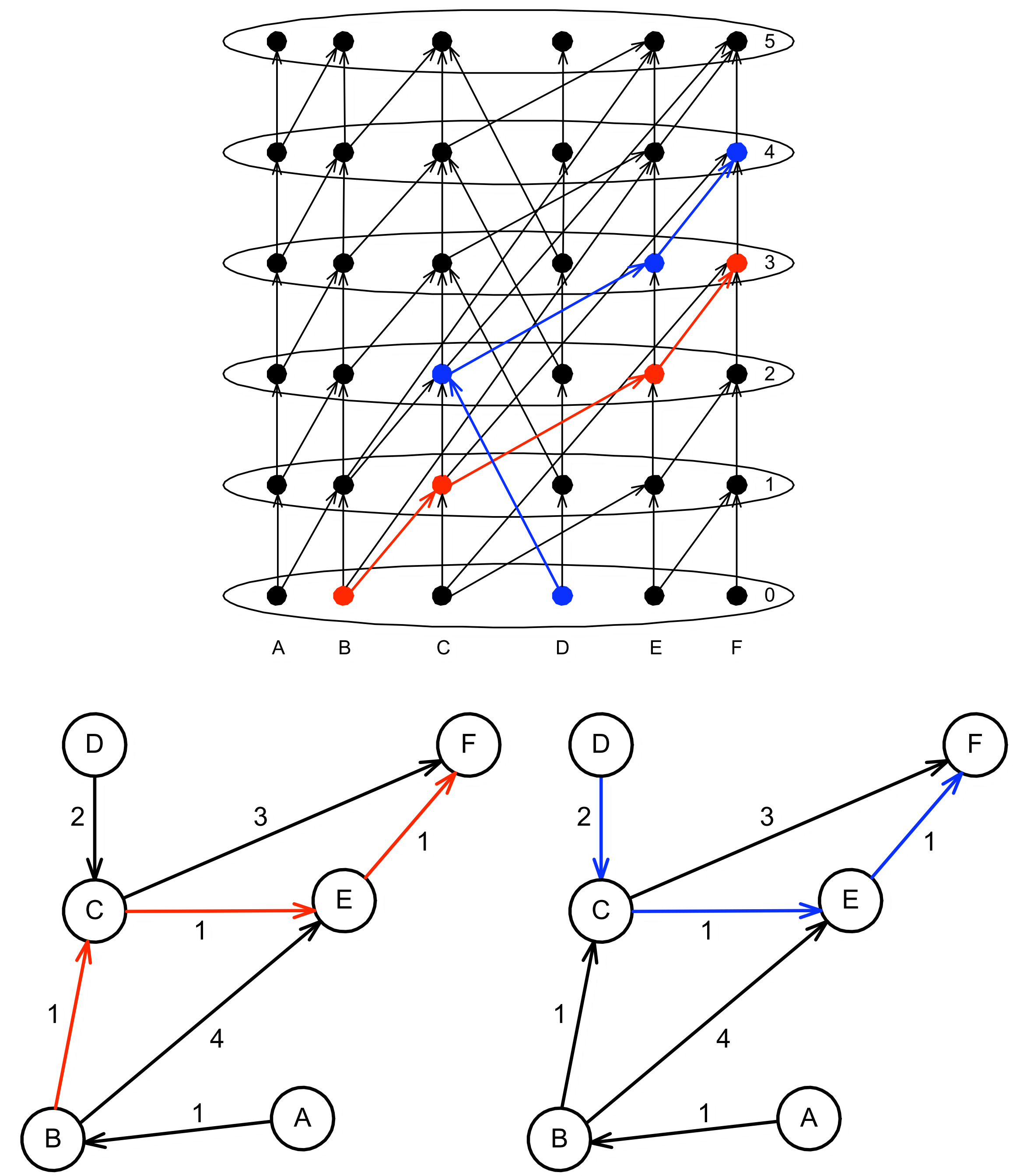


Time-expanded graph

Want disjoint paths in the time-expanded graph

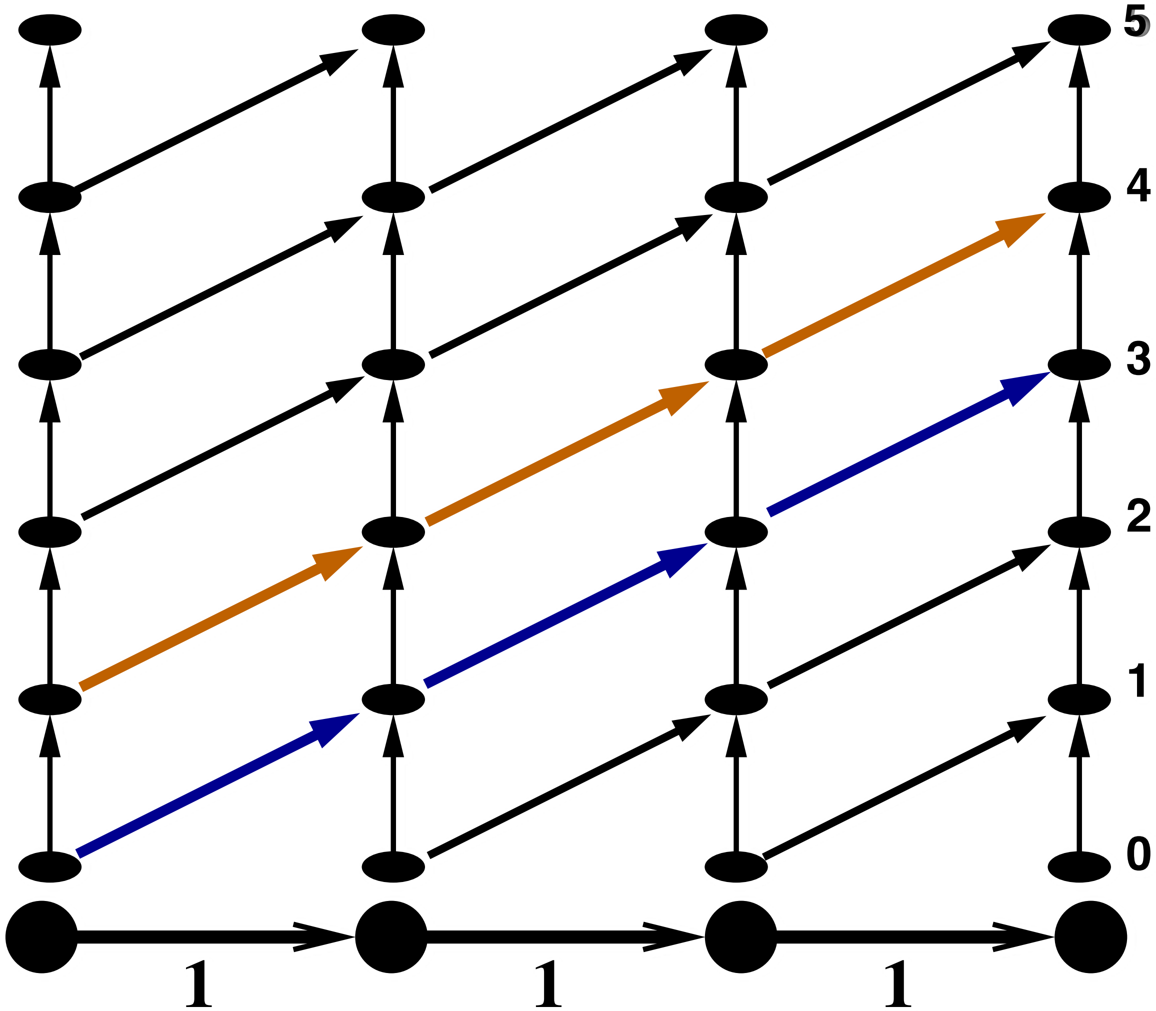


static routing, $T = 5$

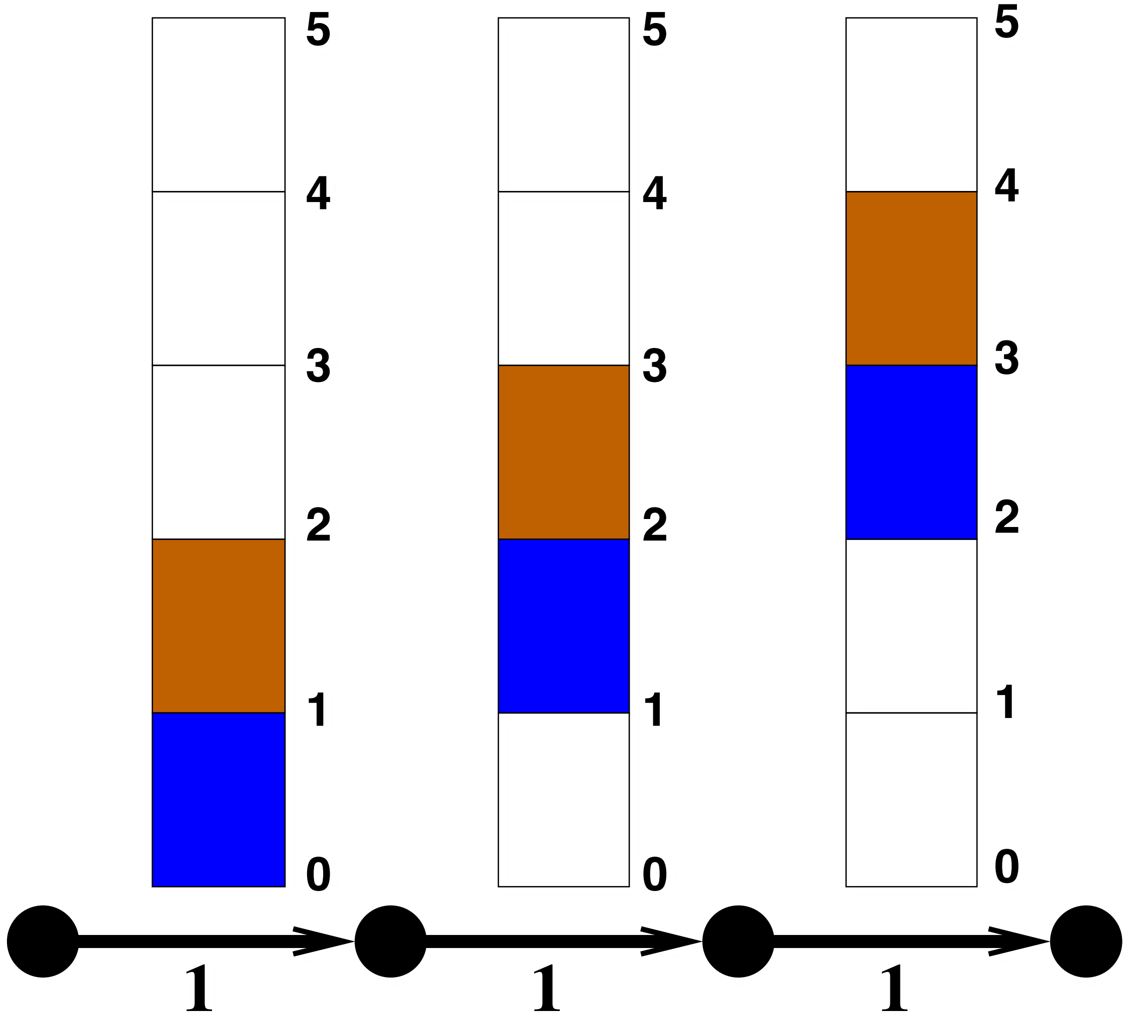


dynamic routing, $T = 4$

Modeling the time expansion



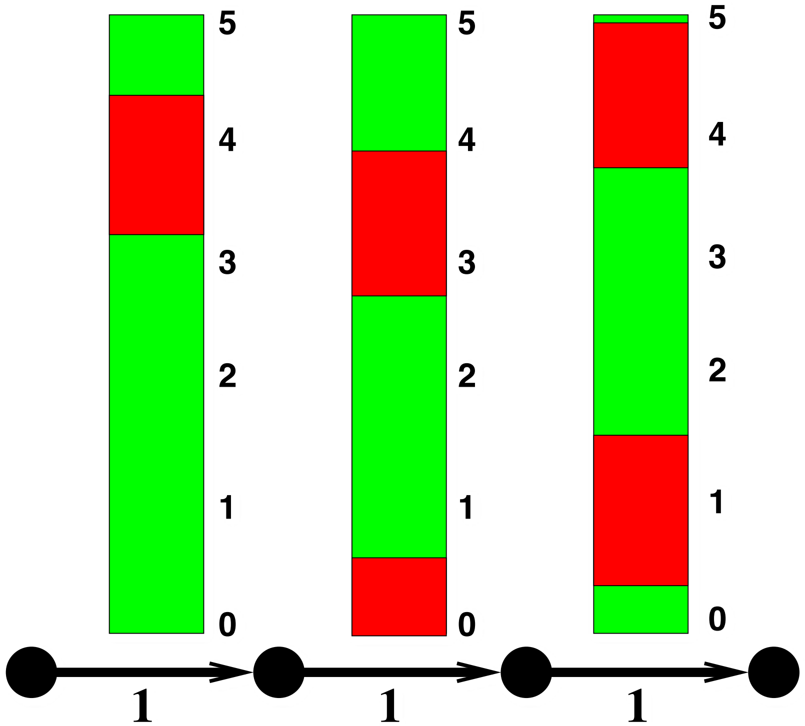
explicit time expansion



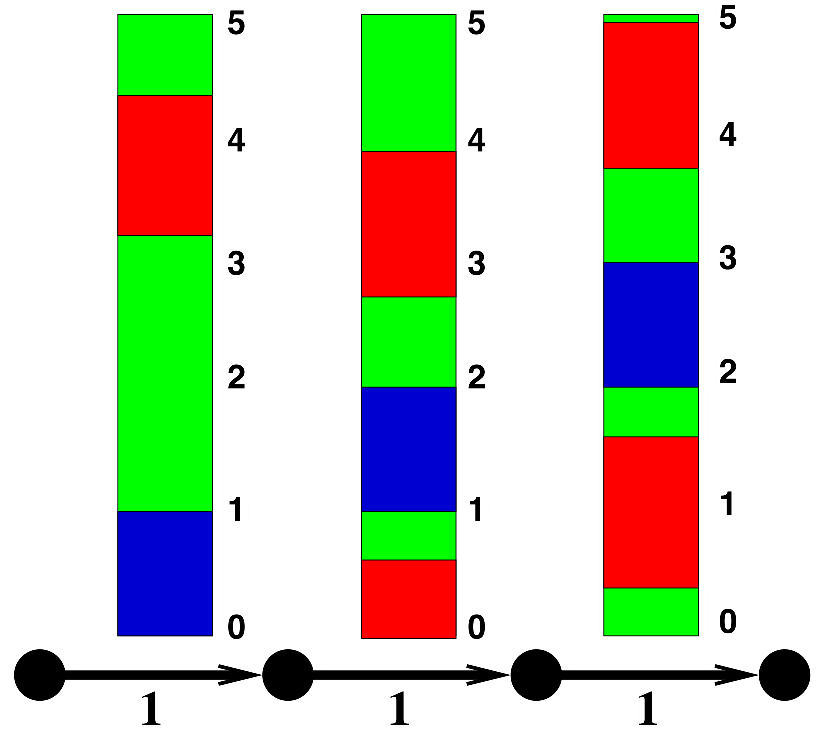
implicit time expansion

Shortest paths with time-dependent blockings

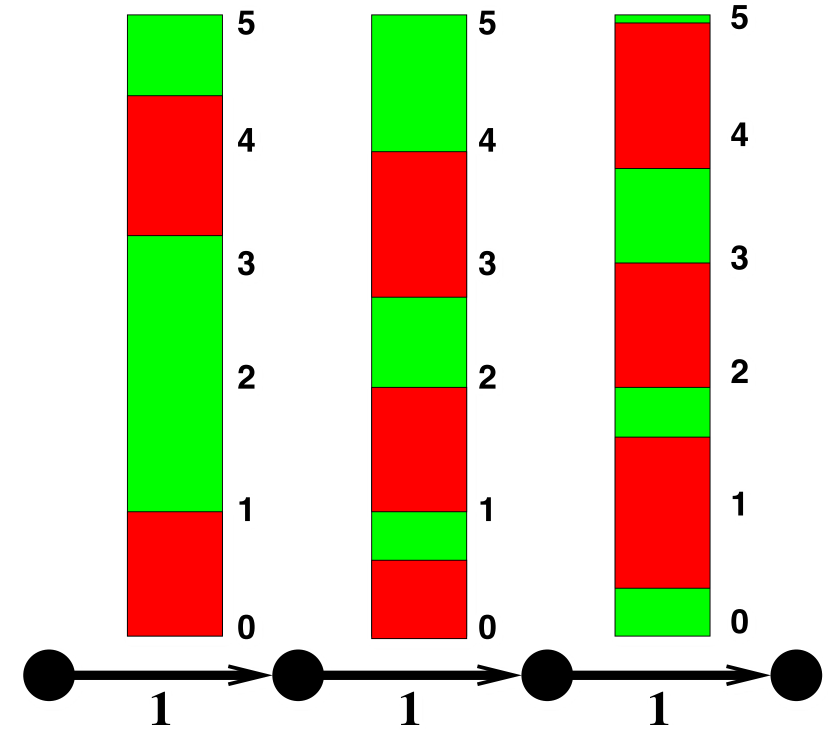
modeled by implicit time expansion



Graph with blockings



New path compatible with blockings



Updated blockings

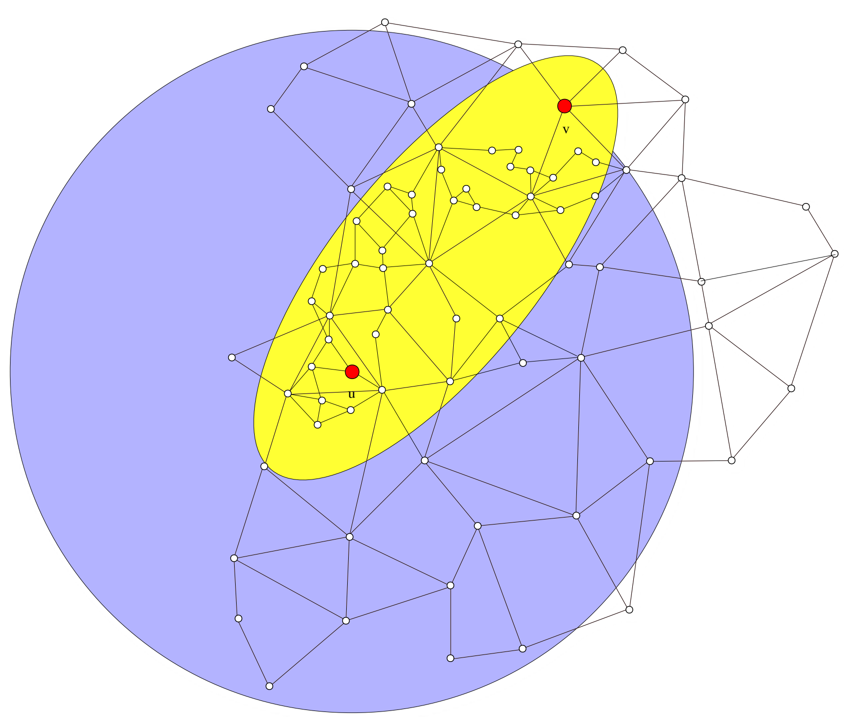
Known: shortest paths with time windows

J. Desrosier, Y. Dumas, M. Solomon, F. Soumis:
Time Constrained Routing and Scheduling
in: Handbook in Operations Research and
Management Science Vol. 8
Chapter 2: Network Routing, pp. 35 - 139
Elsevier 1995

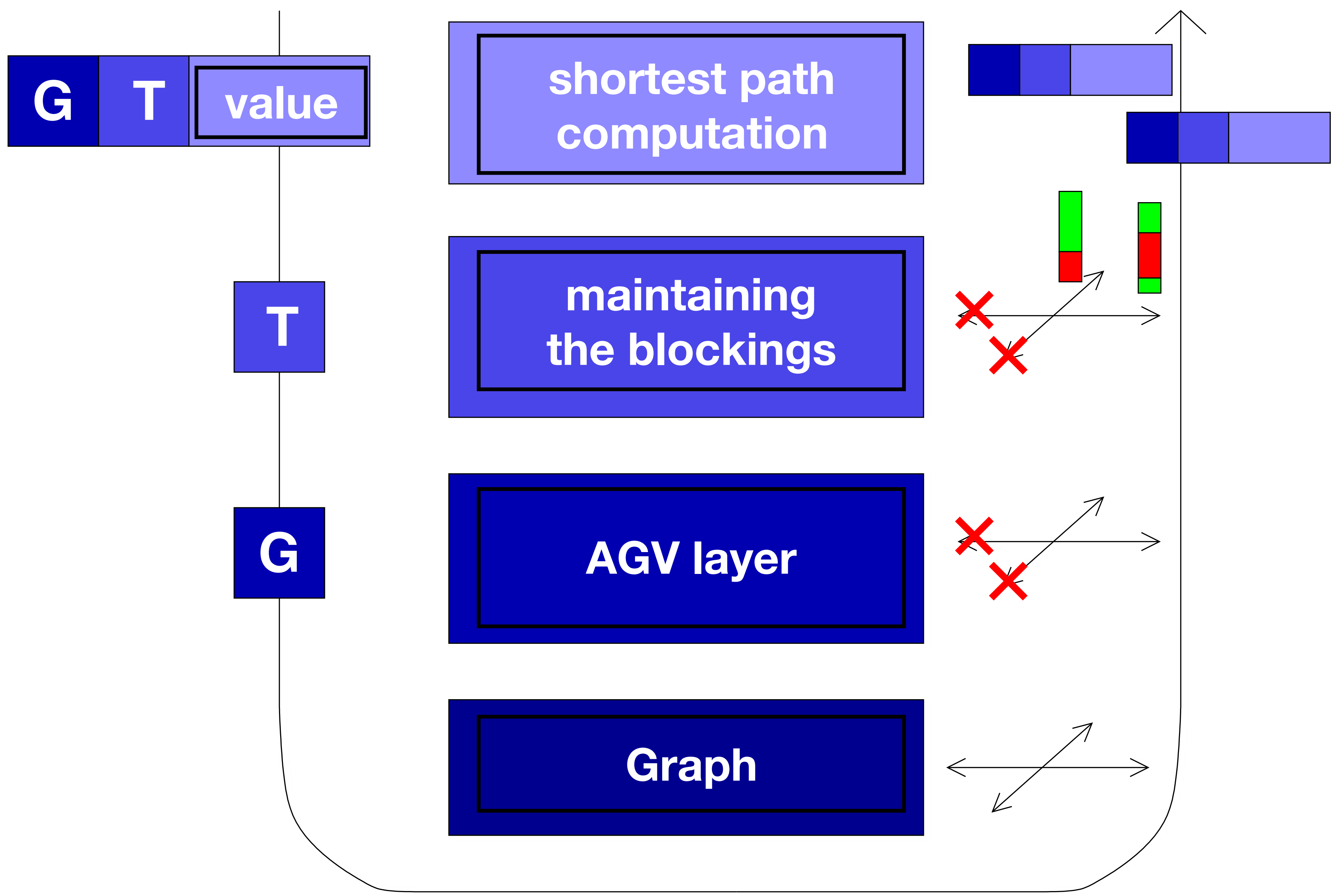
- Given: Graph $G = (V,E)$ with cost c_a, travel time τ_a and time windows F_a^i on every arc a
- Wanted: Shortest path w.r.t. cost c_a that respects the time windows w.r.t. the τ_a
- algorithmically difficult (NP-hard)
- easy here, as $c_a = \tau_a + \textit{time spent waiting}$

Efficient algorithm

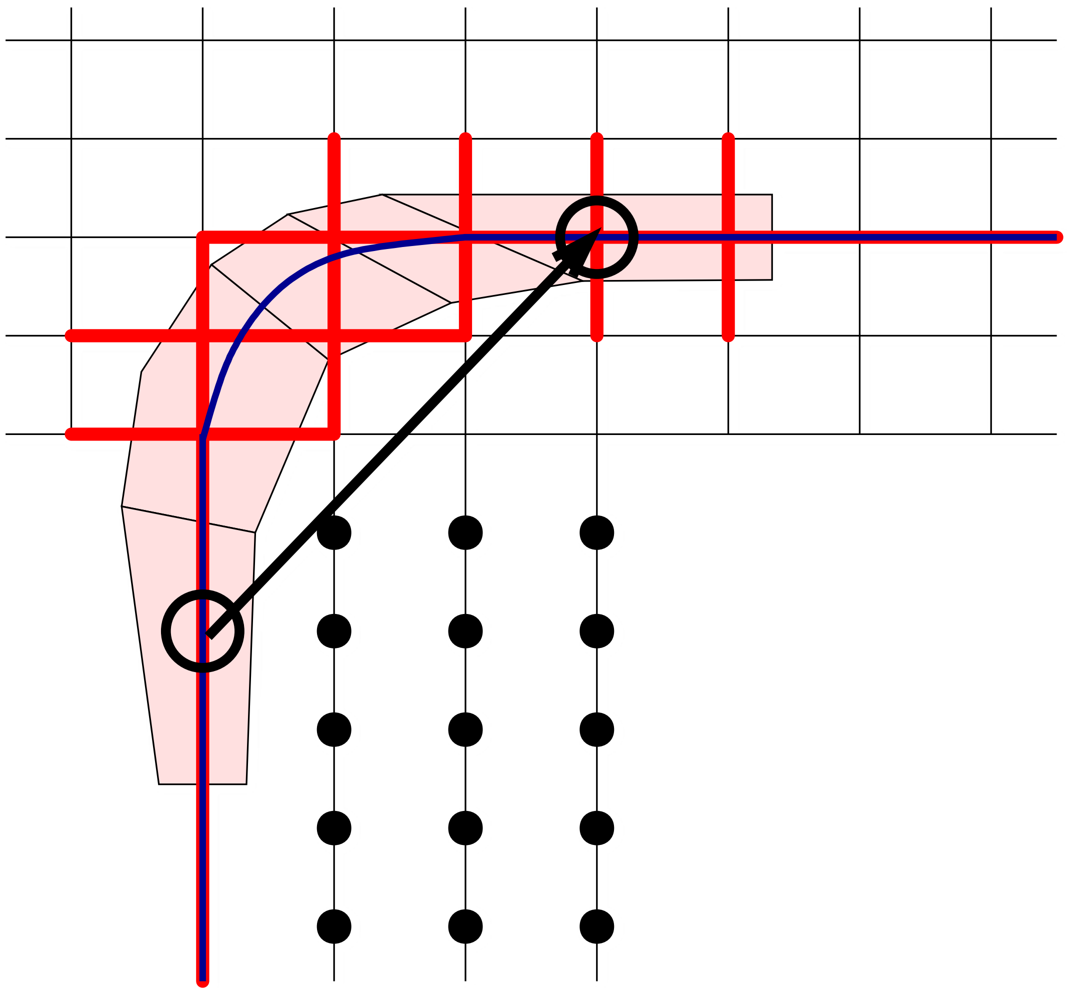
- Generalizes Dijkstra‘s algorithm, it minimizes
  travel time τ_a + *time spent waiting*
- Polynomial run time and very fast in practice
- Works also w.r.t. orientation and turning behavior of the AGVs
- Additional speed up by goal-directed search



Architecture of the algorithm

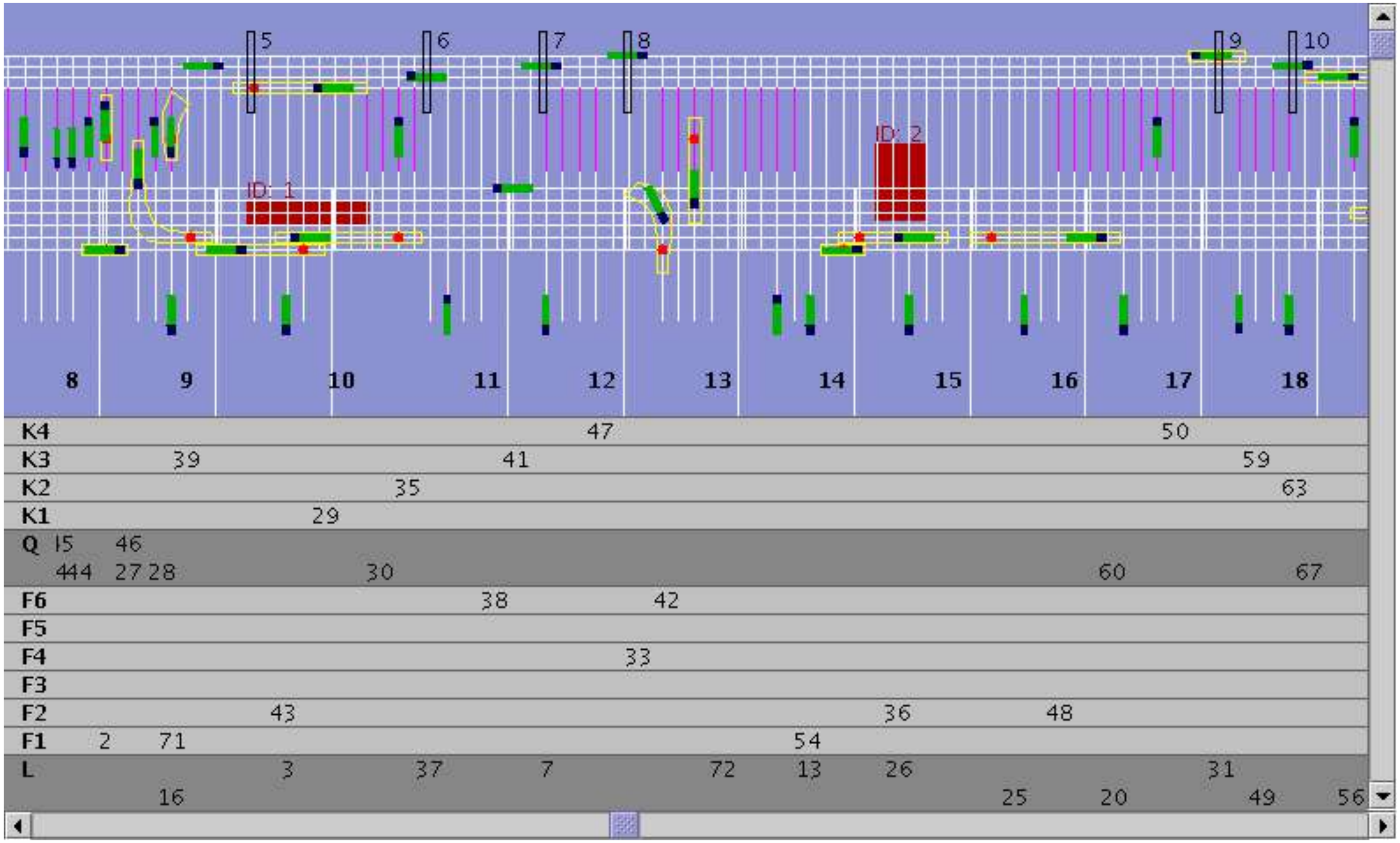


Details of the AGV layer

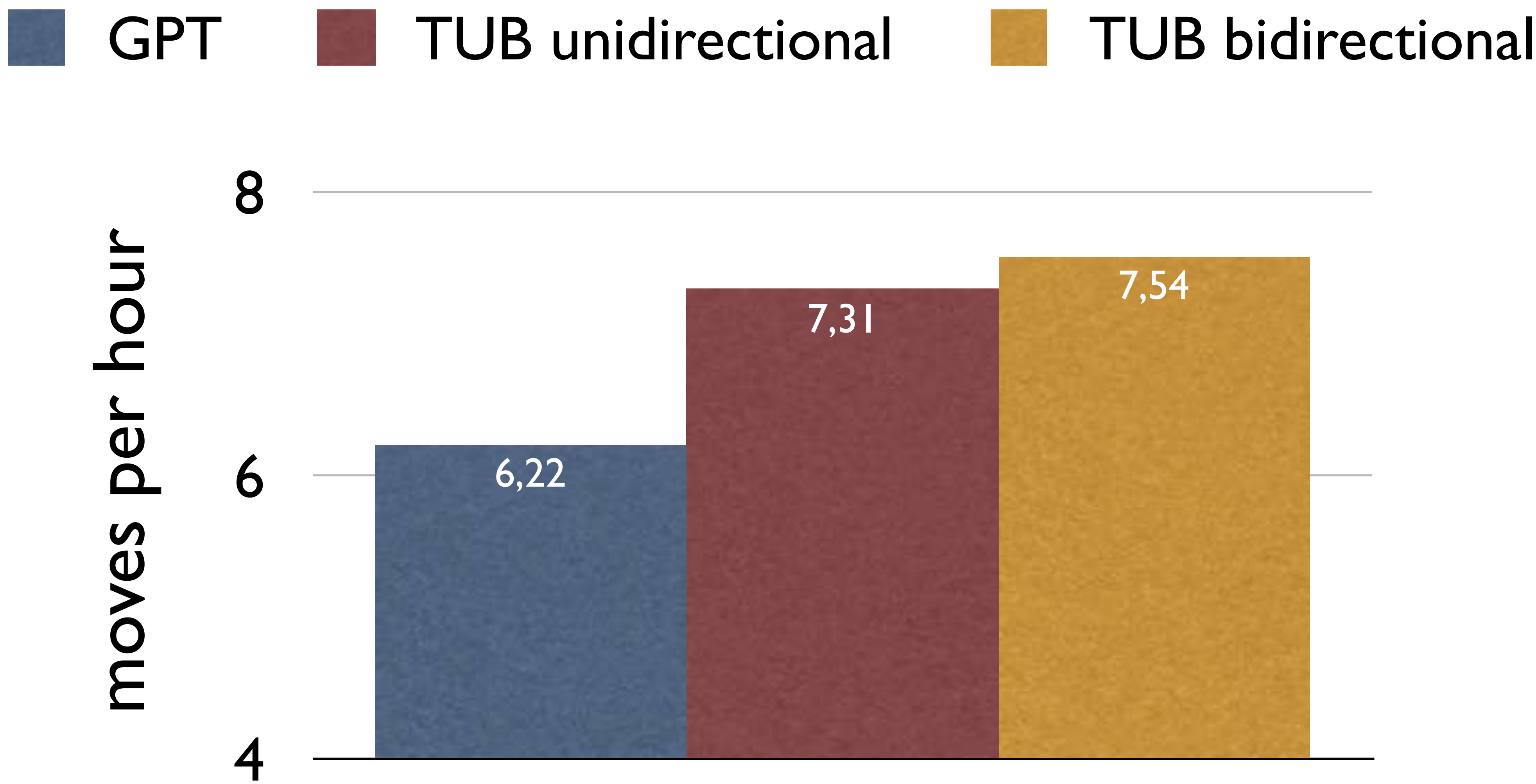


- Model the turning behavior through preprocessing
- Increases graph size to 5,445 vertices and 43,324 arcs

Dynamic routing in action

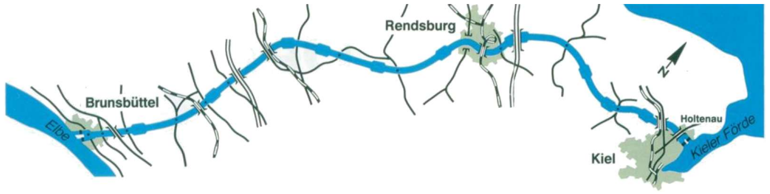


Results for 79 AGV scenario - overview

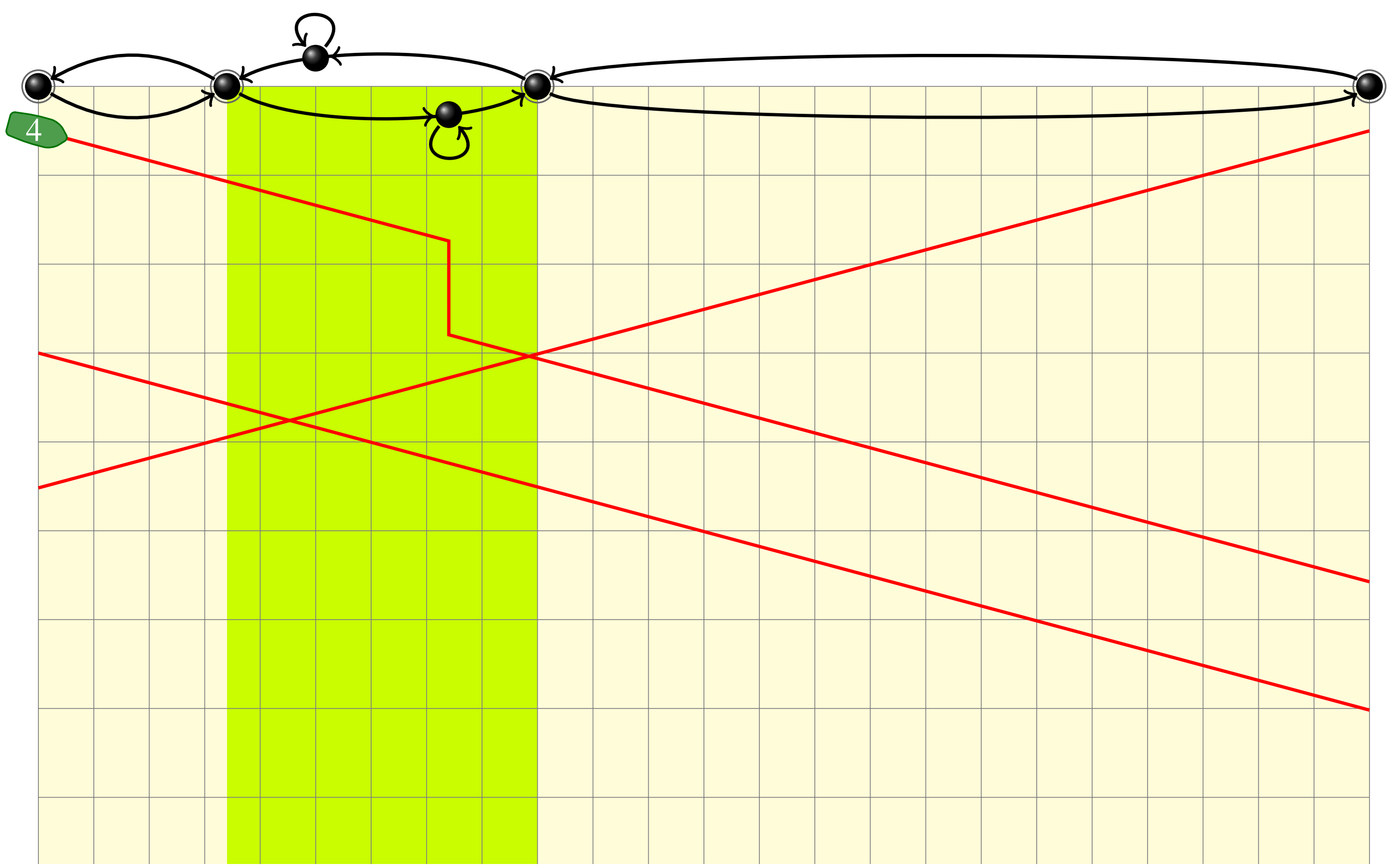


- 20% improvement in high traffic scenarios
- HHLA bought our software in 2009

Back to the Kiel canal



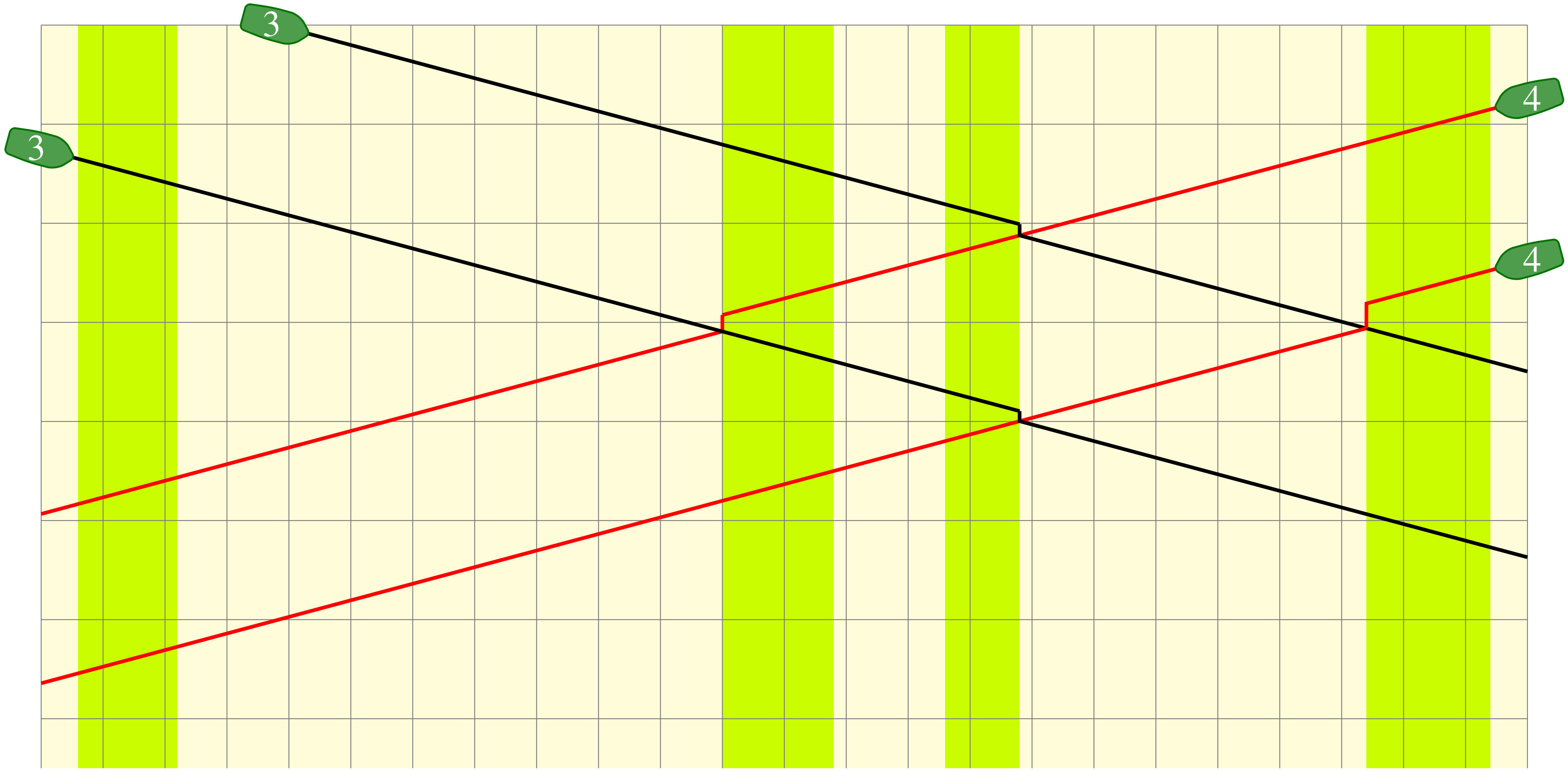
The routing part is polynomial in the canal …
use the AGV routing algorithm



… but the whole problem is strongly NP-hard

Sequential routing

- Can be arbitrarily bad
- There is no ordering that leads to an optimal solution



Mixed integer optimization models are too weak

even for simplifications of the model

$$\min \sum_{s \in S, t \in \mathcal{T}} w_{s,t}$$

s.t.

routing constraints

$$d_{s,e_{-s}} + \tau_{s,e} = d_{s,e} \qquad s \in S, e \in \mathcal{E} \setminus \mathcal{T}$$

$$d_{s,t_{-s}} + \tau_{s,t} + w_{s,t} = d_{s,t} \qquad s \in S, t \in \mathcal{T}$$

scheduling constraints

$$z_{s_1,s_2,e} = 1 \quad \Rightarrow \quad d_{s_1,e} + \Delta(s_1, s_2, e) \leq d_{s_2,e} \qquad e \in \mathcal{E} \setminus \mathcal{T}, (s_1, s_2) \in C_e$$

$$z_{s_1,s_2,e} = 0 \quad \Rightarrow \quad d_{s_2,e} + \Delta(s_2, s_1, e) \leq d_{s_1,e} \qquad e \in \mathcal{E} \setminus \mathcal{T}, (s_1, s_2) \in C_e$$

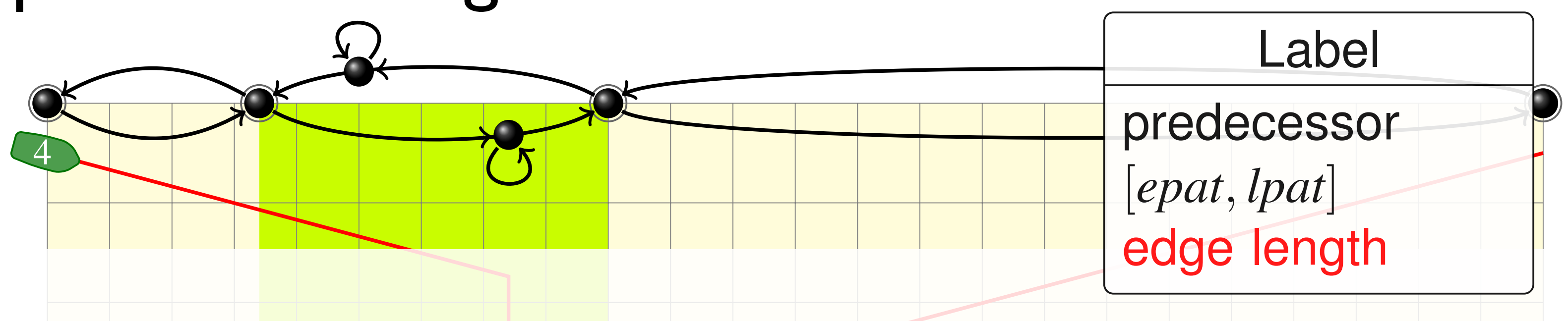
$$\underline{d}_{s,e} \leq d_{s,e} \leq \overline{d}_{s,e} \qquad s \in S, e \in \mathcal{E}$$

$$w_{s,t} \geq 0 \qquad s \in S, t \in \mathcal{T}$$

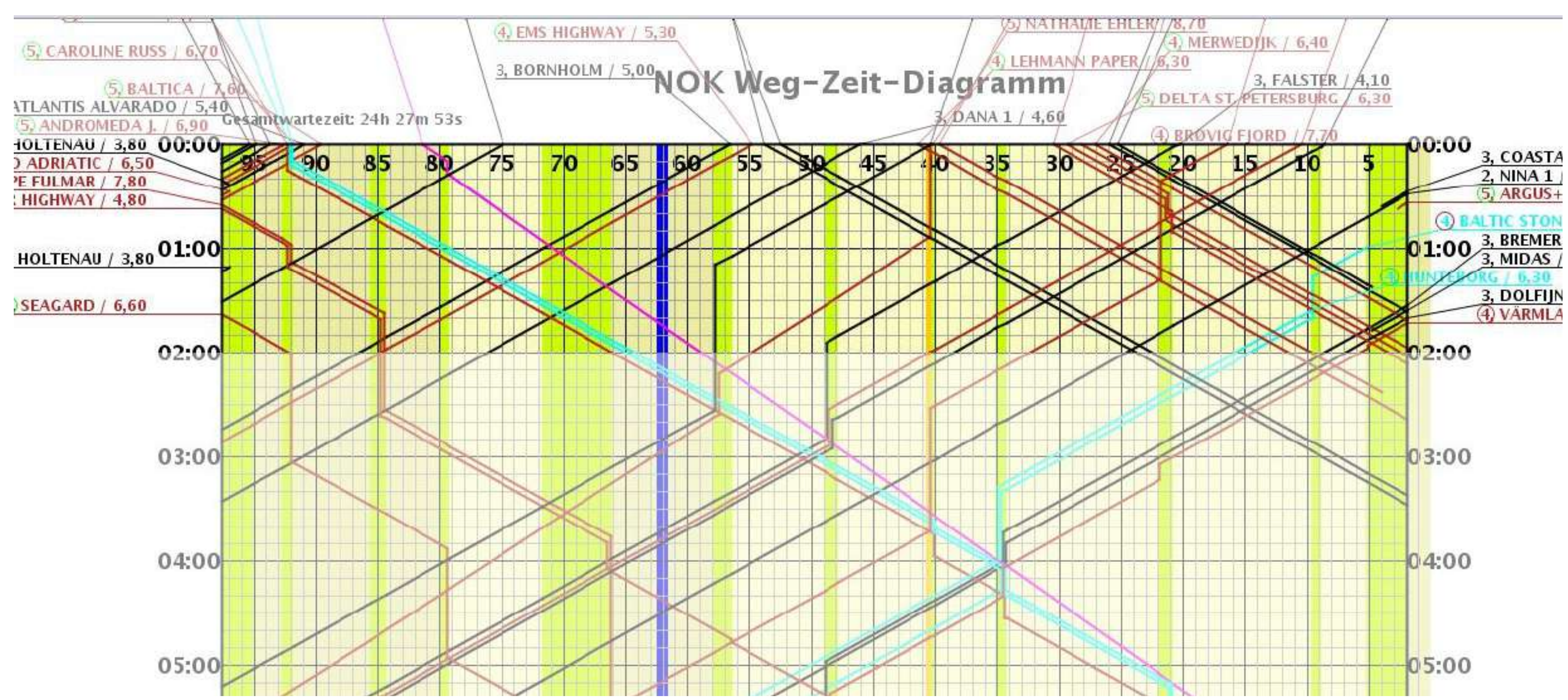
$$z_{s_1,s_2,e} \in \{0, 1\} \qquad e \in \mathcal{E} \setminus \mathcal{T}, (s_1, s_2) \in C_e$$

Our algorithm

- The routing part is polynomial ... but the scheduling makes the problem strongly NP-hard
- Use the router developed for routing AGVs in a container terminal ...

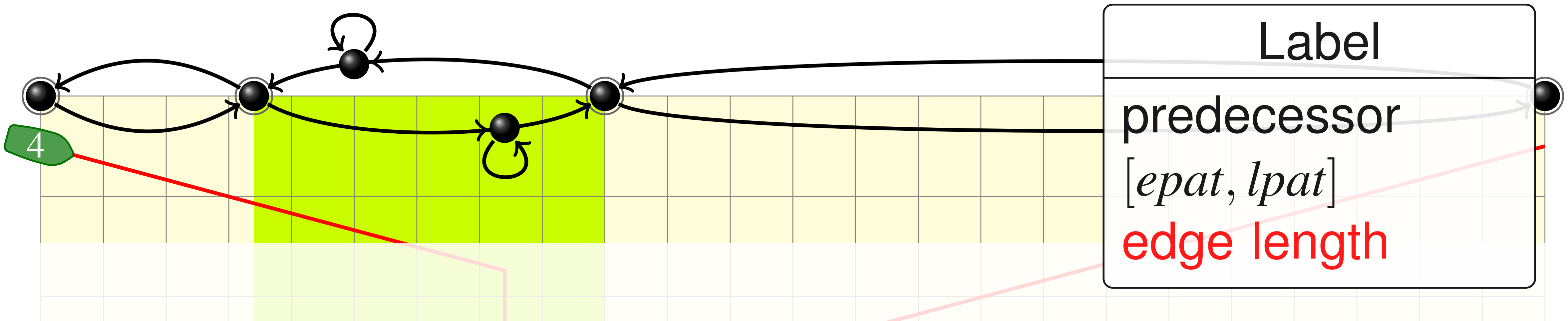


- ... and combine it with local search and a rolling time horizon for the scheduling



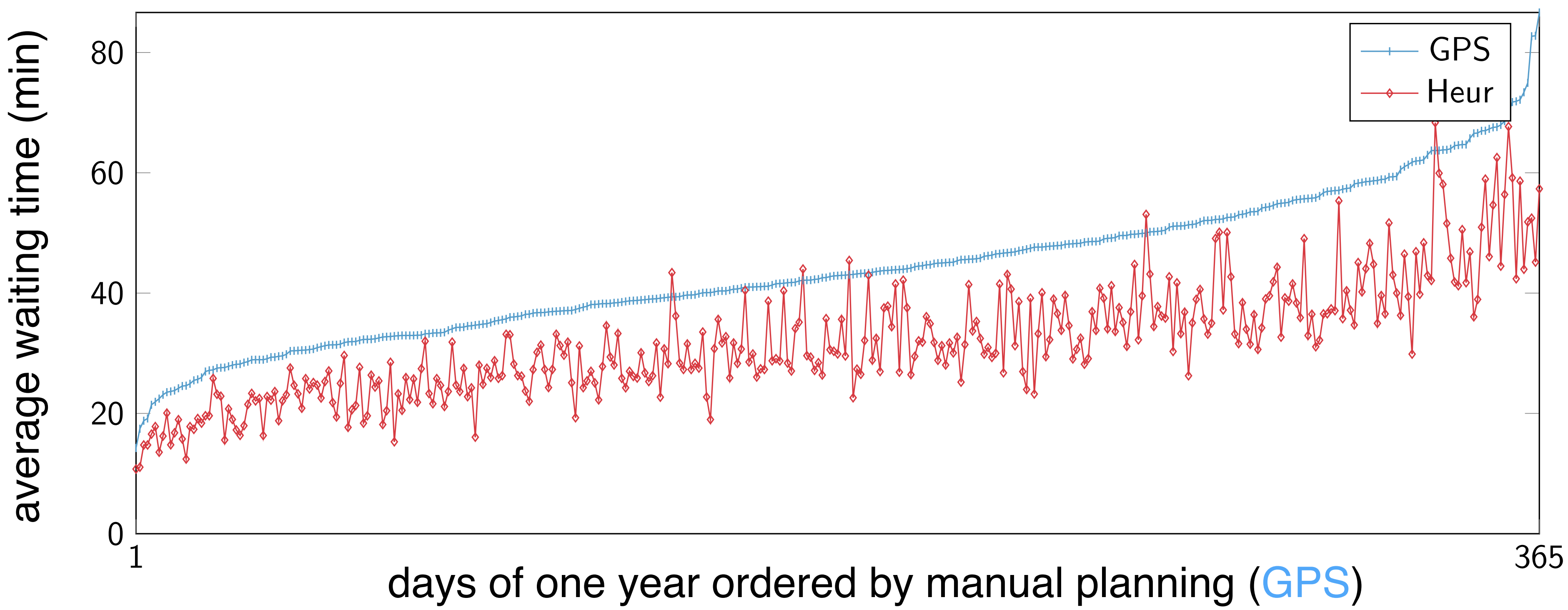
- Includes lock scheduling at both ends of the canal

Some of the many more details



- algorithm takes all sidings at once into account
- ensures that partial routes can be extended to a complete route
- respects different ship properties, locations in sidings
- uses a special graph with "implicit discretization" and advanced blocking calculation for this purpose
- covers all real world details

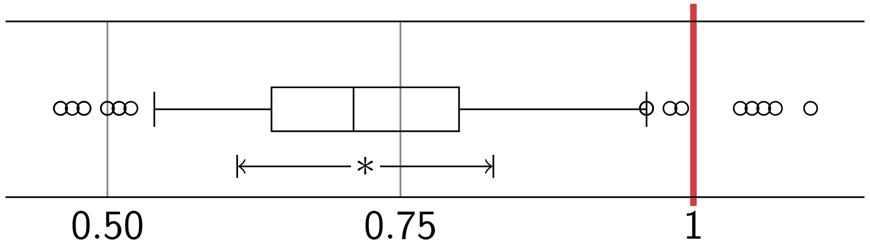
Results



GPS = manual planning
Heur = our algorithm

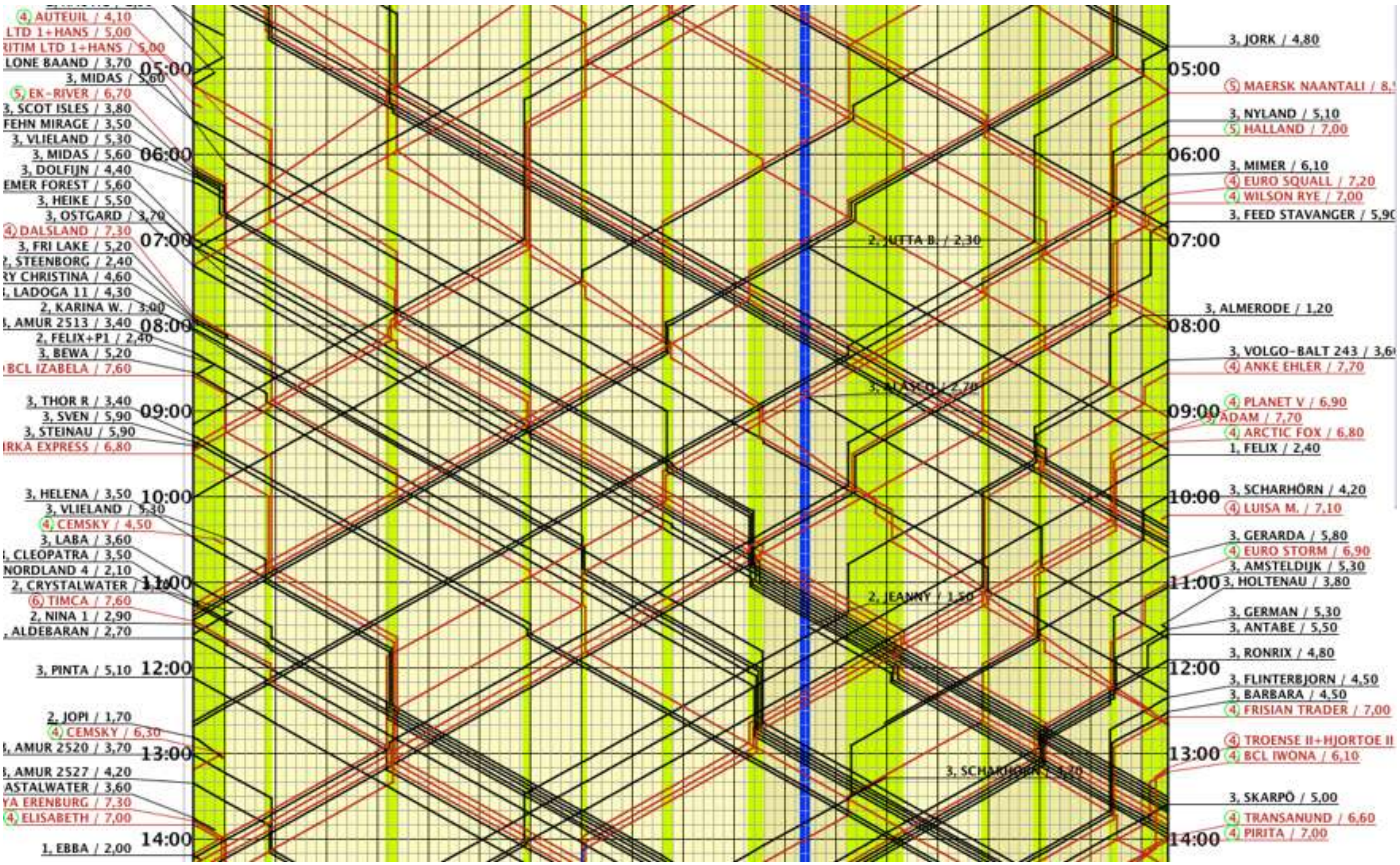
data from the box

box plot Heur/GPS

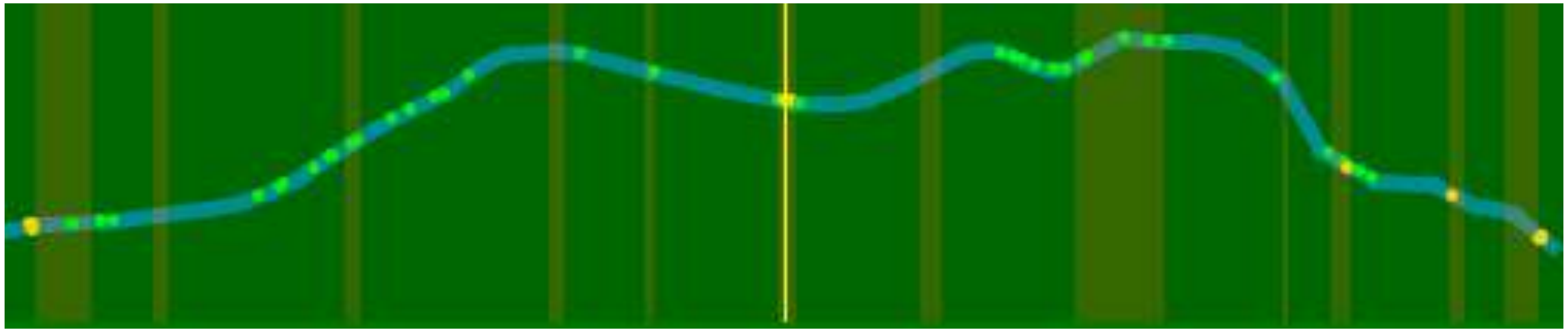


- Similar behavior as manual planning
- 25% improvement on average
- thus suited for studying different options for the canal enlargement
- recommendations for enlargement made in 2011
- continuation of the project for the construction phase was planned

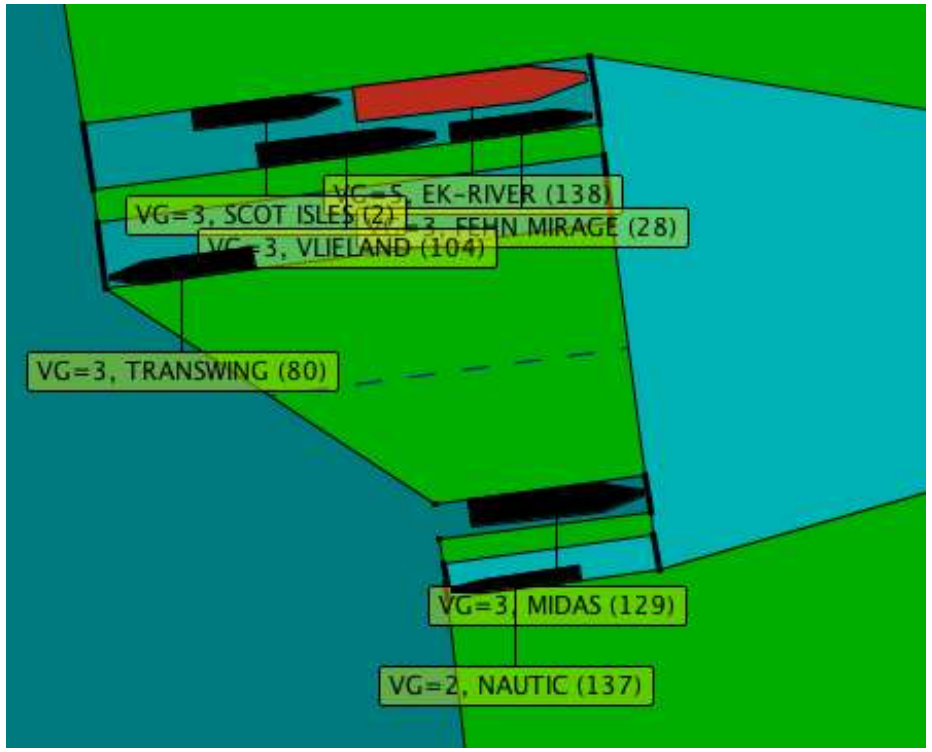
Glimpses of the algorithm: Space-time diagram



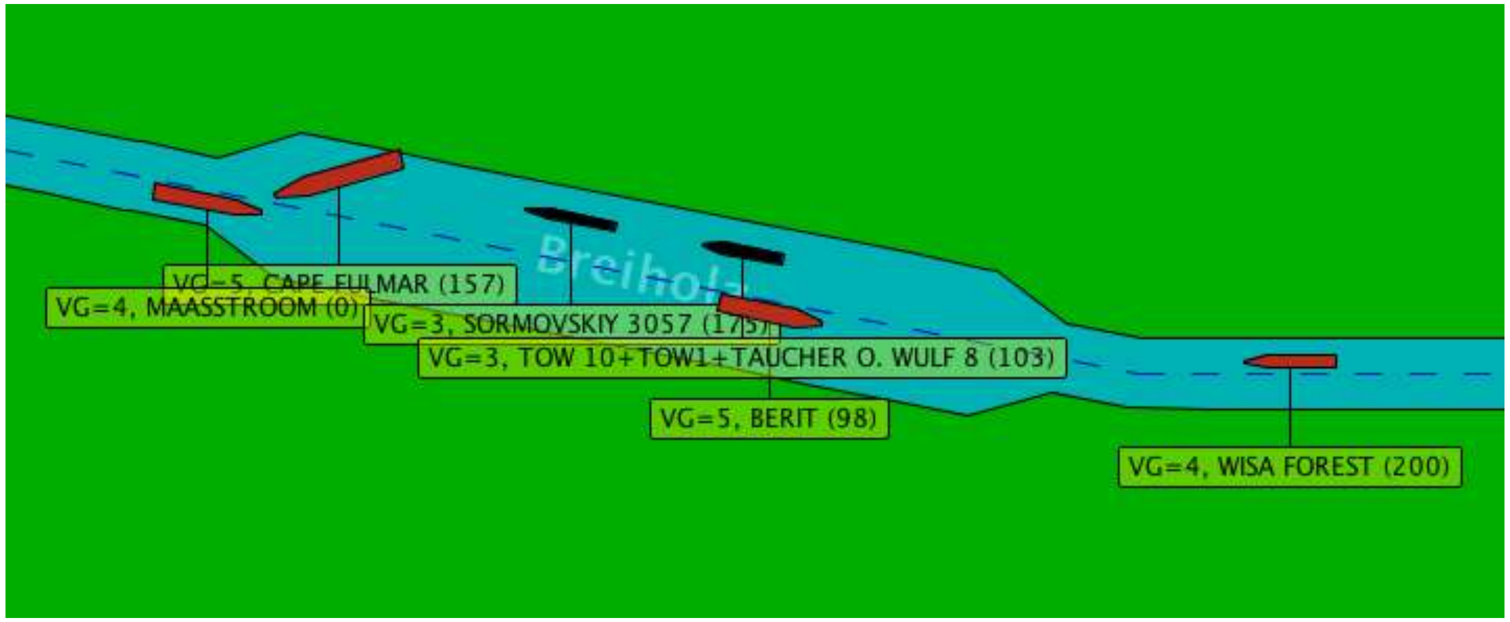
Glimpses of the algorithm: Traffic visualization



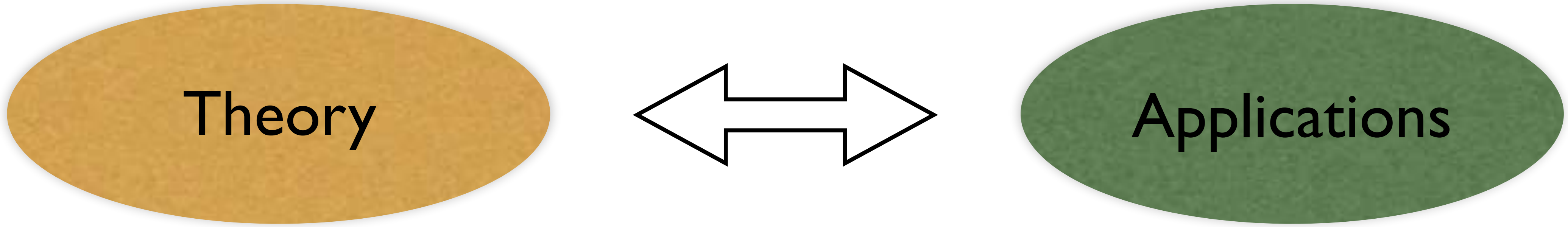
Global view



Locks in Brunsbüttel



Siding in Breiholz



Practice generates many theoretical questions
that often are only solved after completion of the project

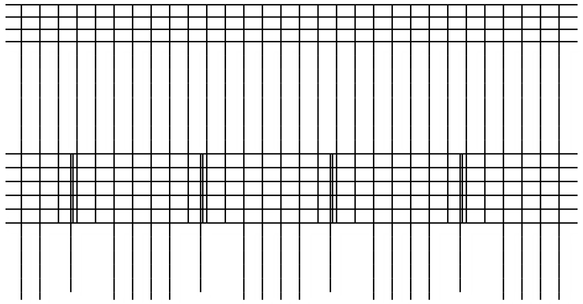
Research questions from the AGV routing project

- Why route AGVs sequentially?
- What is the sequential gap?
- Can the static approach be improved?
- Is it competitive?

[Ewgenij Gawrilow, Max Klimm, R. M., Björn Stenzel]
EURO J Transp Logist 2012

Summary ex post analysis

- Complexity results justify sequential routing algorithm
  - polynomial in theory and fast in practice
- Sequential gap is small for harbor grid layout
  - less than 4% for 4-6 horizontal tracks



- Static approach can be improved by load balancing and proper deadlock avoidance
  - load balancing improves runtime
  - travel time for deadlock avoidance increases rapidly with traffic density
- Dynamic router is is the clear winner for dense traffic
  - but (slightly) inferior in low traffic scenarios

Research questions from the Kiel canal project

Scheduling Bidirectional Traffic on a Path

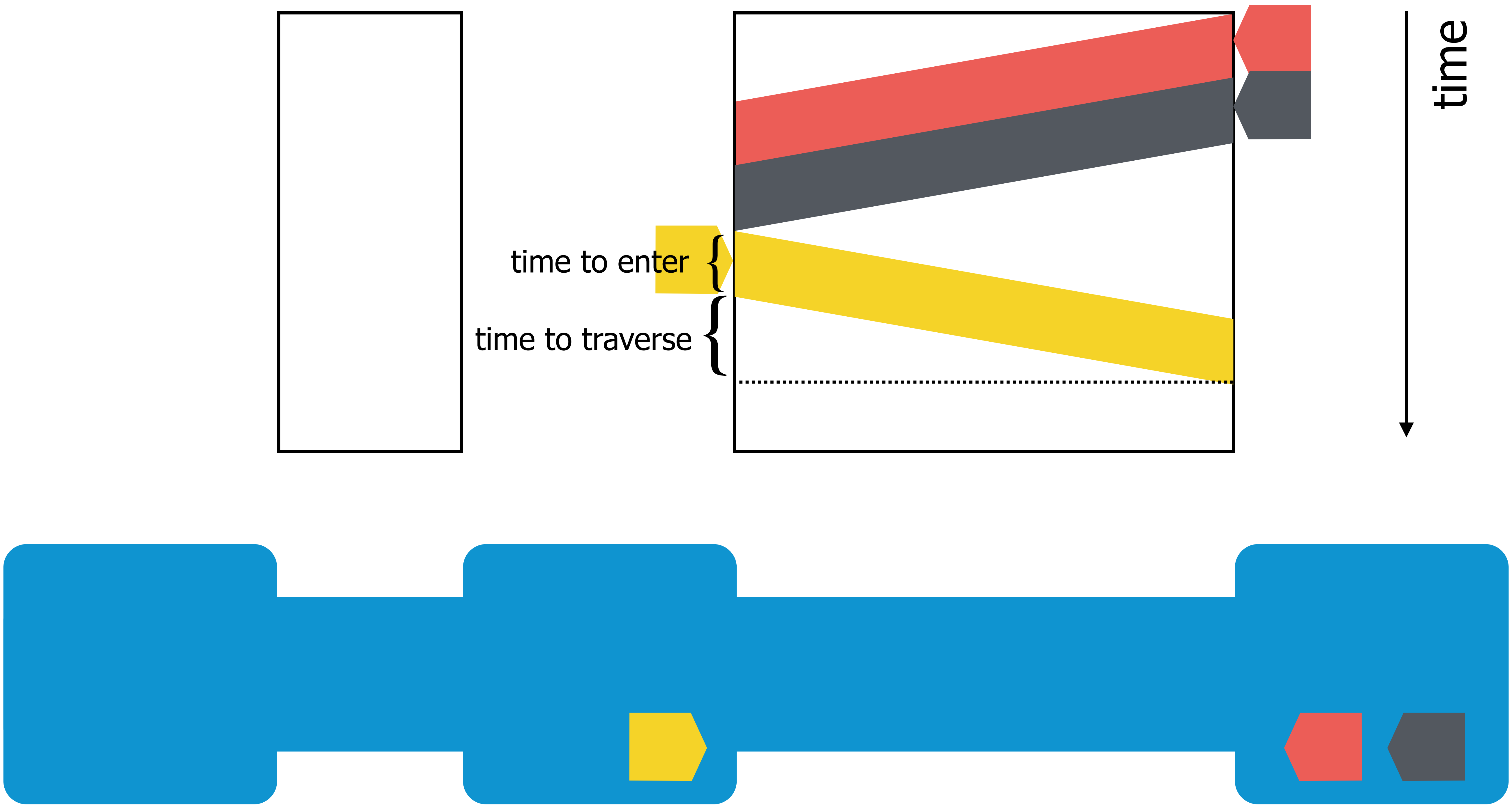
Max Klimm | Technische Universität Berlin

joint work with Yann Disser and Elisabeth Lübbecke

ICALP 2015, LNCS 9134, pp. 406–418

slide thanks to Max Klimm

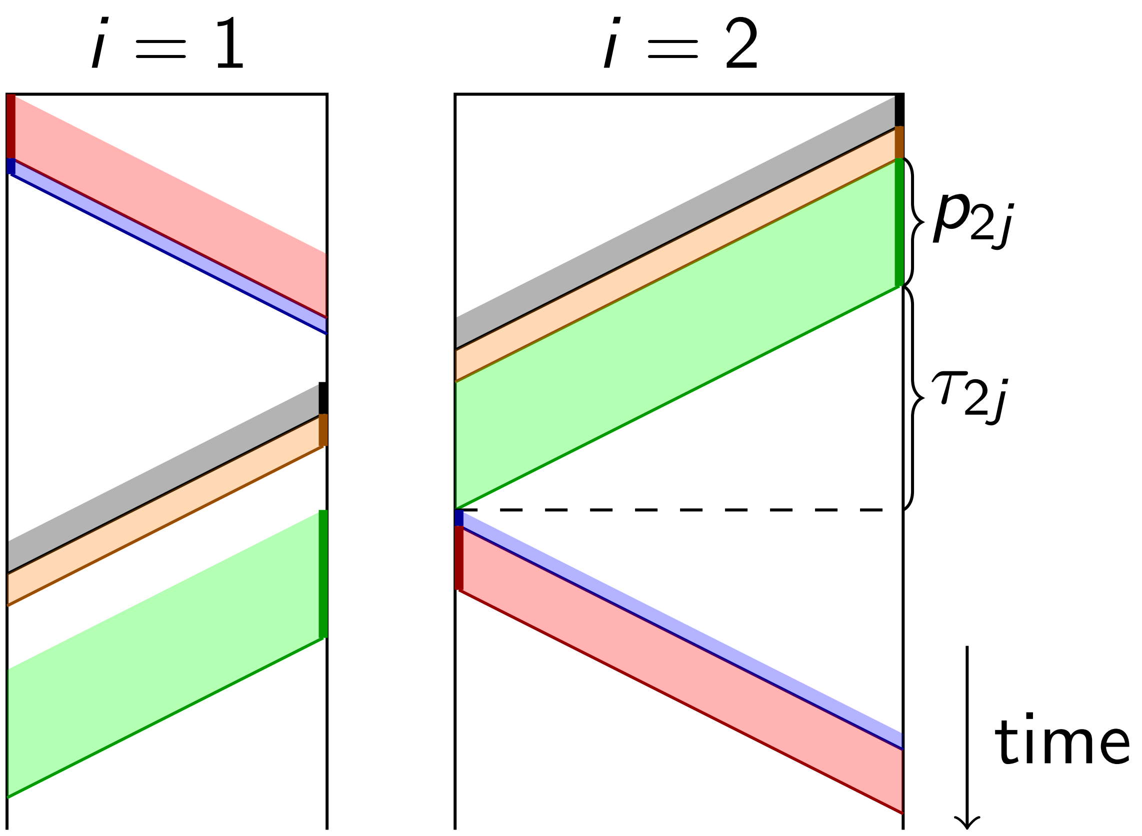
Space-time diagrams



slide thanks to Max Klimm

Model

- segments $1, \ldots, m$ ordered from left to right
- transit time τ_{ij}
- rightbound and leftbound jobs $J = J^{\mathrm{r}} \cup J^{\mathrm{l}}$
- release date r_j
- processing time p_{ij}
- start and target segments s_j, t_j



no passing in opposing directions

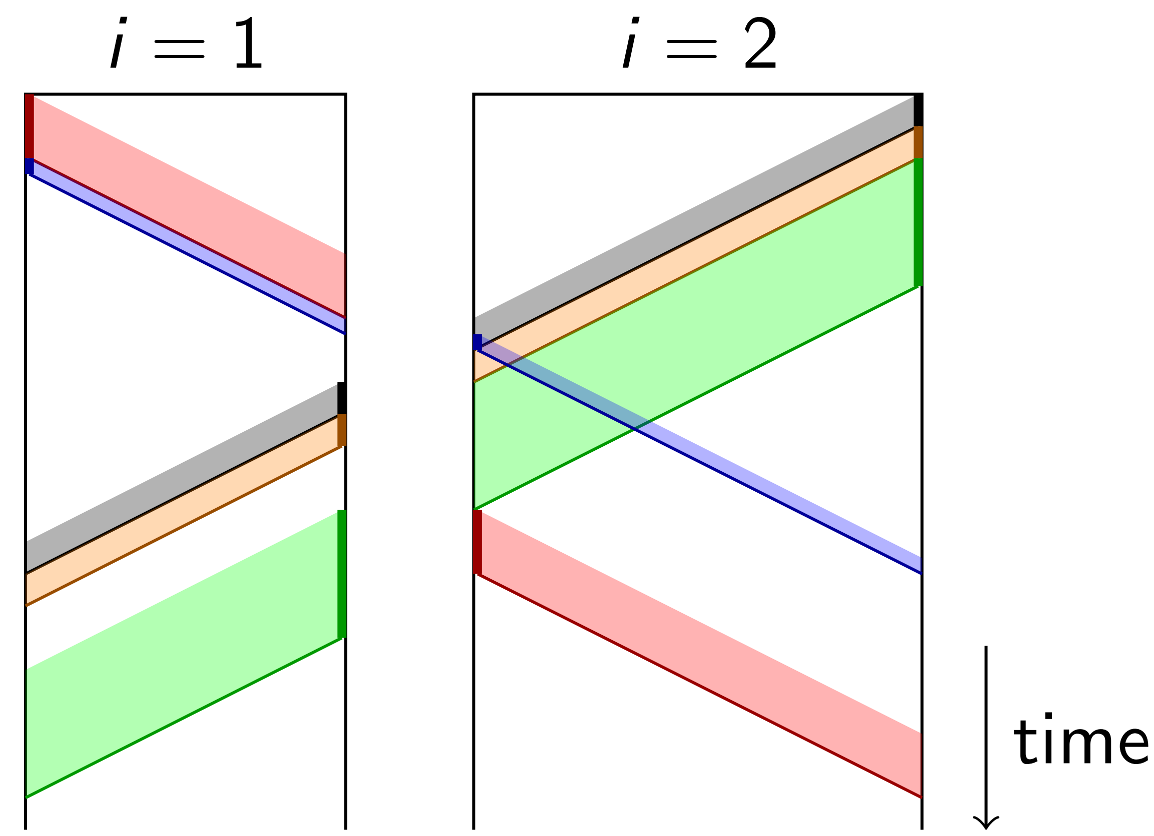
- objective: $\sum C_j$

  (also $\sum W_j$ or $C_{\max}$)

Model

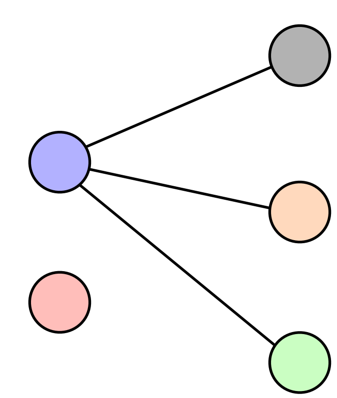
- segments $1, \ldots, m$ ordered from left to right
- transit time τ_{ij}
- compatibility graph G_i

- rightbound and leftbound jobs $J = J^{\mathrm{r}} \cup J^{\mathrm{l}}$
- release date r_j
- processing time p_{ij}
- start and target segments s_j, t_j



blue ship may pass others

- objective: $\sum C_j$
  (also $\sum W_j$ or $C_{\max}$)



slide thanks to Max Klimm

Main results

compatibilities	$m = 1$	m const.	m arbitrary
	Number m of segments		
Identical jobs ($p_{ij} = p$), $\tau_{ij} = \tau_i$			
none compatible / const. types	polynomial	polynomial[1]	NP-hard[2]
arbitrary	NP-hard[3]		
Different jobs ($p_{ij} = p_j$), $\tau_{ij} = \tau_i$			
none or all	NP-hard		NP-hard[2]

[1] only if $p = 1, \tau_i \leq$ const, [2] even if $p = 0$, $\tau_i = 1$, [3] even if $\tau_i = p = 1$

slide thanks to Max Klimm

Main results

compatibilities	Number m of segments: $m = 1$	m const.	m arbitrary
Identical jobs ($p_{ij} = p$), $\tau_{ij} = \tau_i$			
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Different jobs ($p_{ij} = p_j$), $\tau_{ij} = \tau_i$			
none or all	PTAS	NP-hard	NP-hard[2]

[1] only if $p = 1, \tau_i \leq$ const, [2] even if $p = 0$, $\tau_i = 1$, [3] even if $\tau_i = p = 1$

slide thanks to Max Klimm

Related work in „classical“ scheduling

Single machine scheduling:

- NP-hard [Lenstra et al., 1977]
- PTAS [Afrati et al., 1999]
- of two job families with setup times

Flow shop scheduling:

- without release dates:
  - NP-hard already for $m = 2$ [Garey et al., 1976]
  - no PTAS for arbitrary m [Hoogeveen et al., 1998]
- with release dates:
  - polynomial for $p_{ij} = 1$ [Brucker et al., 2005]

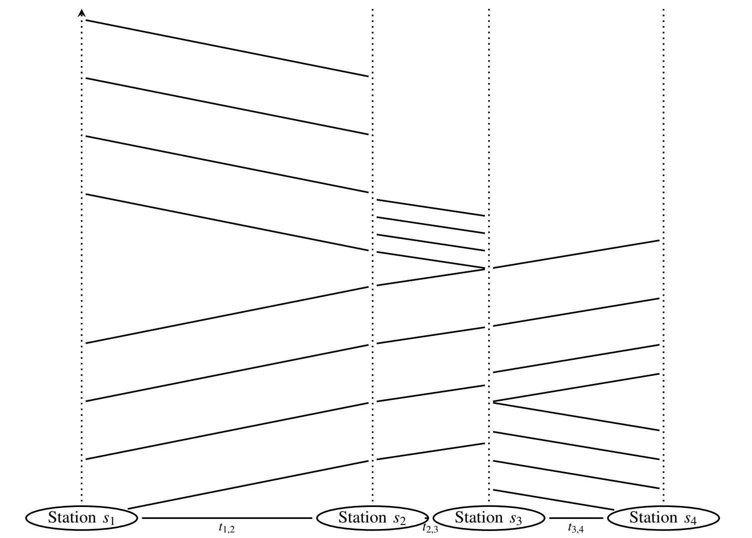
Job shop scheduling:

- with release dates:
  - PTAS for constant m [Fishkin et al., 2003]

slide thanks to Max Klimm

Related work about bidirected traffic (1)

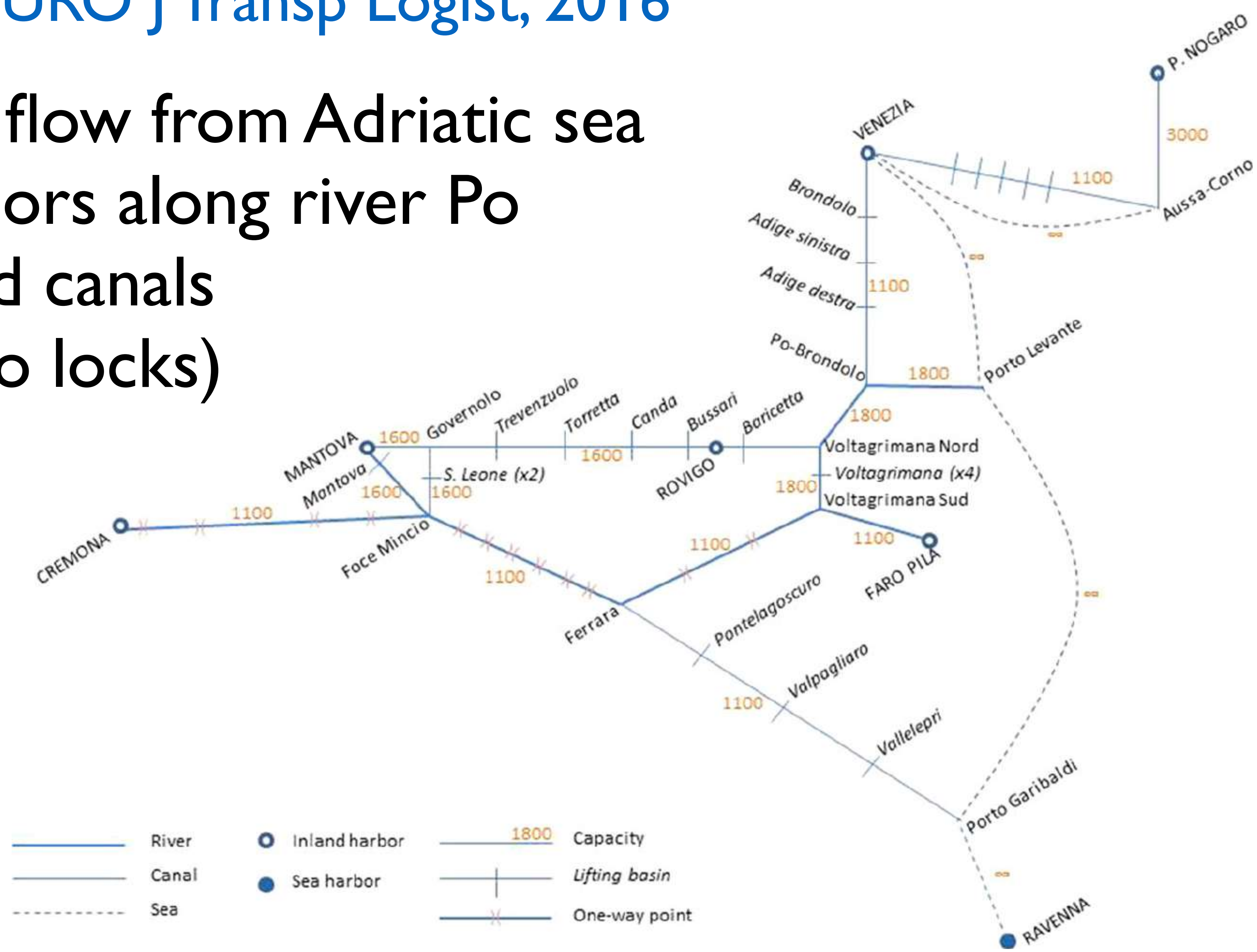
- Single Track Train Scheduling
  J. Harbering, A. Ranade, M. Schmidt, Preprint, 2015
  - complexity results about the scheduling (no compatibility graph)



- The generalized lock scheduling problem: An exact approach
  J. Verstichel, P. De Causmaecker, F. Spieksma, G. Vanden Berghe, Transportation Research 2014
  - ship placement, chamber assignment and lockage operation scheduling solved with mixed integer linear programming

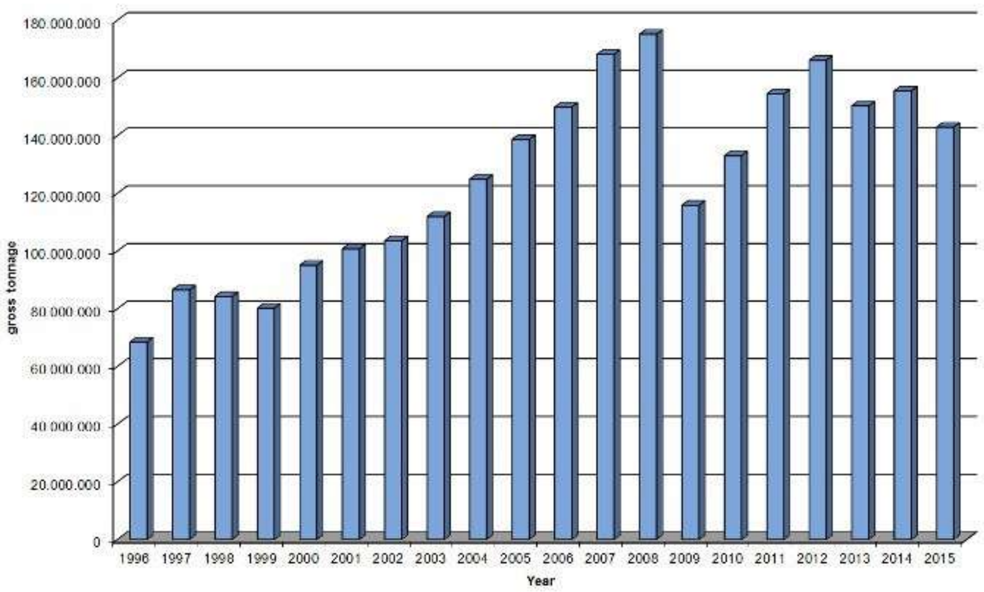
Related work about bidirected traffic (2)

- A network flow model of the Northern Italy waterway system
  Giovanni Righini, EURO J Transp Logist, 2016
  - estimate max flow from Adriatic sea to inland harbors along river Po and connected canals (considers also locks)



After the completion of the project

- Total tonnage decreased after 2008



- 2014: Government provides € 265 million for enlargement of the Eastern part
  - New lock chamber in Kiel, starting in 2018
  - Improvements of bends in the Eastern part
  - Enlargements of sidings in the Eastern part

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Thanks!

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