Capacity Estimation

Based on
Joe Mitchell's slides

Output: Capacity

- What is capacity?
- Estimate of number of aircraft that can be safely routed within a constrained airspace.
- Demand-driven capacity
- Sector-induced capacity: MAP, human factors, depends on complexity of traffic flows and presence of hazardous weather

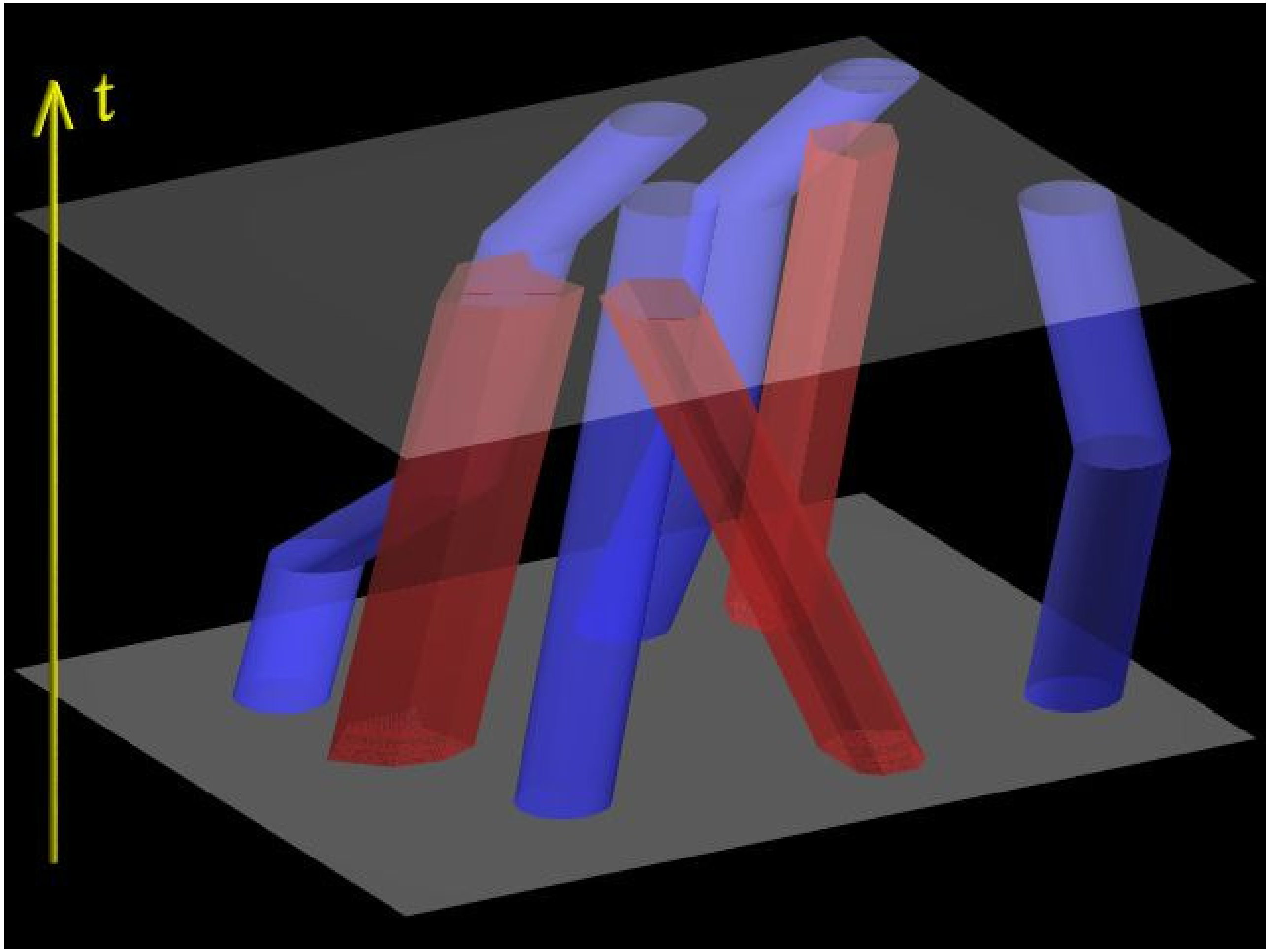
Output: Capacity

- We focus on airspace-induced capacity
  - (vs. sector-induced capacity)
  - What are the fundamental geometric limitations on throughput induced by constraints?
- Possible measures:
  - Yes-or-no: Can demand be met?
  - What is maximum α so that α-scaled demand can be met?
  - How many aircraft per hour of class i can be safely routed from source to sink through airspace?
  - Multiclass capacity: Can we route k_1 lanes of class 1, k_2 lanes of class 2, k_3 lanes of class 3, etc?

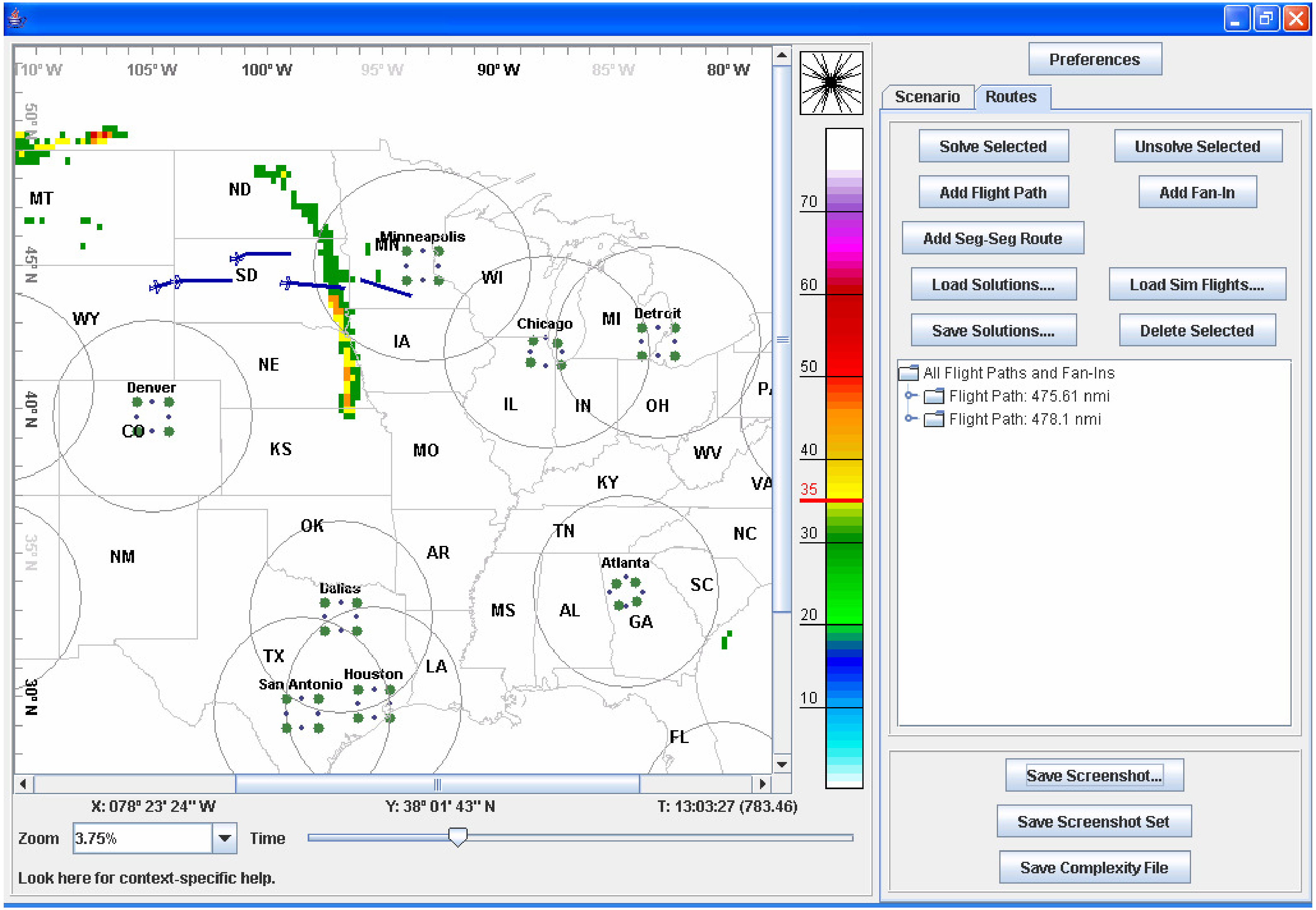
Capacity: Theoretical View

- More formally, capacity computation is a *packing* problem in 4D space-time:
  - Can a given number of flows (“tubes” in space-time) be packed within an airspace so that each flow is constraint-free for its aircraft class?
- Many other constraints, including sector-induced capacity, route dynamics, interactions between classes, contingency routes, holding patterns, etc.
- Stochastic model: Each flow must be feasible with at least a certain probability.
- Capacity is a random variable: Determine the distribution of capacity.

The View in Space-Time



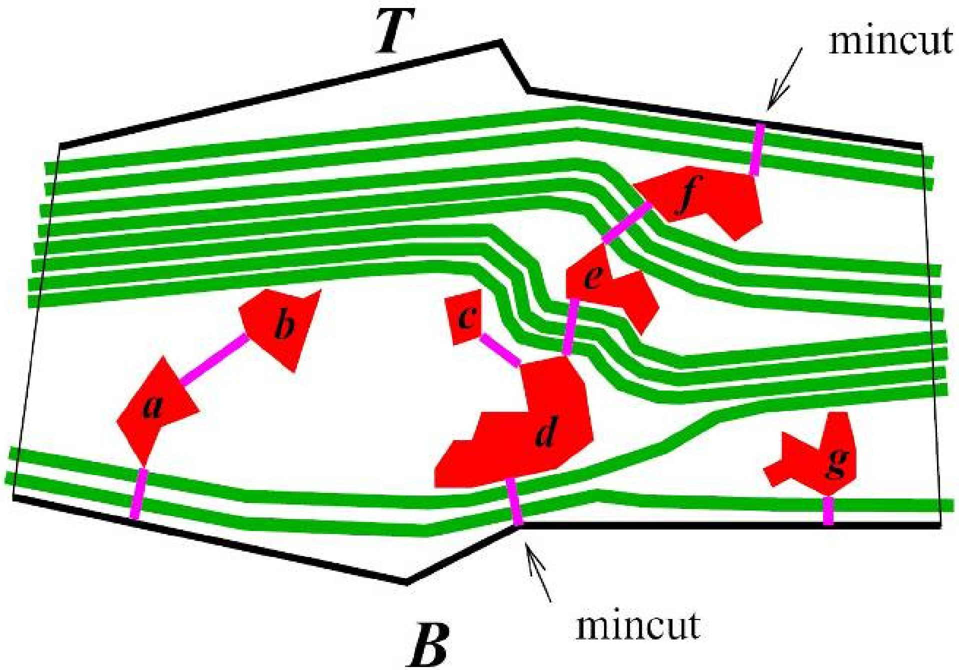
Flow-Based Route Planner (FBRP)



Joe Prete

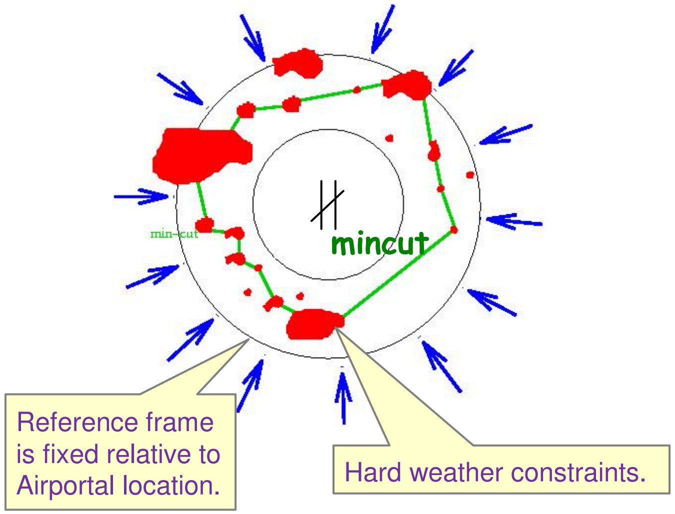
Single Class Capacity Estimation:
Determining # Air Lanes Among Constraints

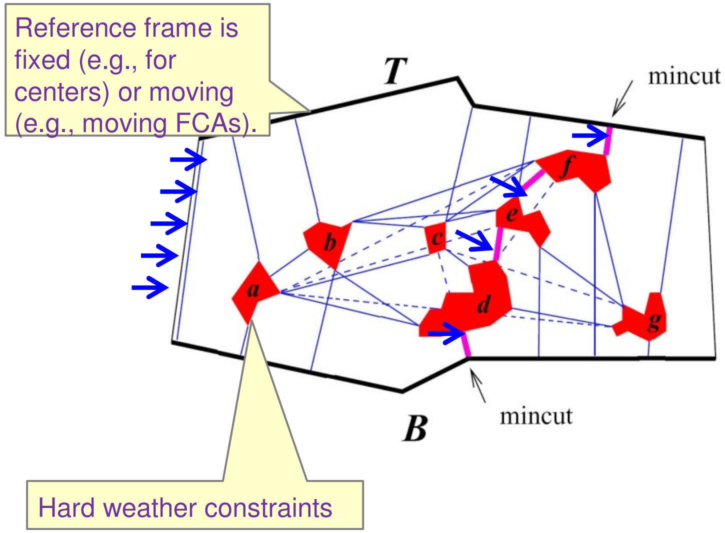
All constraints Hard



Applies to ensemble-based probabilistic weather: Produces a probability distribution for capacity, X

Mincuts Among Hard Constraints





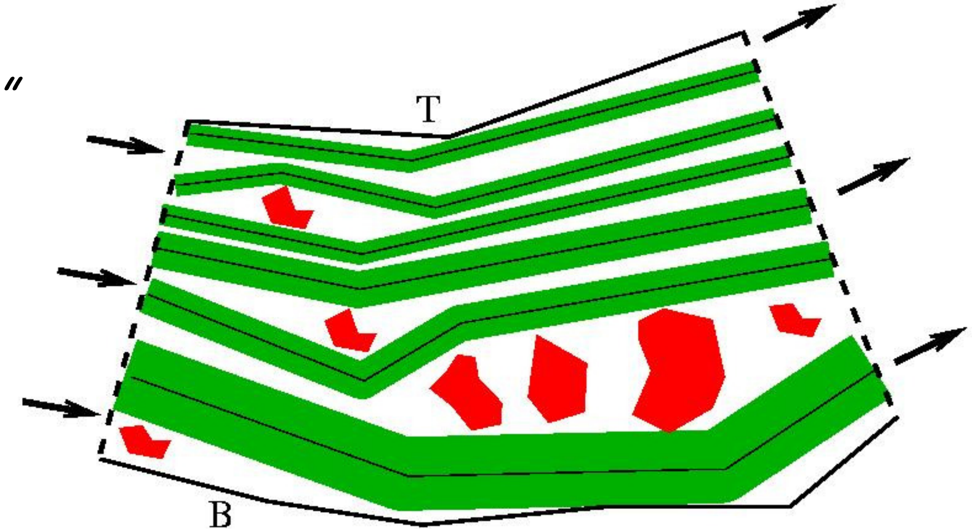
Mincut for traffic through an annulus to the airportal

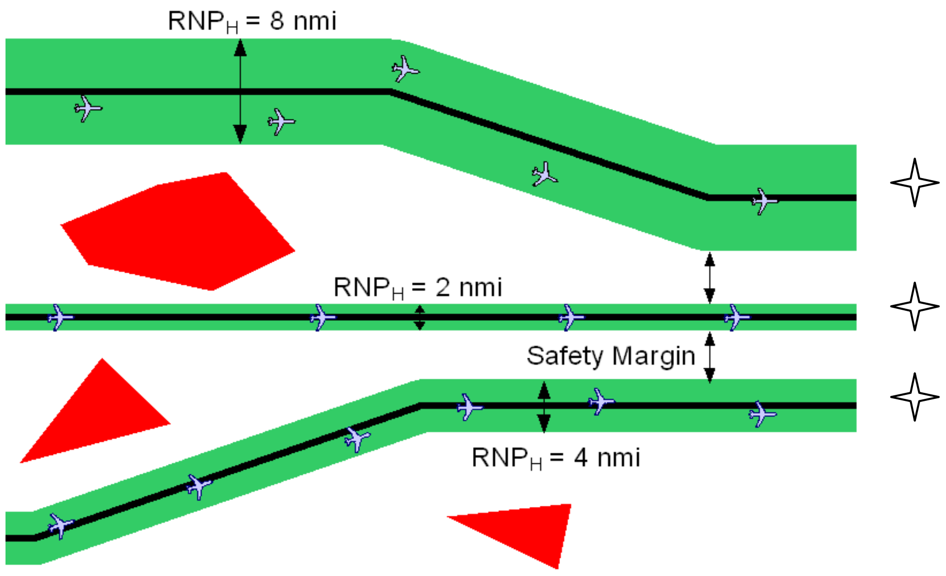
Mincut for traffic across a sector or FCA

Mincuts computed using a geometric shortest path algorithm, treating constraints as regions of 0-weight

Mixed RNP Air Lanes

RNP="Required Navigation Performance"





Performance-based services

Satisfying Different RNP Demands

Demands:

20% (2 lanes) RNP-3

30% (3 lanes) RNP-5

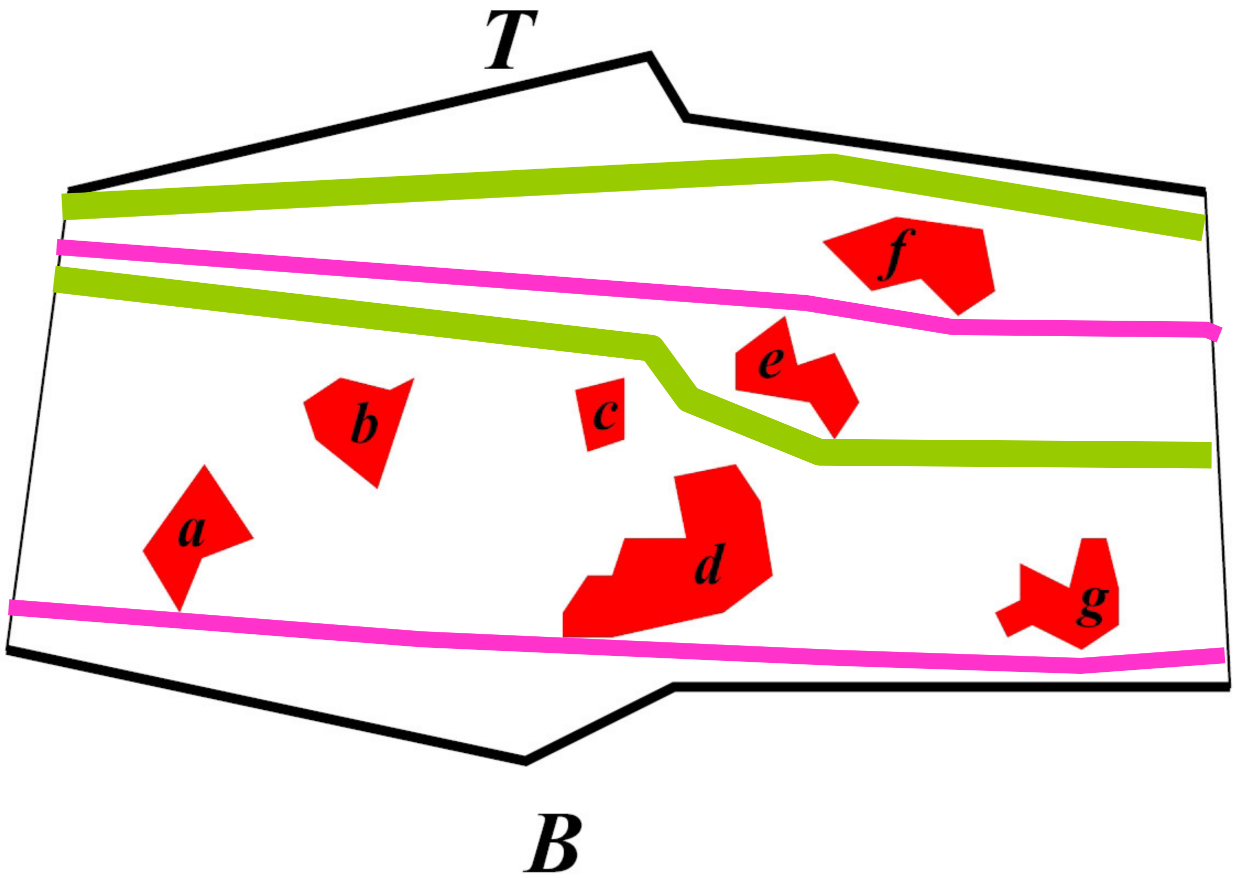
50% (5 lanes) RNP-10

Prioritized min-cost flow

#1: RNP-3

#2: RNP-5

#3: RNP-10



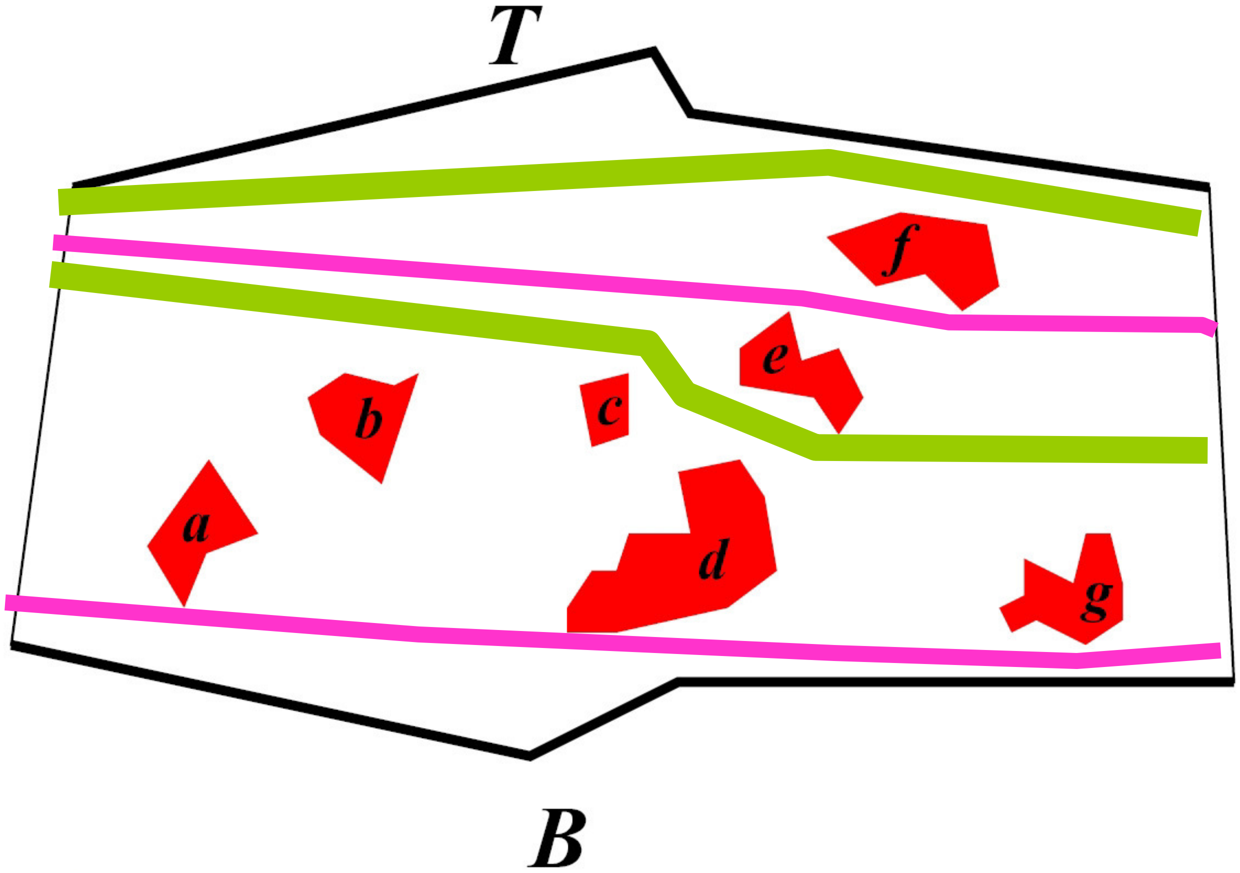
2 of 2 RNP-3 lanes routed; 2 of 3 RNP-5 lanes routed; 0 of 5 RNP-10

Lexicographic Min-Cost Flow

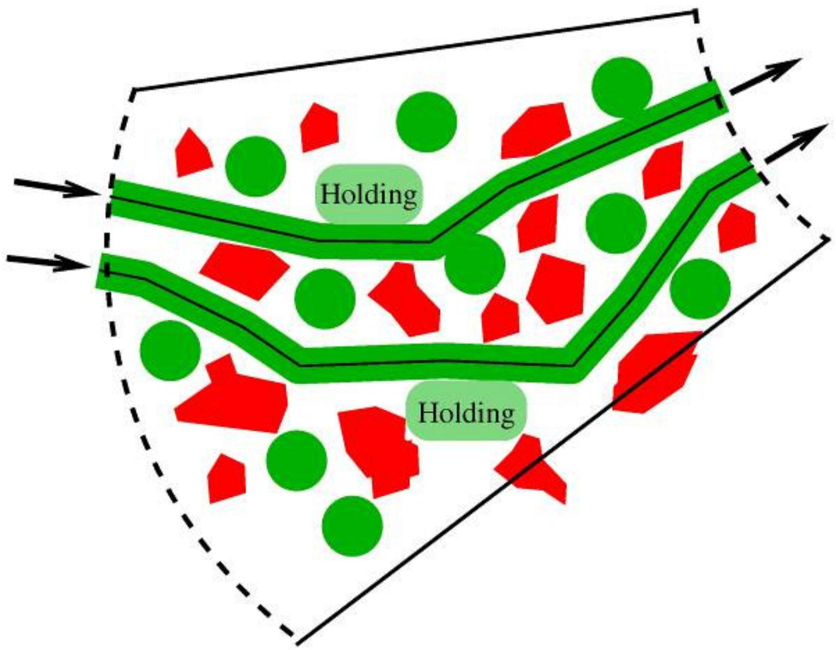
First, route as much of RNP-3 demand as possible (2 of 2)

Then, subject to those lanes as constraints, route as much RNP-5 demand as possible (2 of 3)

No room for RNP-10 lanes



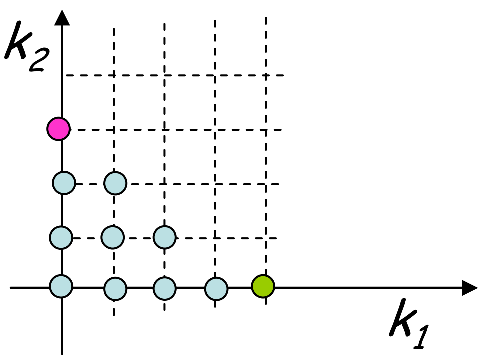
Buffers, Holding Patterns, and Wiggle Room

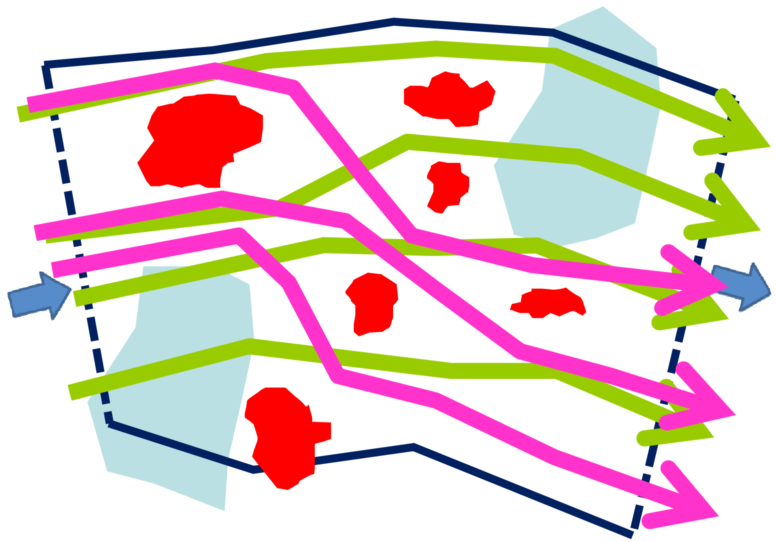


Multiclass Capacity

- Can we route k_1 lanes of class 1, k_2 lanes of class 2, k_3 lanes of class 3, etc?
- Example: 2-class, 2-type model of Hard/Soft constraints
  - Class 1: Avoid type-1 (red) constraints ("Hard"), but can ignore type-2 (blue) constraints ("Soft")
  - Class 2: Must avoid both type-1 and type-2 constraints (Hard and Soft)

Bicriteria decision:

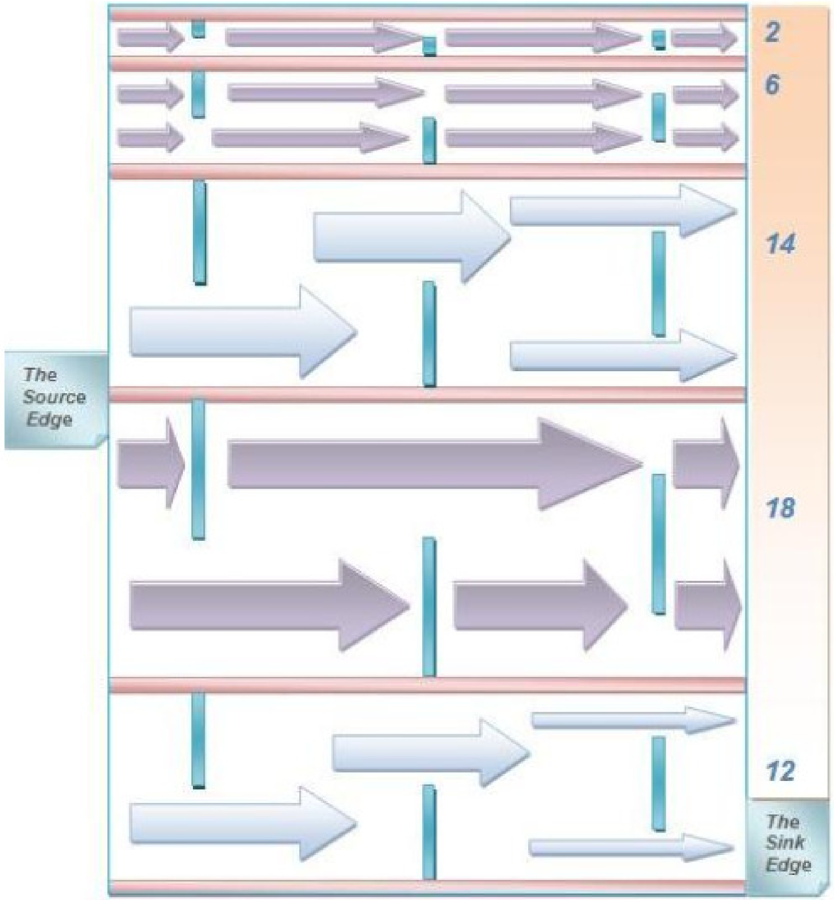




Other combinations of air lanes for class-1 and class-2 aircraft.

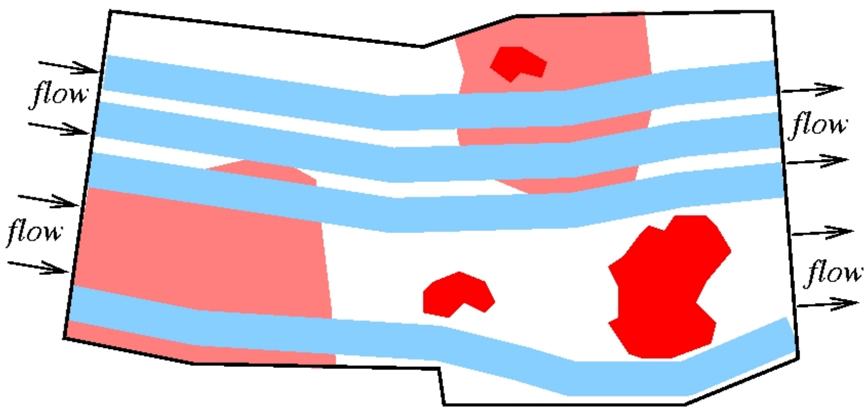
Hardness

- Weak NP-hardness (from PARTITION)

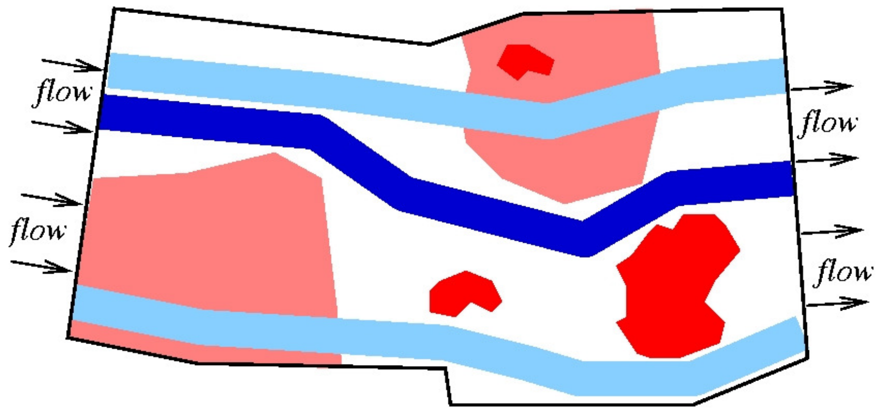


[Shang Yang'08]

Flows Among Hard and Soft Constraints



4 airlanes avoiding only hard constraints

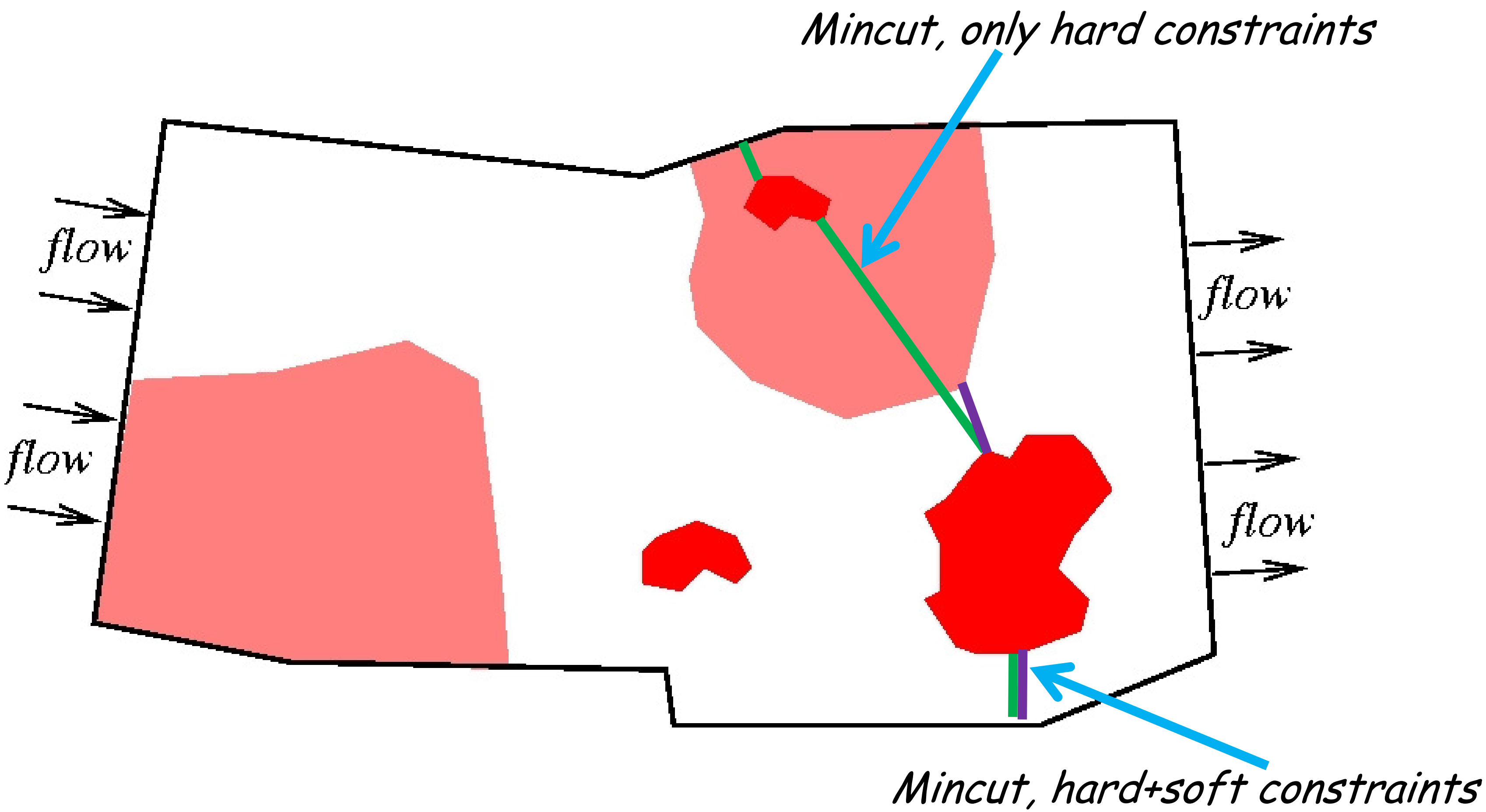


Once one airlane is established avoiding hard+soft constraints, There is capacity for only 2 additional airlanes for "well-equipped" aircraft

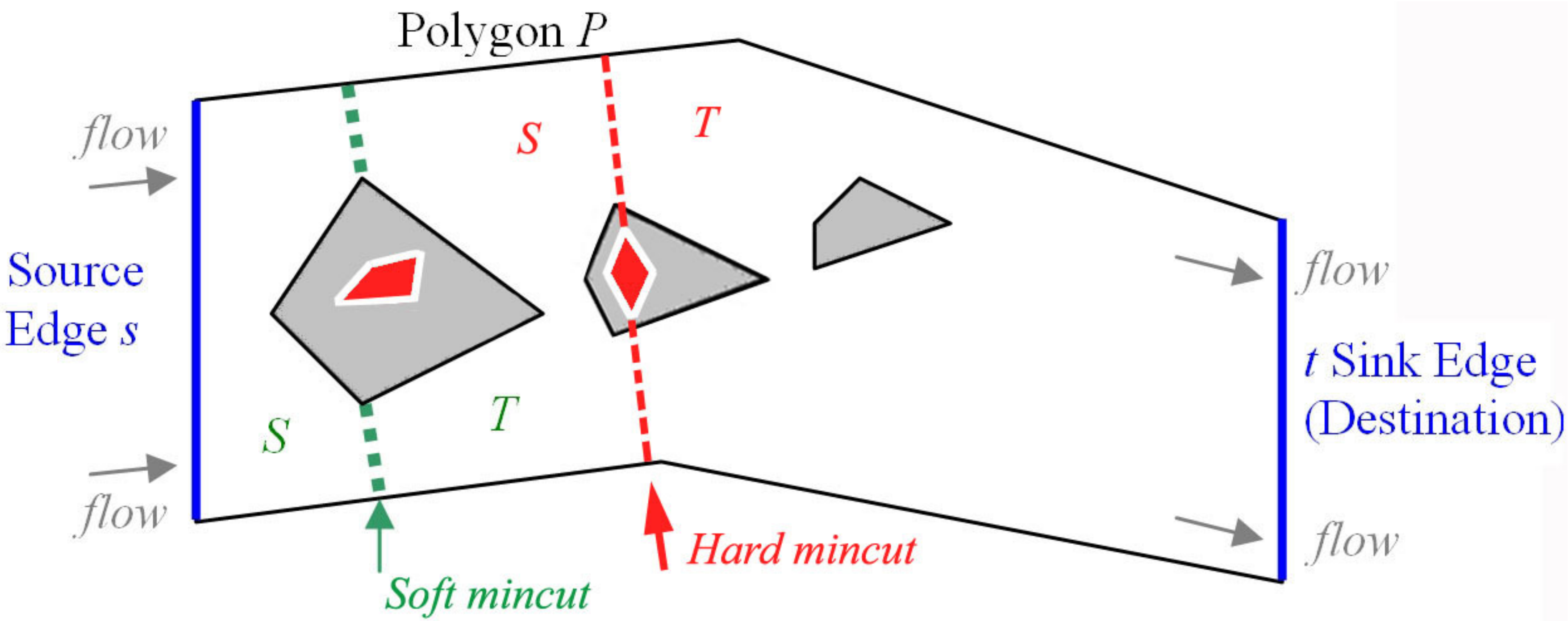
Competing for airspace resources: Two levels of equipage yields a "multicommodity" flow problem

NP-hard, in general

Hard and Soft Mincuts

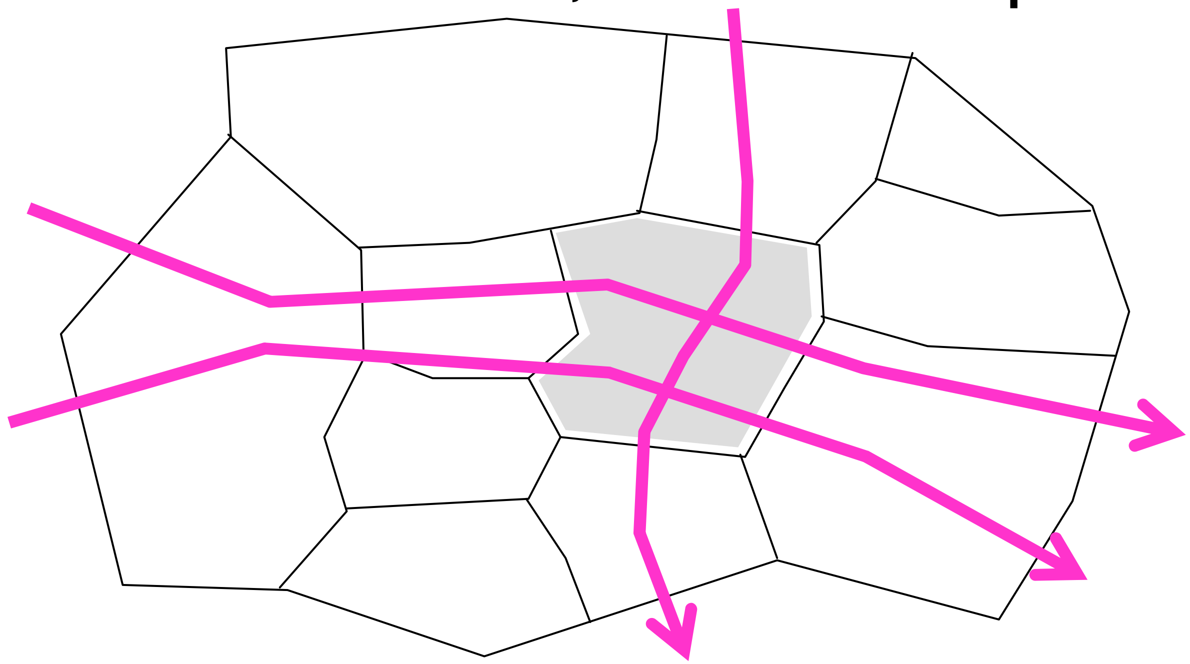


Hard/Soft Mincuts



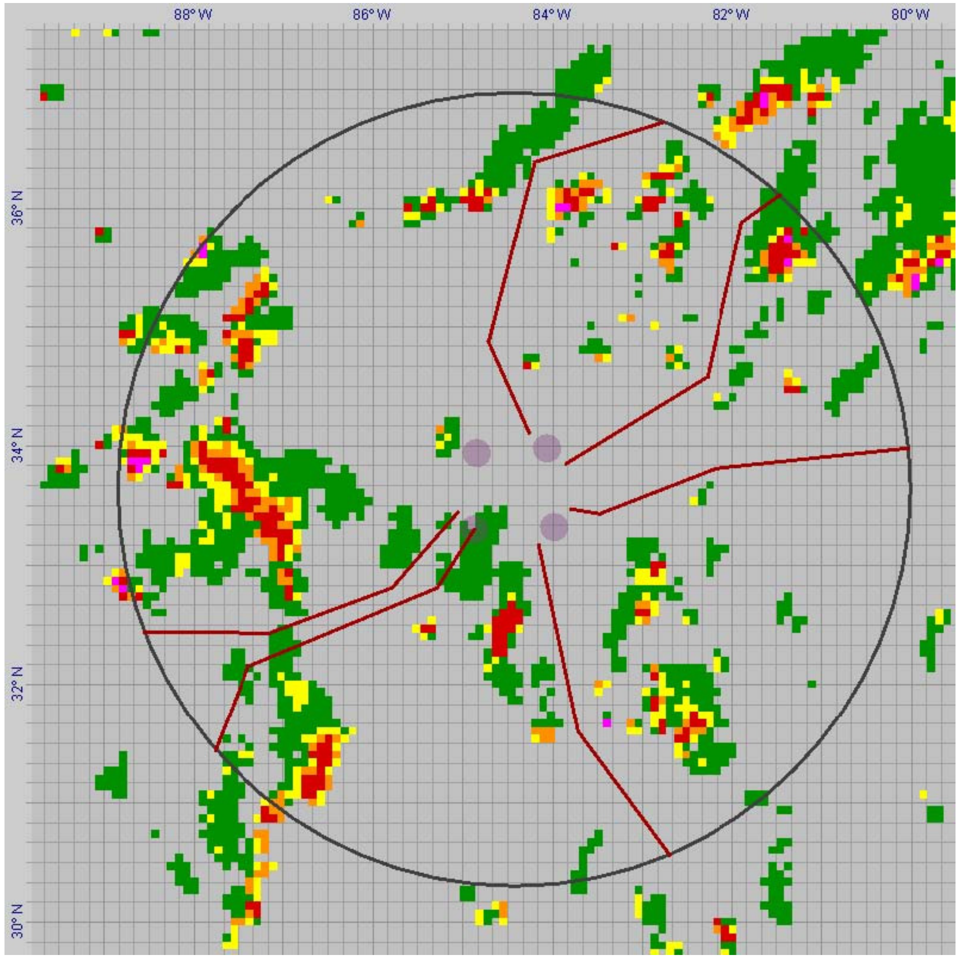
Workload Issues: Sector-Induced Capacity Bounds

- Max-flow/mincut theory determines airspace-induced throughput
- “Capacity” must include workload constraints: MAP, traffic complexity

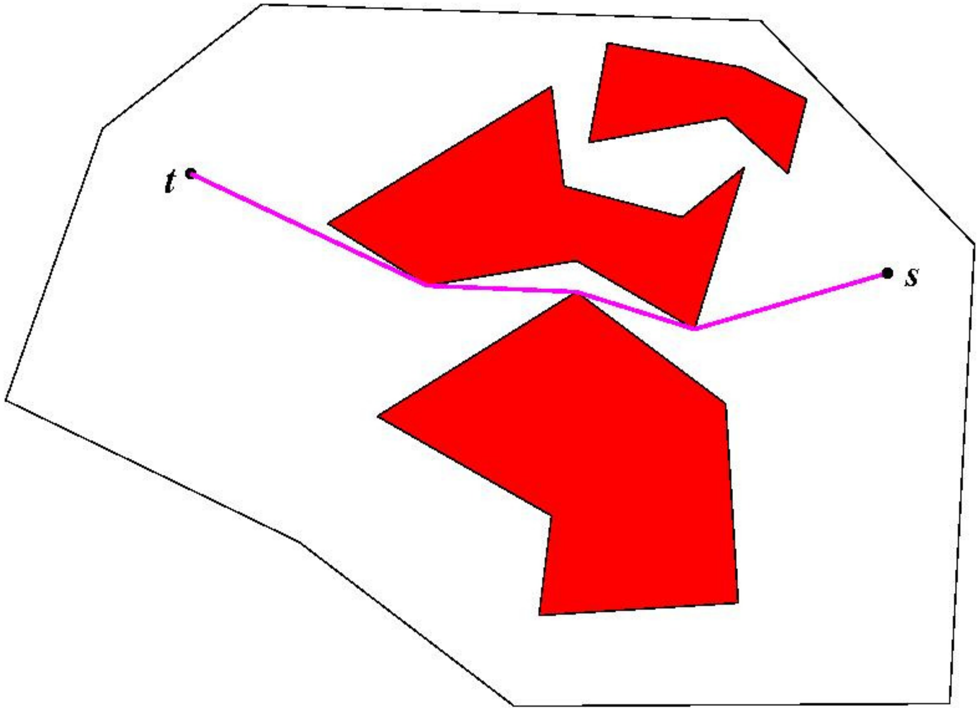


Flows and Routes

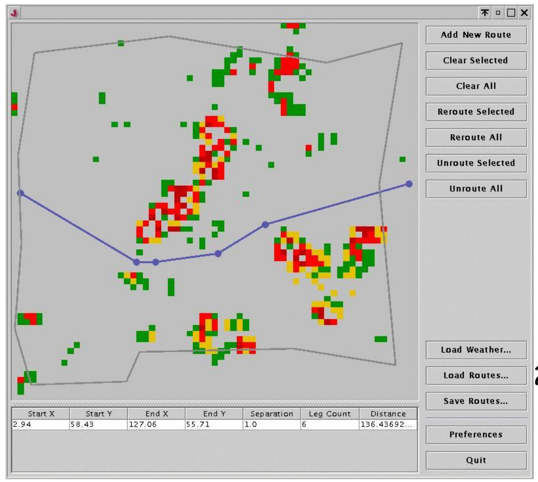
Routing to Avoid Hazardous Weather



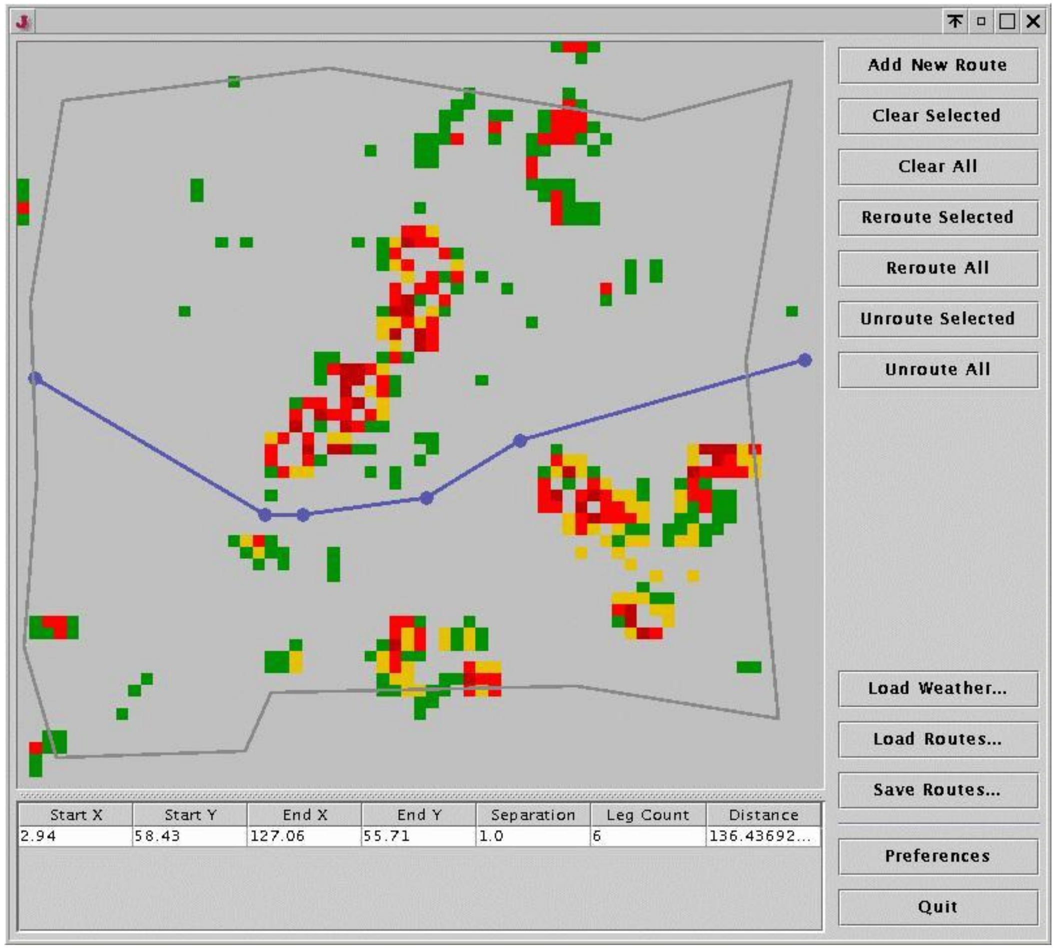
Geometric Shortest Paths



- Given:
  - (Outer) Polygon P
  - Polygonal obstacles
  - Points s and t
- Find:
  - shortest s-t path
  - avoiding obstacles
- Robotics motion planning



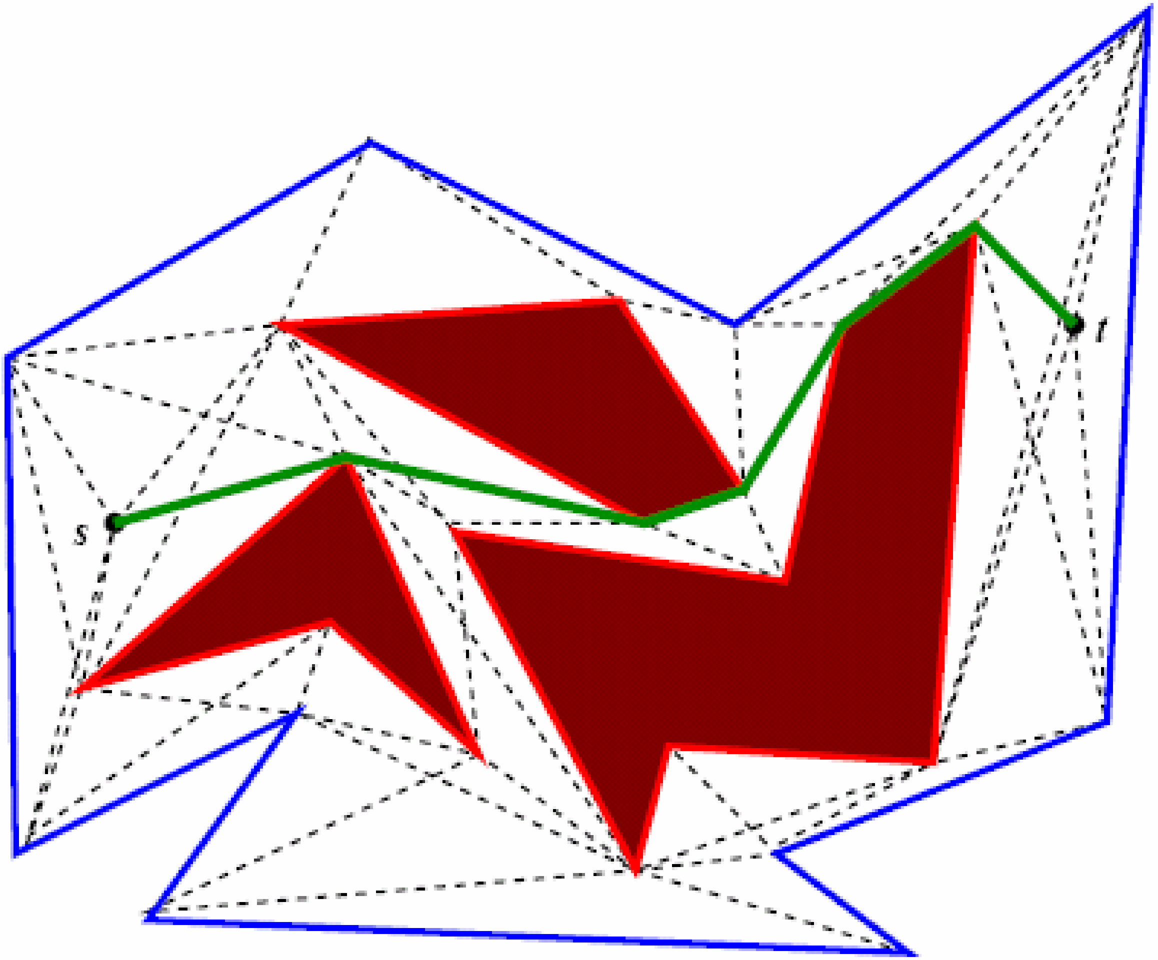
Application: Weather Avoidance



Basic Optimal Paths

Visibility Graph

Local optimality: taut string



Naïve algorithm:

$O(n^3)$

Better algorithms:

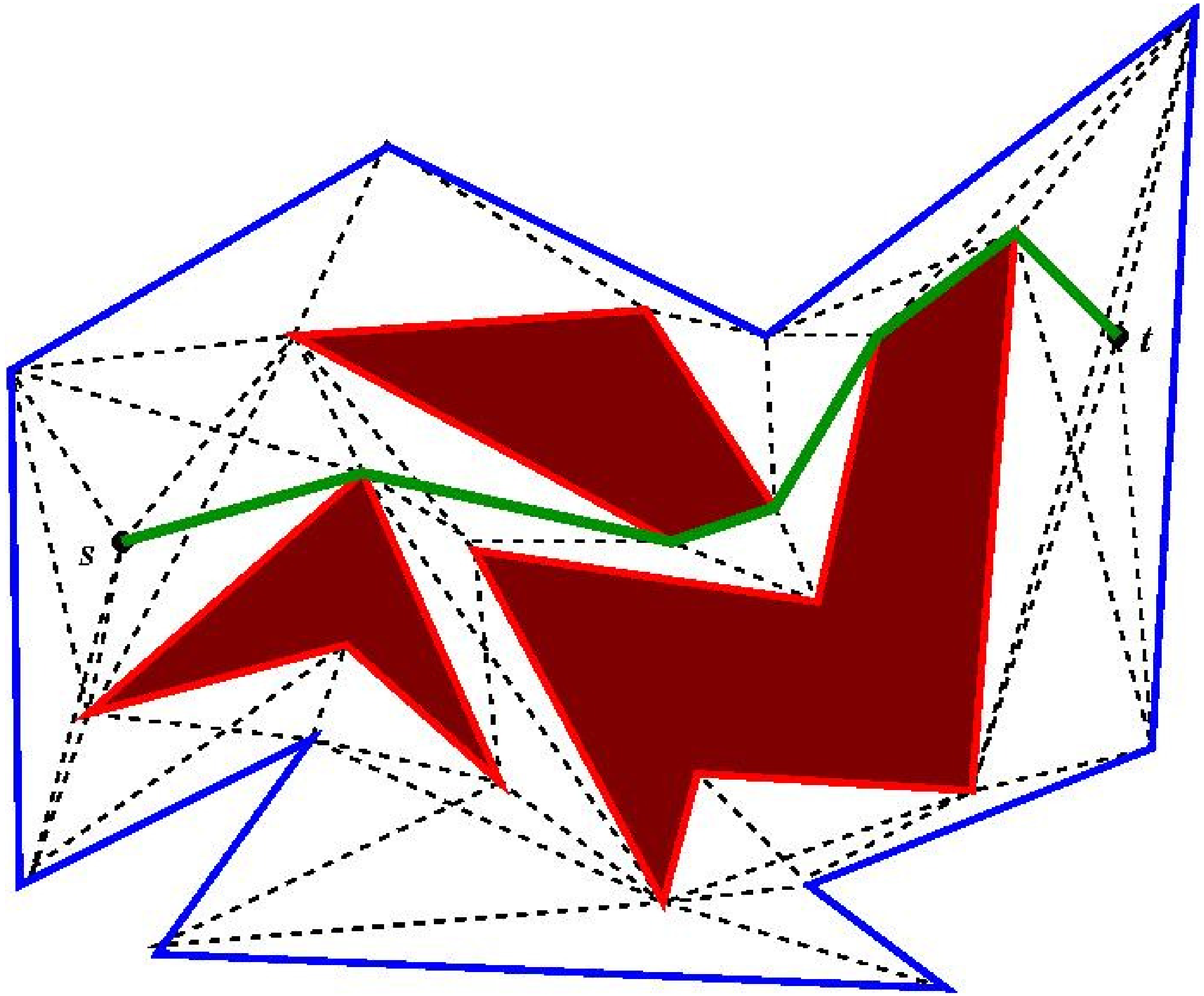
$O(n^2 \log n)$ sweep

$O(n^2)$ duality

BEST: Output-sensitive alg: $O(|E|+n \log n)$

Visibility Graphs

Visibility Graph [applet]



Shows also the topological sweep of an arrangement, animated.

Example: Shortest Path in Simple Polygon

- Triangulate *P*
- Determine the “sleeve” defined by the triangles in a path in the dual tree, from start to goal
- WUSTL applet

Other Applets

STIP online applet : search for a target in polygon

Rectilinear watchman, online applet

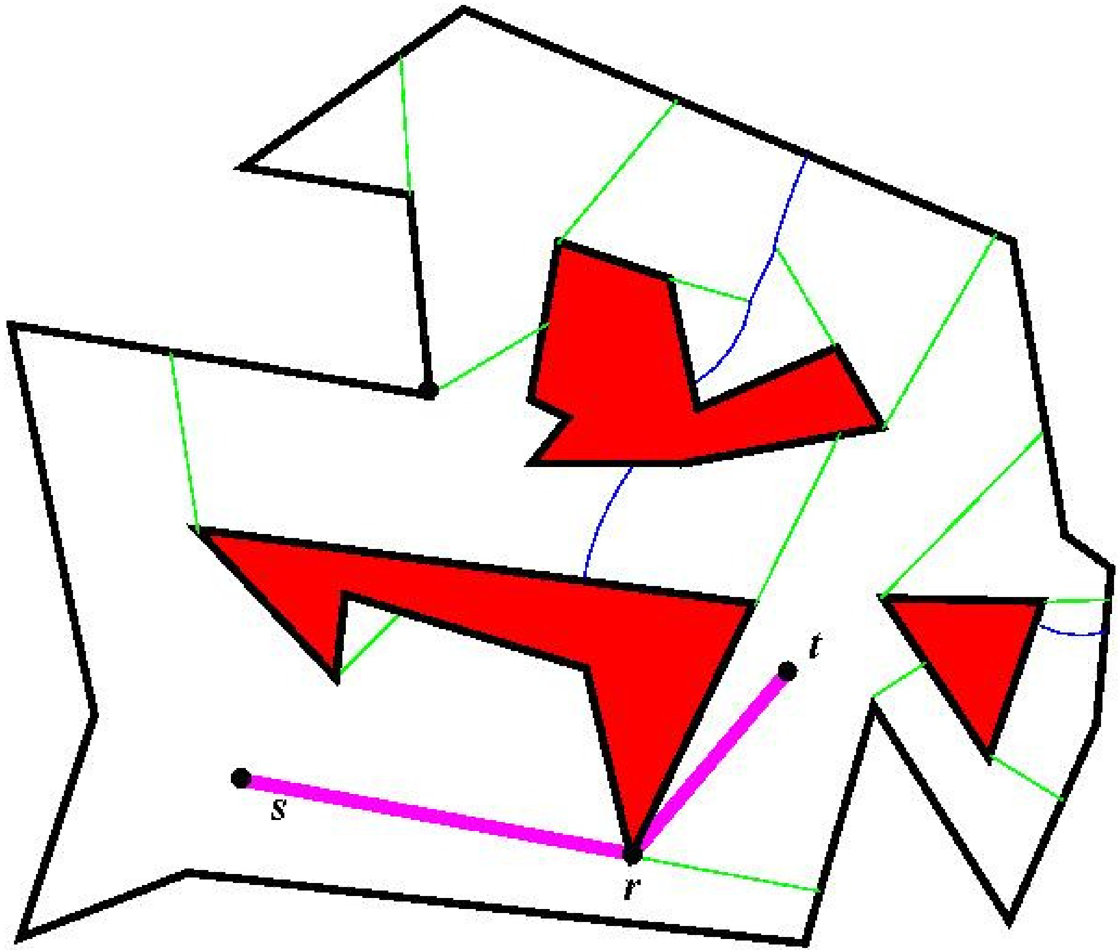
Shortest Path Map

Decomposition of the free space

Shortest Paths

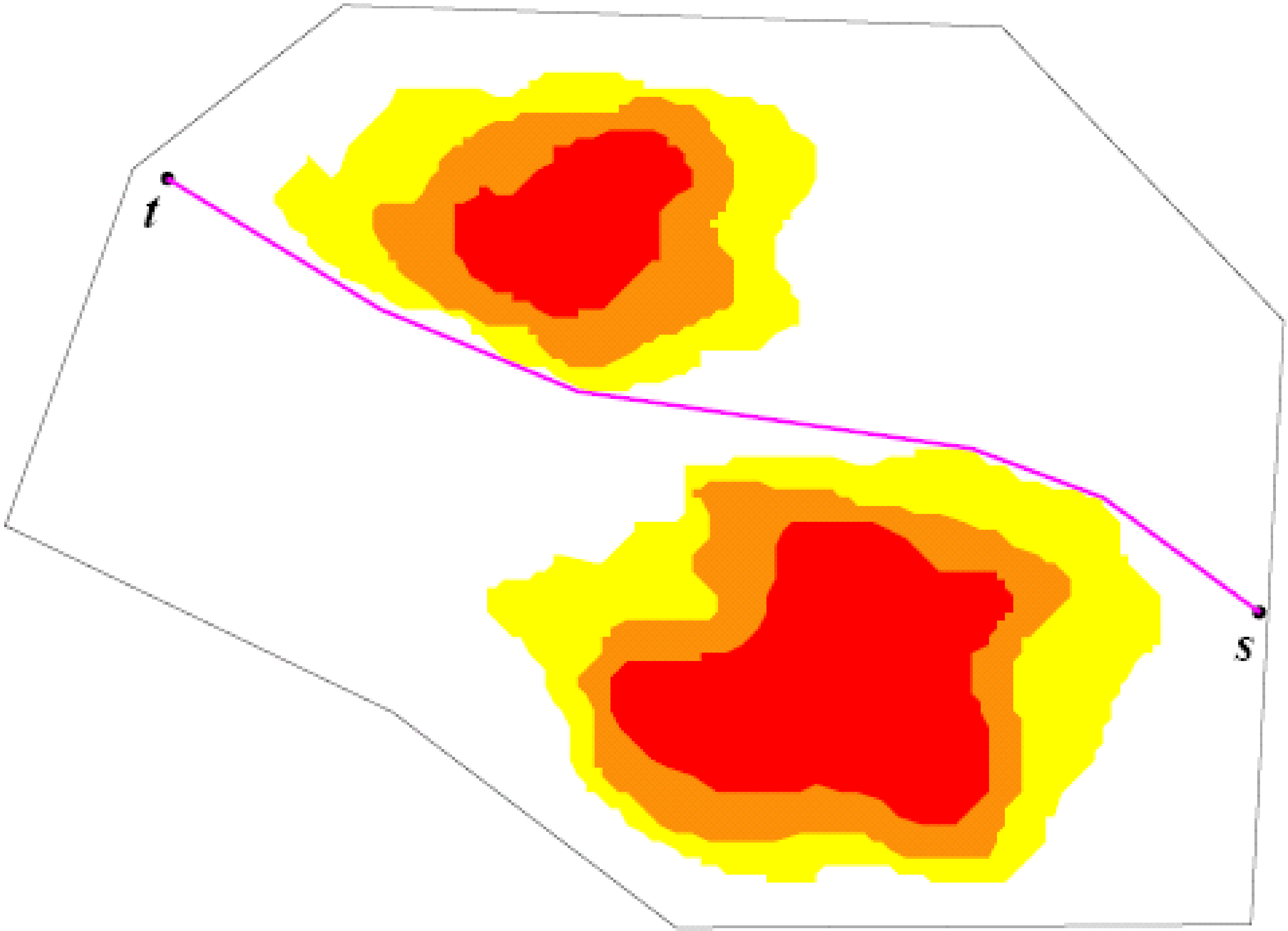
go through

same vertices



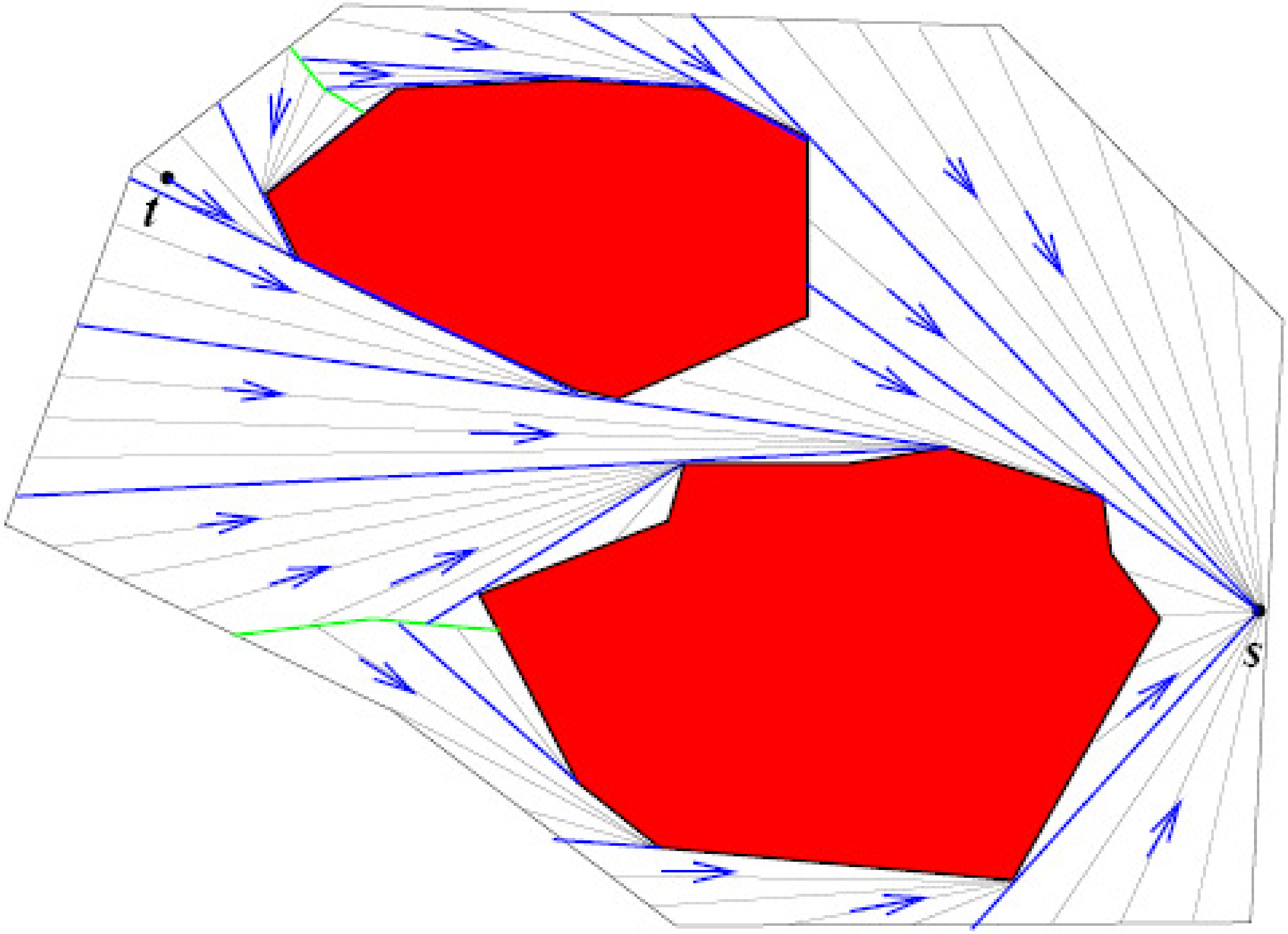
Construct in time: O(n log n); size O(n)

Avoiding Hazardous Weather



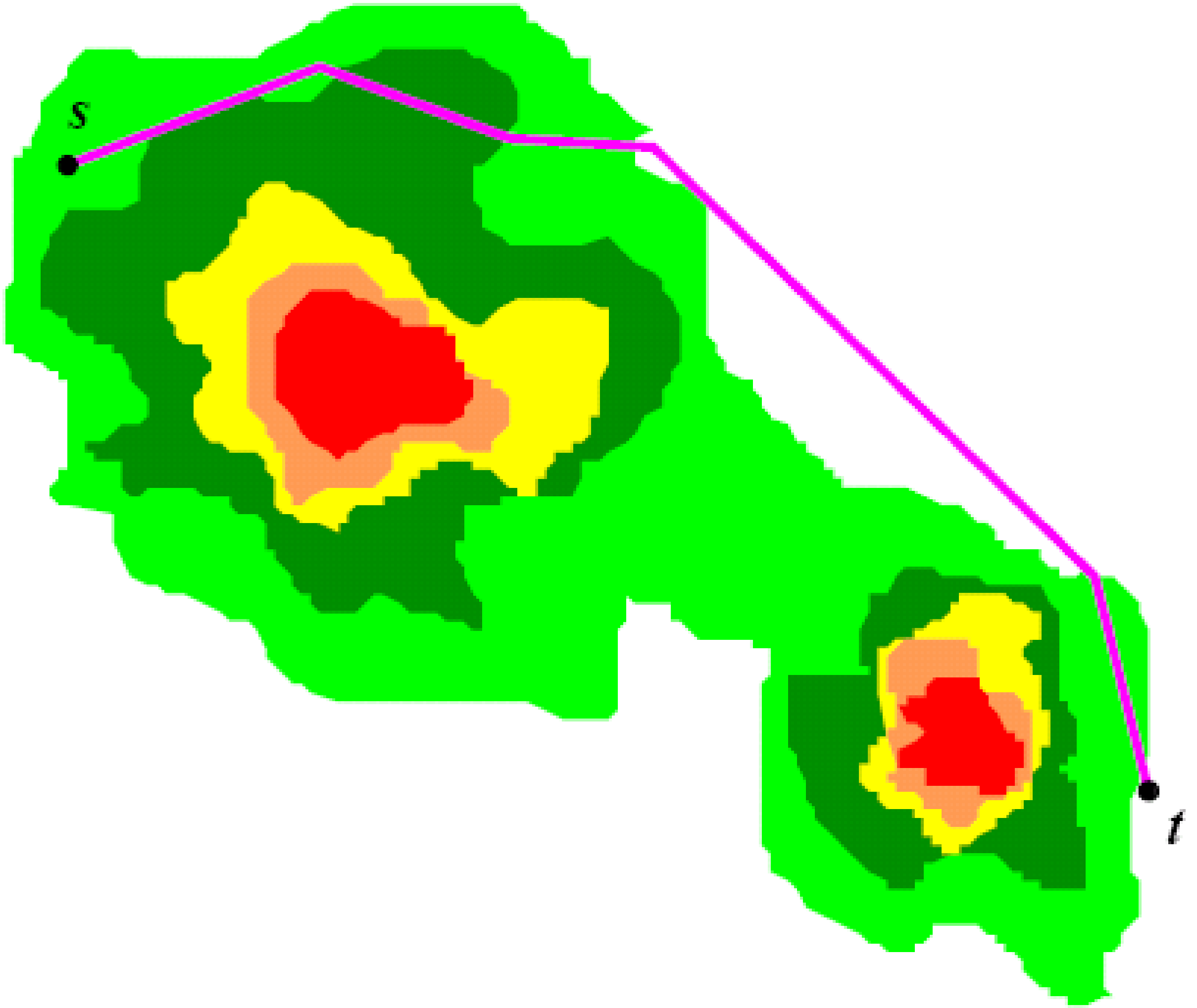
Optimal Path Map: Control Law

Fix s

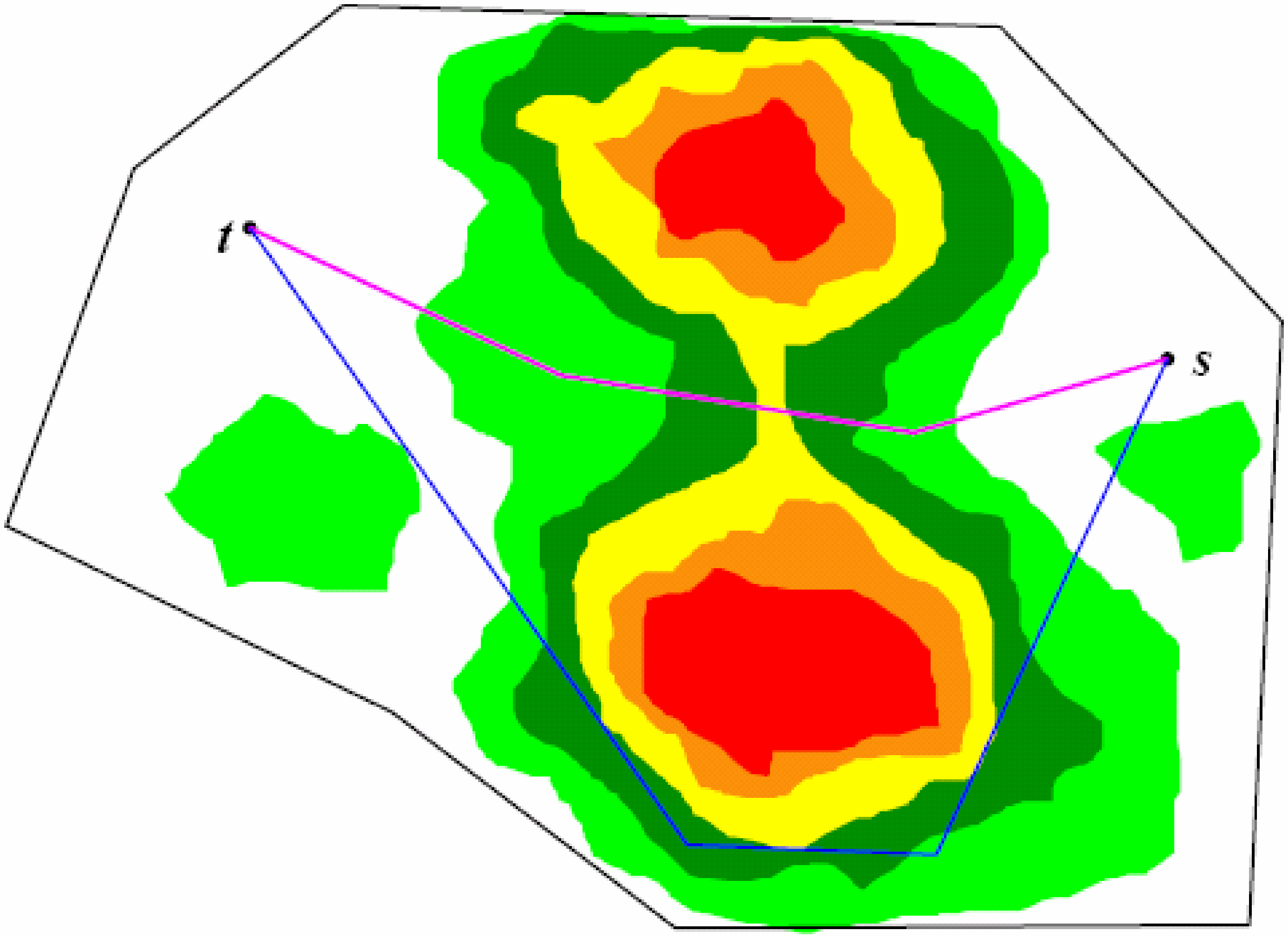


Vary t

Hazardous Weather Avoidance



Hazardous Weather Avoidance

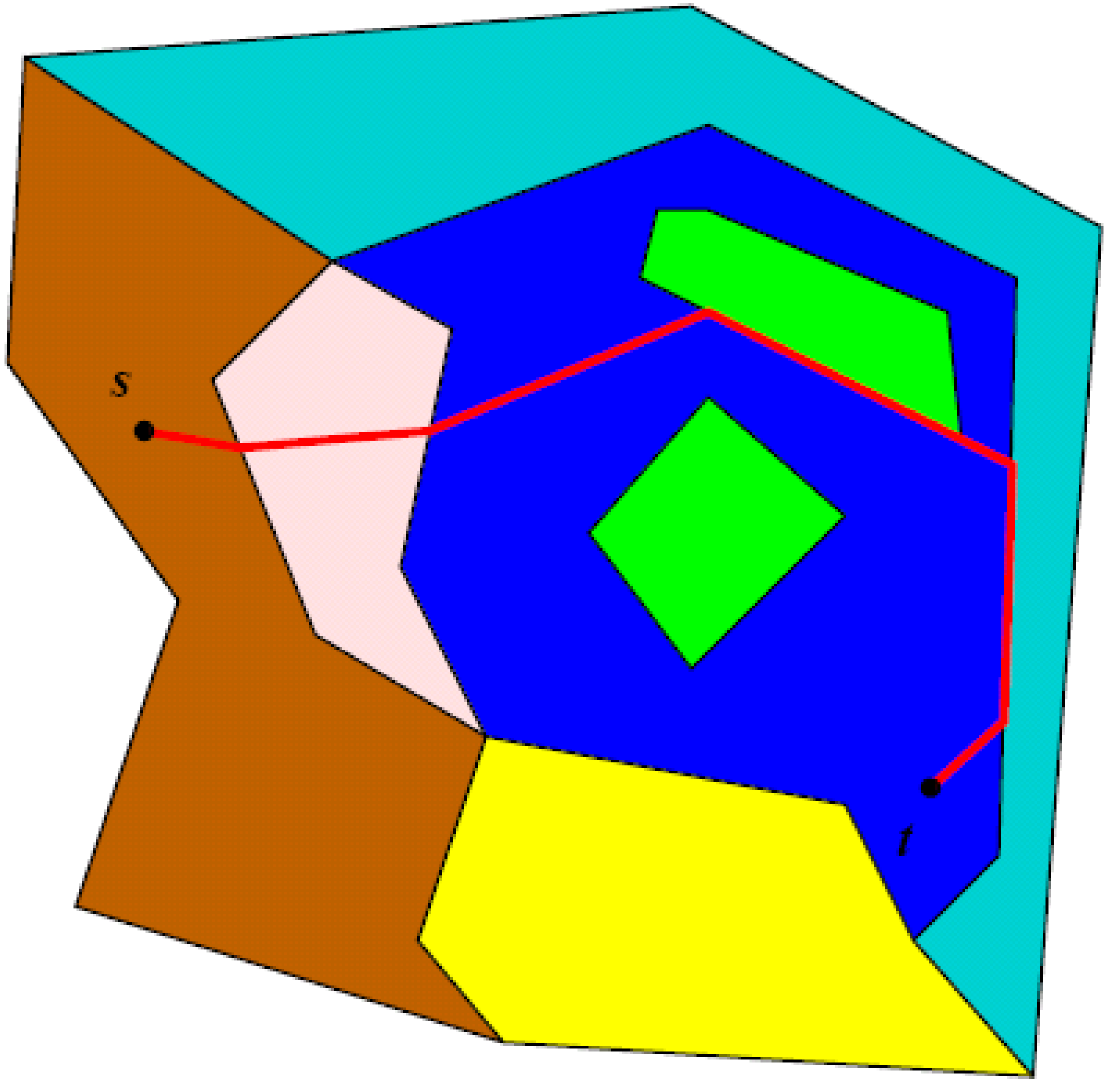


Optimal Paths: Weighted Regions

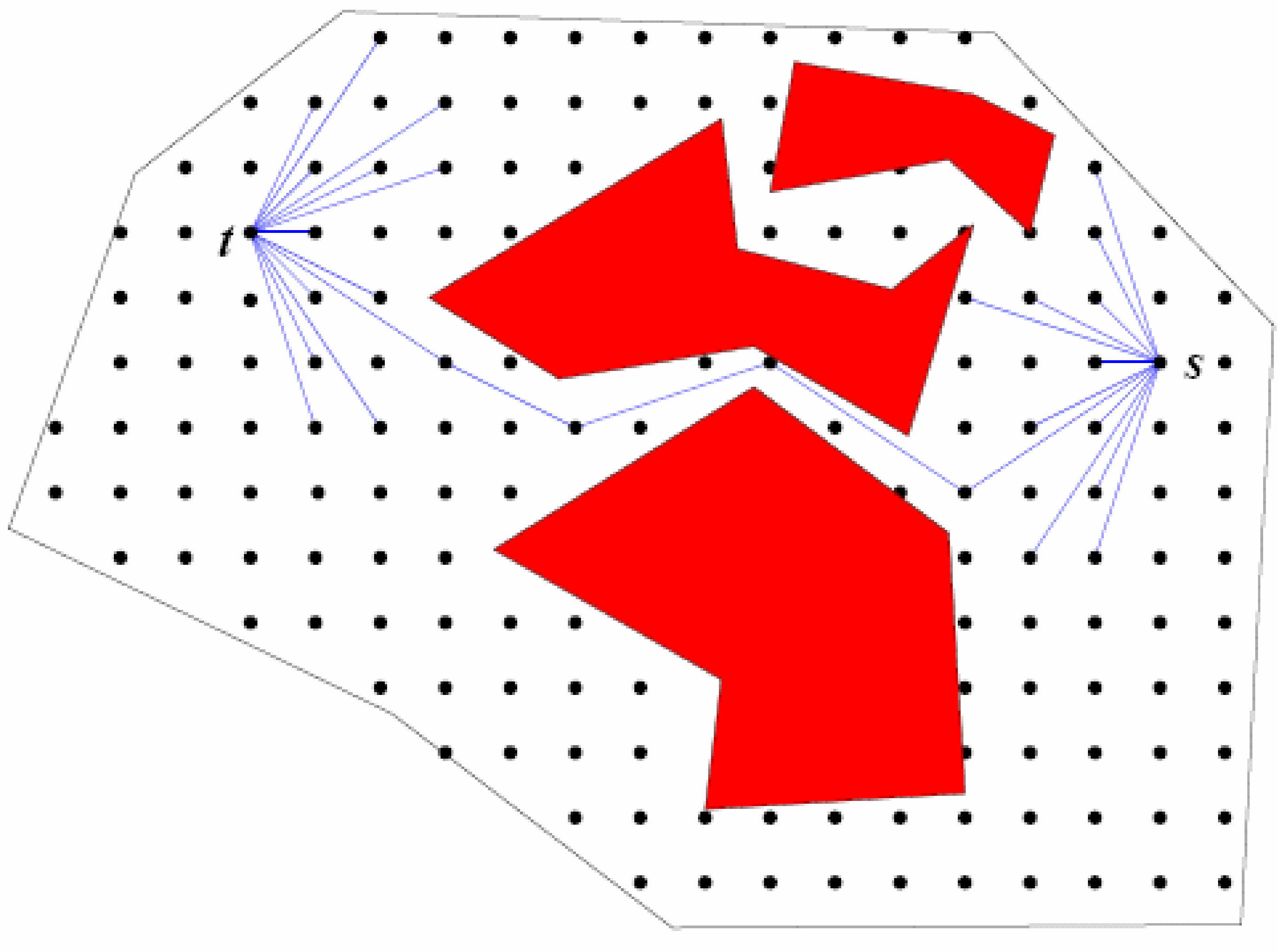
Different costs/nmi in different regions (e.g. weather intensity)

Local optimality: Snell's Law of Refraction

Can also apply grid-based searching



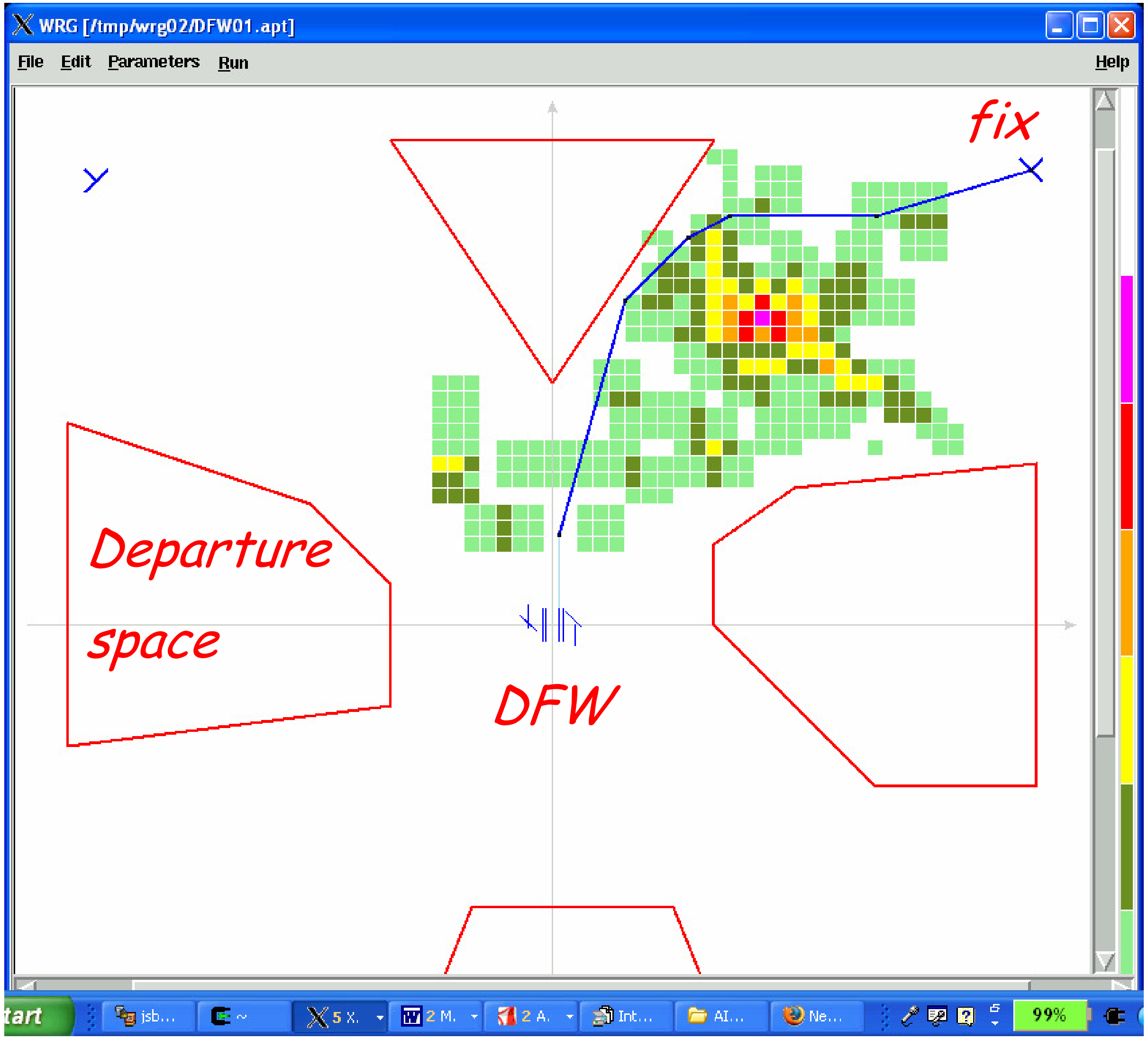
Grid-Based Searches



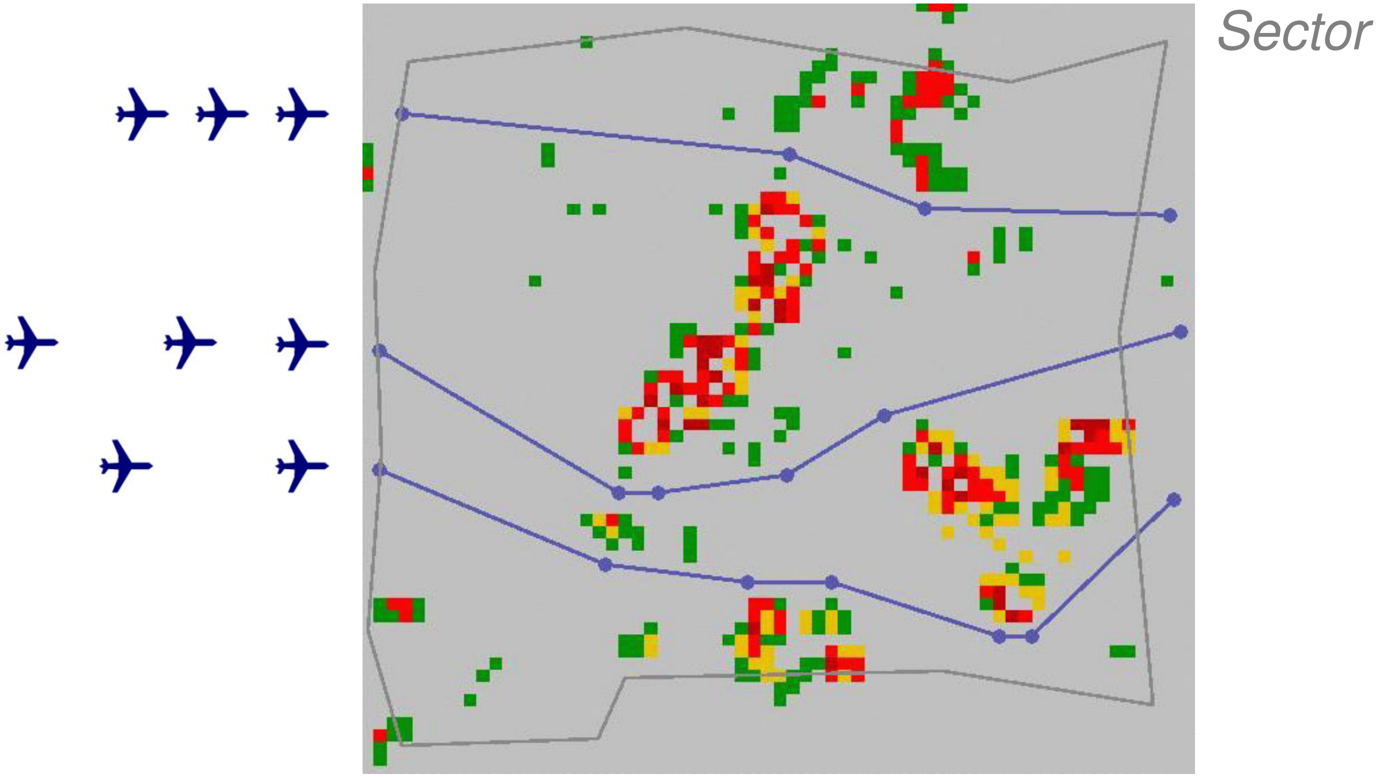
Other Optimal Path Problems

- 3D shortest paths: NP-hard
  - But good approximations
- Turn constraints:
  - Min-# turns: Link distance
  - Bounds on turn angles (radius of curvature)
- "Thick" paths (for air lanes)

Turn-Constrained Weighted Costs: Weather Route Generator (WRG)



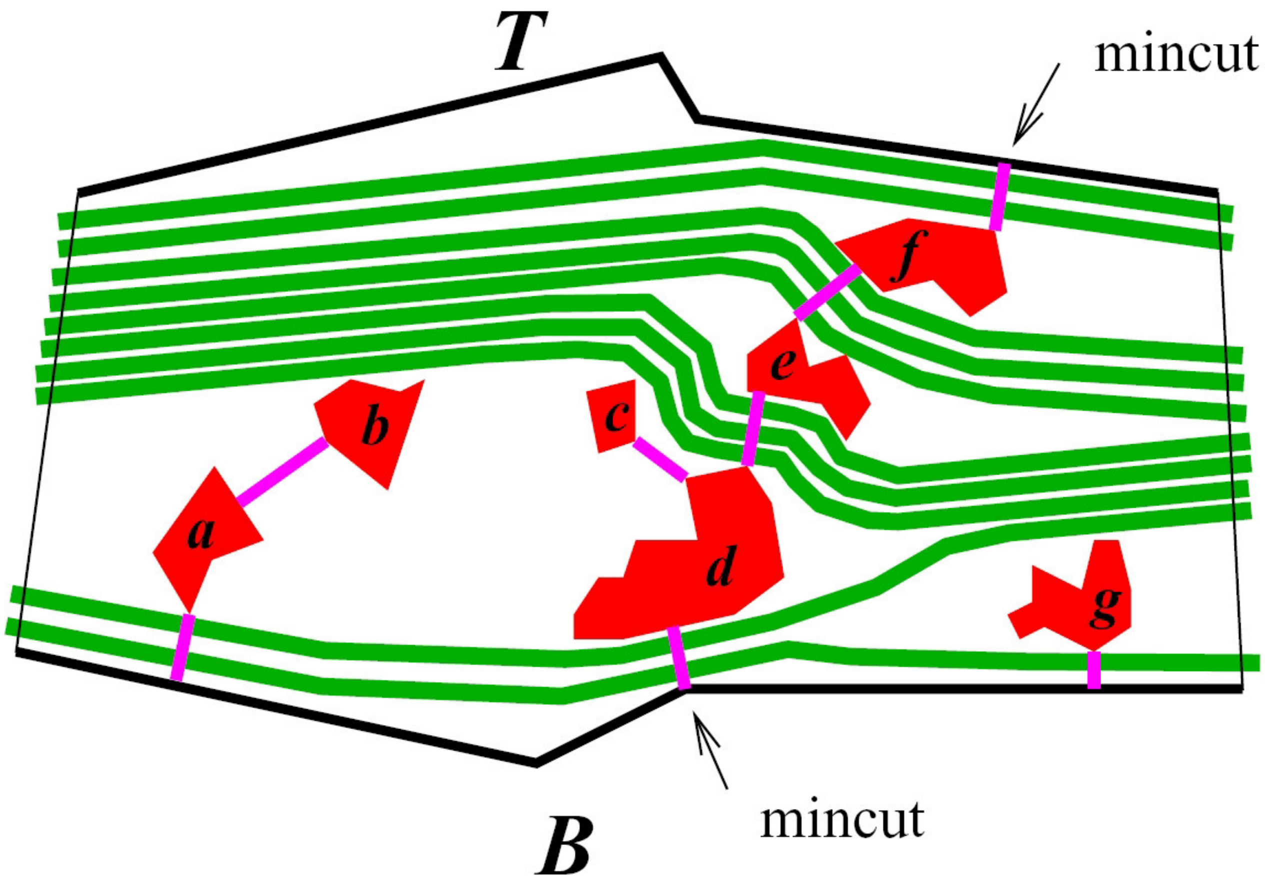
Weather Avoidance Algorithms for En Route Aircraft

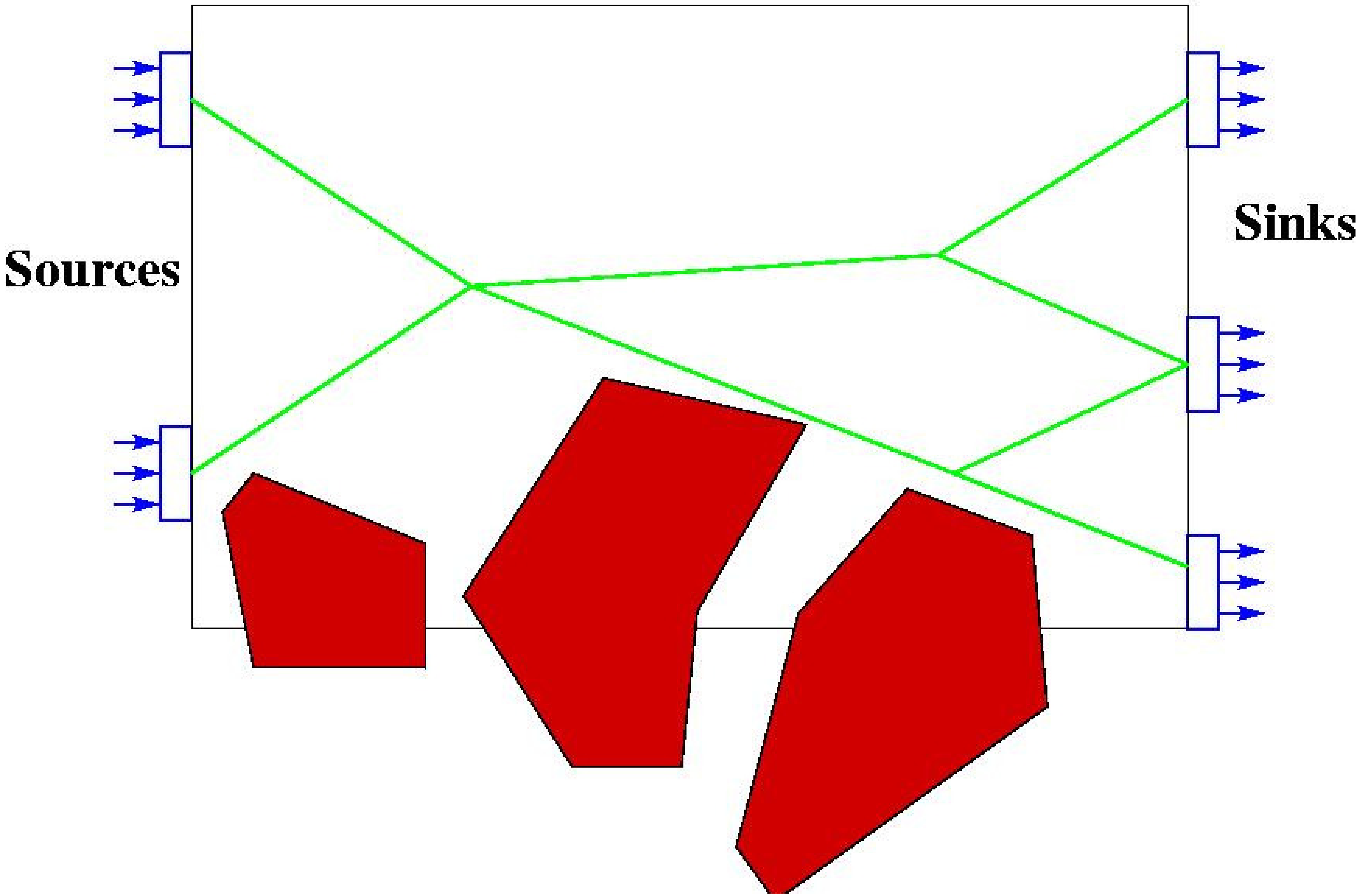


3 Flows

Routing MaxFlow

Find maximum number of air lanes through the mincut

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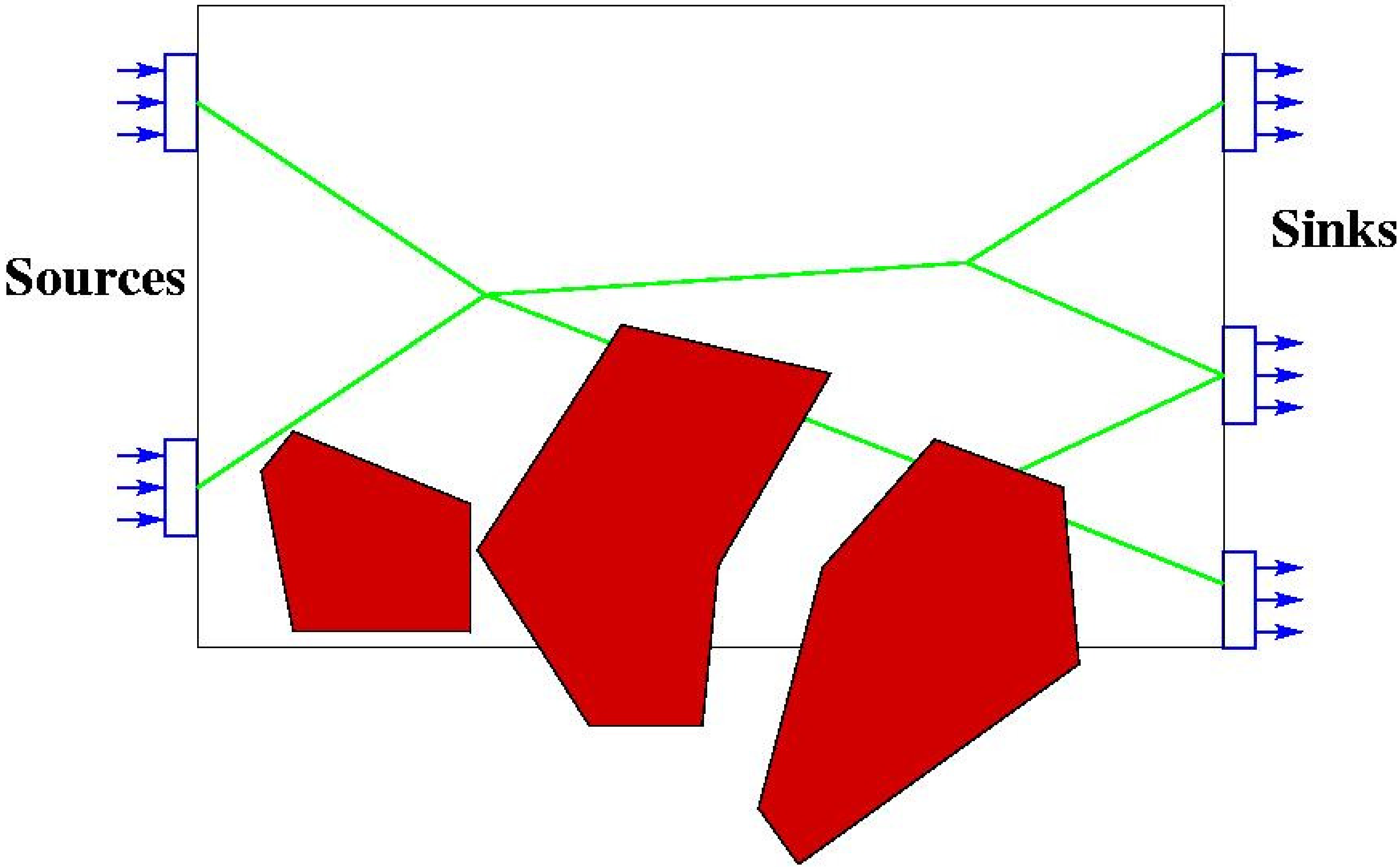
Sinks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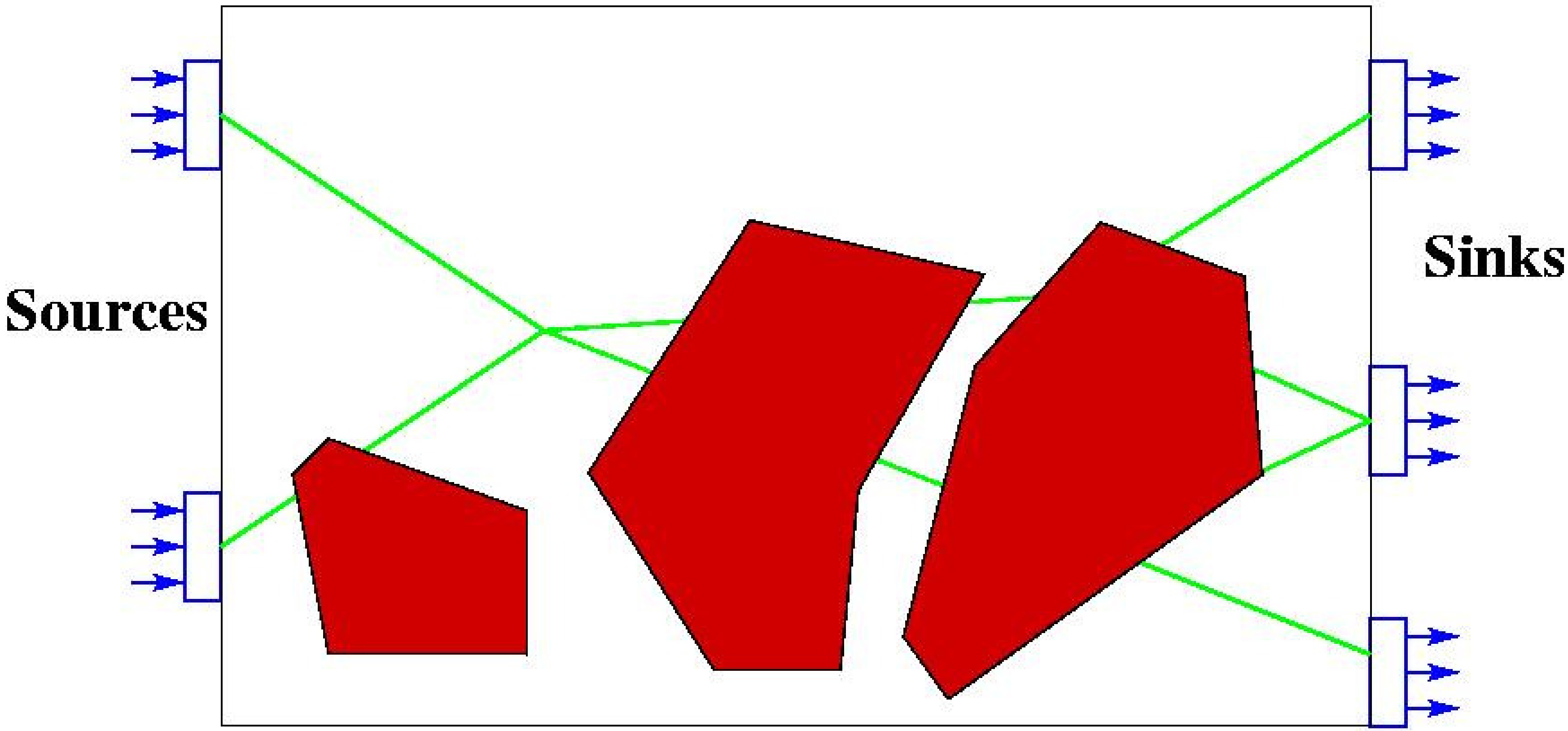
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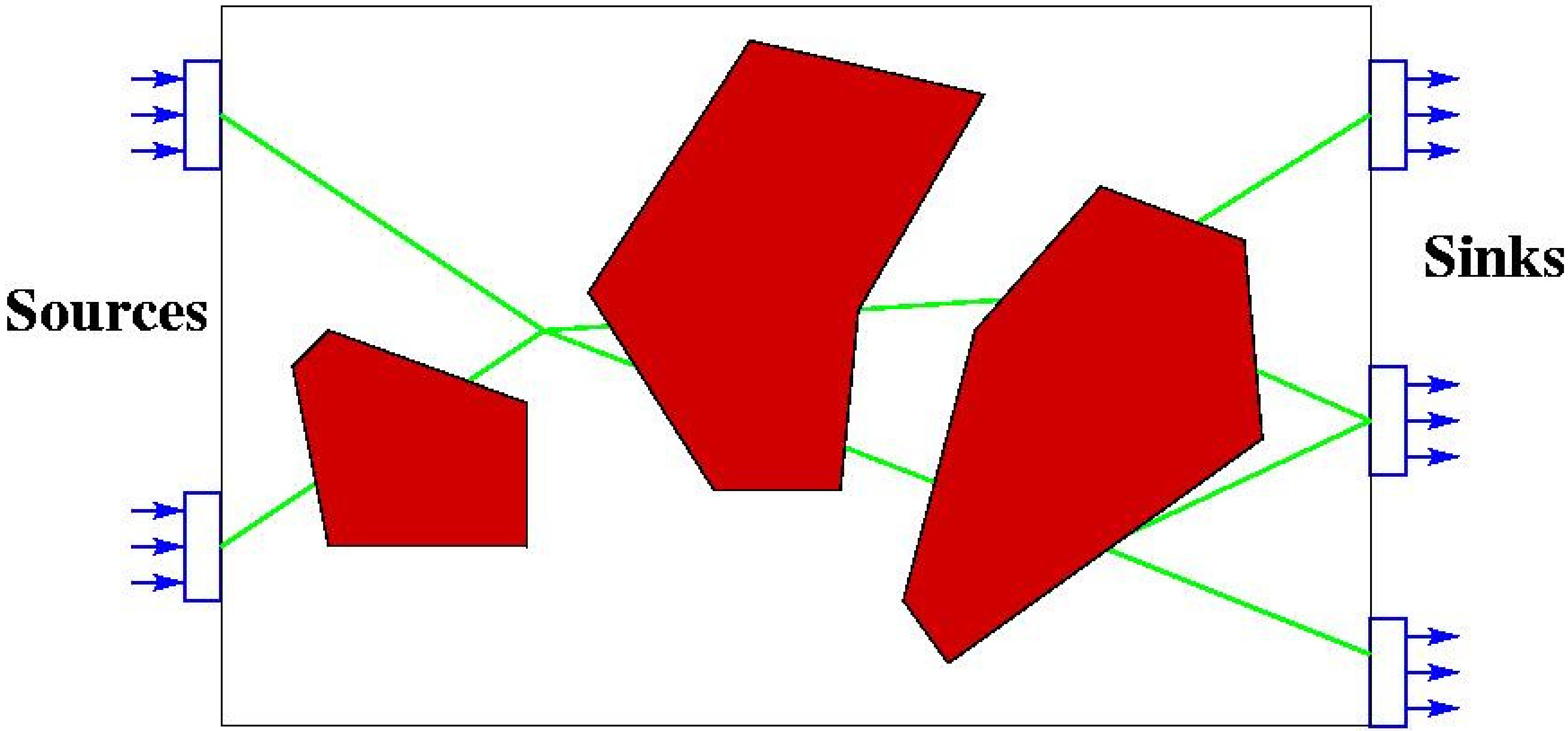
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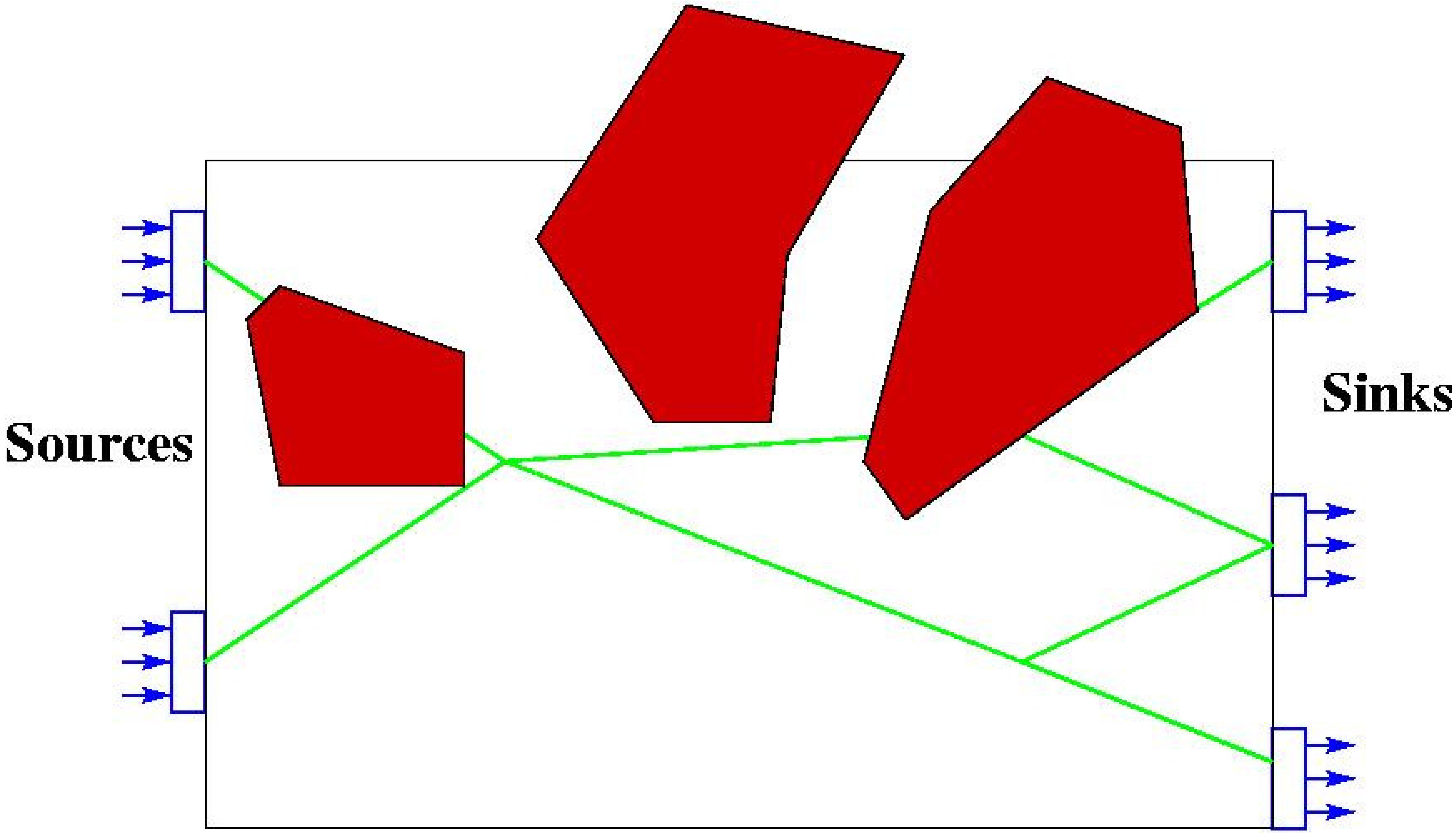
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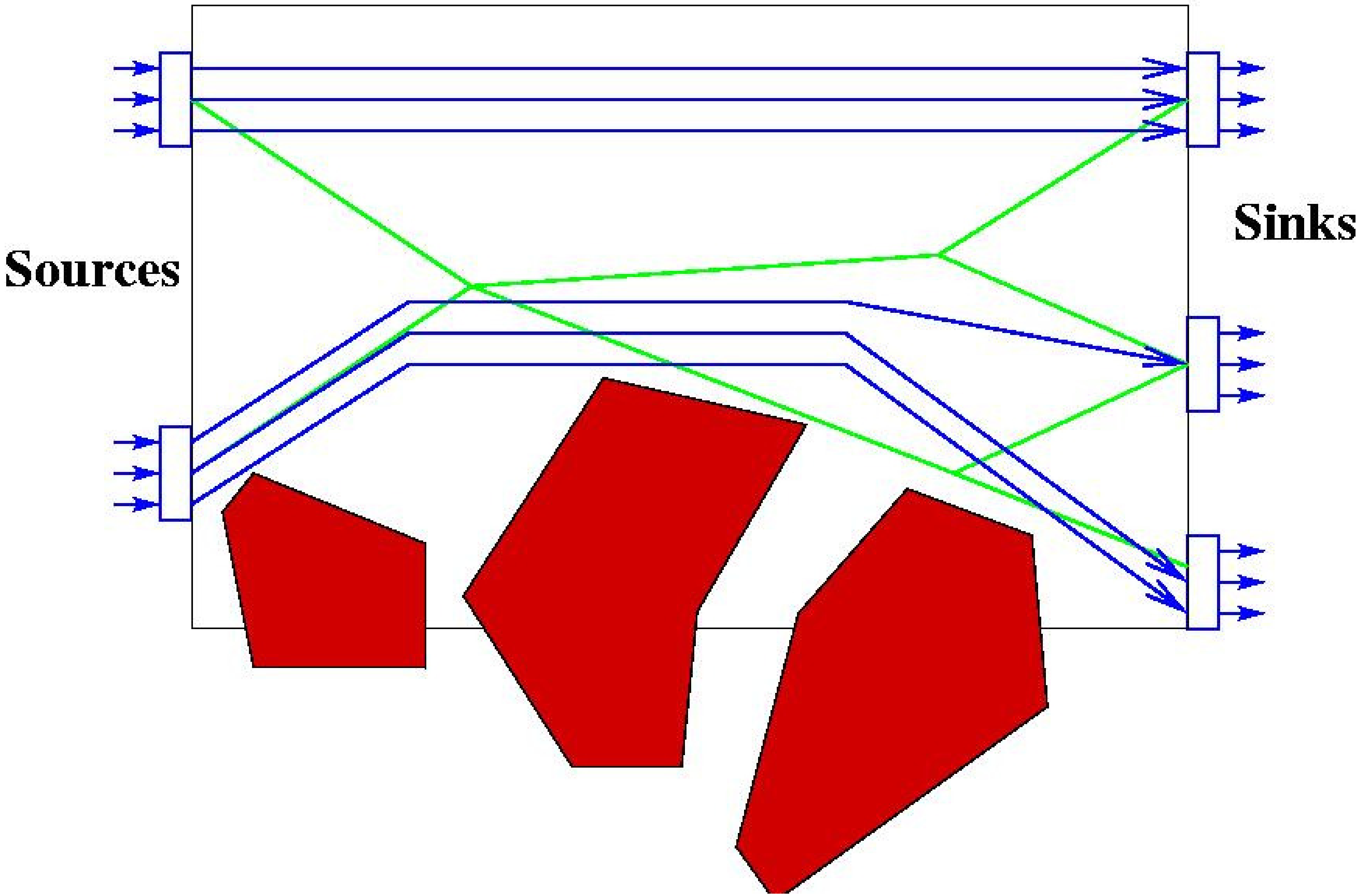
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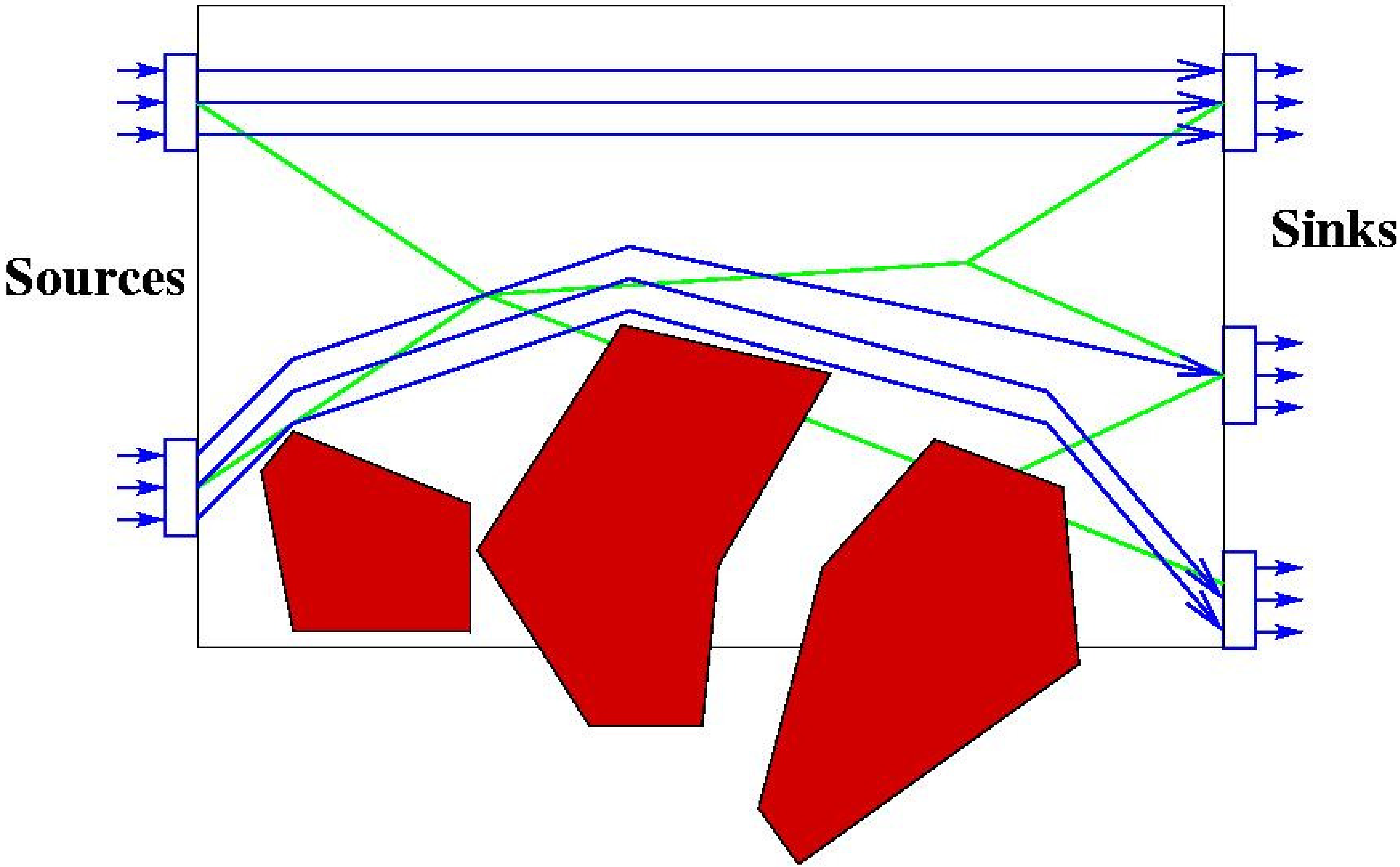

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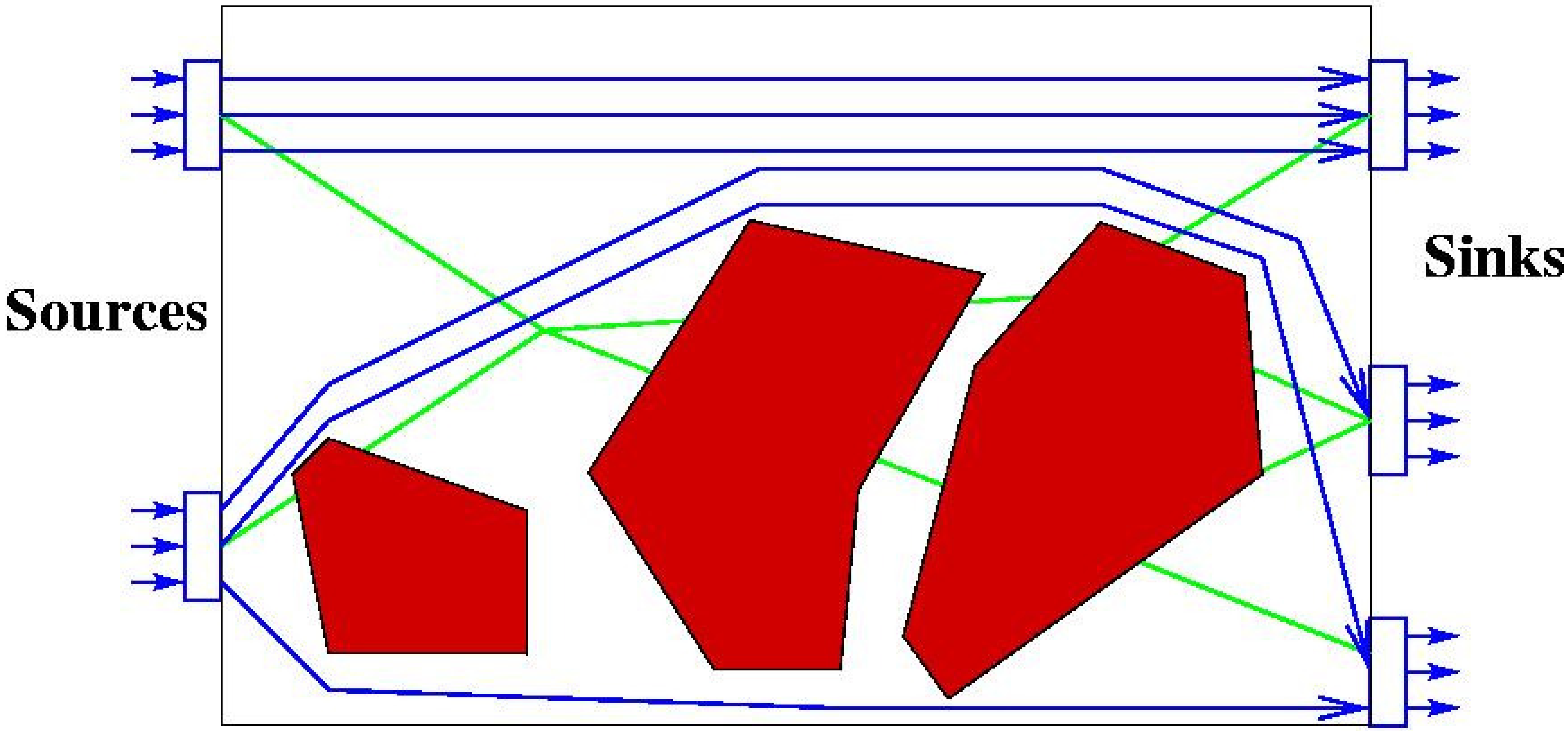
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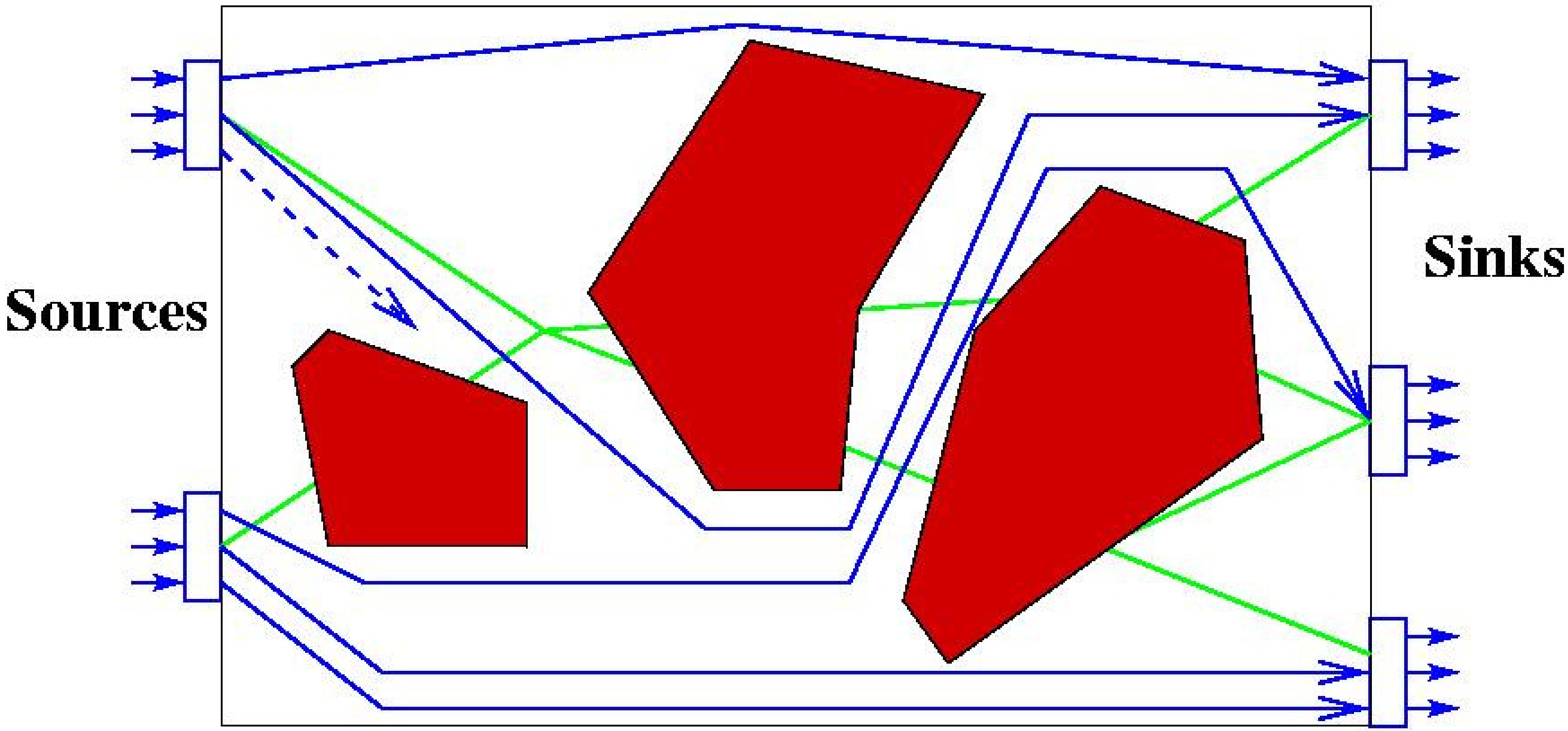
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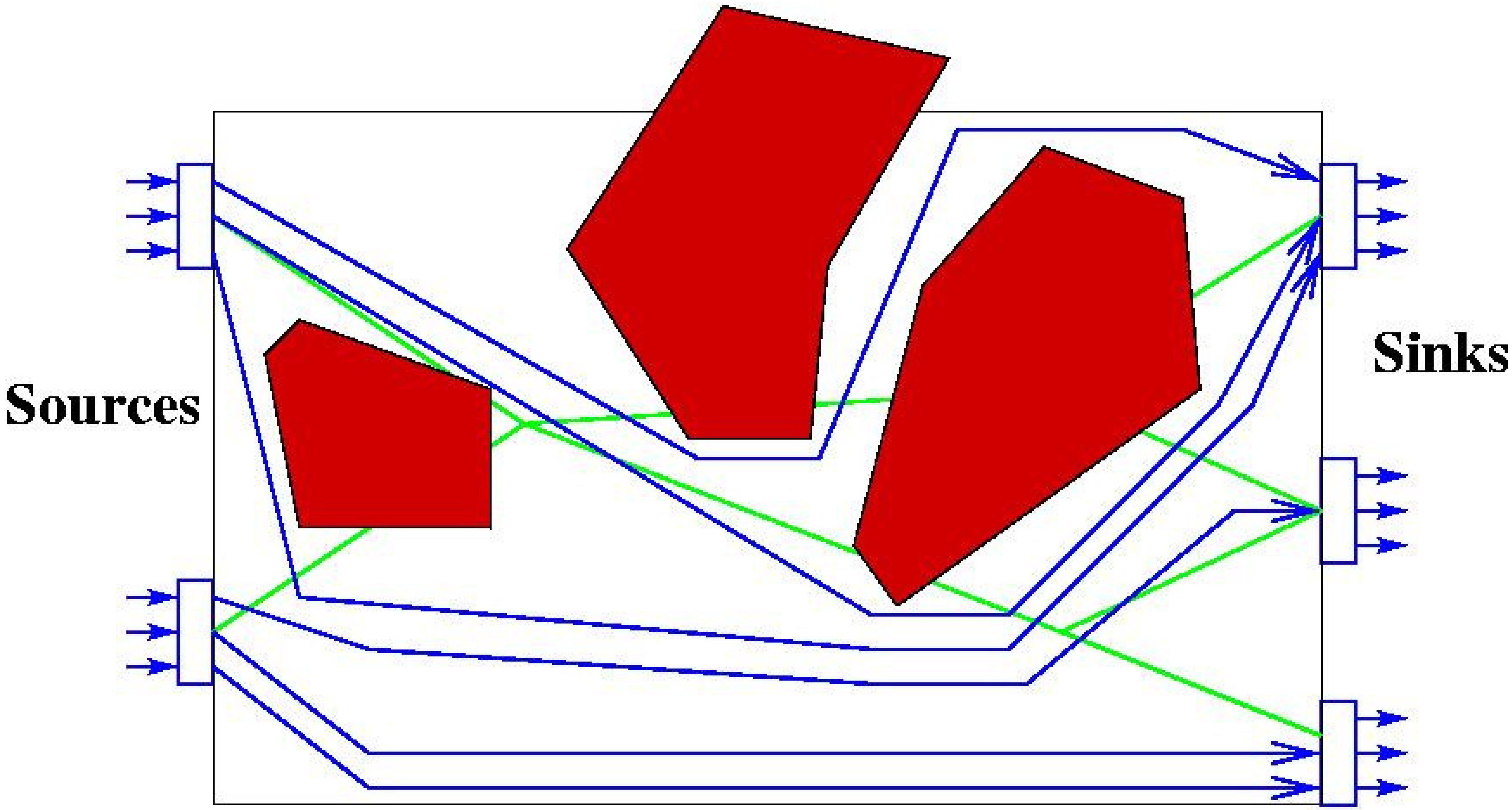
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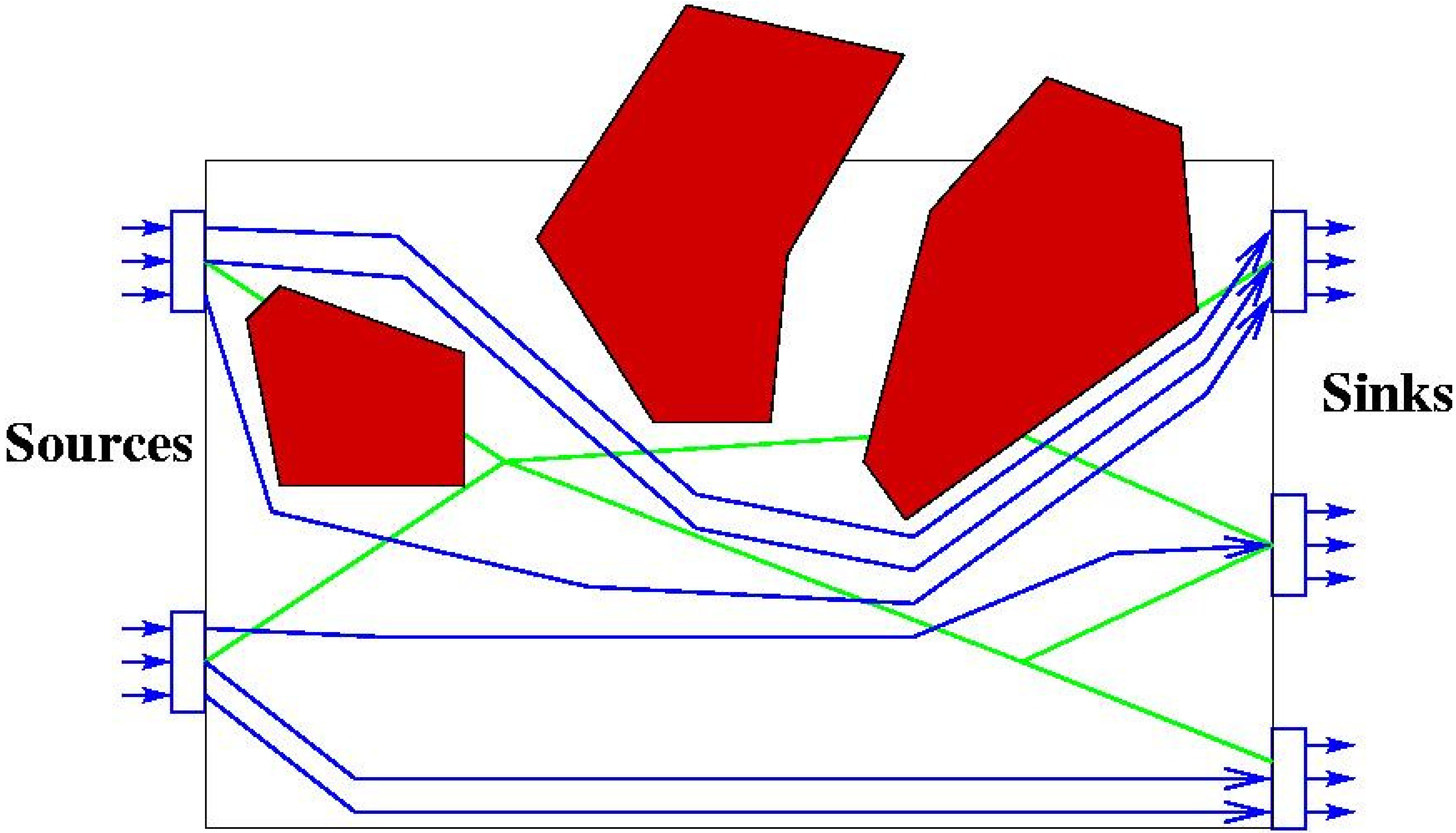
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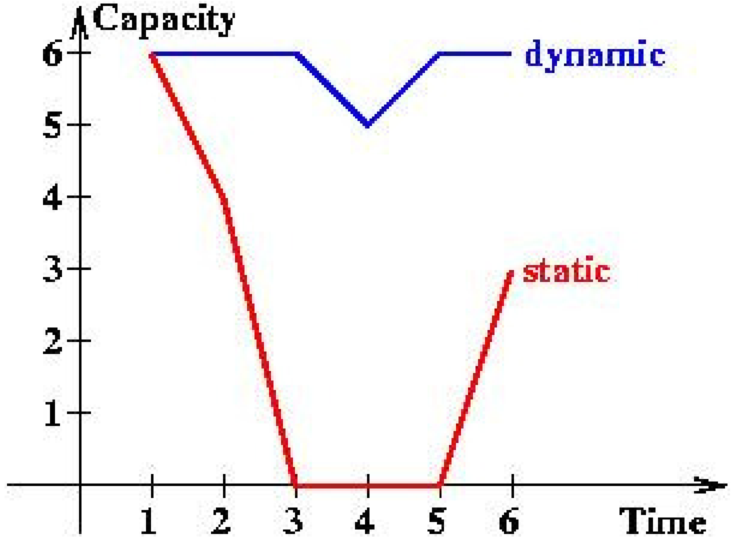
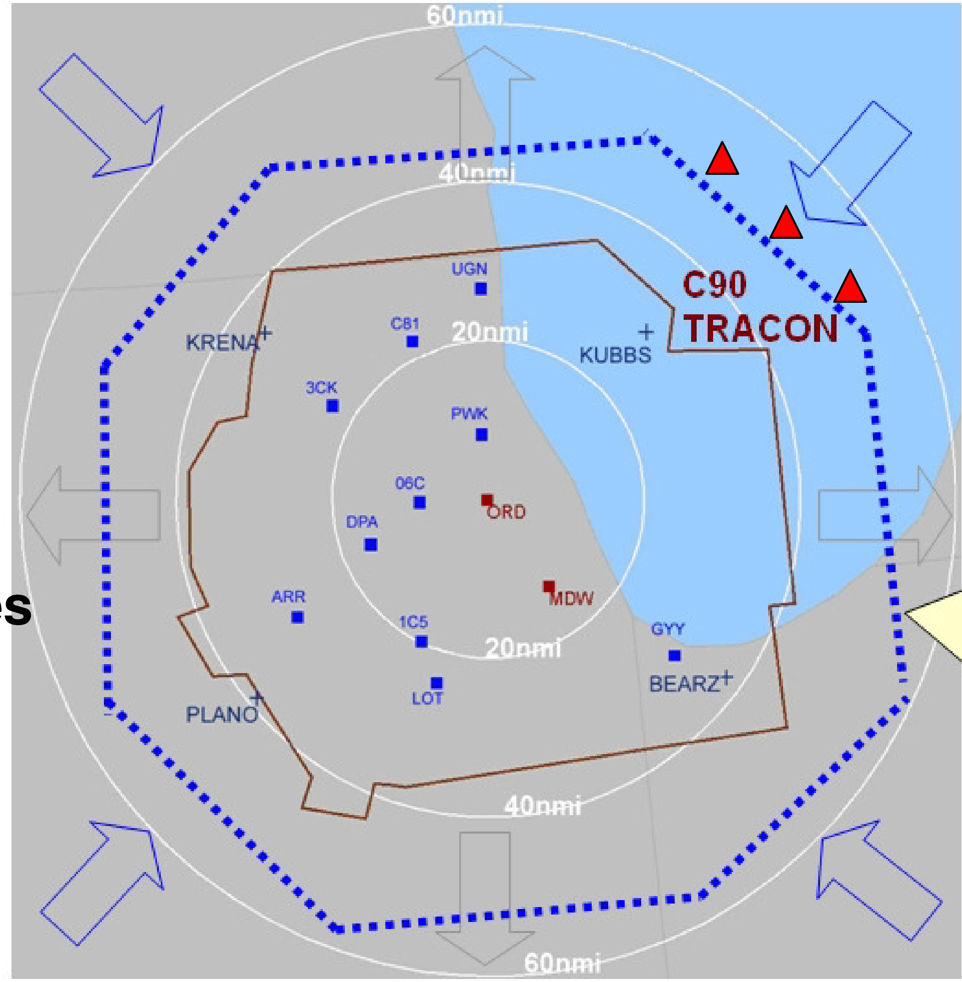
Comparison of Throughput

- Compare number of lanes using static jetway network versus dynamic max-flow air lanes:



Special Case: Airportal

- **A geographic region, usually surrounding a major population region, that contains large, high-density airports and additional satellite airports**
- **We allow 1, 2, or 3 arrival fixes per quadrant (cornerpost) passing over anchor points**



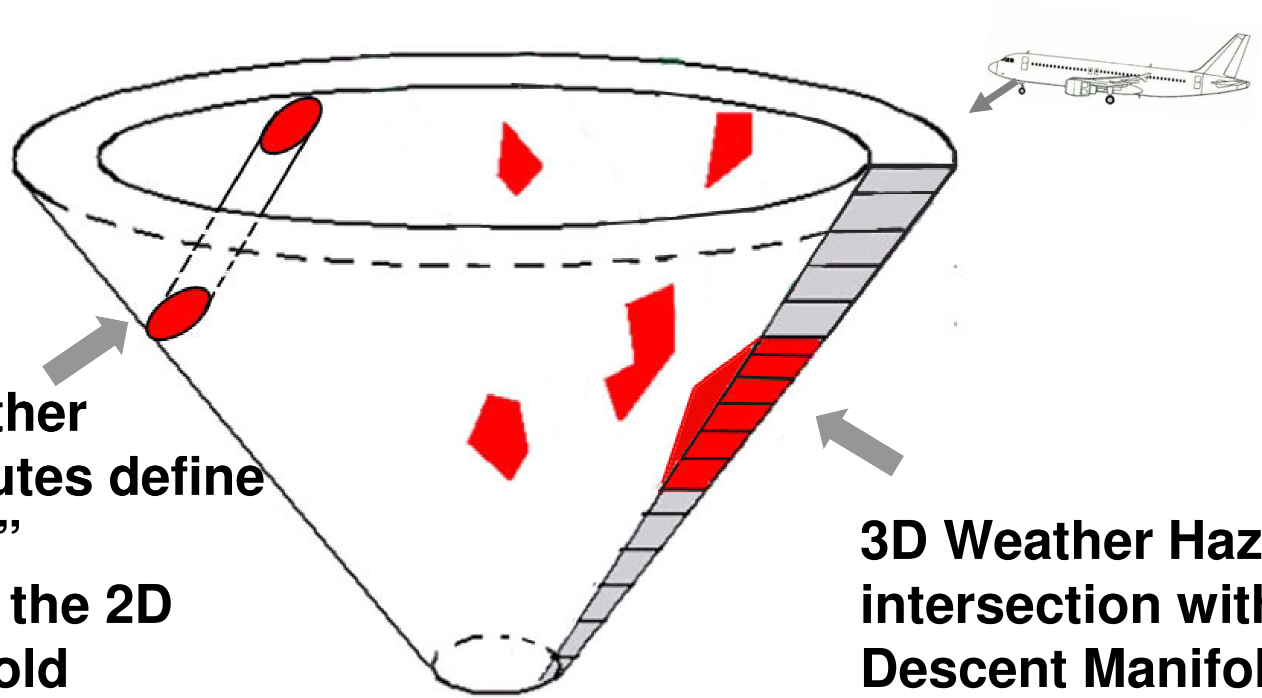
Chicago Airportal would include all these airports and optimize their collective performance as an Airportal system.

Airportal boundary may extend beyond the current day C90 boundaries based on Airportal flow optimization rather than radar coverage limitations.

METRON AVIATION

Jimmy Krozel (Metron)

3D Weather, 2D Manifold



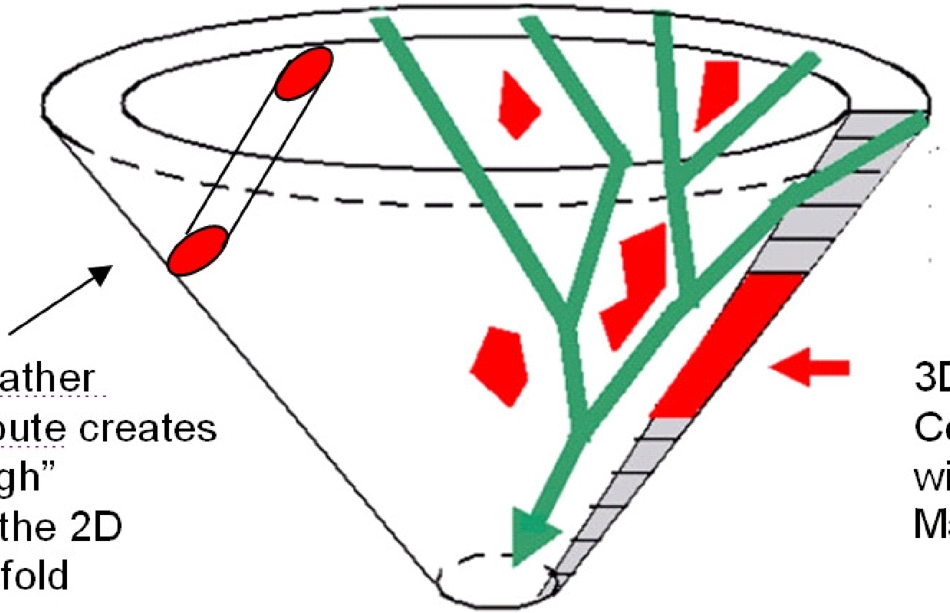
En Route Weather Avoidance Routes define "poke through" constraints on the 2D Descent Manifold

3D Weather Hazard intersection with 2D Descent Manifold

METRON AVIATION

Jimmy Krozel (Metron)

Arrival Tree: Merging Traffic



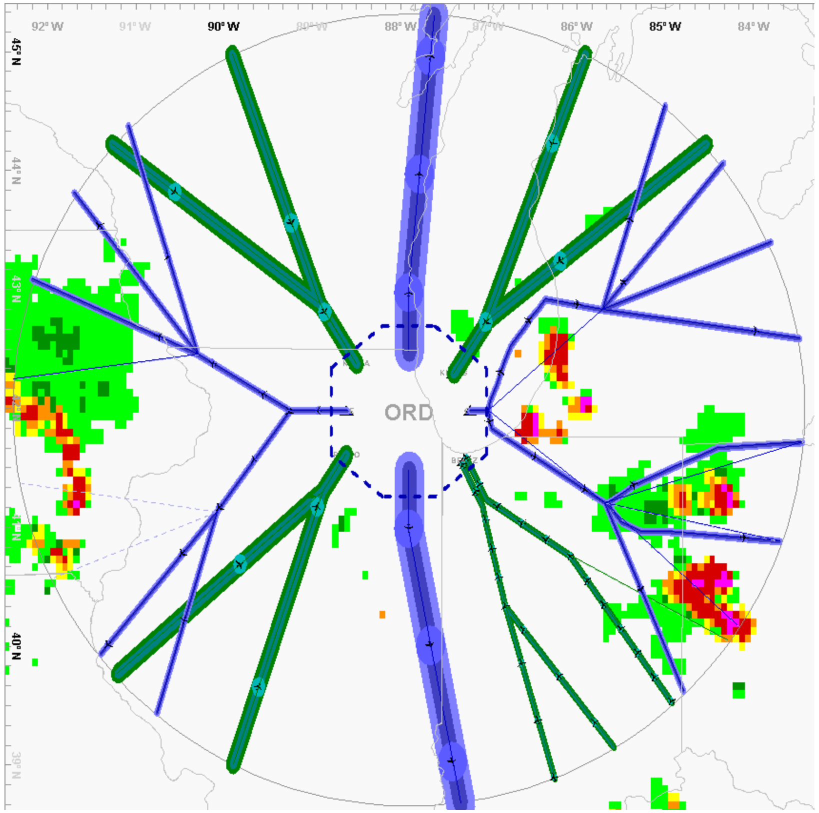
En Route Weather Avoidance Route creates a “poke through” constraint on the 2D Descent Manifold

3D Weather Hazard Constraint intersecting with 2D Descent Manifold

METRON AVIATION

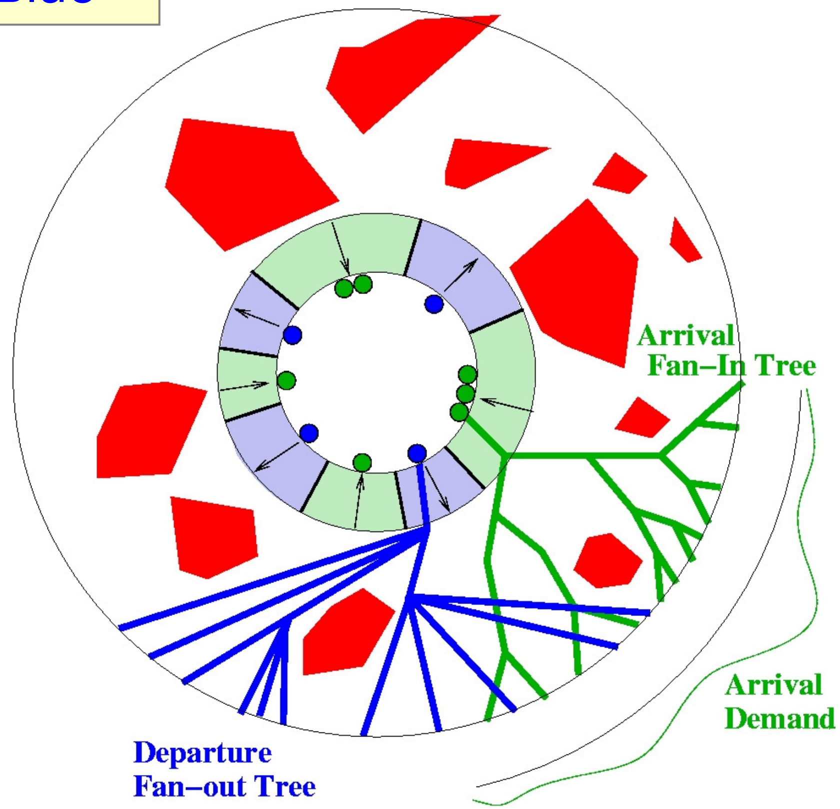
Jimmy Krozel (Metron)

Arrival and Departure Trees

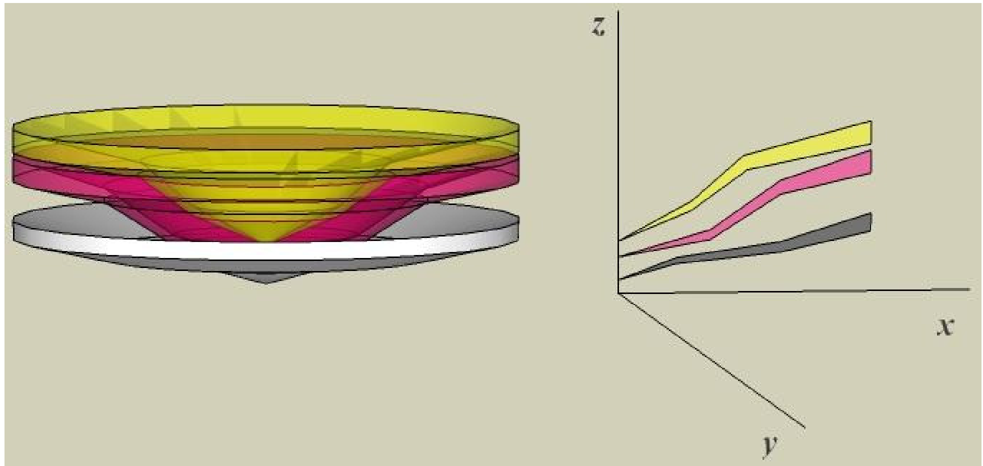


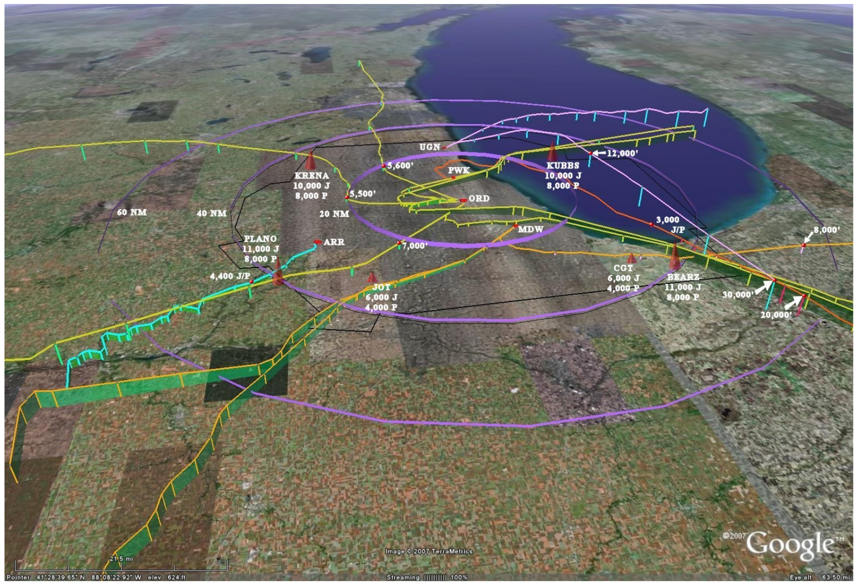
Arrivals in Green

Departures in Blue

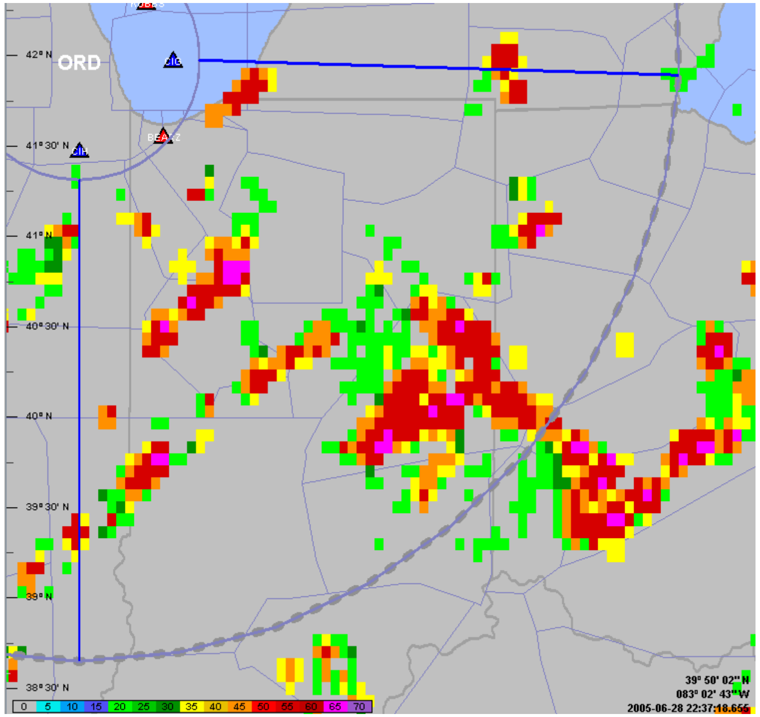


Descent Profiles

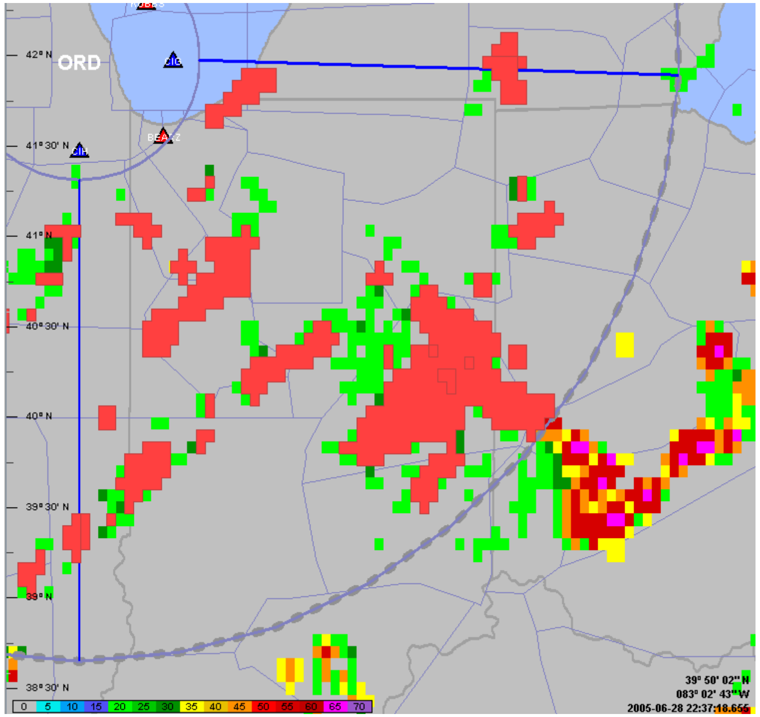




ASDO Capacity Estimation



CIWS
Convective Wx VIL Data



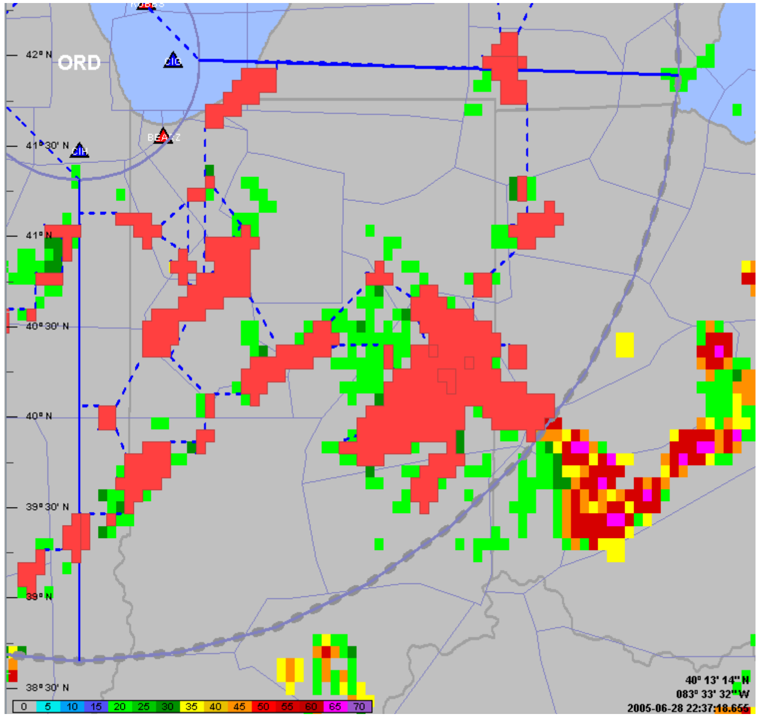
CWAM
Hazard Identification

CIWS="Corridor Integrated Weather System"

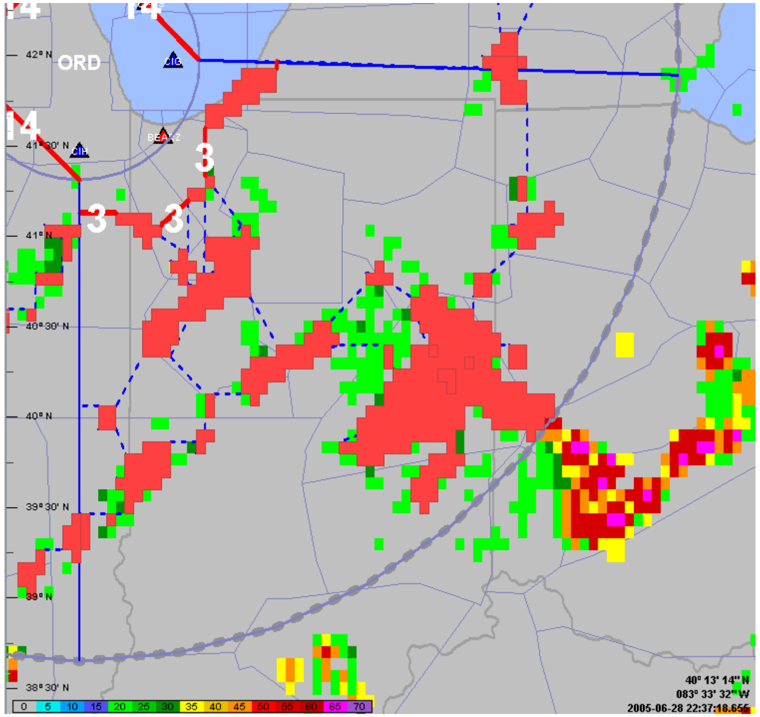
CWAM="Convective Weather Avoidance Model"

ASDO="Air Services Development Office"

ASDO Capacity Estimation



Define Critical Graph



Mincut Capacity given RNP