Combinatorial optimization for design and operations of telecommunication systems

Talk given at the Department of Systems and Industrial Engineering
University of Florida — Gainesville, Florida
October 18, 2005

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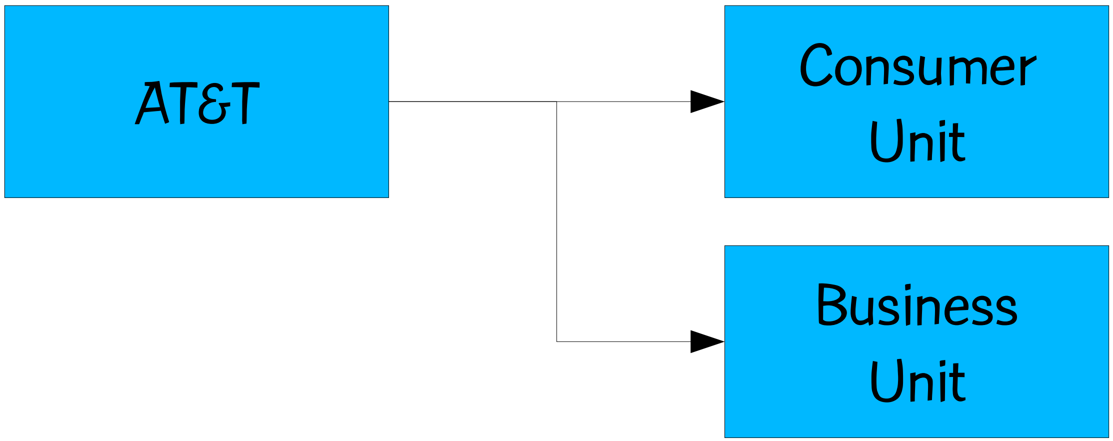

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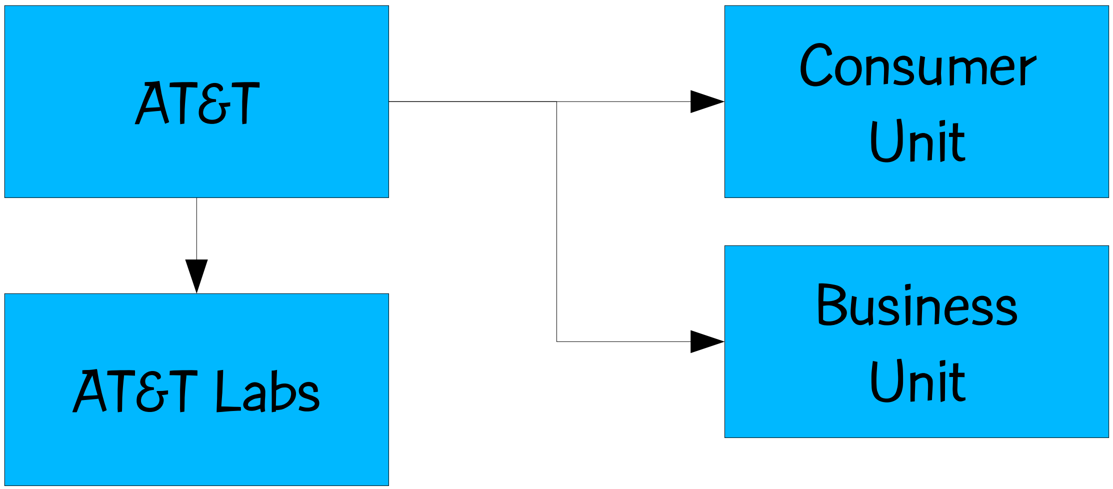

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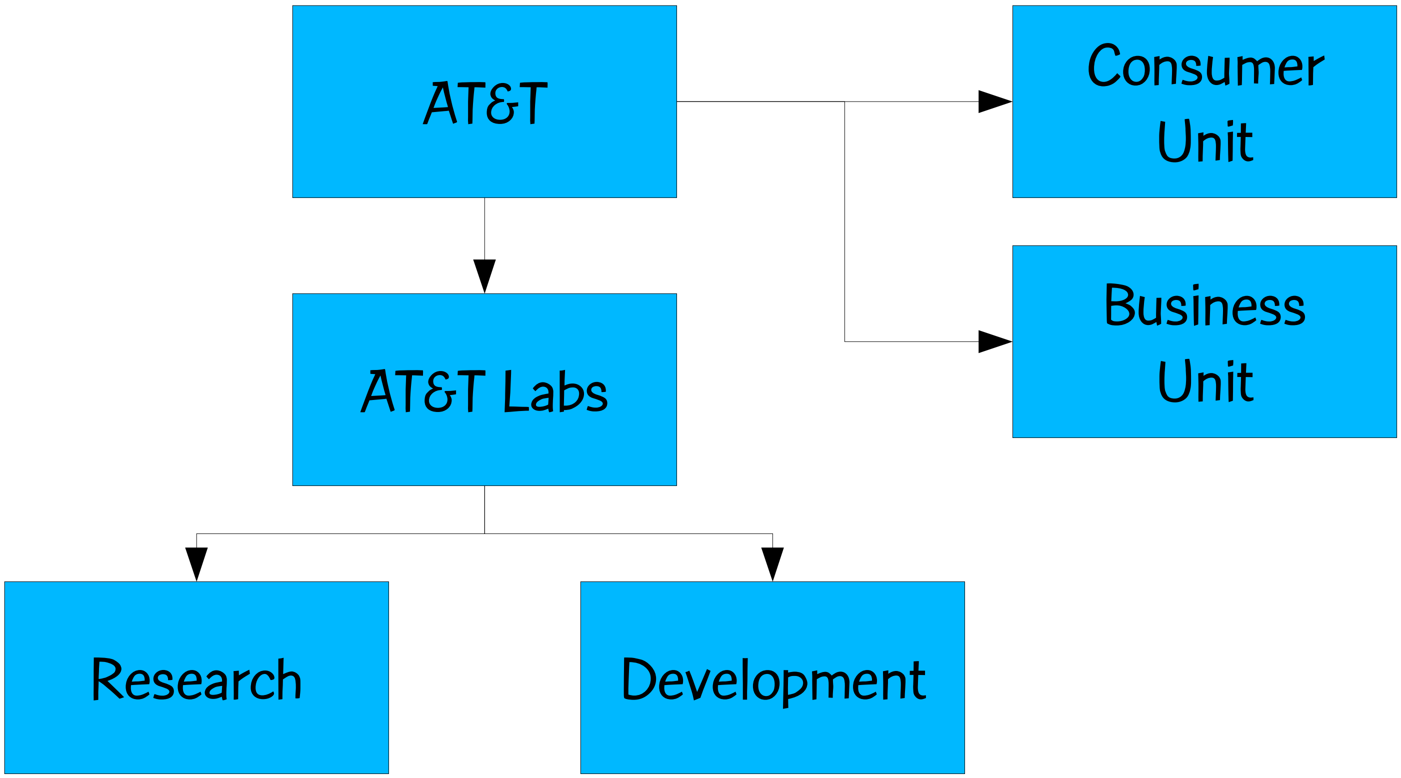

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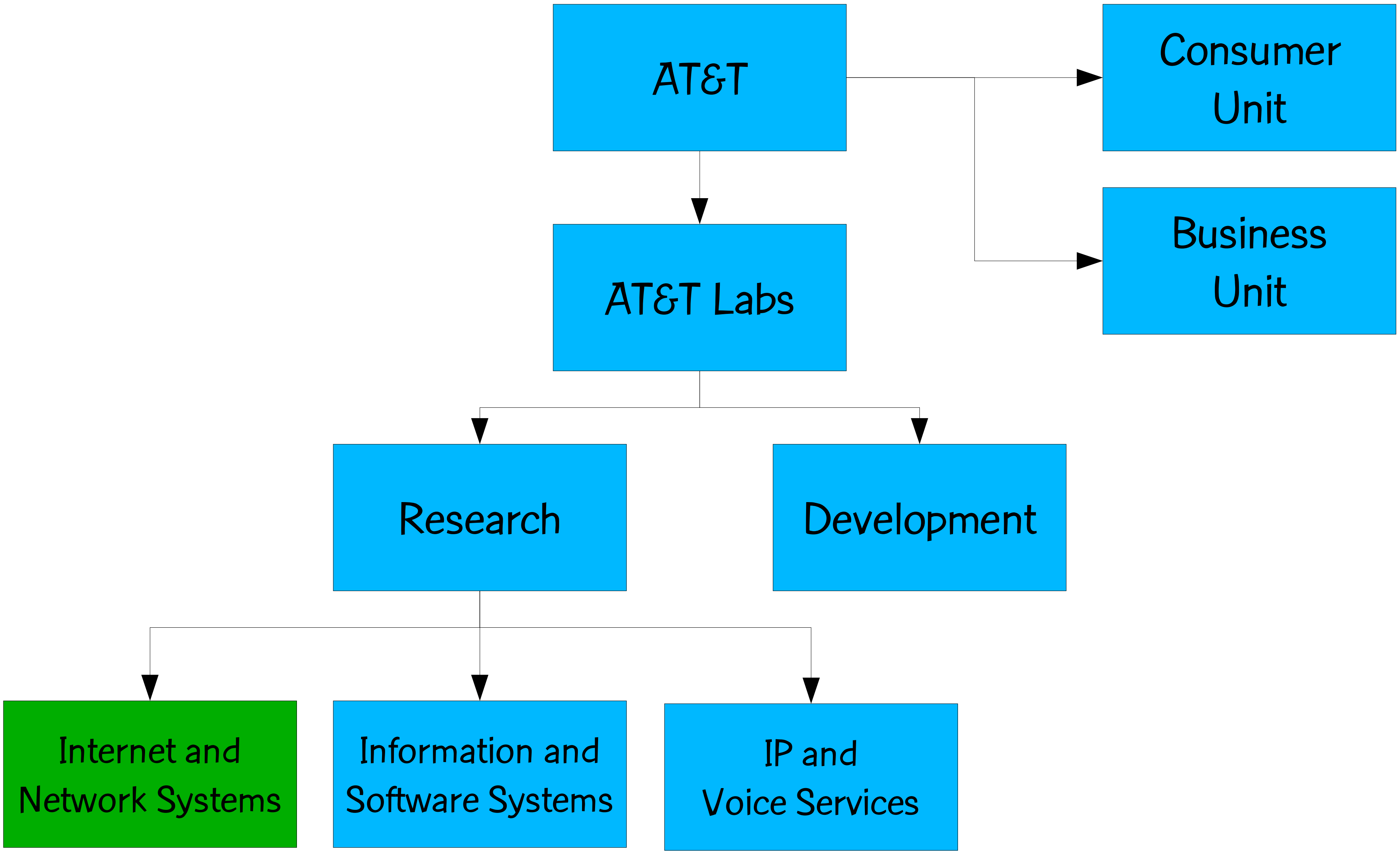

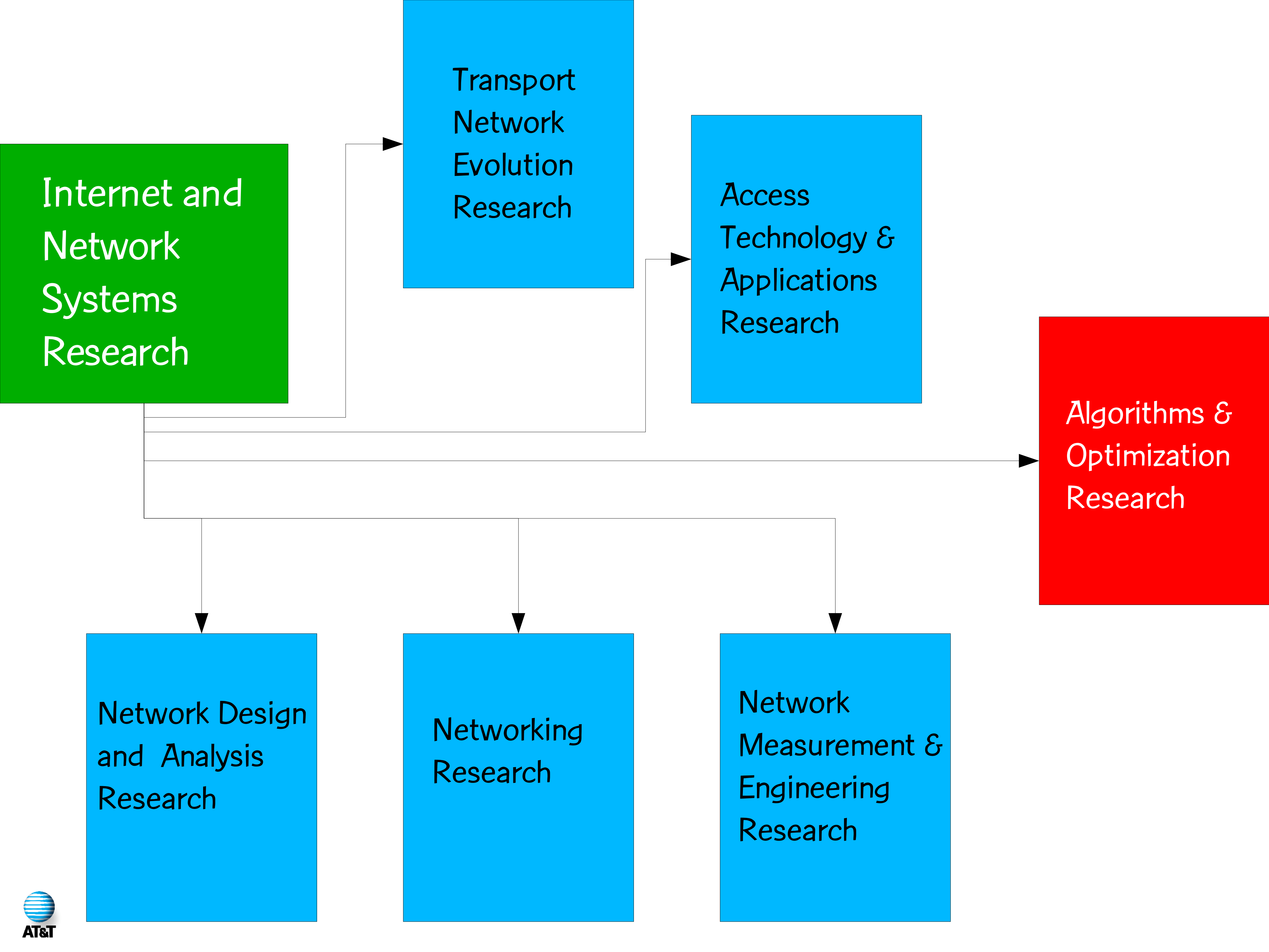

Internet and Network Systems Research
Transport Network Evolution Research
Access Technology & Applications Research
Algorithms & Optimization Research
Network Design and Analysis Research
Networking Research
Network Measurement & Engineering Research
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Summary of talk

- Network migration
- Modem pool placement for Internet service provider
- Local access network design
- Traffic routing on a virtual private network
- Internet traffic engineering
- Survivable IP network design

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Application 1:

Network migration scheduling

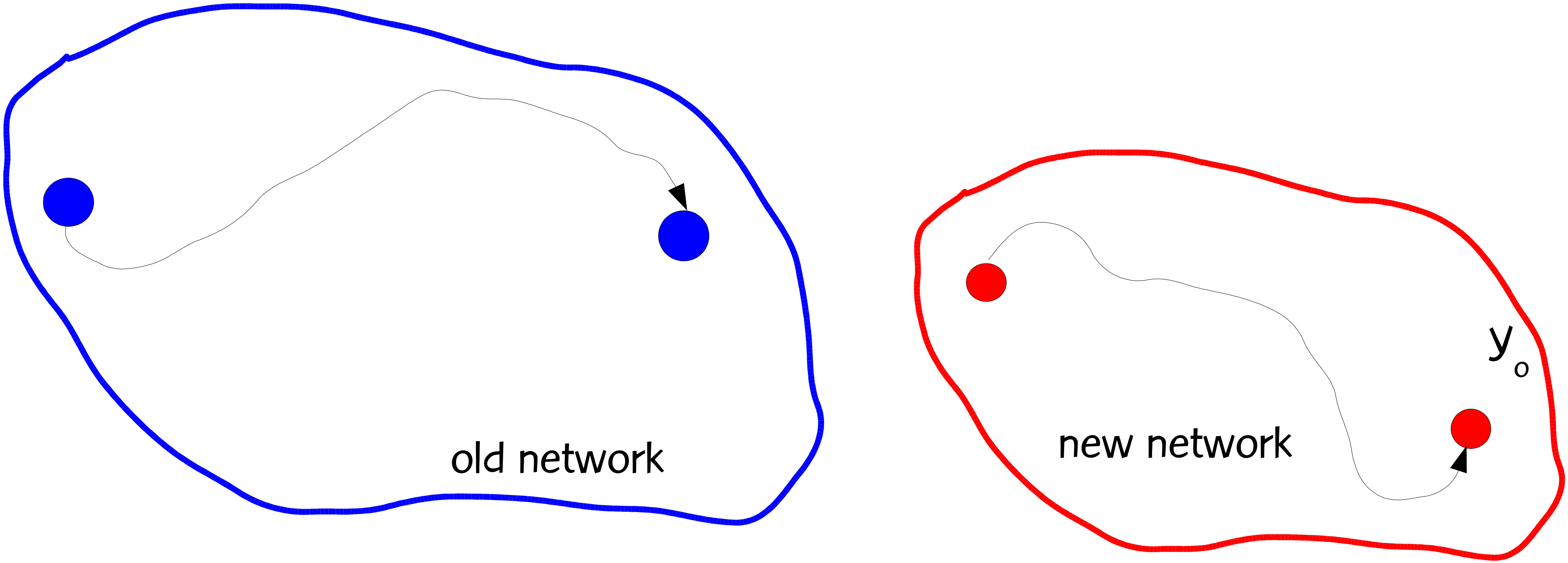
Network migration scheduling

- Voice service is moving from traditional switch-based networks to modern IP networks.
- Traffic has to be transitioned from old network to new network.
- How traffic transition is done can lead to different costs.

Network migration scheduling

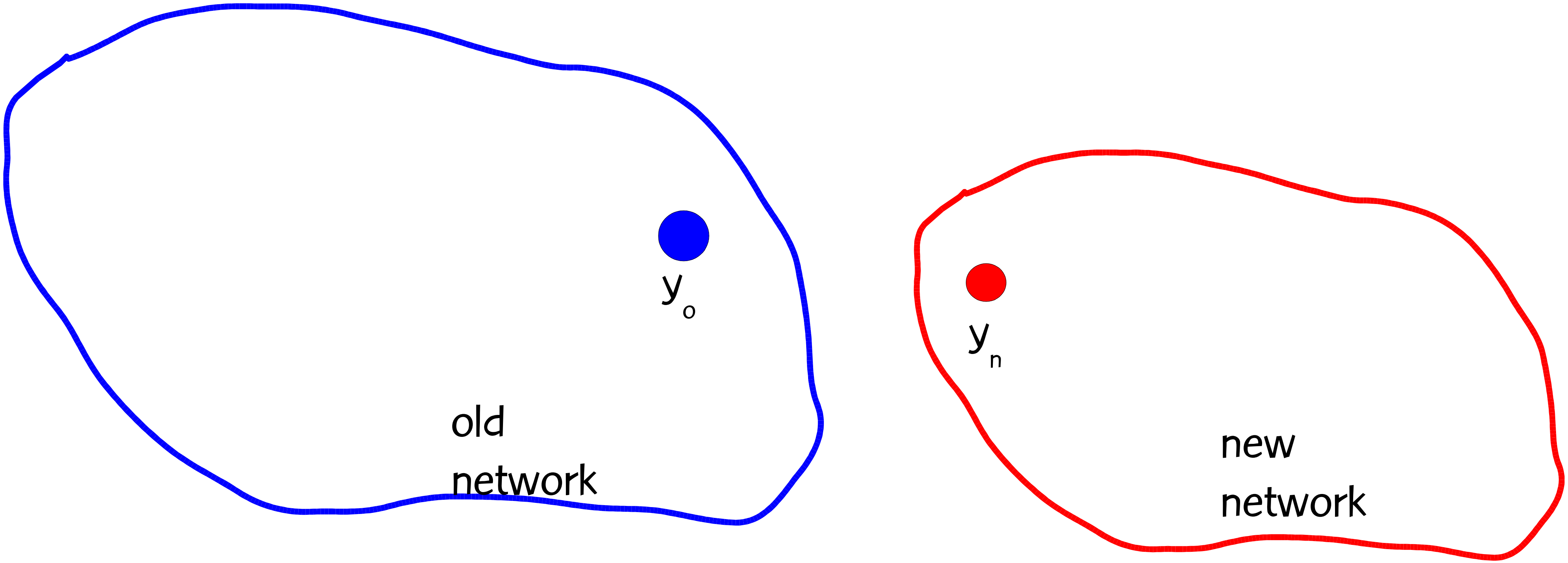
- Inter-nodal traffic from an outdated network is migrated to a new network.
- All traffic originating or terminating at a given node in the outdated network is moved to a specific node in the new network.
- Routing is predetermined in both networks and therefore capacities are known.

Network migration scheduling



Traffic between nodes in the same network is routed in that network.

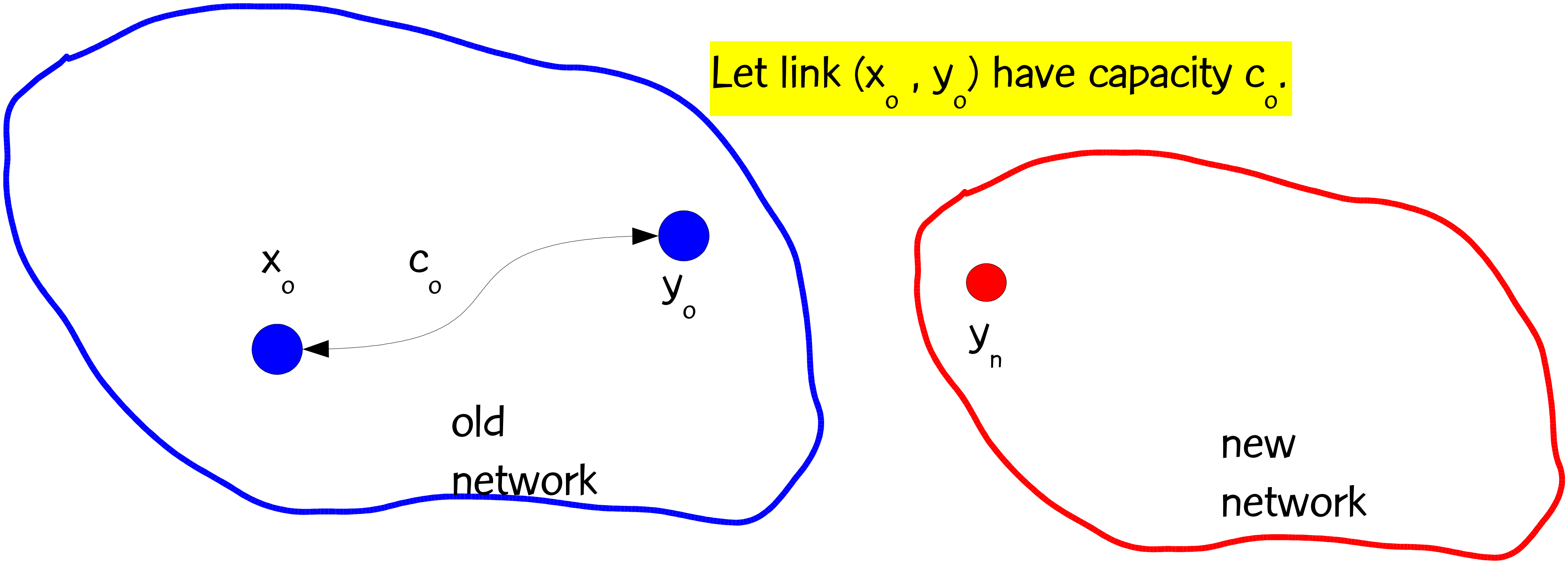
Network migration scheduling



Suppose node y_o in the old network is migrated to node y_n in the new network.

Network migration scheduling

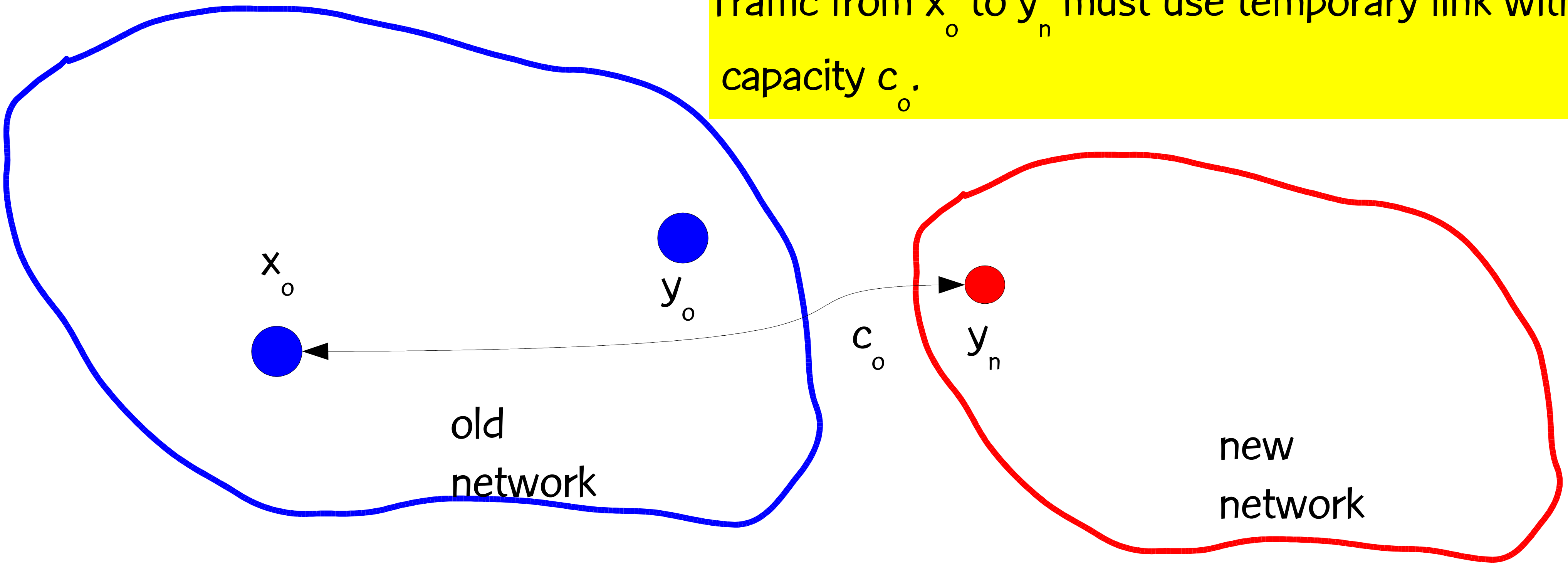
Let link (x_o, y_o) have capacity c_o.



Suppose node y_o in the old network is migrated to node y_n in the new network.

Network migration scheduling

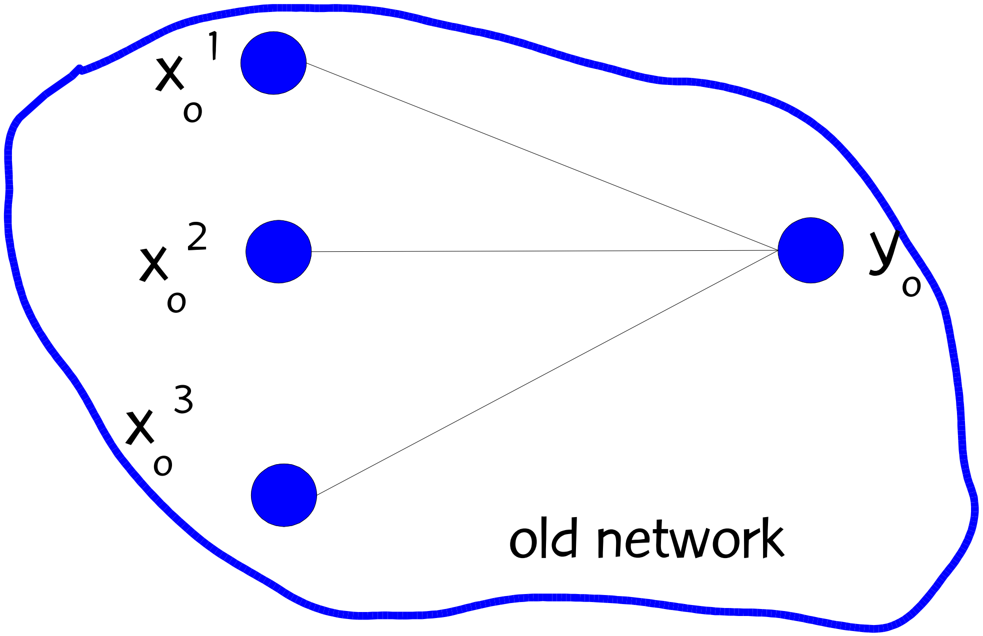
Traffic from x_o to y_n must use temporary link with capacity c_o.



Suppose node y_o in the old network is migrated to node y_n in the new network.

Network migration scheduling

- When node y_o is migrated to y_n in the new network, one or more temporary links may have to be used, since node y_o may be adjacent to one or more still-active nodes in the old network.



Network migration scheduling

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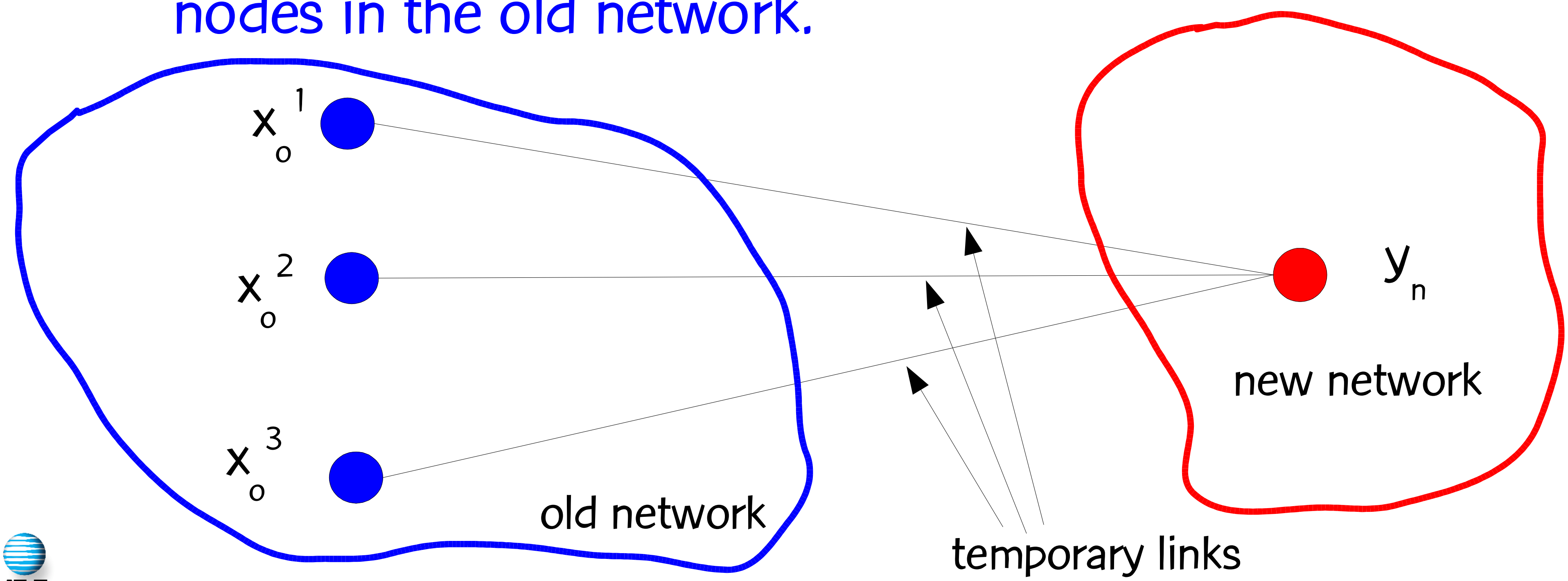
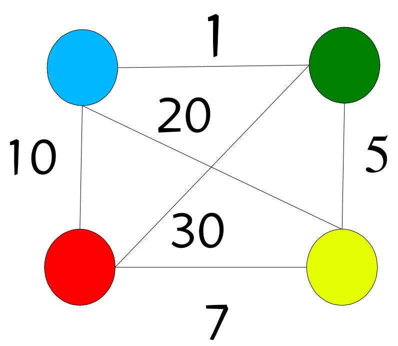


Network migration scheduling problem

- Find a migration ordering of the vertices such that the maximum sum of the capacities of the temporary links is minimized.



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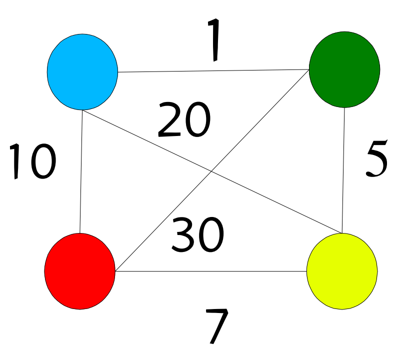

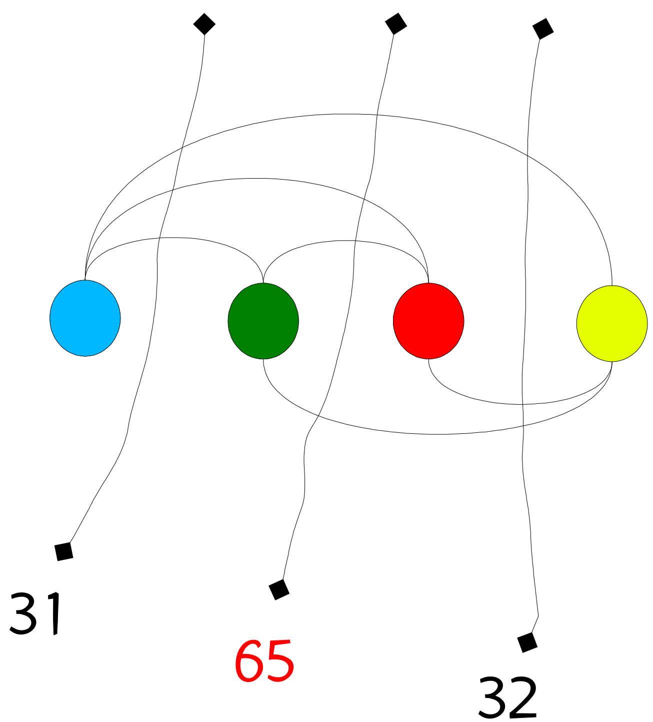

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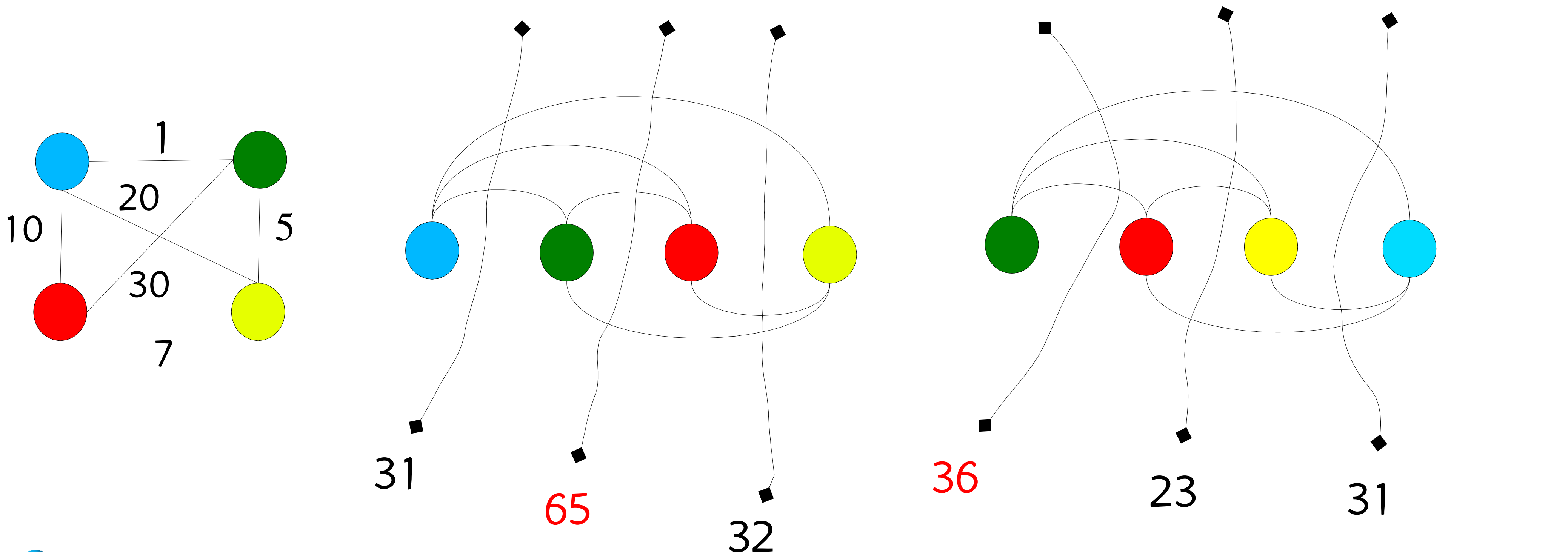

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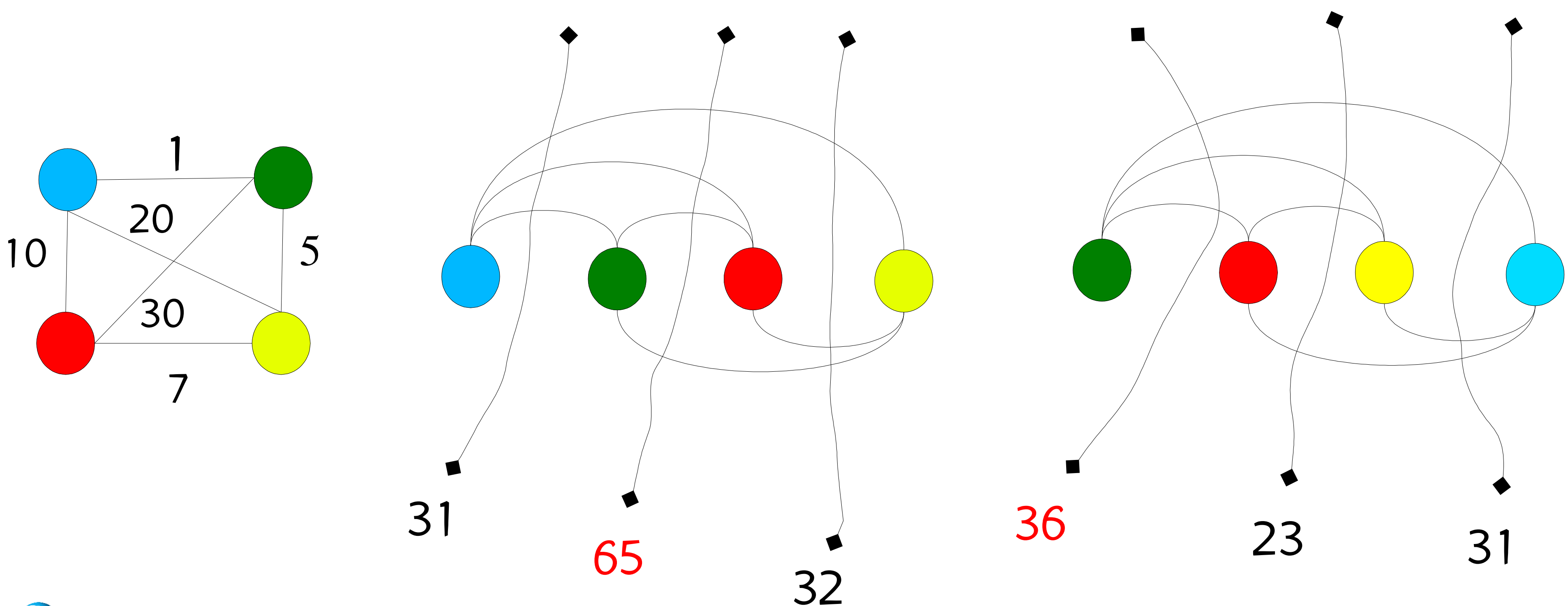

min cut linear arrangement problem

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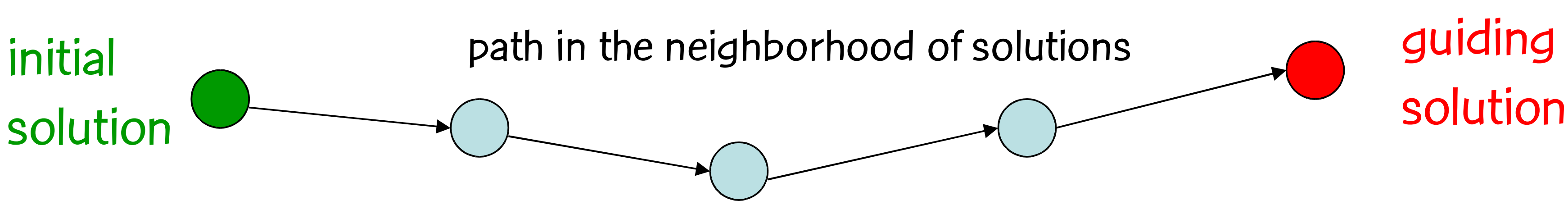
GRASP with Path-relinking for MCLA

```
repeat {
        π = GreedyRandomizedConstruction(■);
        π = LocalSearch(π);
        π = PathRelinking(π);
        save π as π* if best so far;
}
return π*;
```

Path-relinking (Glover, 1996)

- Exploration of trajectories that connect high quality (elite) solutions:



Path-relinking

- Path is generated by selecting moves that introduce in the initial solution attributes of the guiding solution.
- At each step, all moves that incorporate attributes of the guiding solution are evaluated and the best move is selected:

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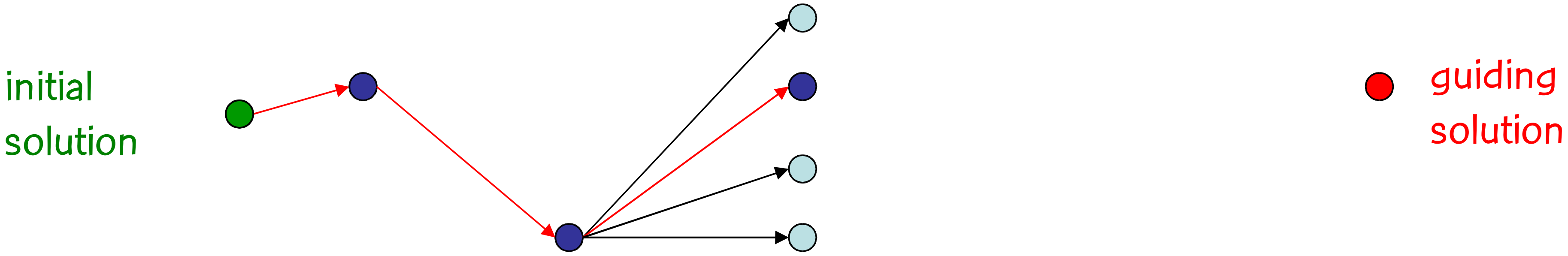

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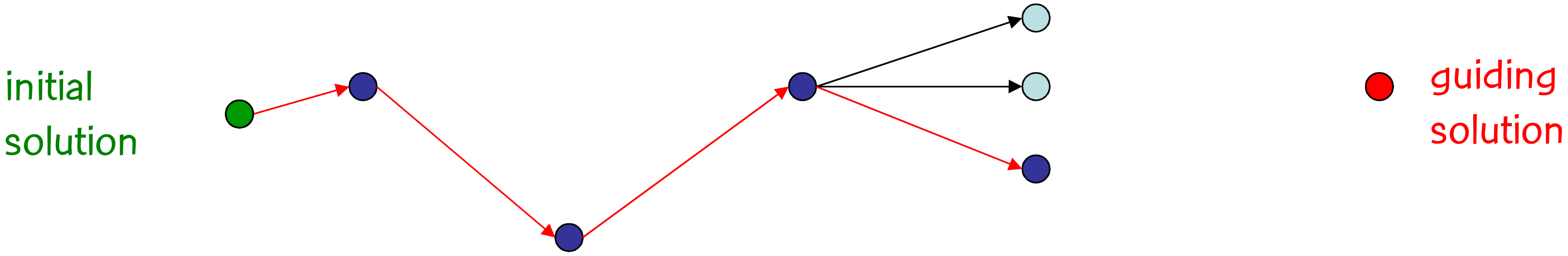

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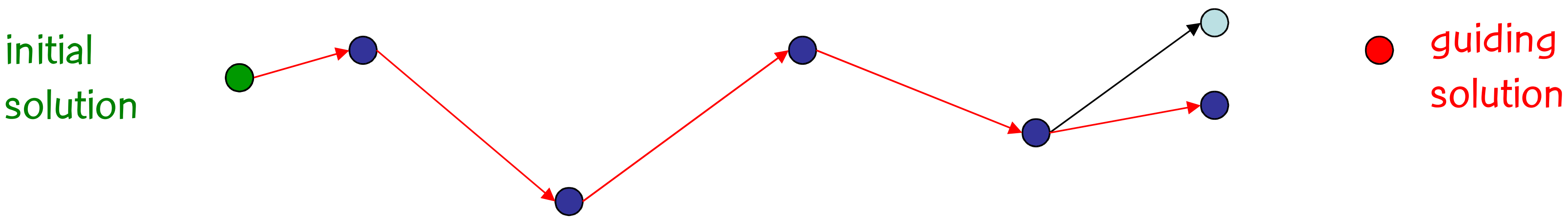

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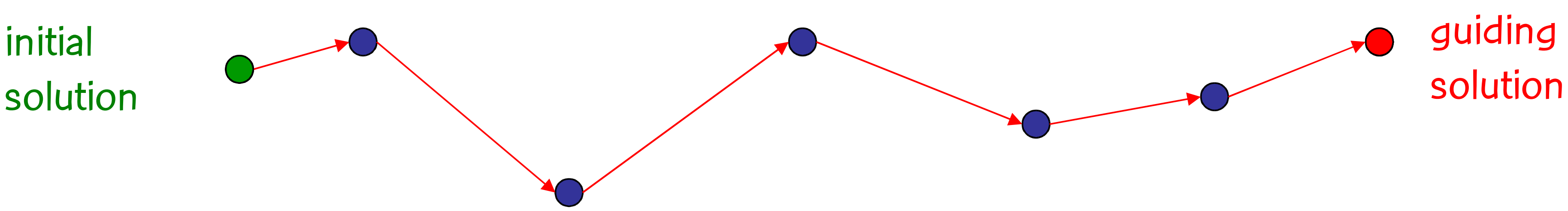
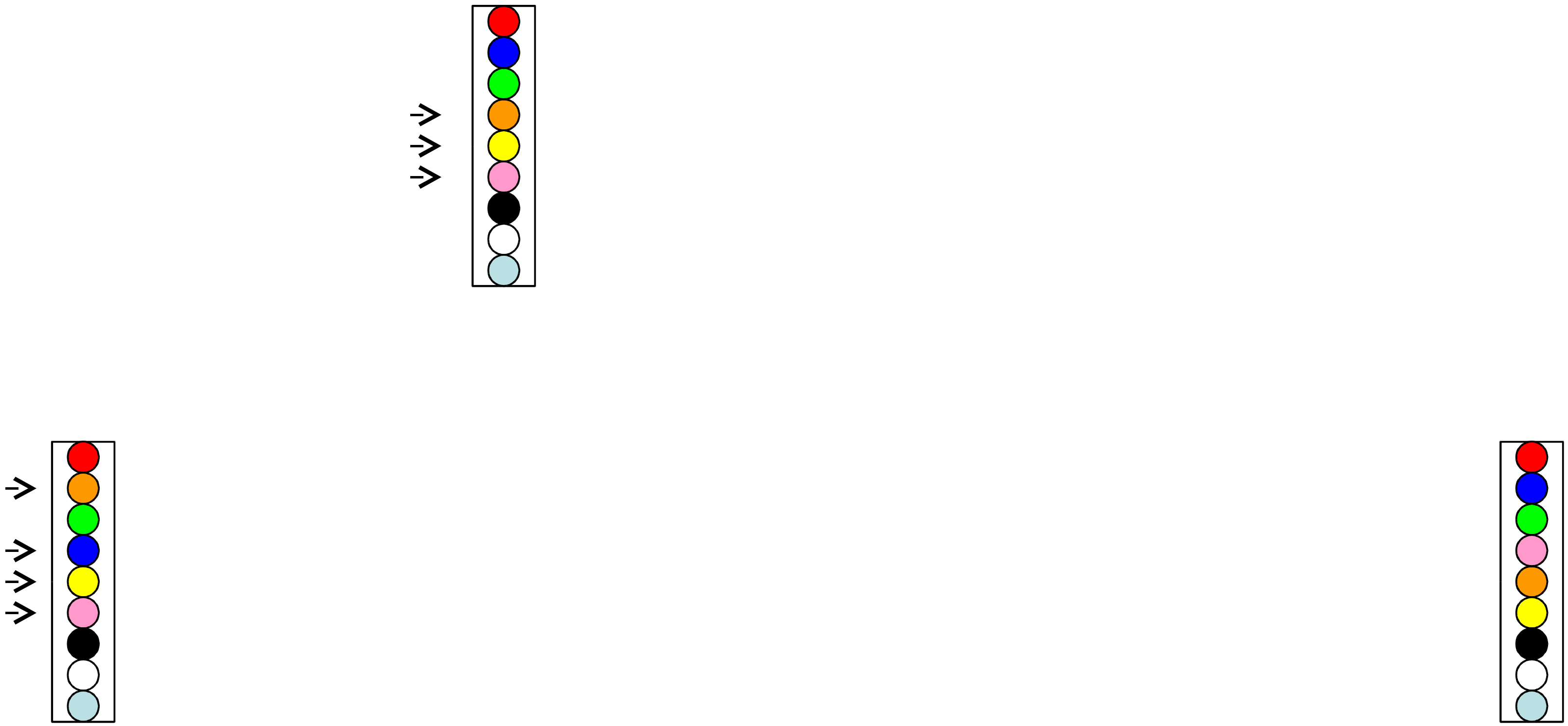
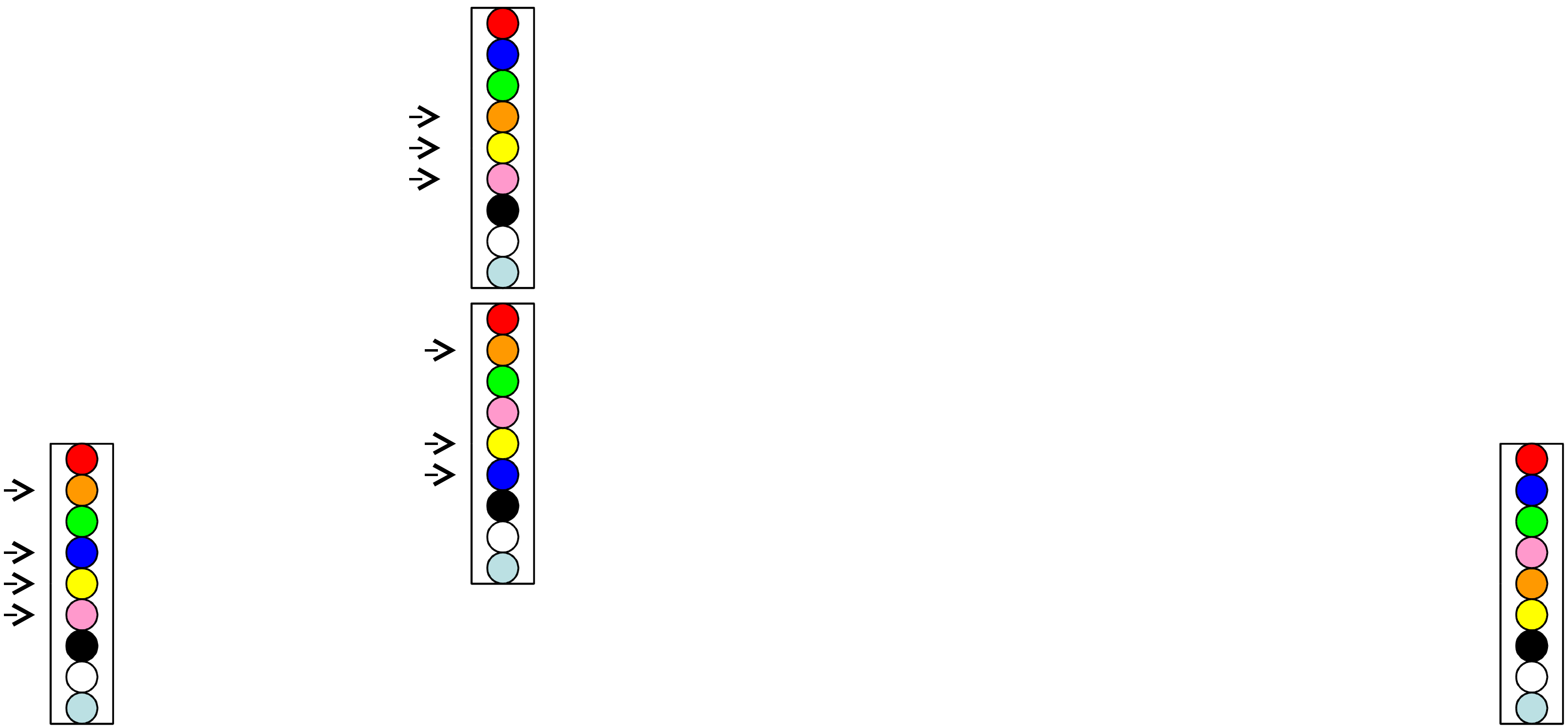
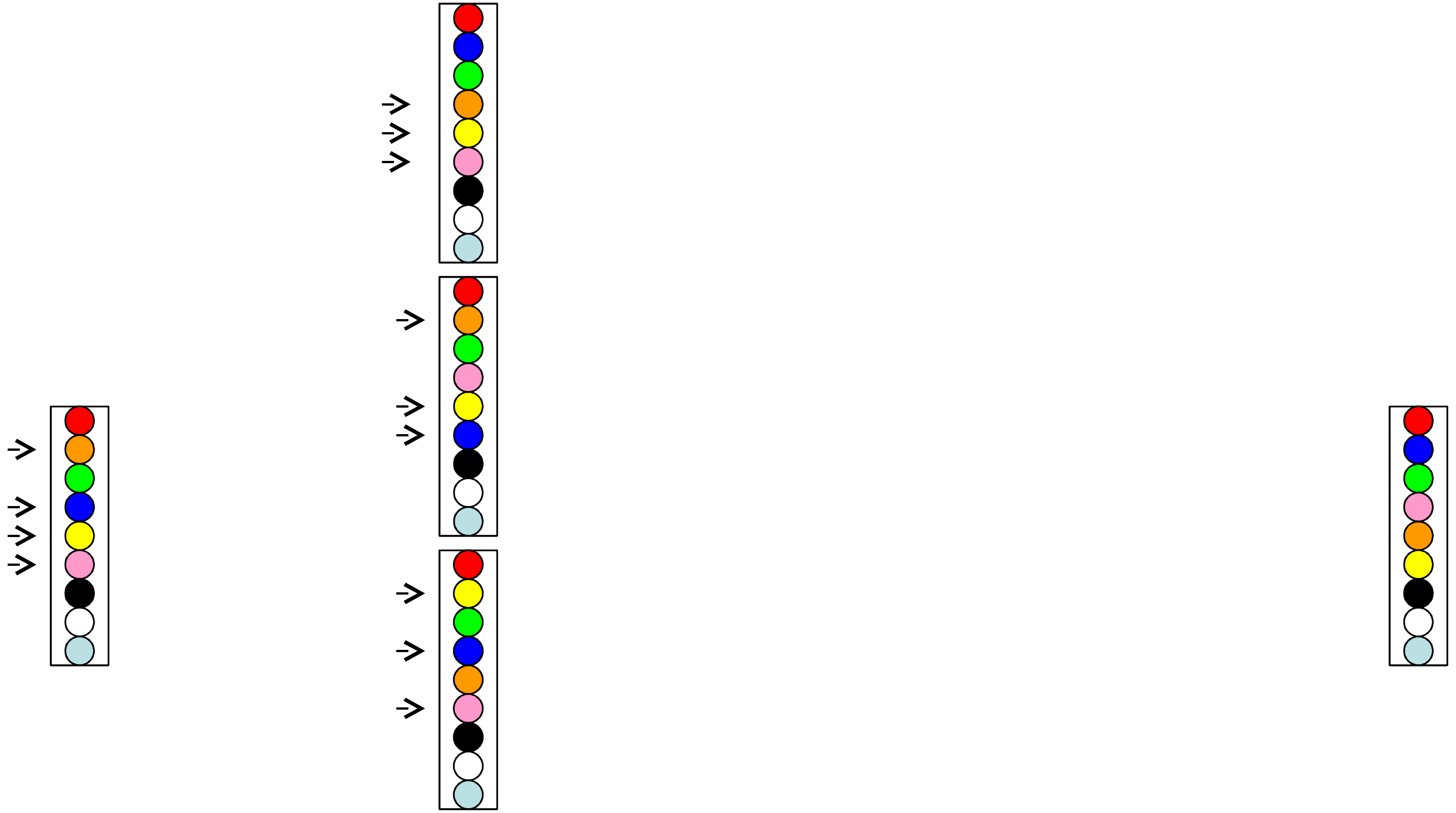
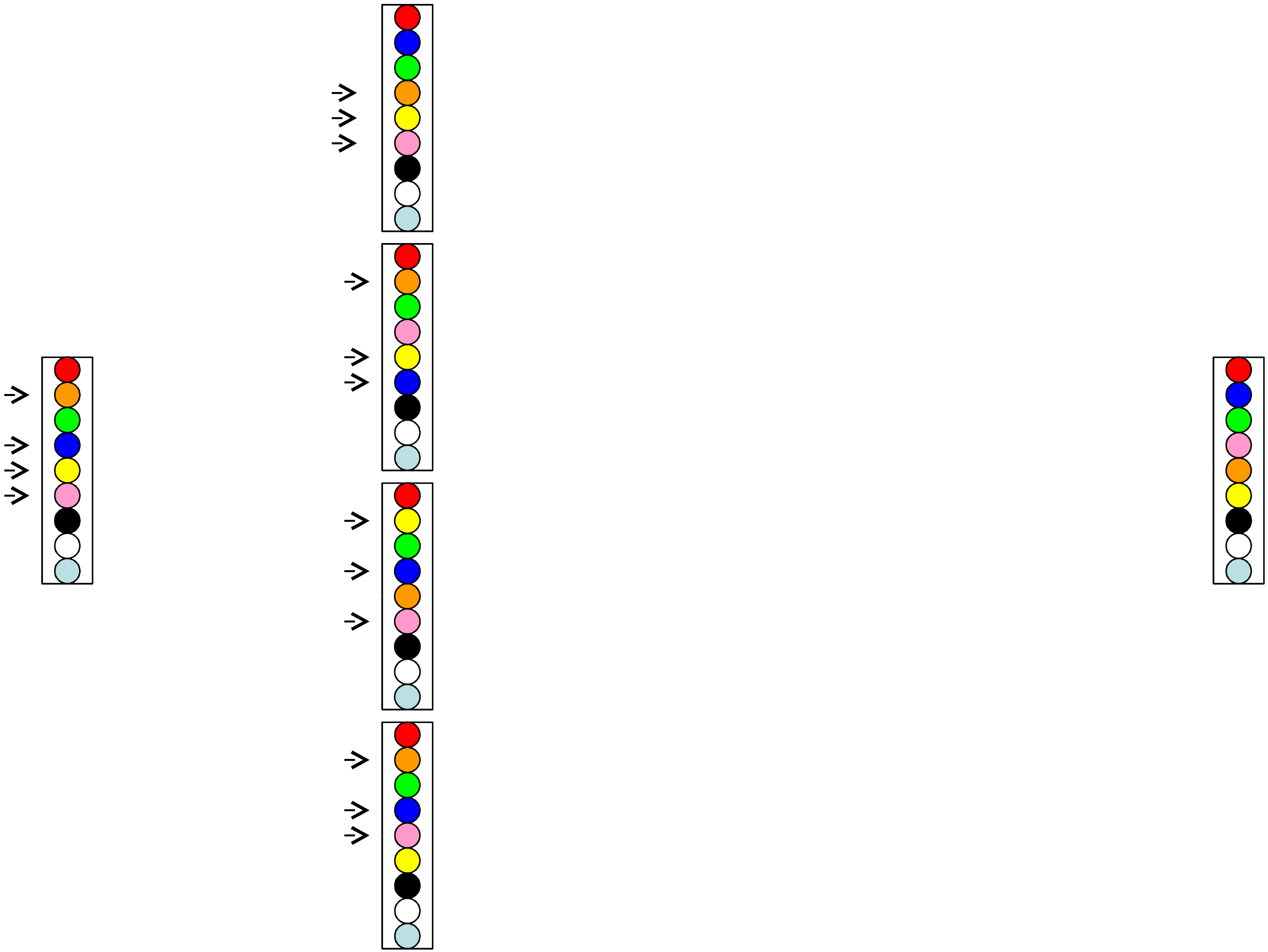


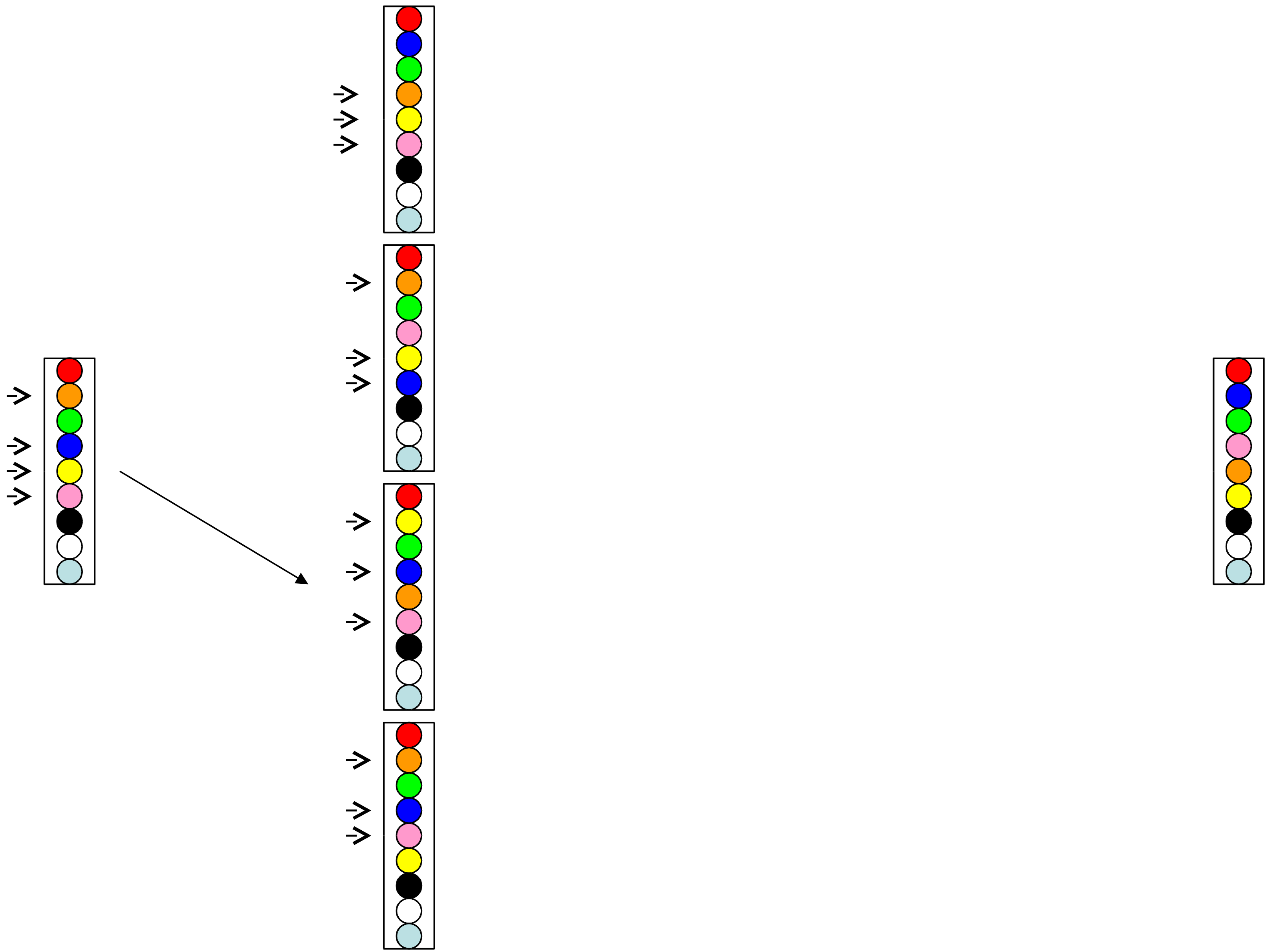


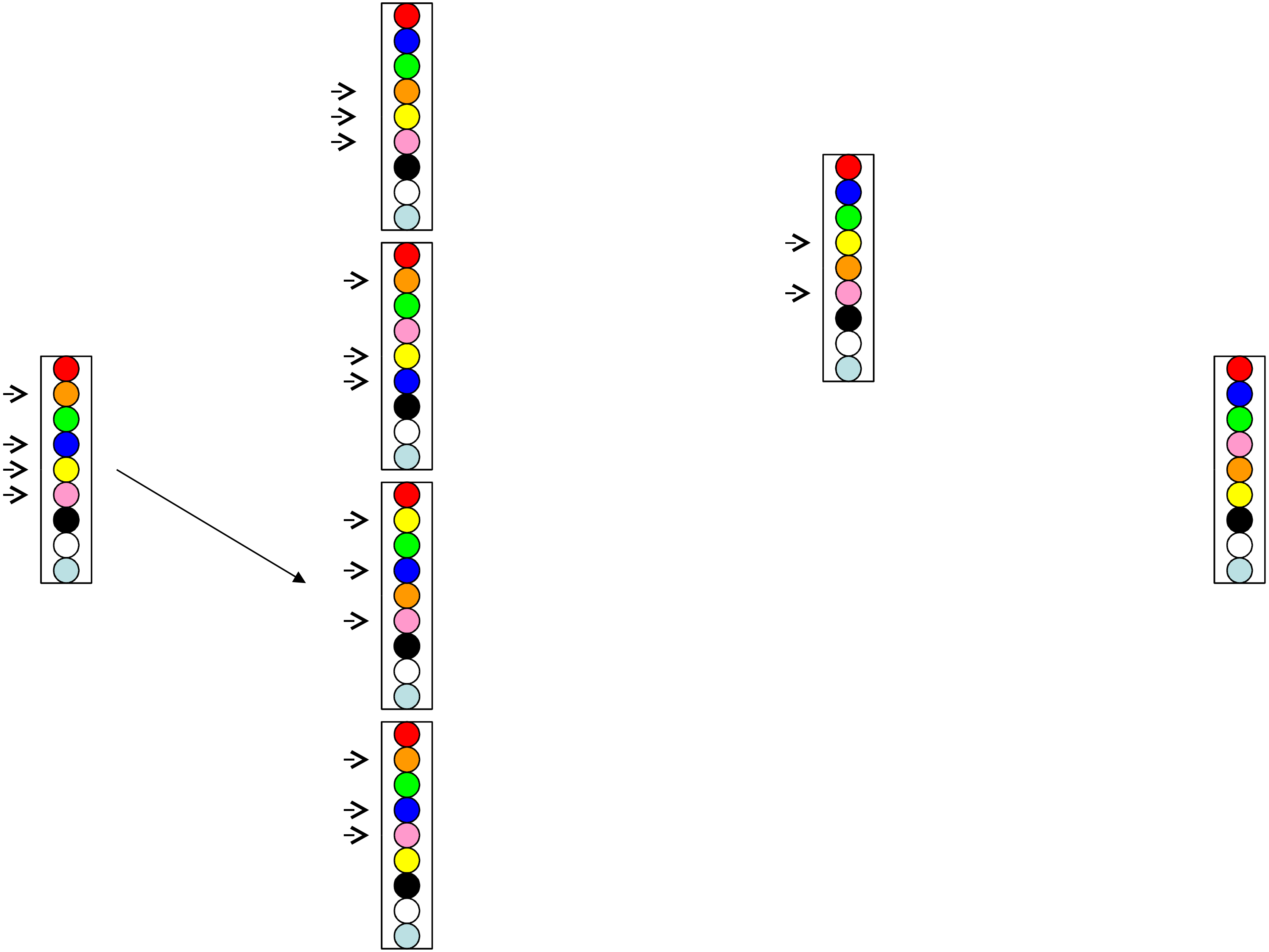






Path-relinking for the MCLA problem





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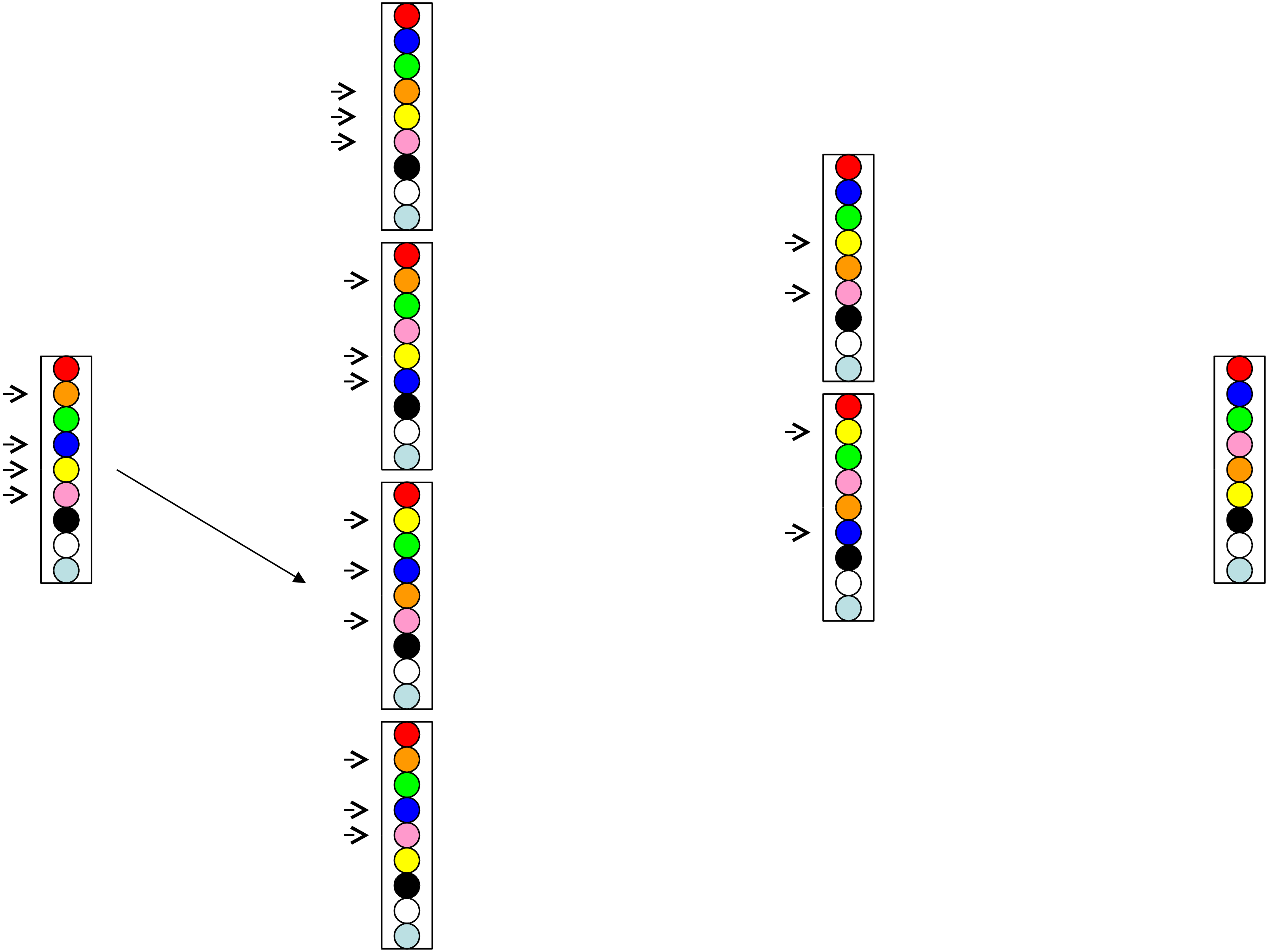
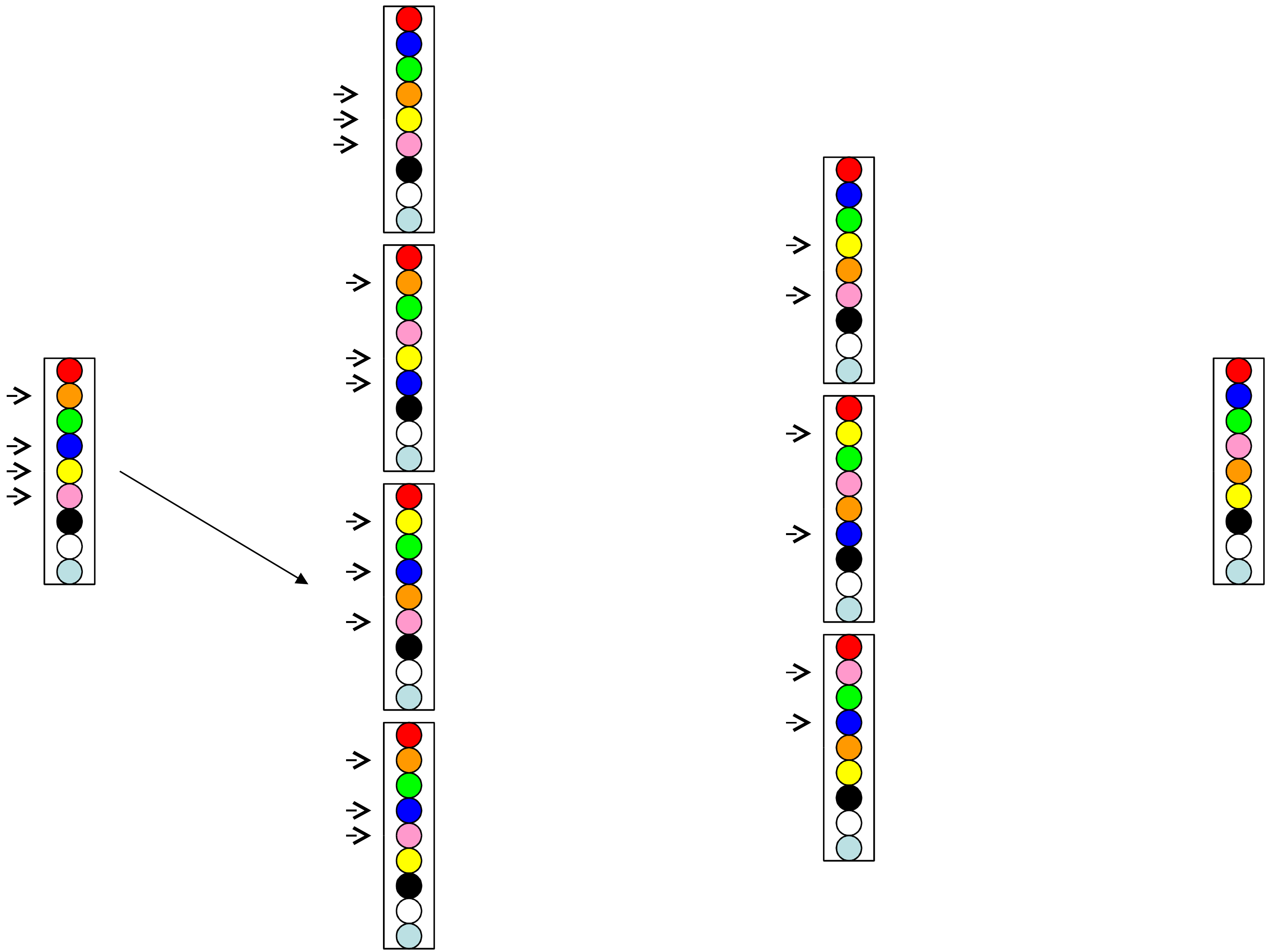
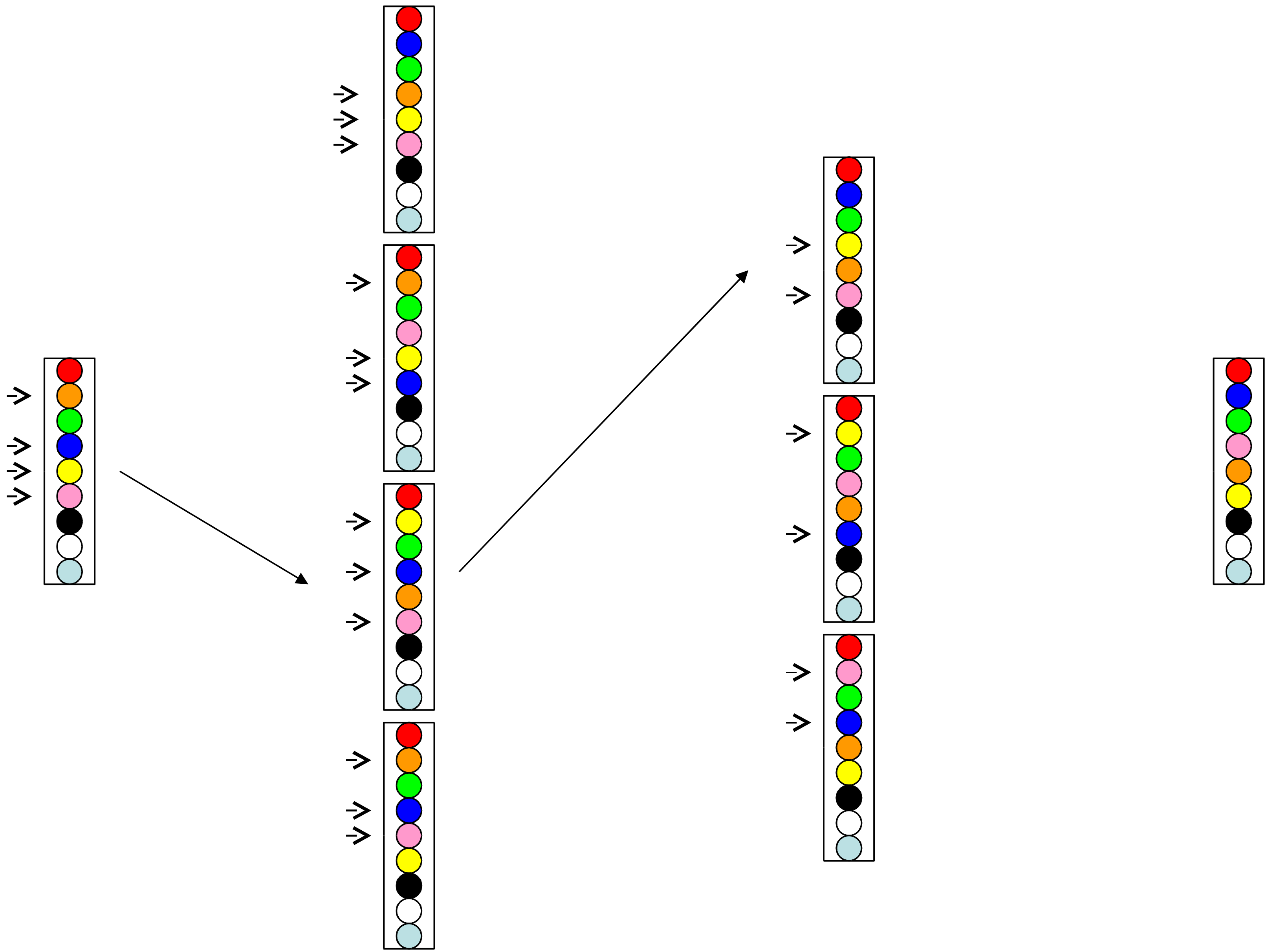
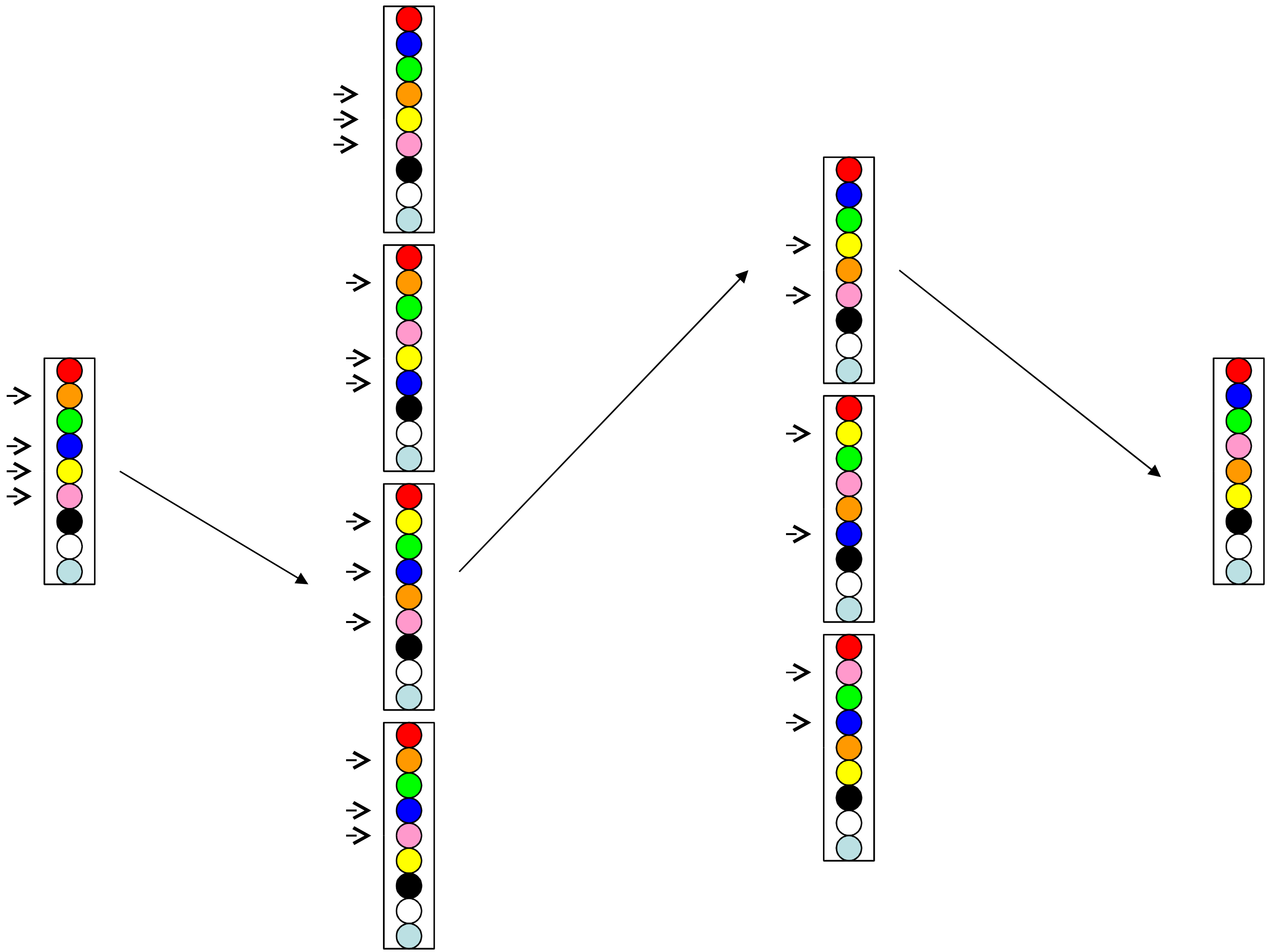


Path-relinking for the MCLA problem



Path-relinking for the MCLA problem





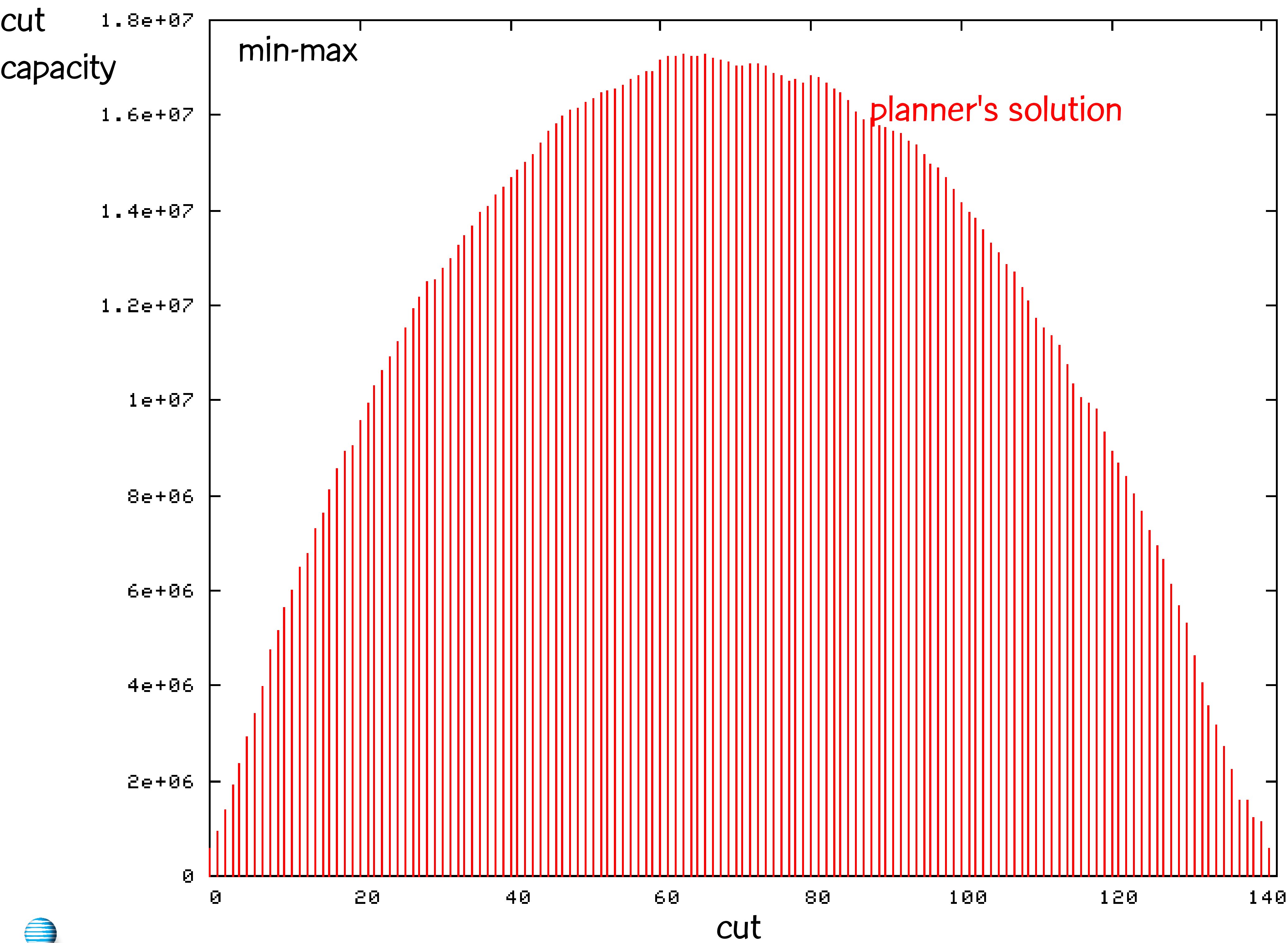
Path-relinking for the MCLA problem

Reference

- M.G.C. Resende & C.C. Ribeiro, "GRASP with path-relinking: Recent advances and applications," in "Metaheuristics: Progress as Real Problem Solvers," Ibaraki, Nonobe and Yagiura, (Eds.), pp. 29-63, Springer, 2005.

A real-world migration example

- Old network has 140 switches (nodes) and 9730 trunks (links).
- Traffic between switches is known.
- One switch is "deloaded" at each time period.
  - All traffic into (out of) deloaded switch is moved to new network.
  - New trunks may have to be temporarily deployed to handle the traffic between the old and new networks.



cut
capacity
min-max
planner's solution
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
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0
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40
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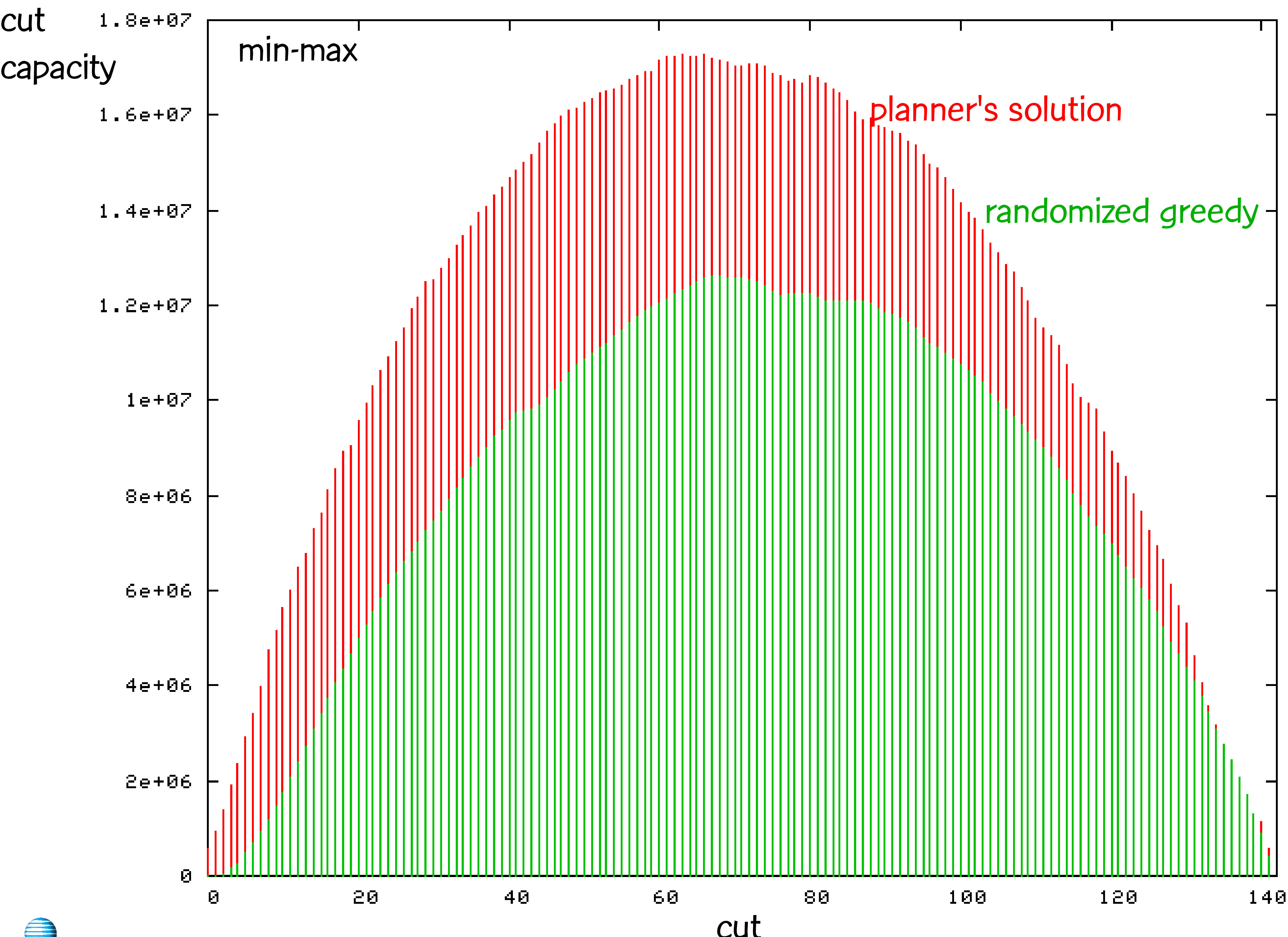
140
cut



cut capacity
min-max
planner's solution
randomized greedy
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
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cut
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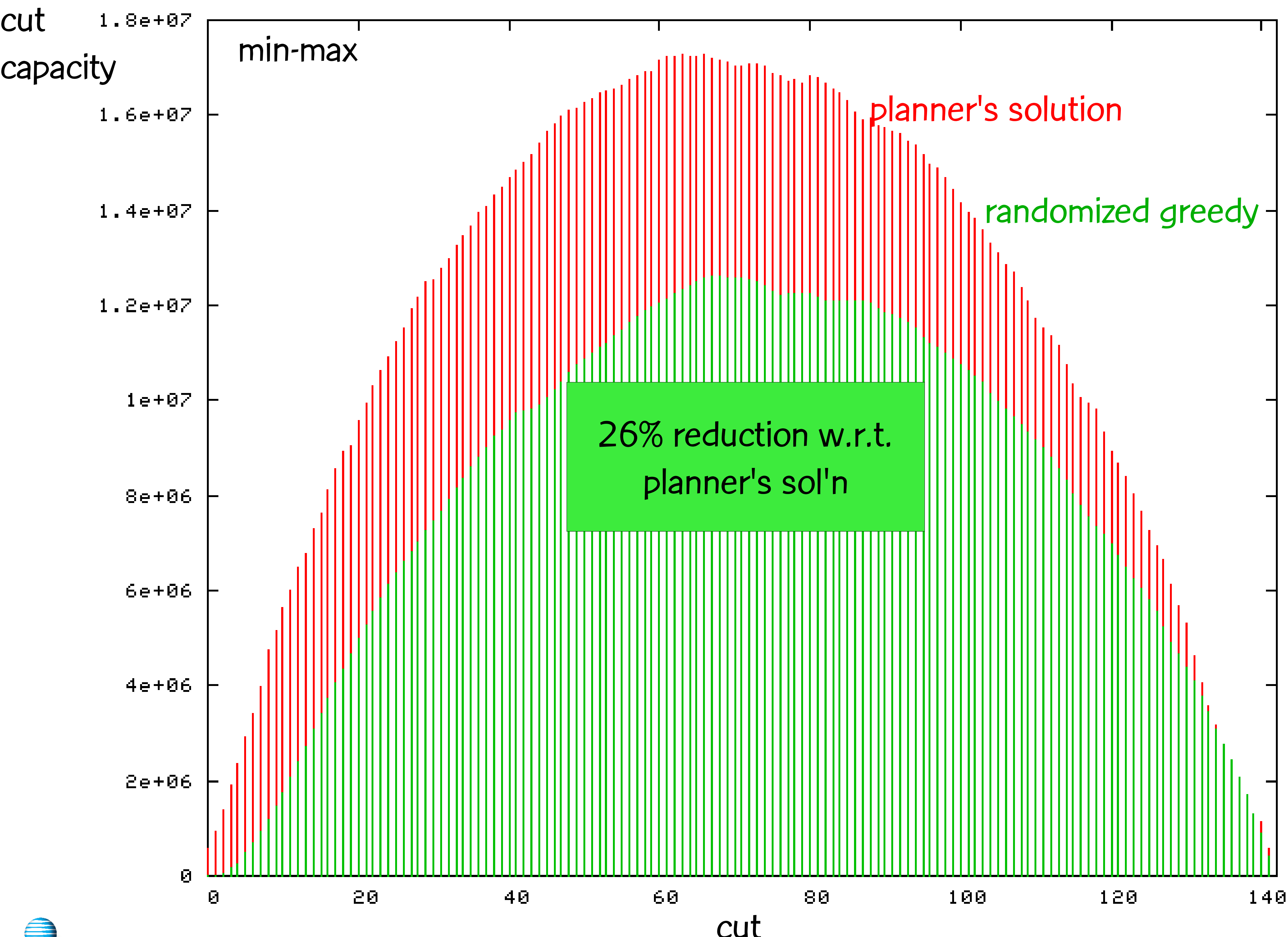
cut
capacity
min-max
planner's solution
randomized greedy
26% reduction w.r.t.
planner's sol'n
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
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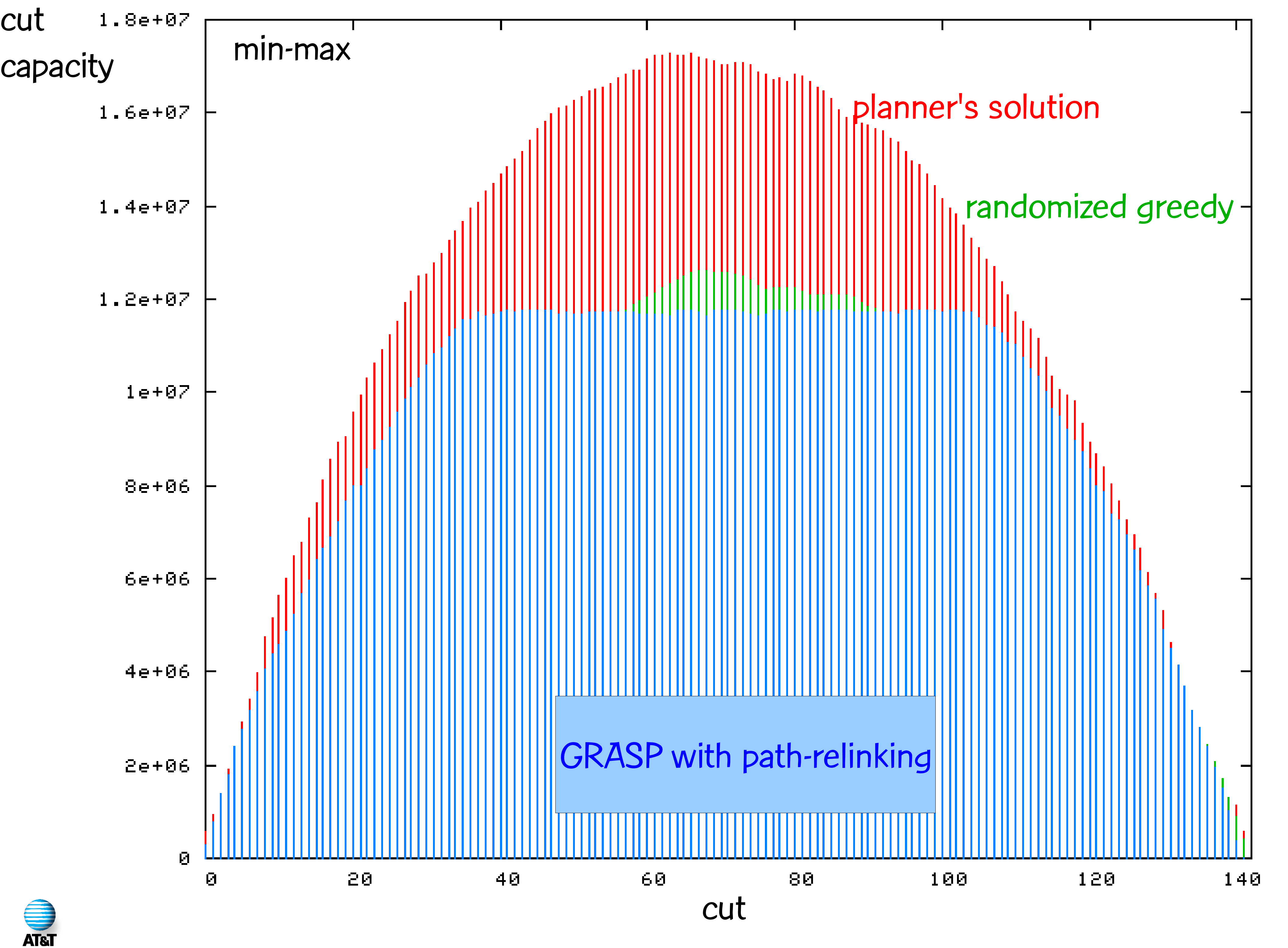
cut
capacity
min-max
planner's solution
randomized greedy
GRASP with path-relinking
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
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4e+06
2e+06
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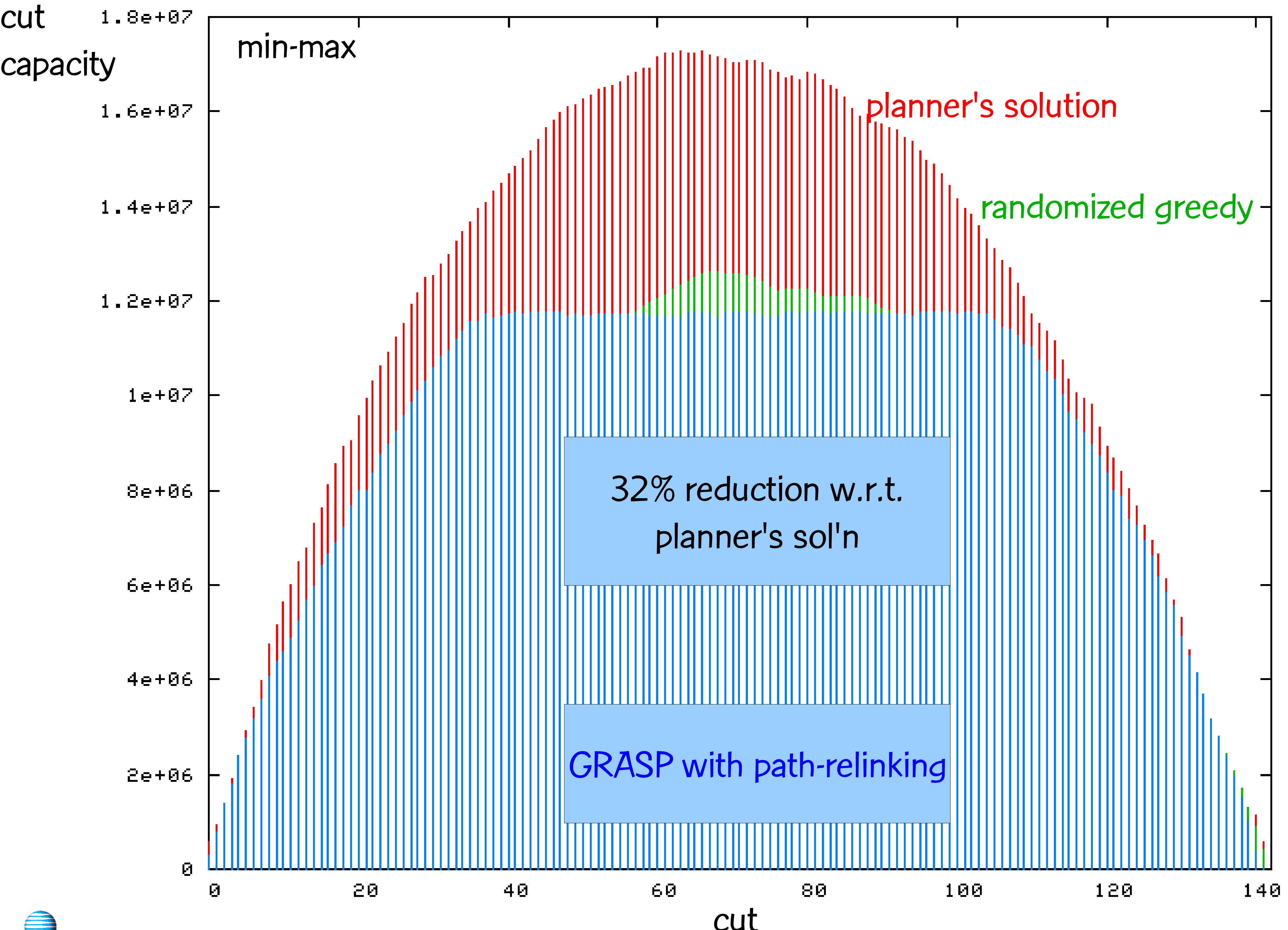
cut
AT&T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capacity
min-max
planner's solution
randomized greedy
32% reduction w.r.t. planner's sol'n
GRASP with path-relinking
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1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
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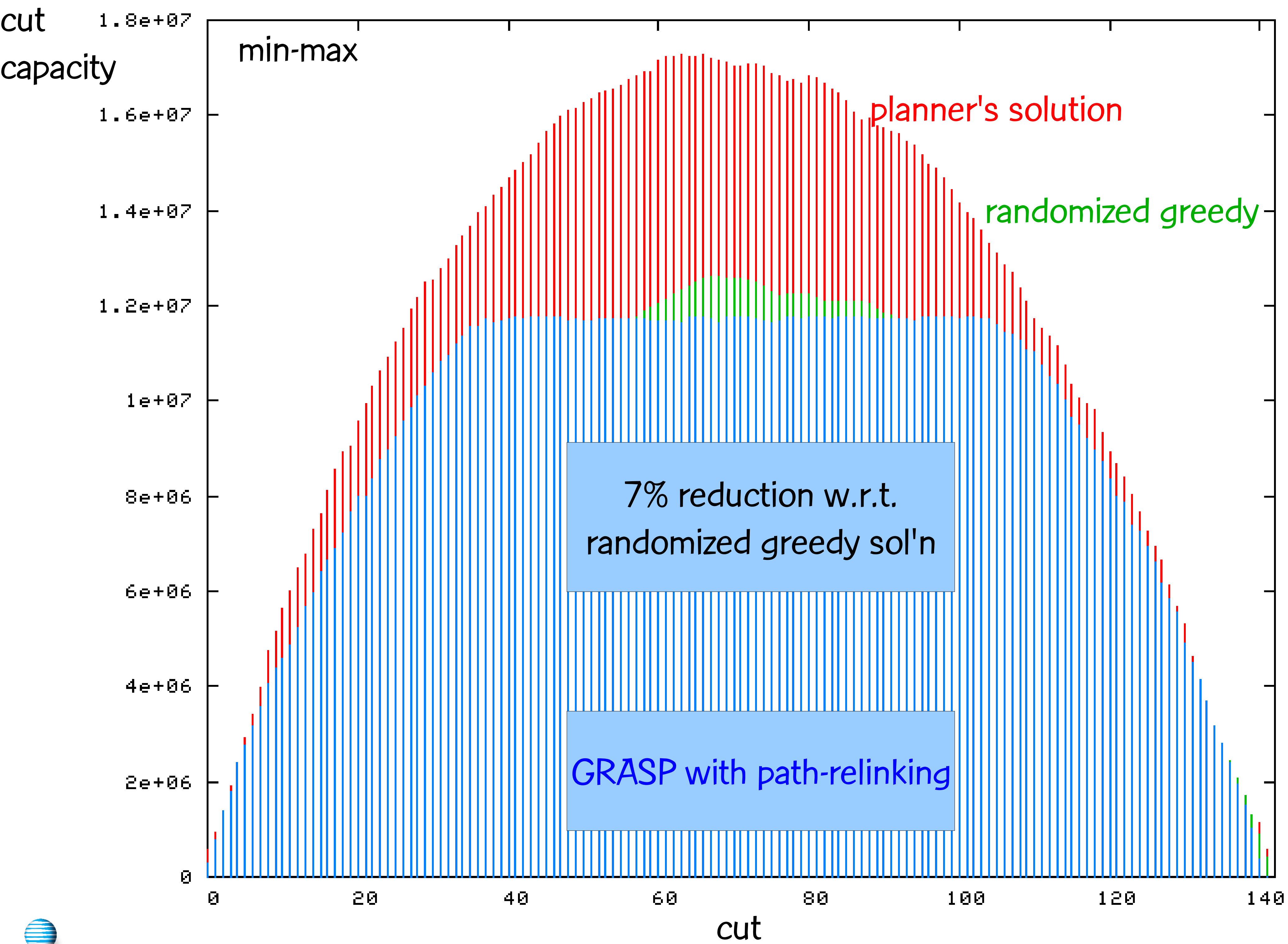
cut
AT&T


cut
capacity
min-max
planner's solution
randomized greedy
7% reduction w.r.t.
randomized greedy sol'n
GRASP with path-relinking
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1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
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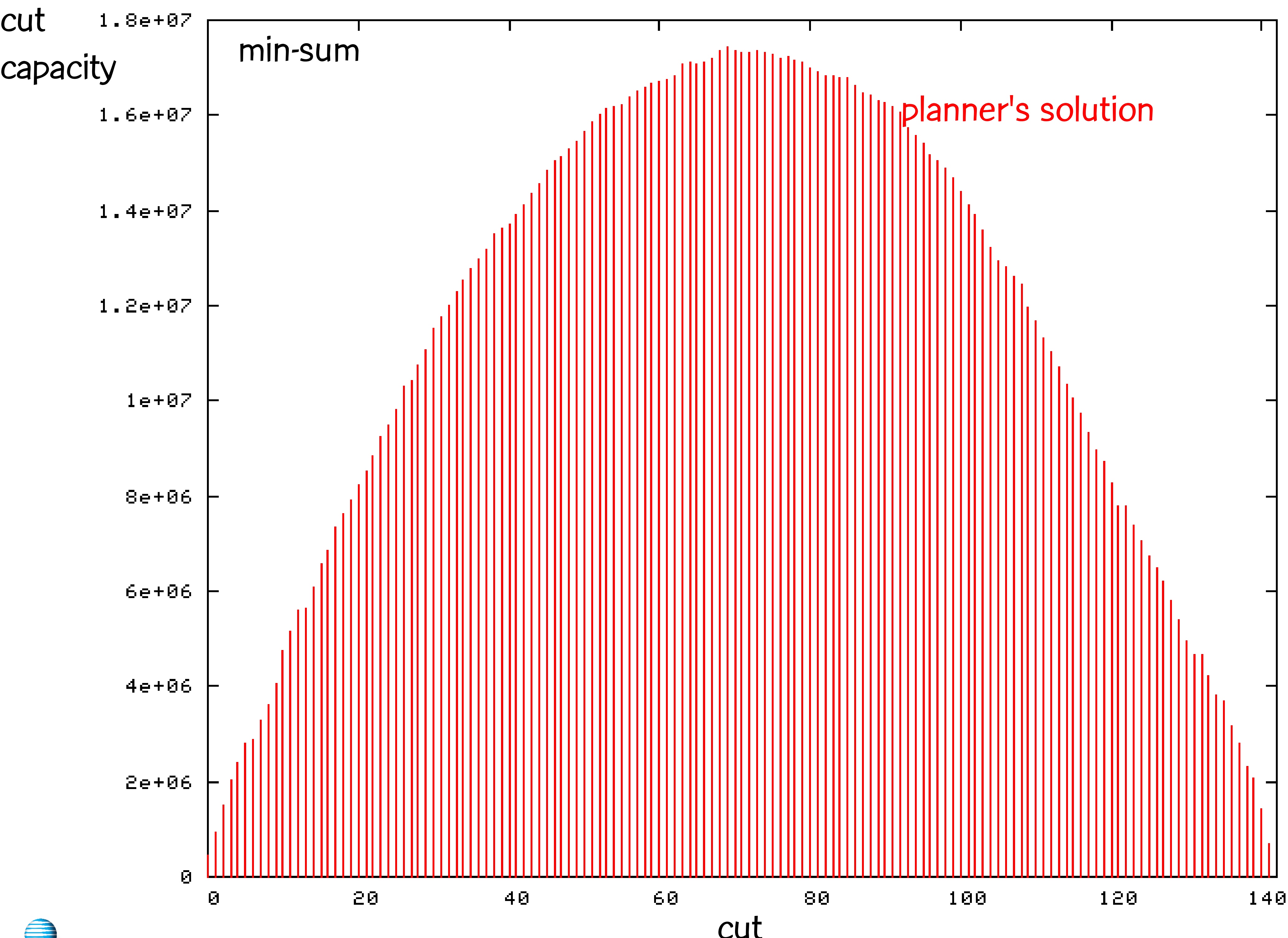
cut
capacity
min-sum
planner's solution
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
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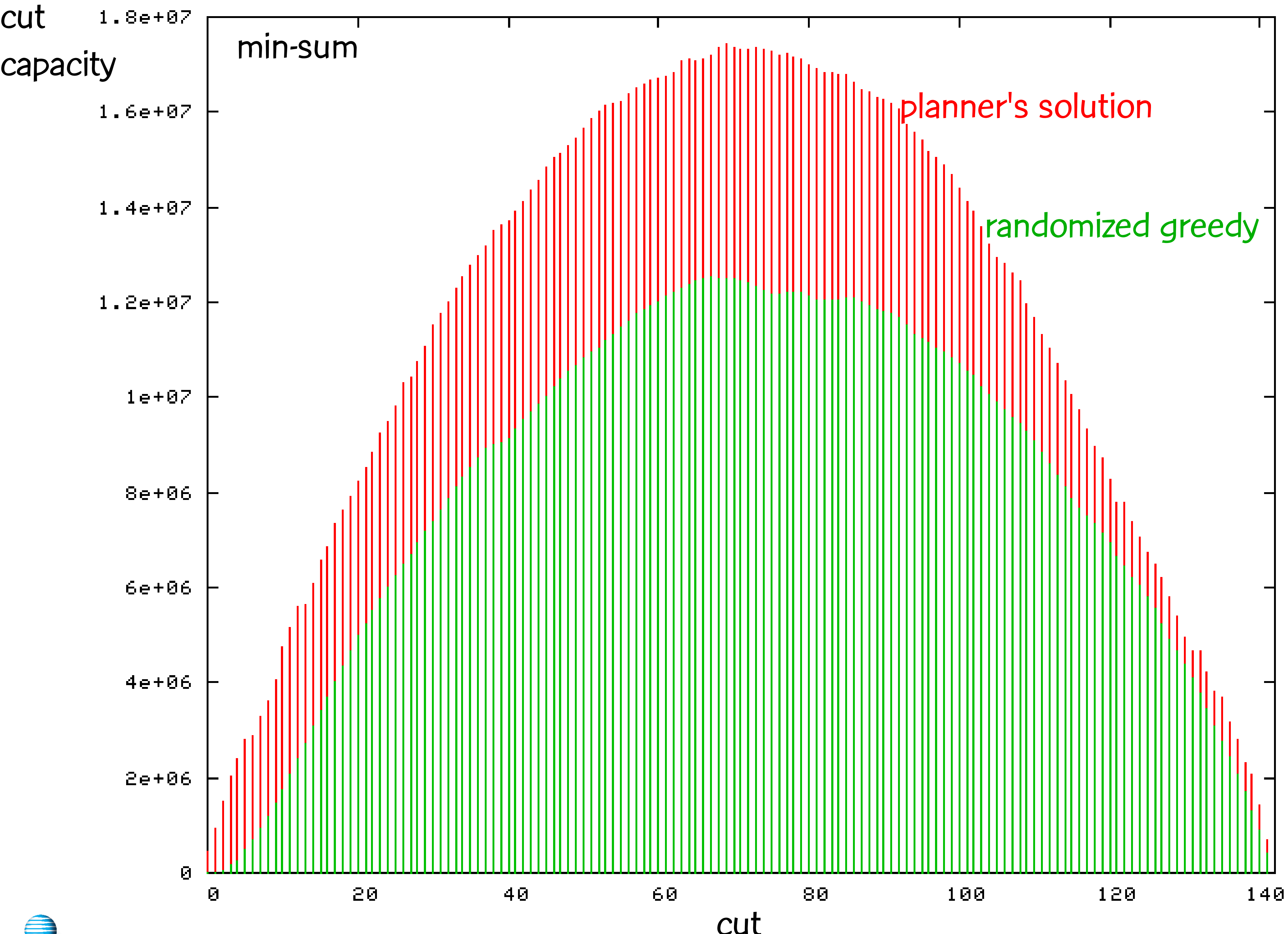
cut
capacity
min-sum
planner's solution
randomized greedy
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
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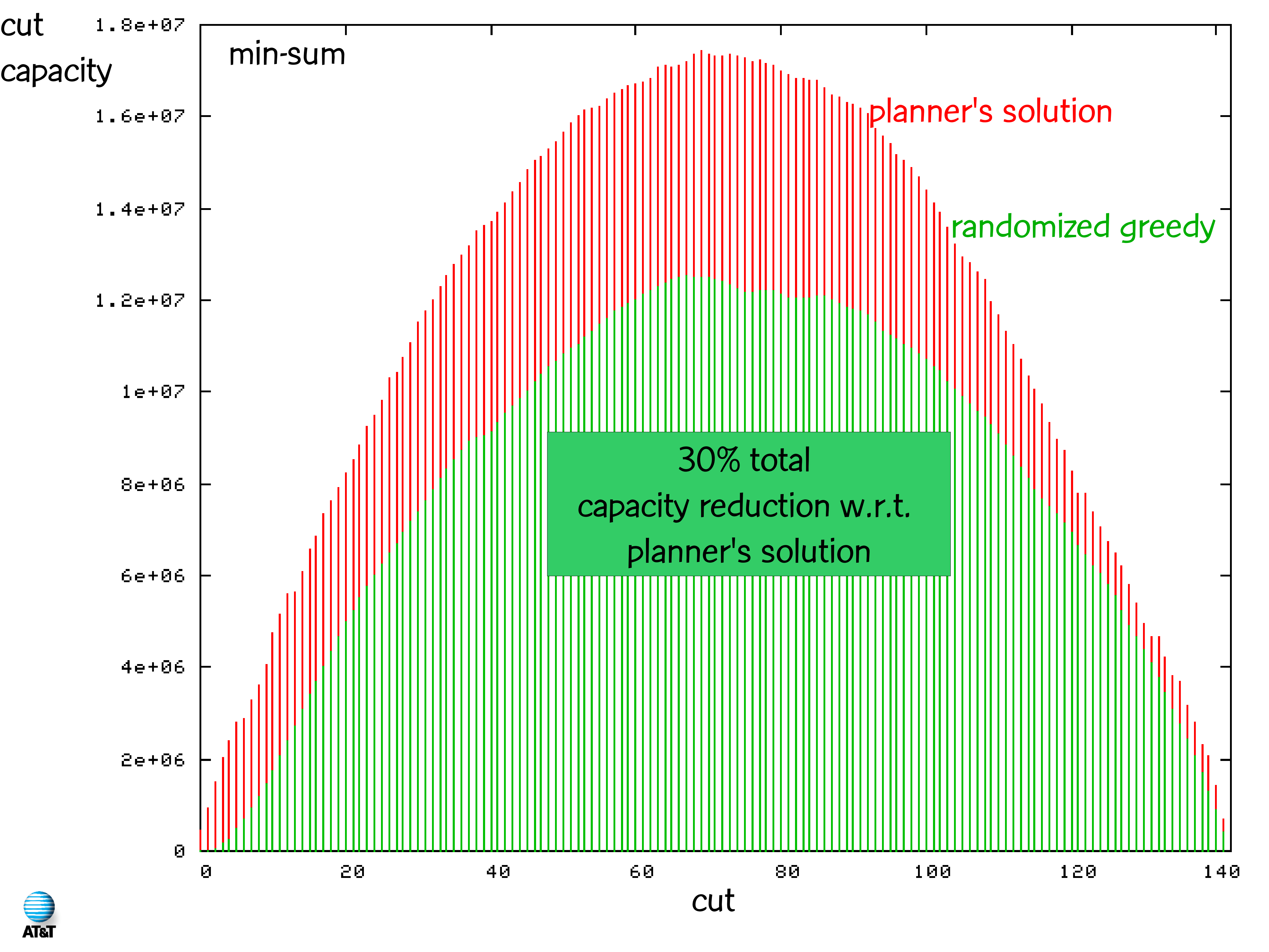
cut


cut
capacity
min-sum
planner's solution
randomized greedy
30% total
capacity reduction w.r.t.
planner's solution
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
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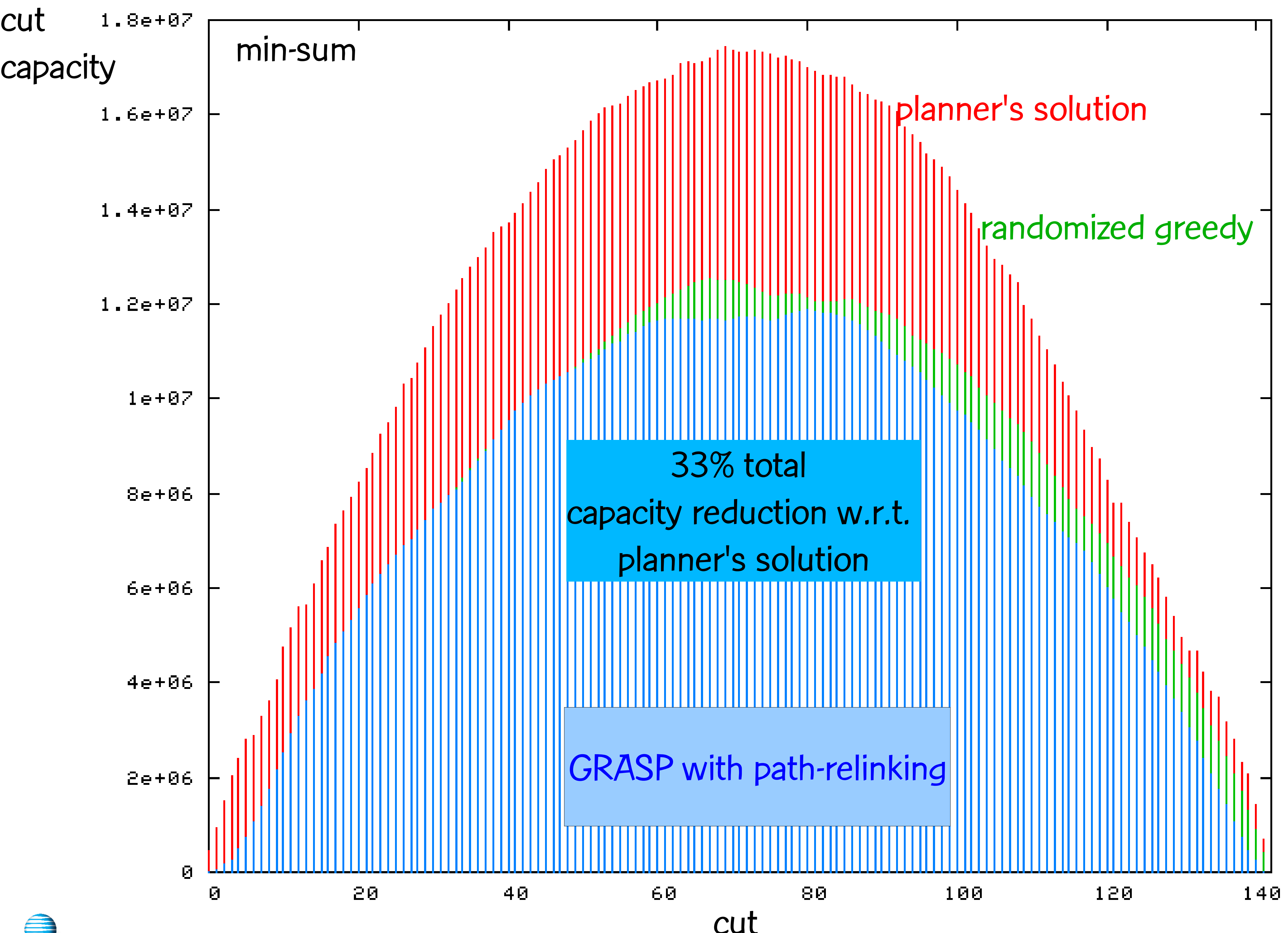
cut
AT&T



cut
capacity
min-sum
planner's solution
randomized greedy
33% total
capacity reduction w.r.t.
planner's solution
GRASP with path-relinking
cut
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
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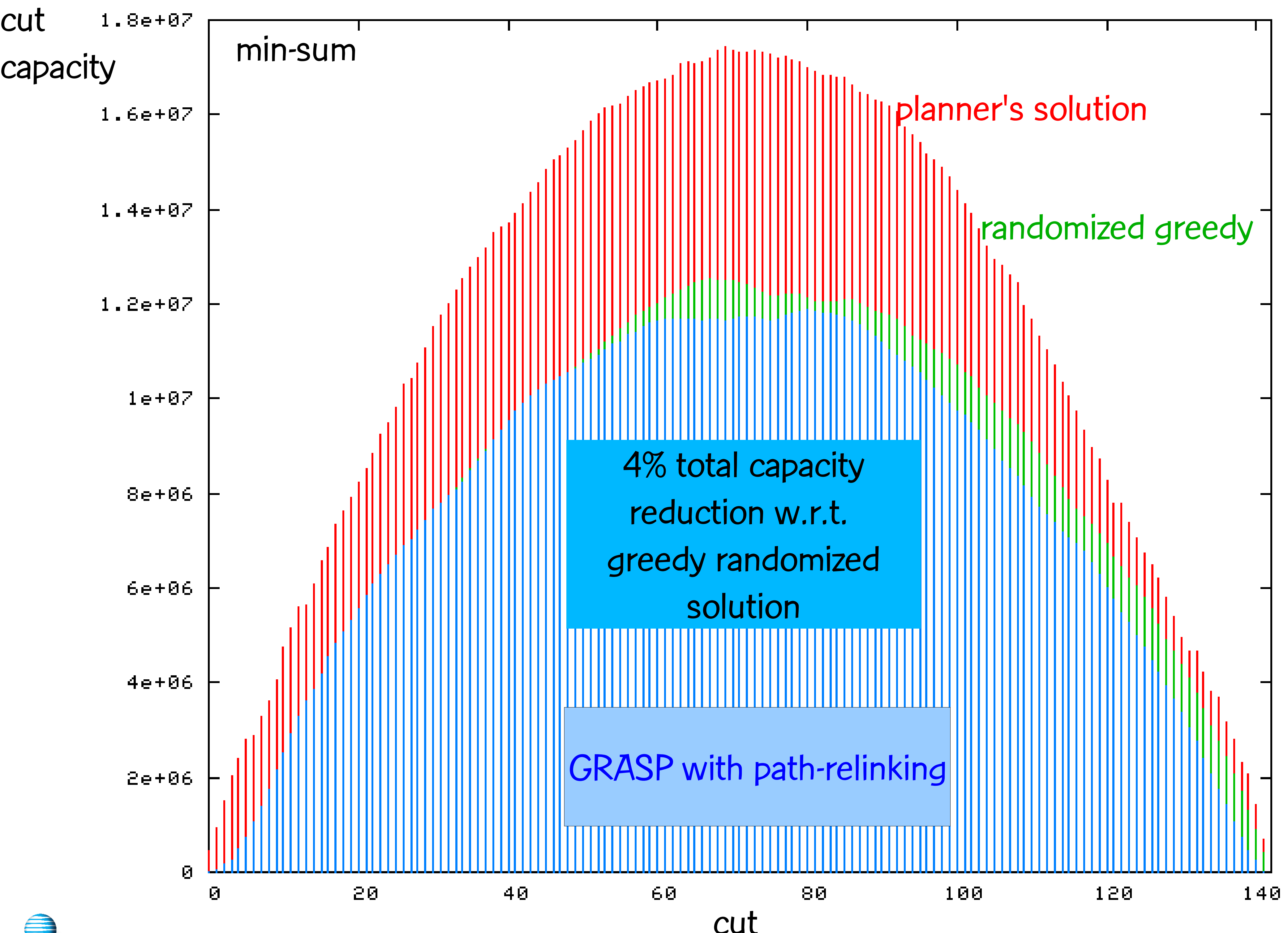
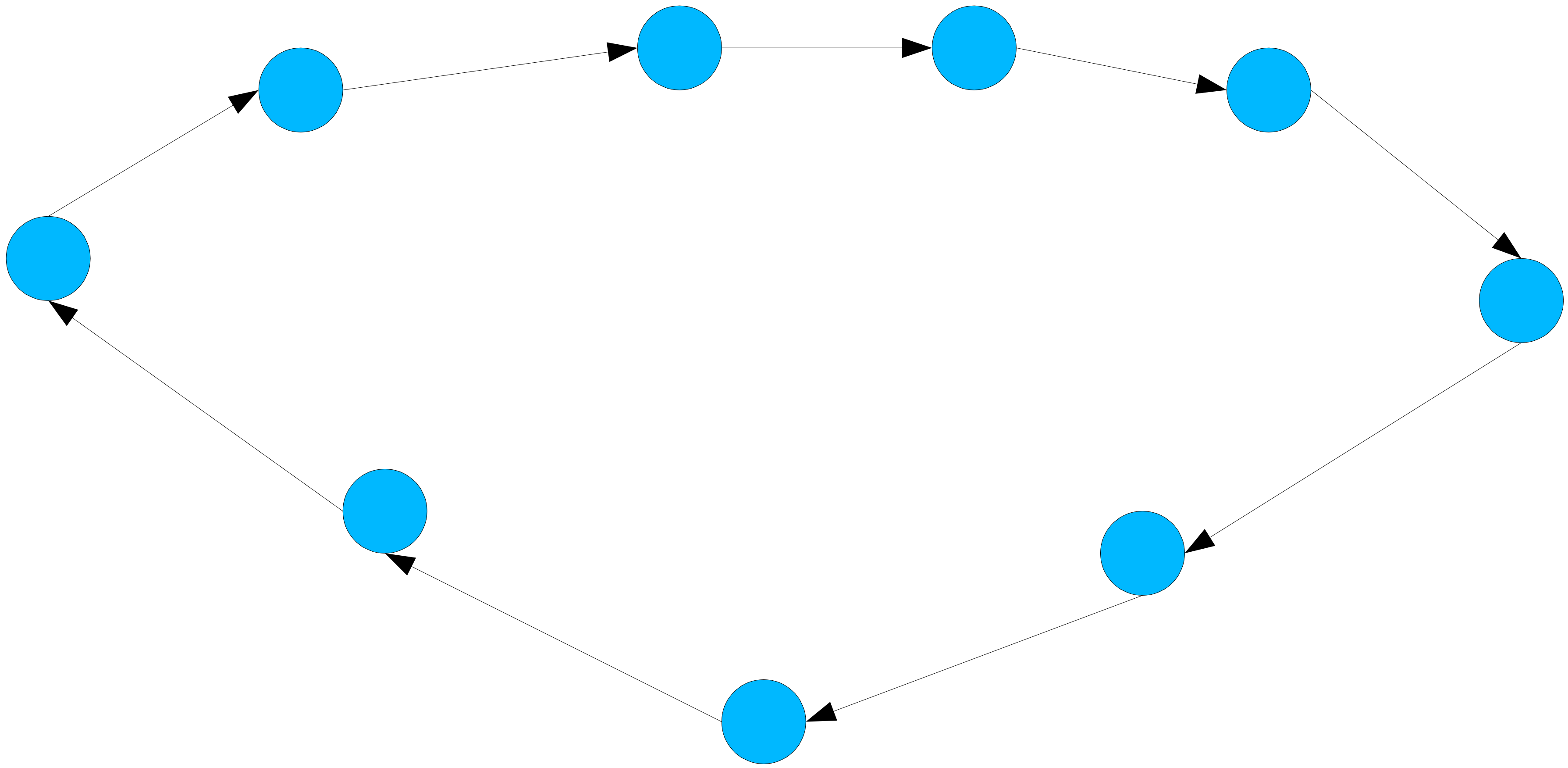


cut
capacity
min-sum
1.8e+07
1.6e+07
1.4e+07
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
0
planner's solution
randomized greedy
4% total capacity
reduction w.r.t.
greedy randomized
solution
GRASP with path-relinking
0
20
40
60
80
100
120
140
cut

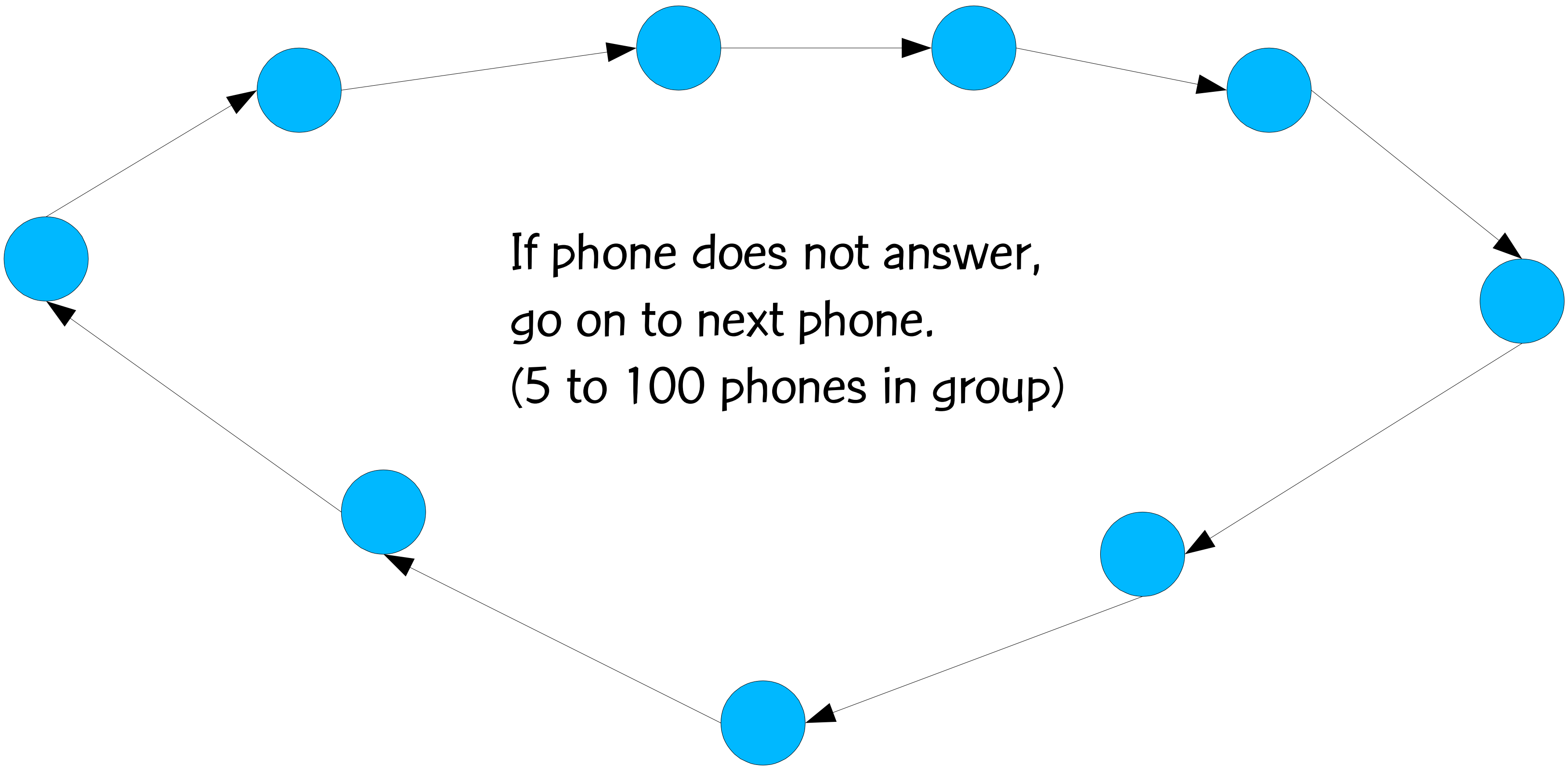
Another example: phone migration

- Phone migration occurs when an organization upgrades to a newer phone switch (PBX).
- All phones using the old PBX must be moved to the new PBX.
- Each phone belong to one of more sets of phones that need to be moved together in same time period.
- Given penalties for not moving a pair of phones together and a maximum number of phones that can be moved in a time period, find groupings such that total penalty is minimized.

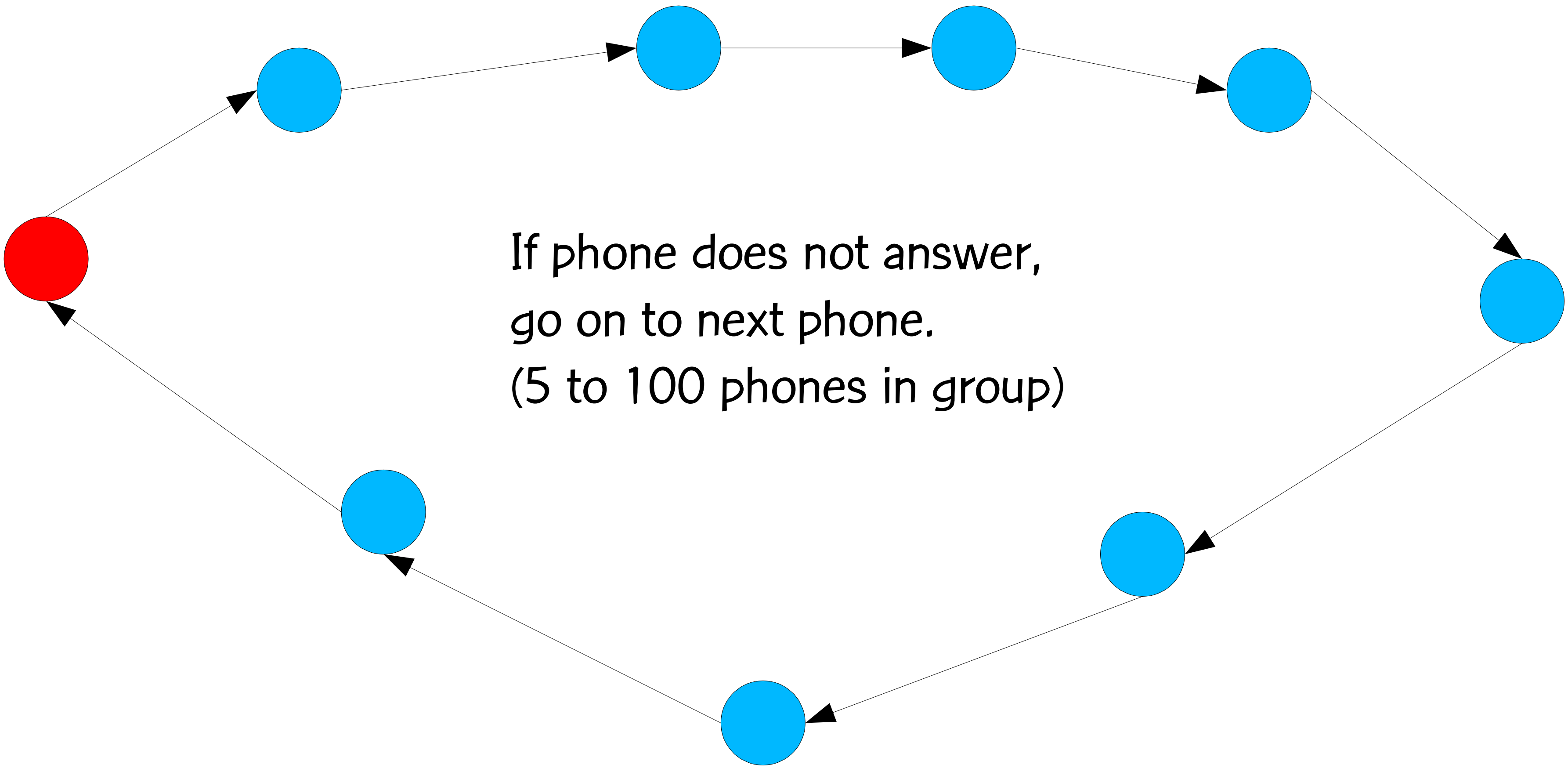
Multi-line hunt group



Multi-line hunt group



Multi-line hunt group



If phone does not answer,
go on to next phone.
(5 to 100 phones in group)

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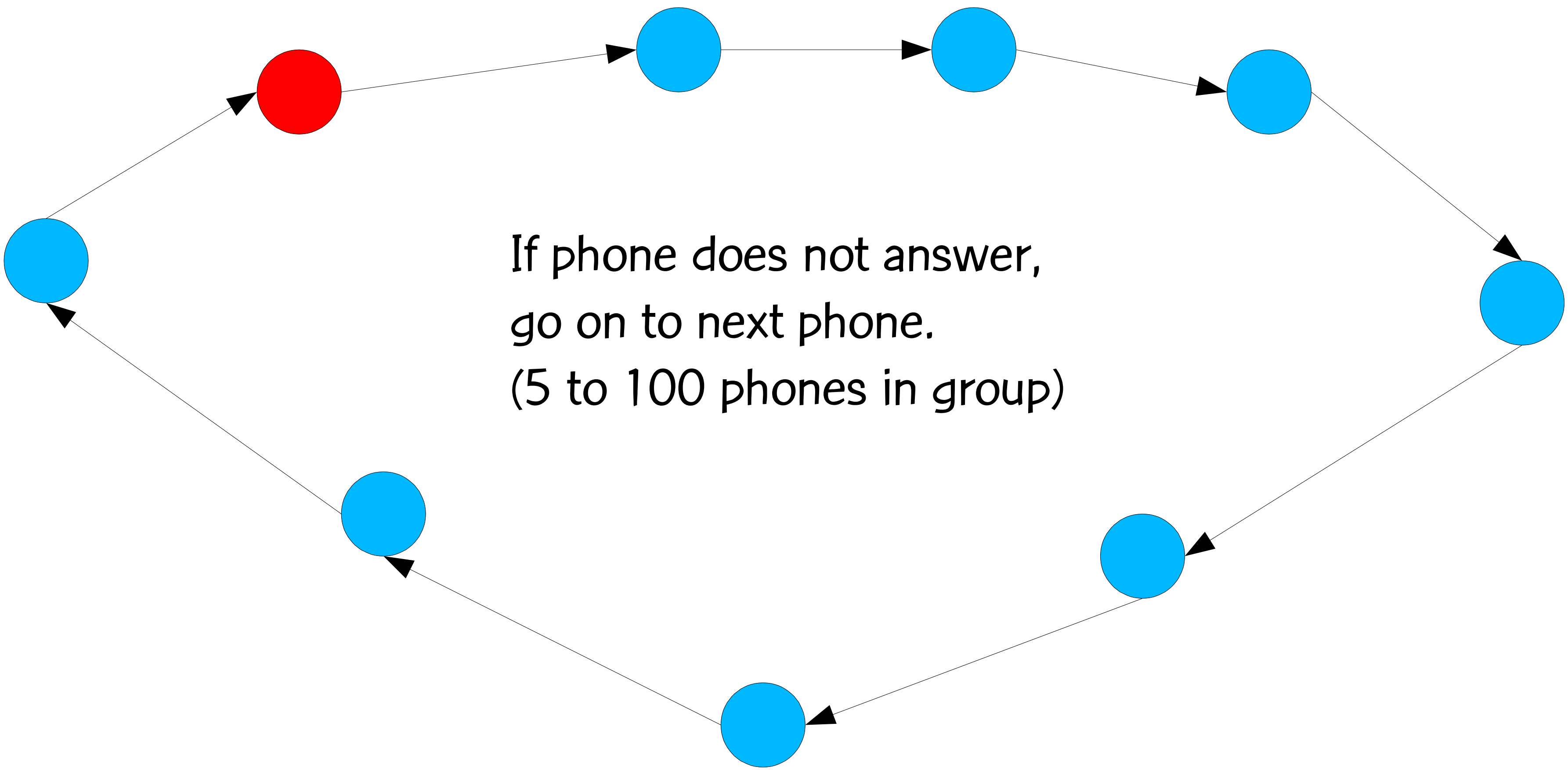
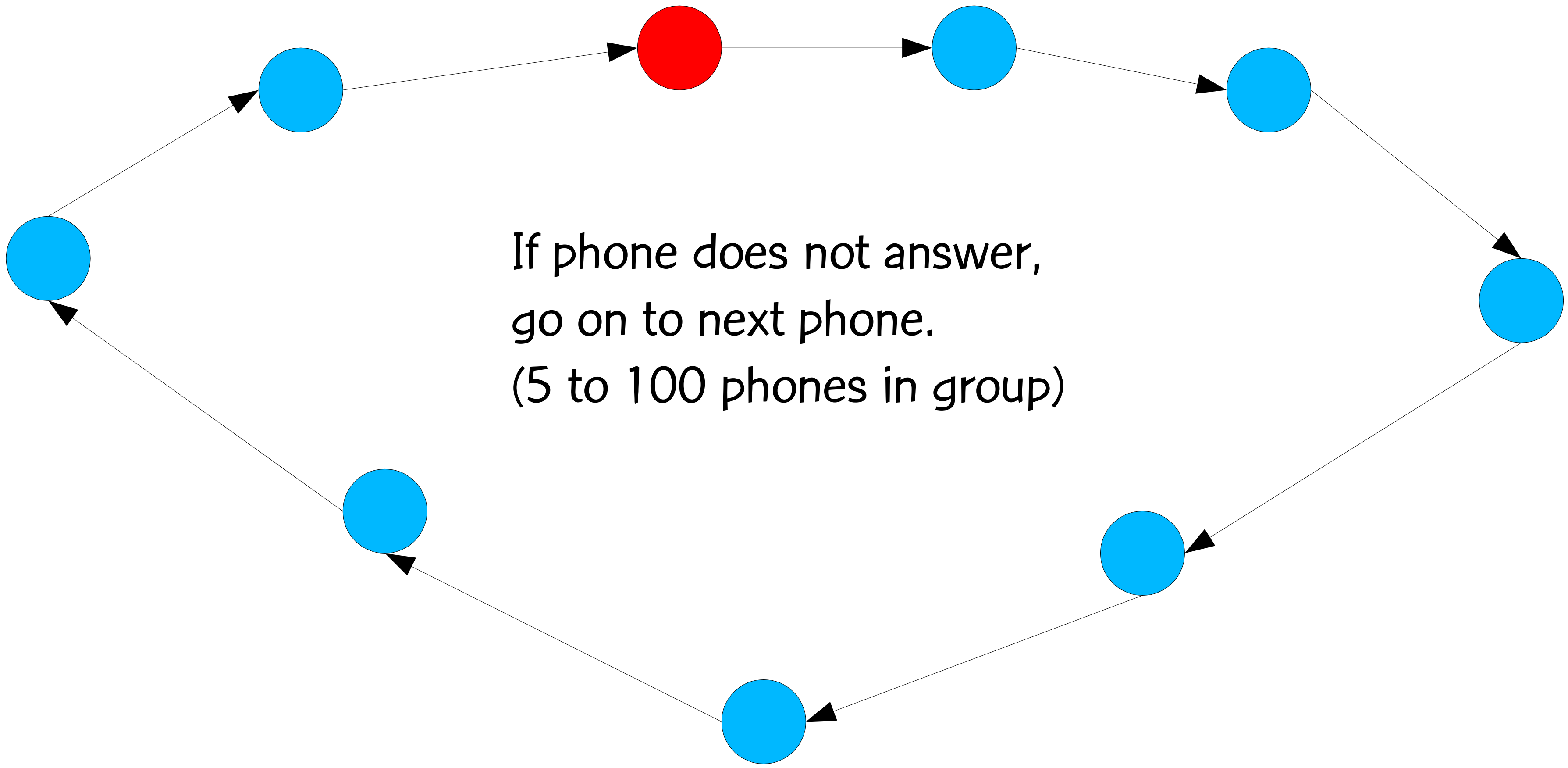
Multi-line hunt group

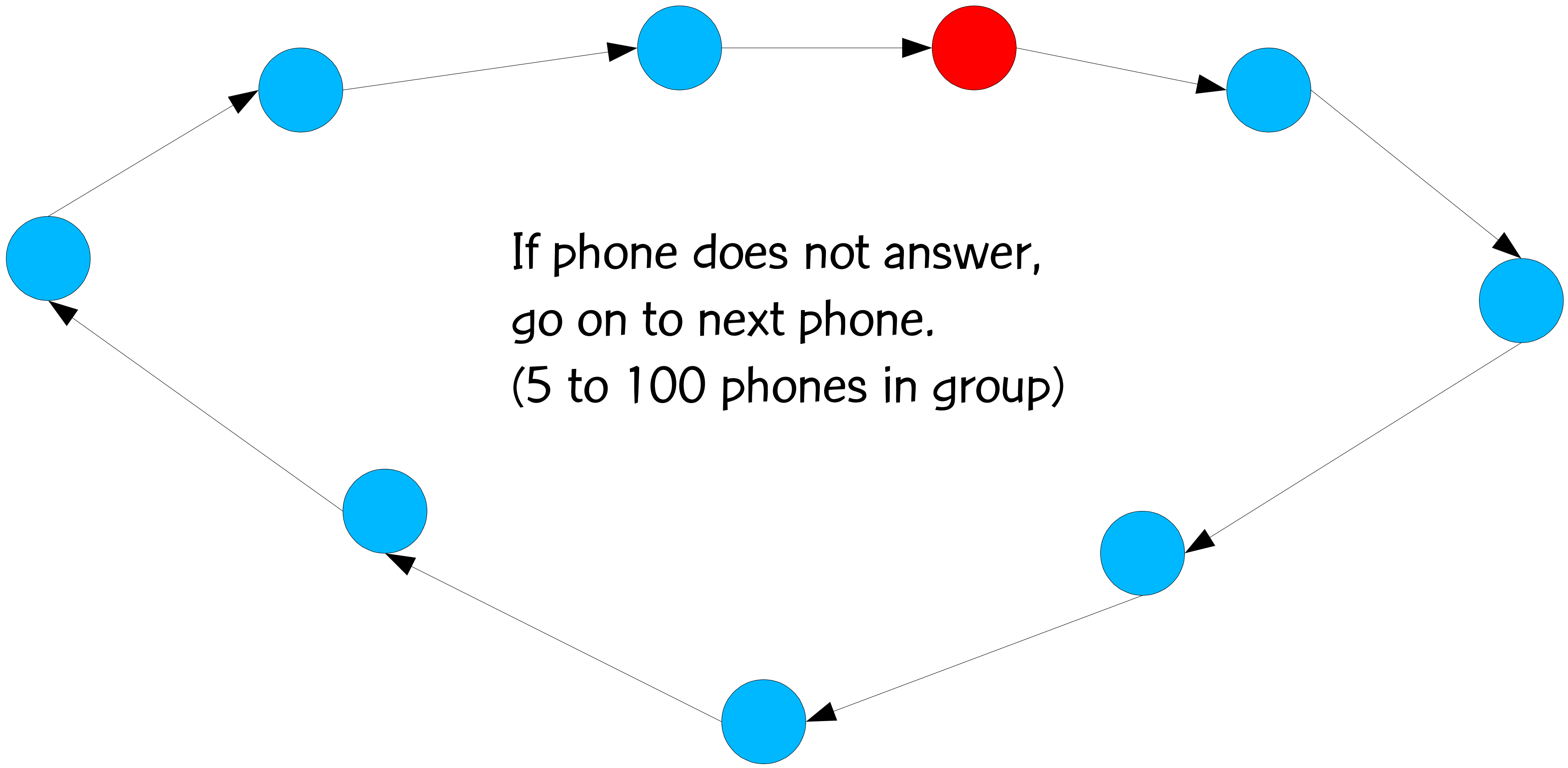


Multi-line hunt group

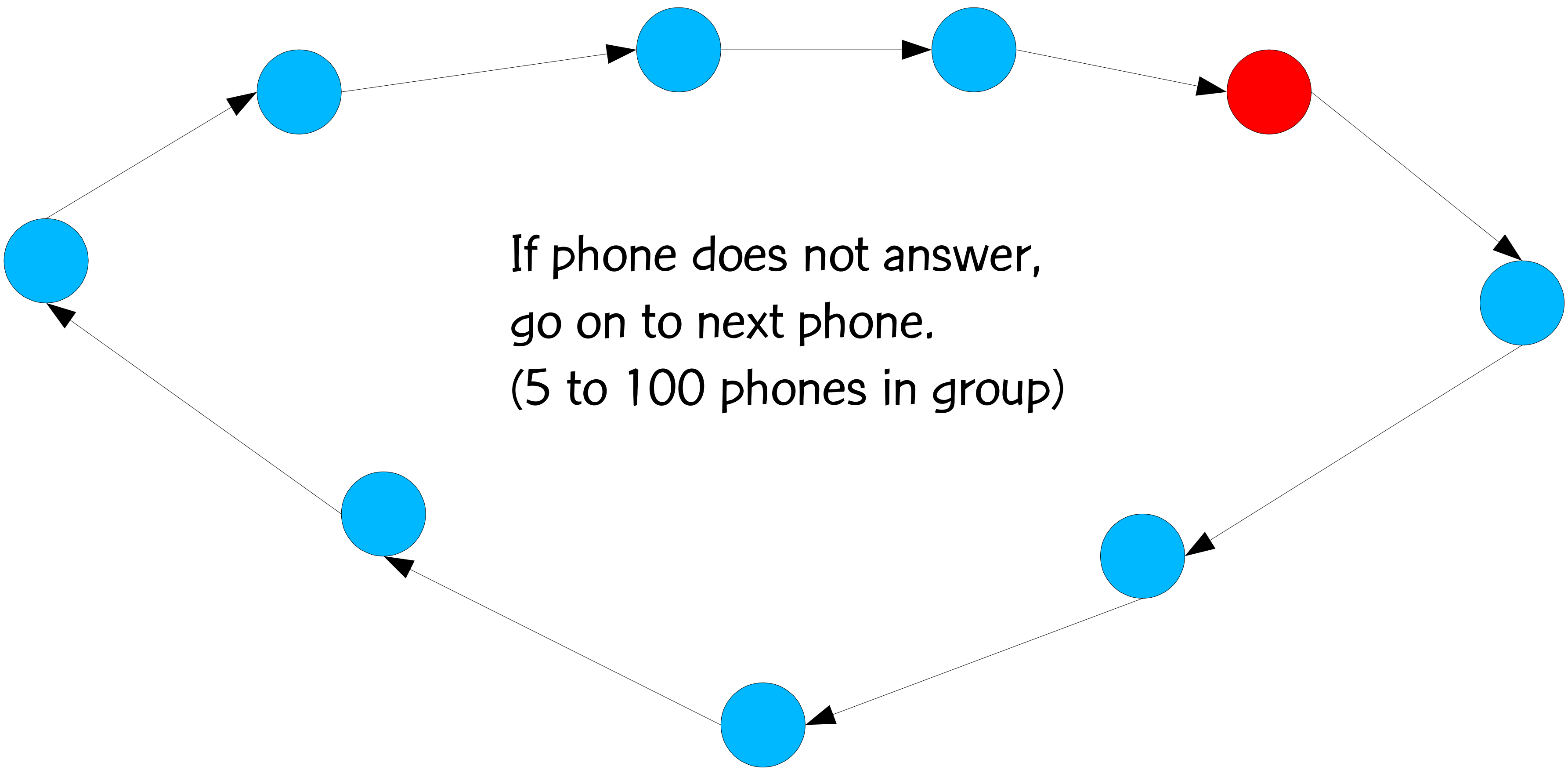


If phone does not answer,
go on to next phone.
(5 to 100 phones in group)

Multi-line hunt group



Multi-line hunt group



If phone does not answer,
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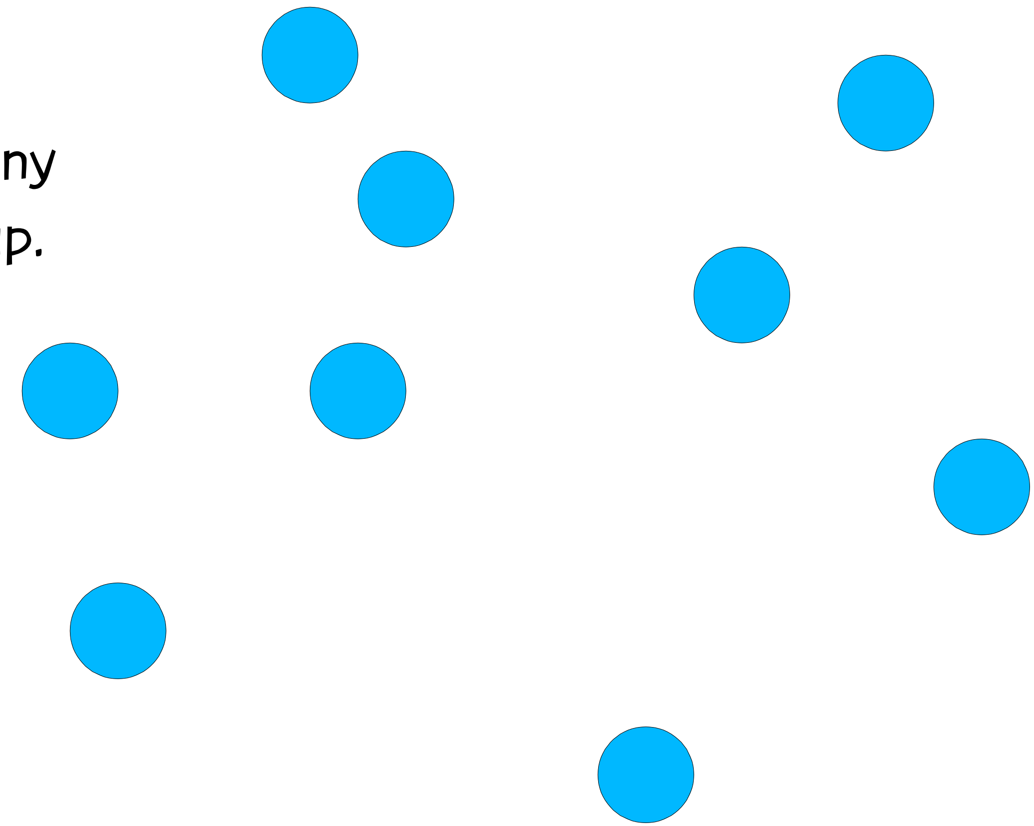
(5 to 100 phones in group)

Call pickup (CPU)

Any phone in group can pickup call for any other phone in group.



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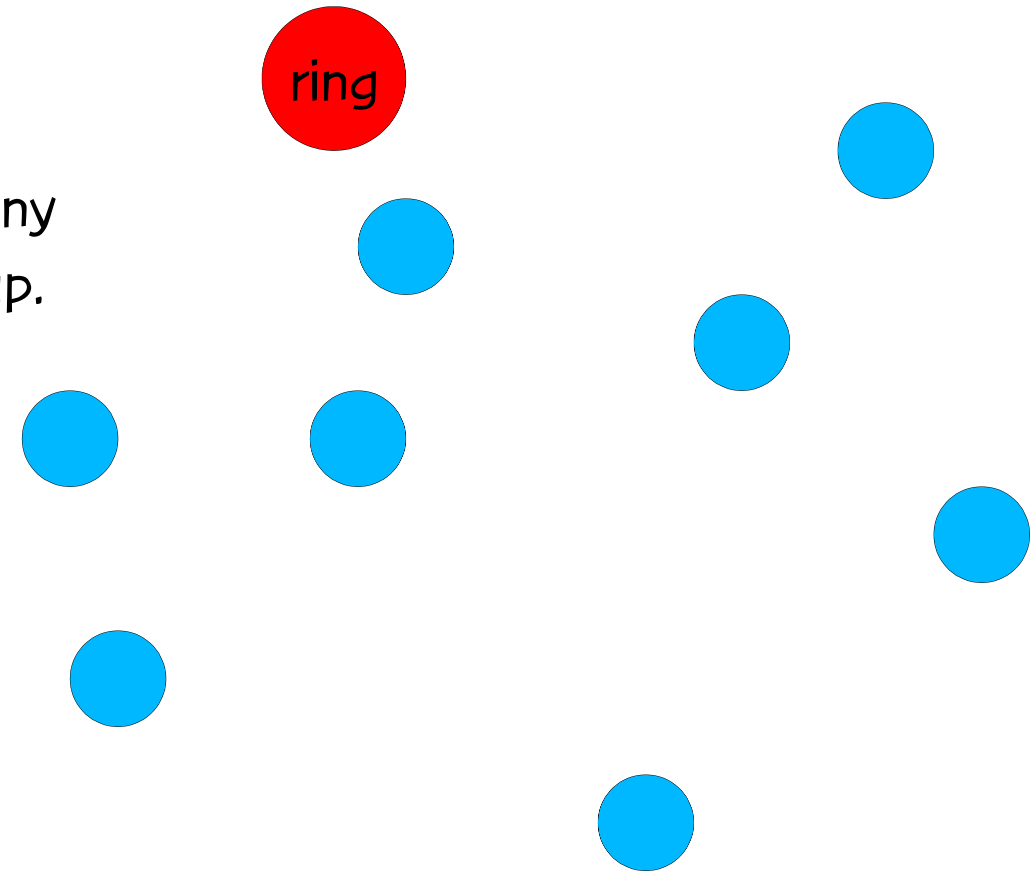

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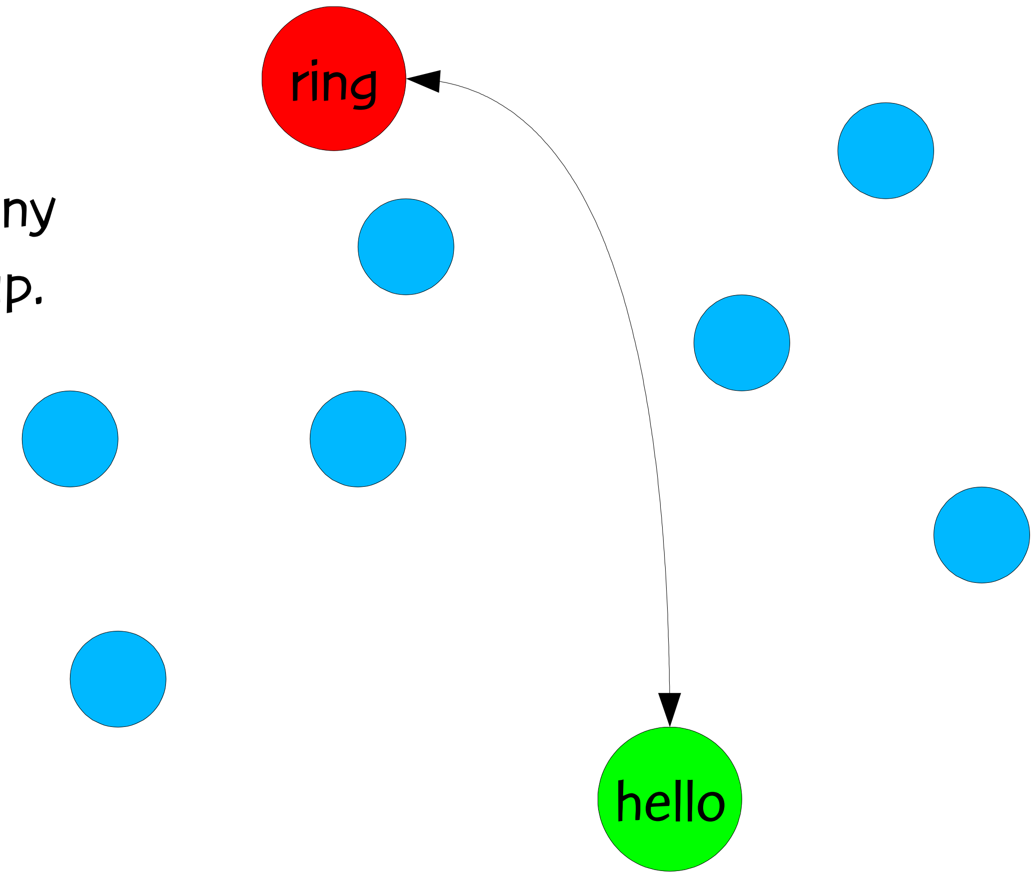
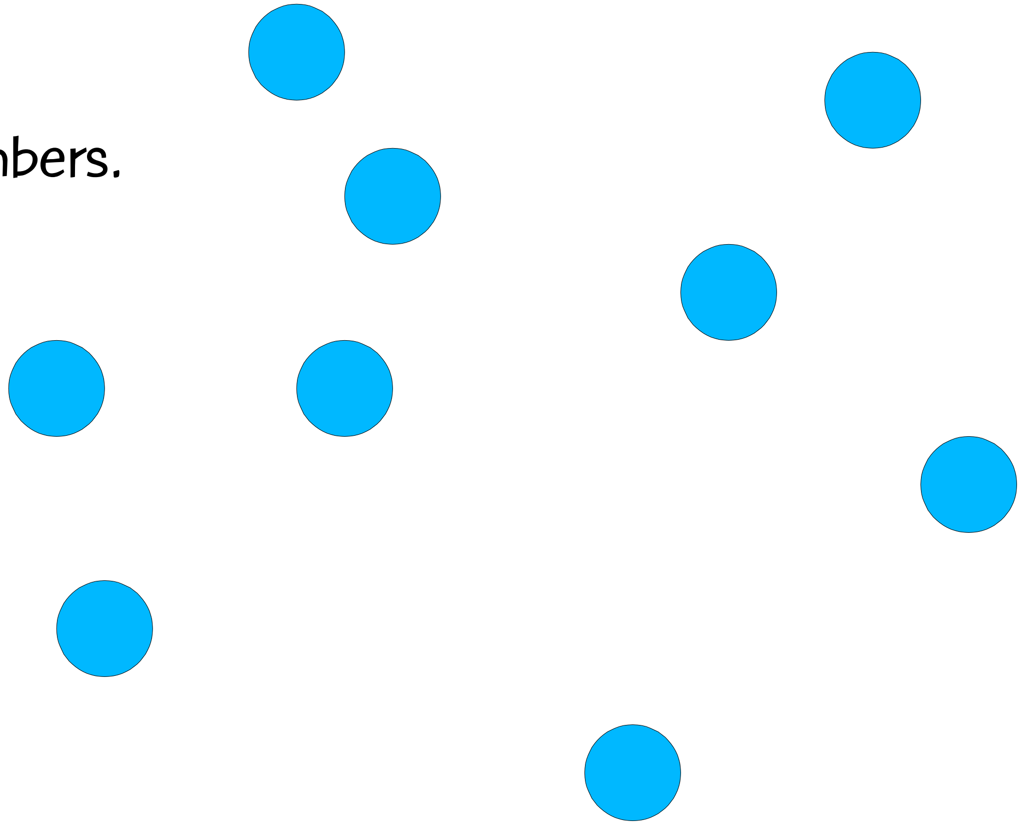


Intercomm (ICOM)

Allows speed dialing
between group members.



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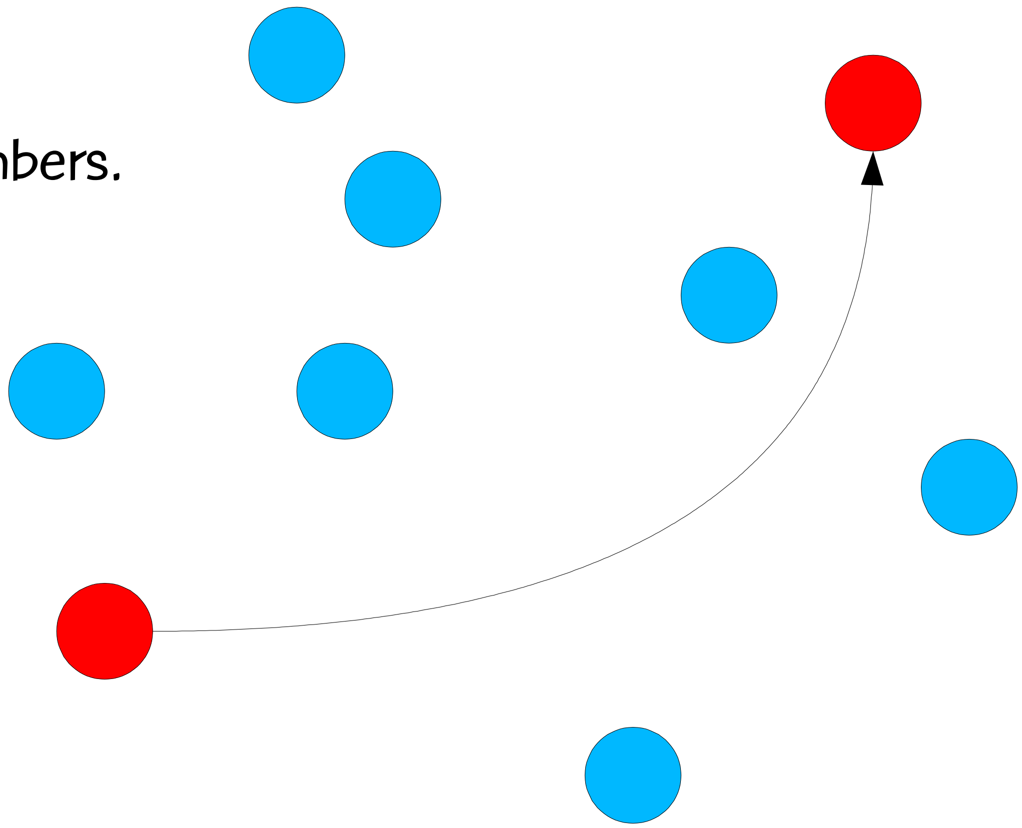

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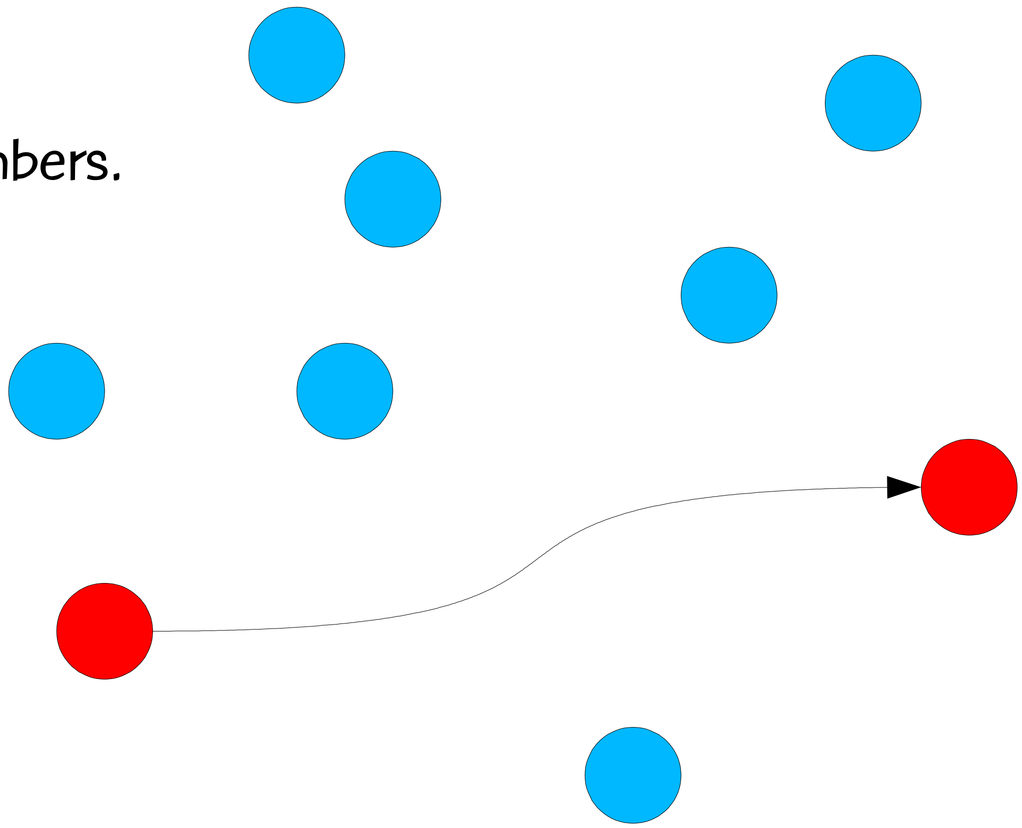

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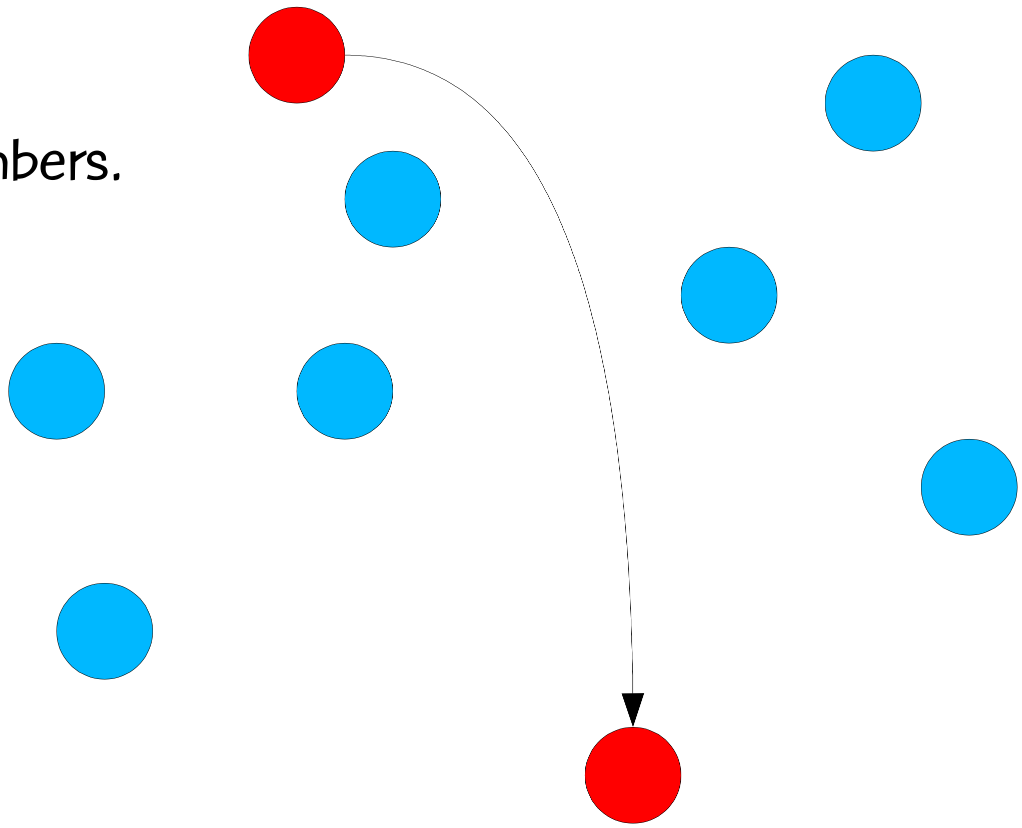
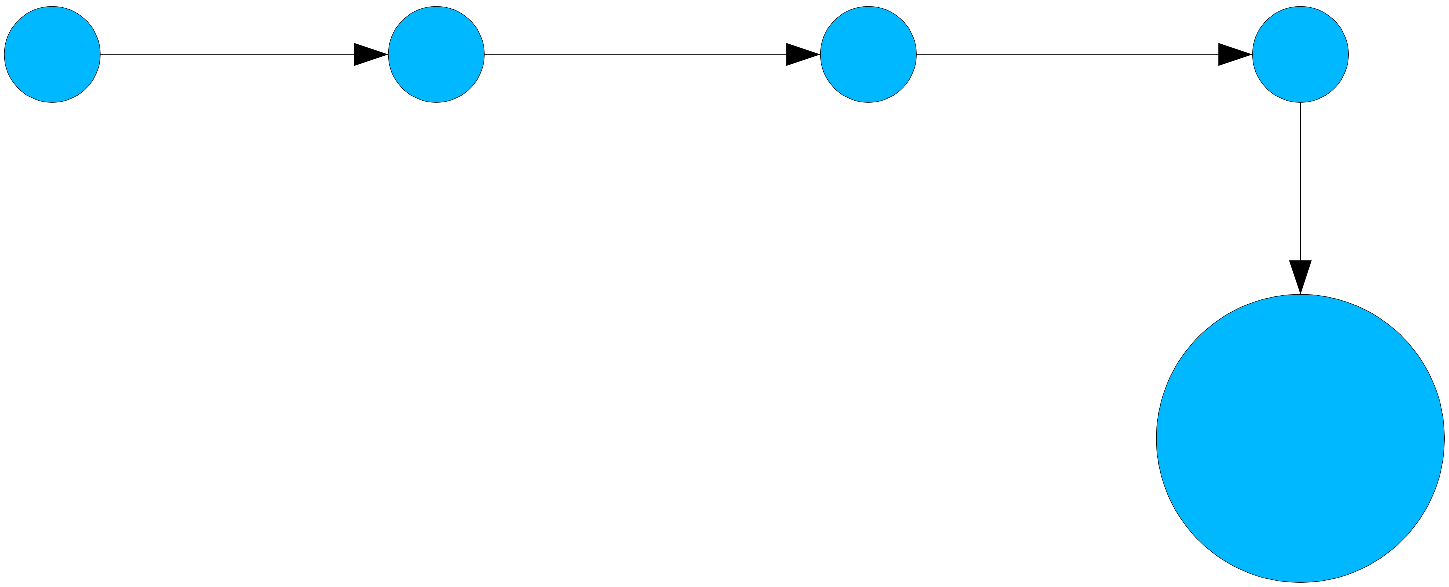
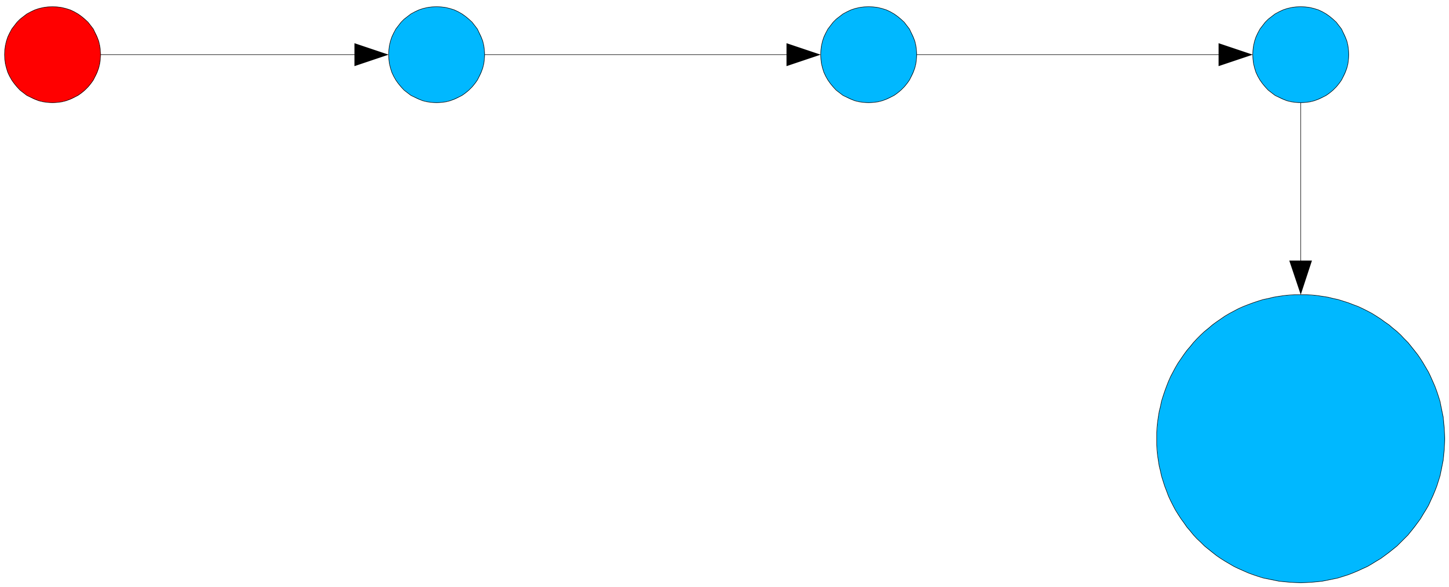


Series completion



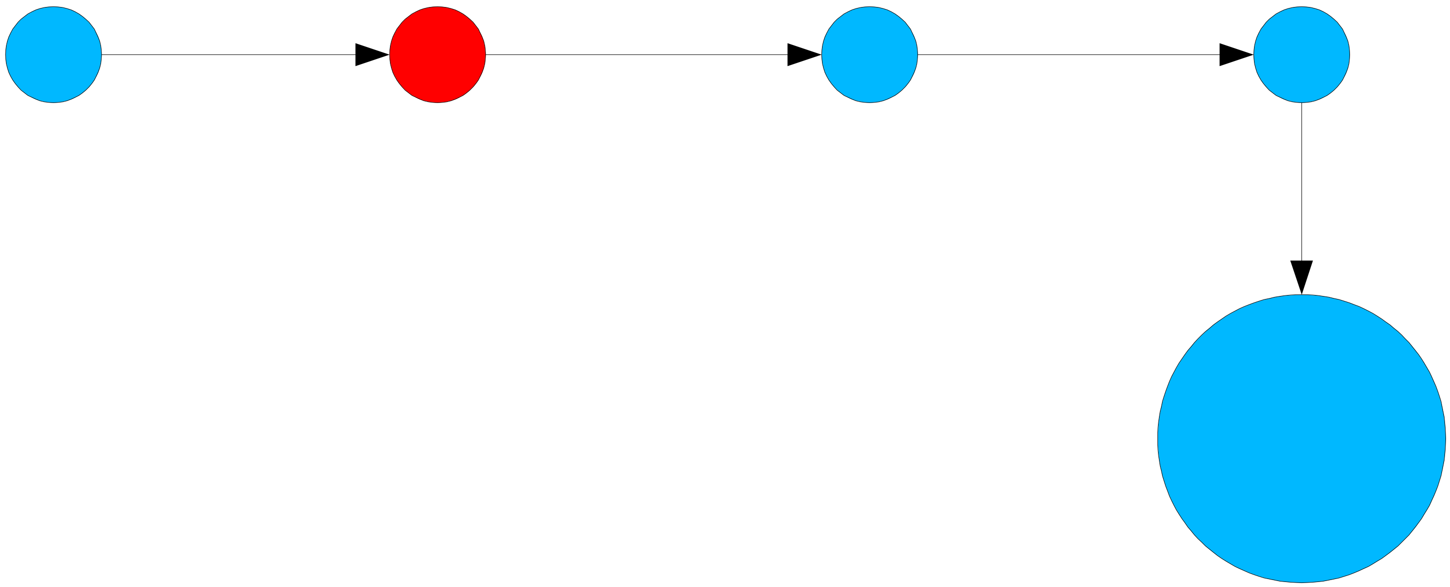
Series completion

If call not answered ...



Series completion

If call not answered, it moves
to ....next in series.



Series completion

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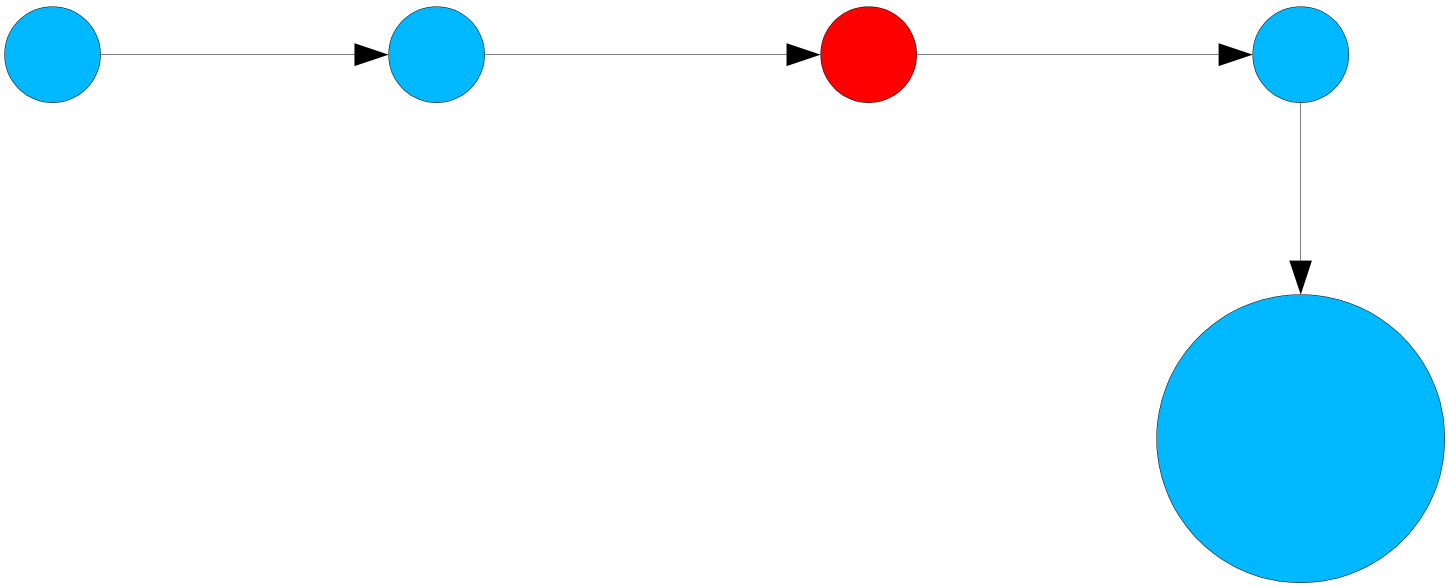

Series completion

If call not answered, it moves

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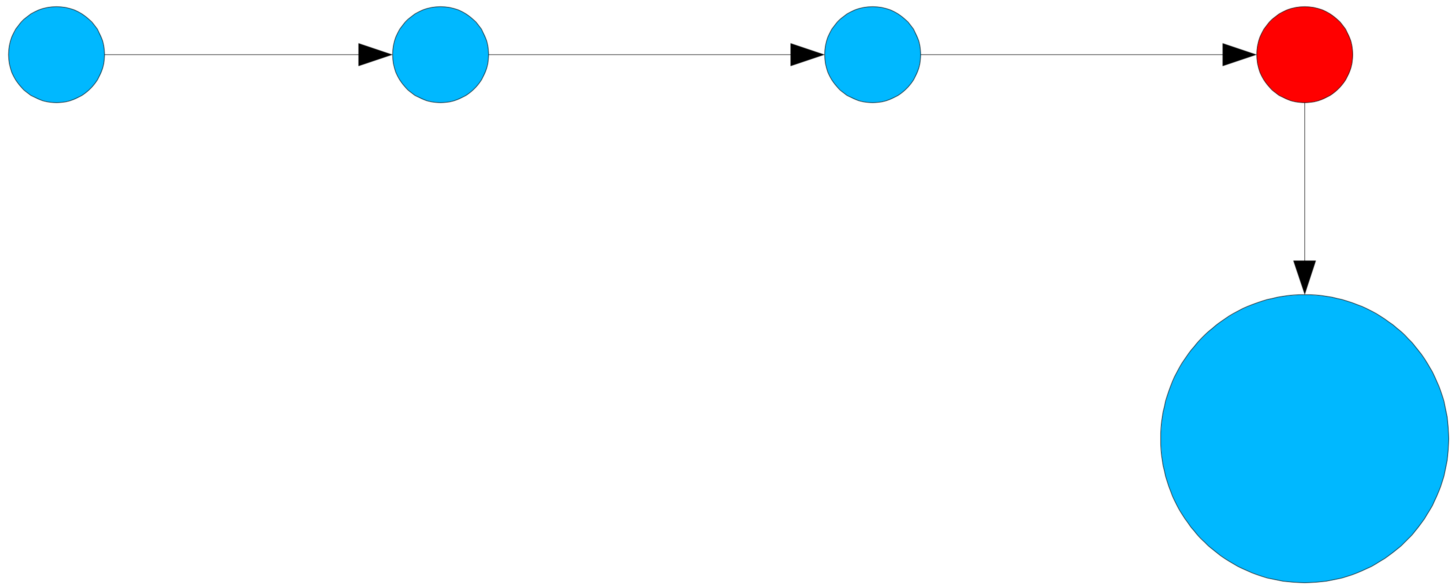
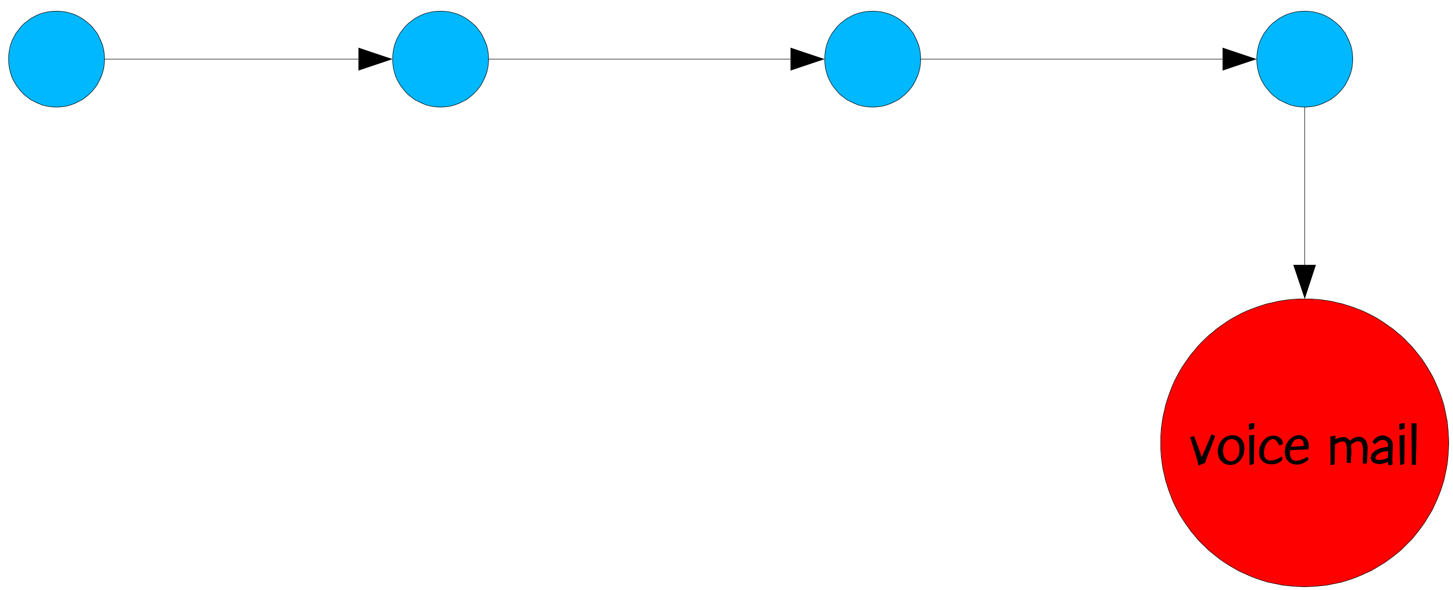


Series completion

If call not answered, it moves

to .... next in series ...

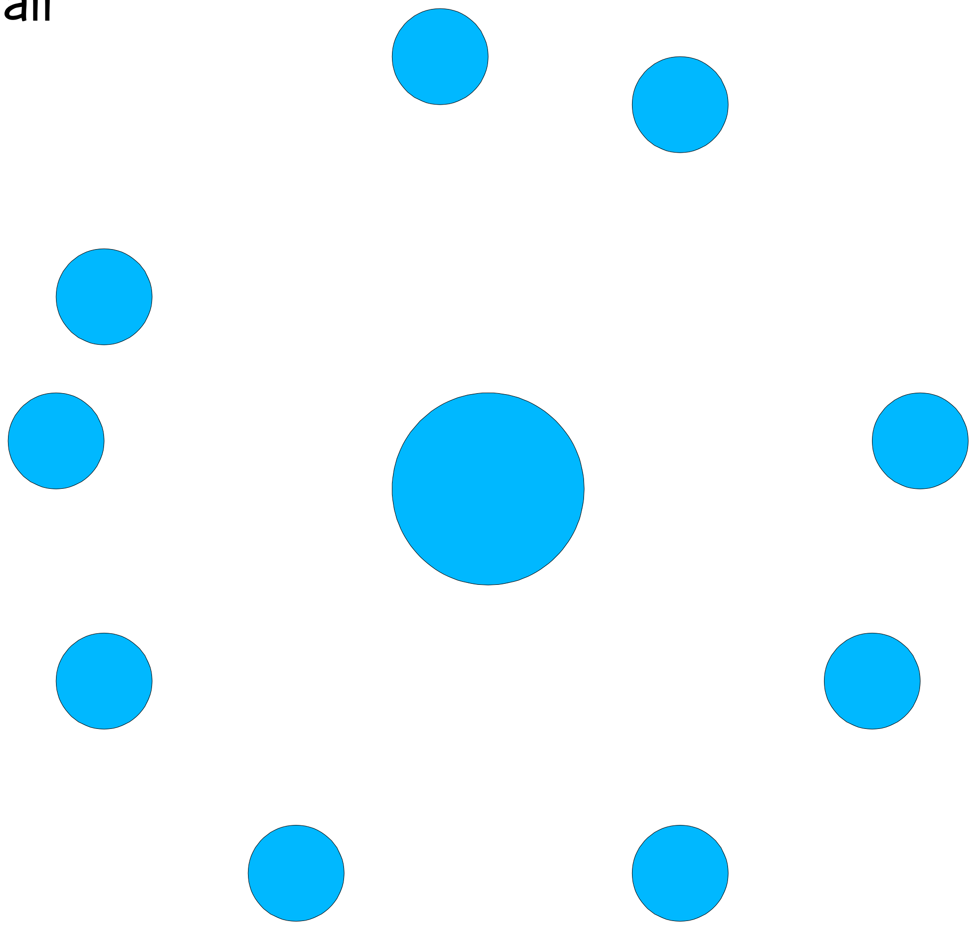


... until it is finally

answered by voice mail.

Shared TN

Assistant answers all calls to group.



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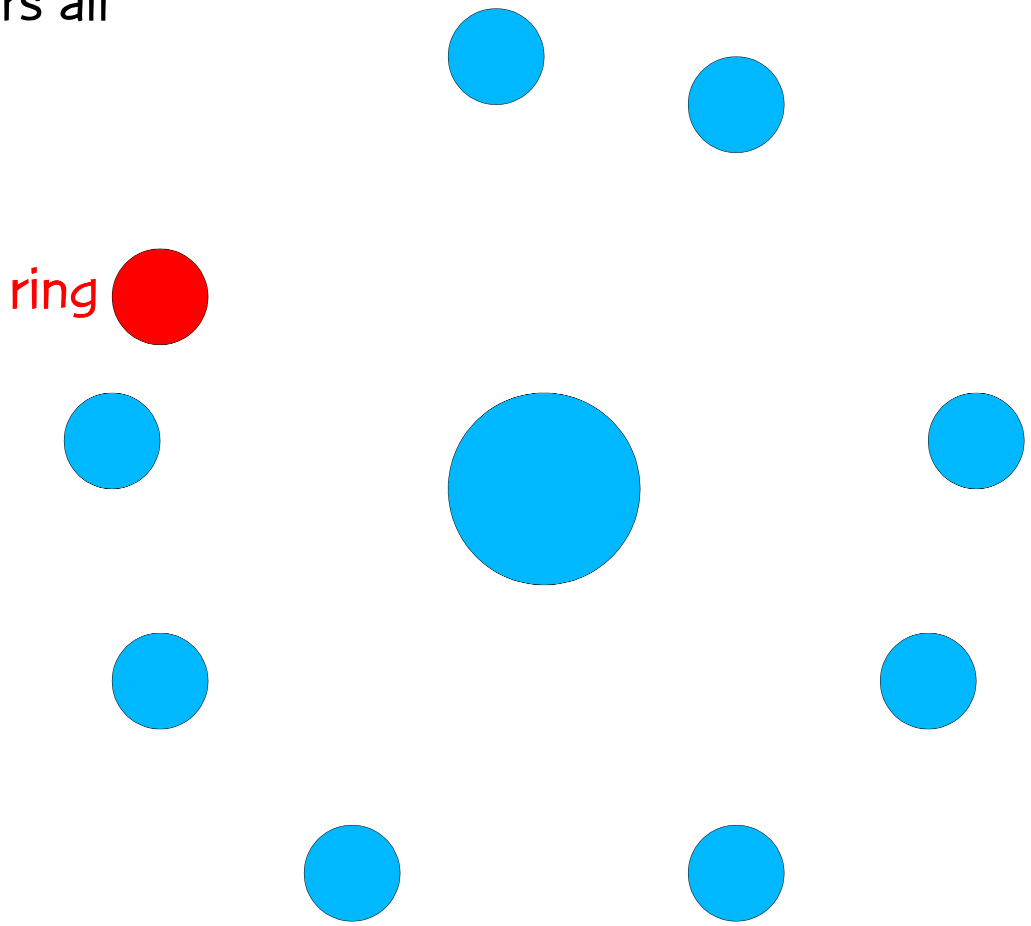

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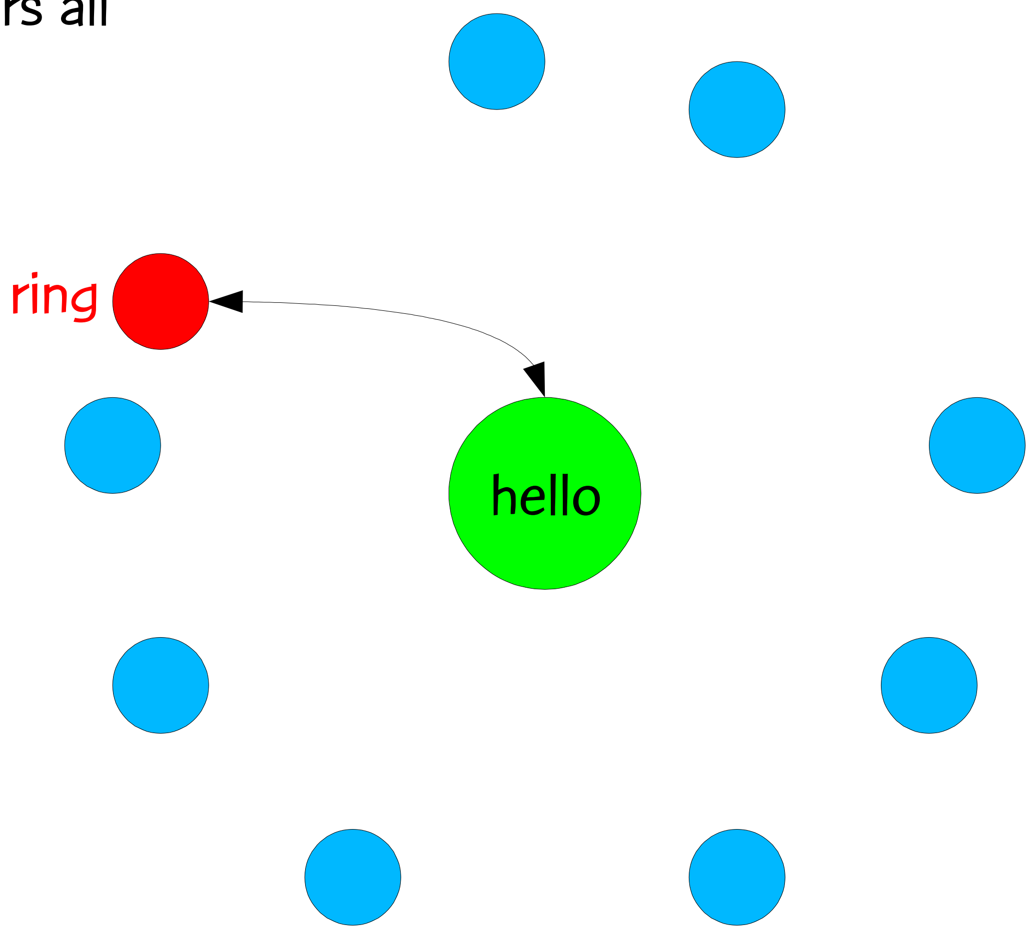

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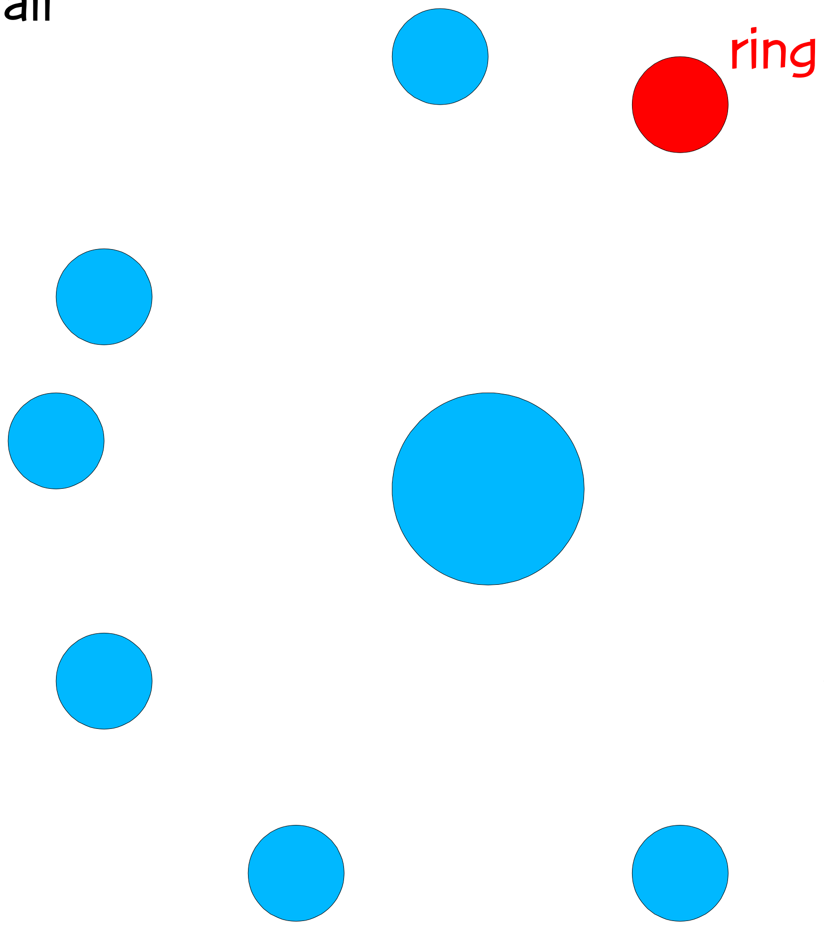

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Shared TN

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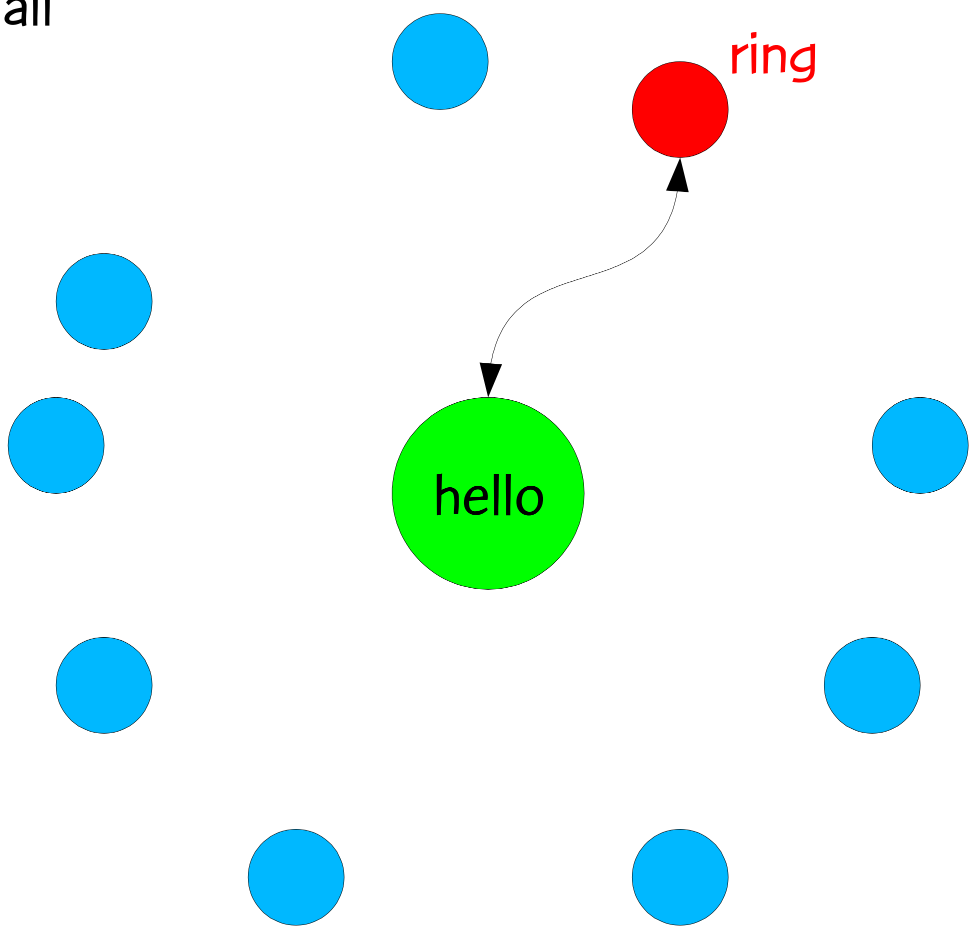
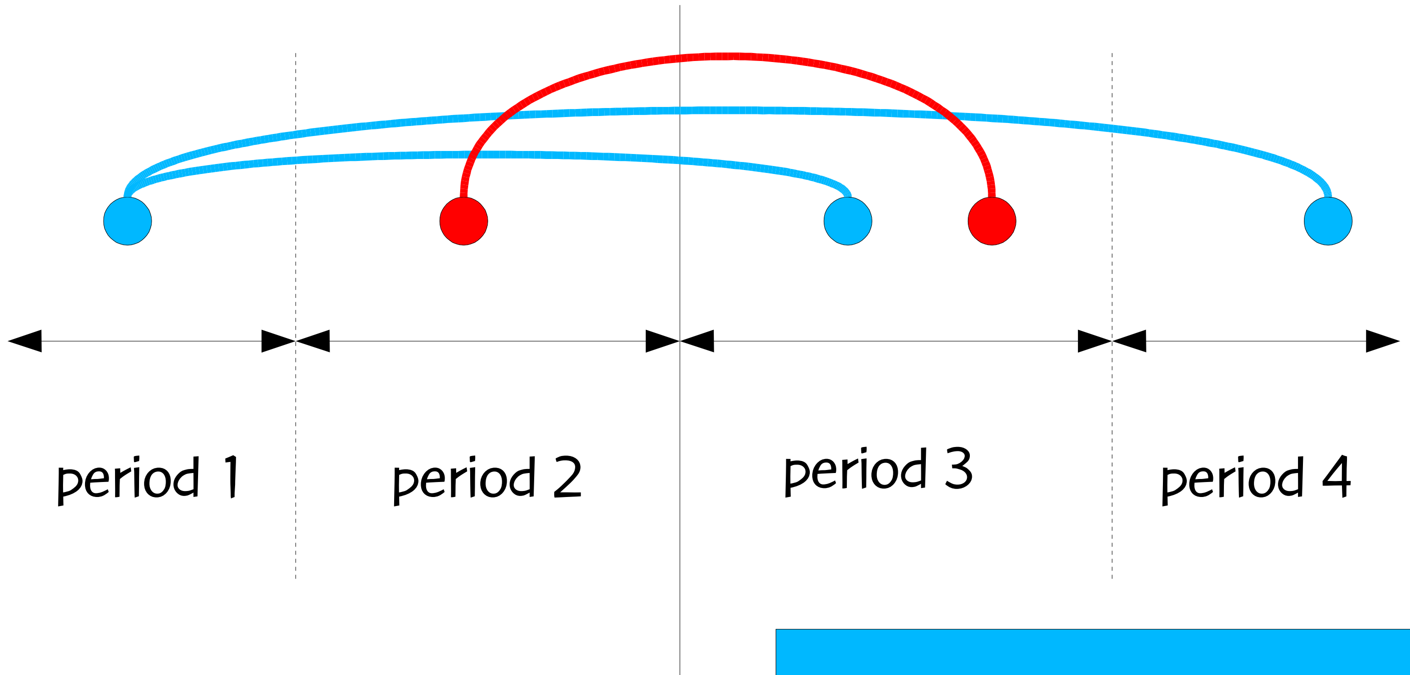


Real-world example

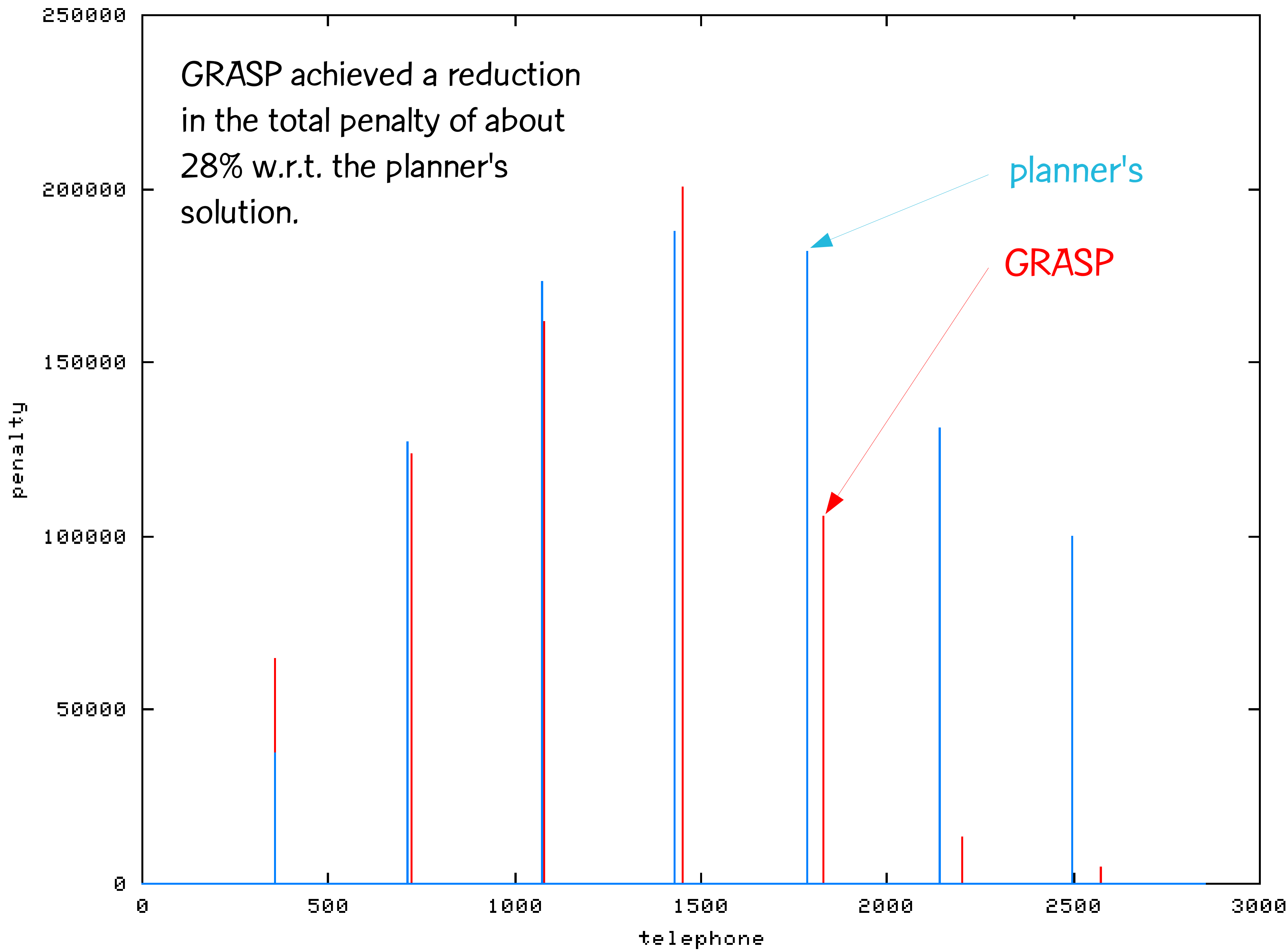
- 8 periods, 2855 phone numbers, 397 groups
- At most 375 phones can be moved in a period.
- Penalties:
  - MLHG: 10
  - CPU : 4
  - ICOM : 3
  - SC : 2
  - STN : 1

Penalty



Local search: swap phones, grow & shrink partitions.

Work with Diogo Andrade


GRASP achieved a reduction in the total penalty of about 28% w.r.t. the planner's solution.
planner's
GRASP
penalty
telephone
250000
200000
150000
100000
50000
0
0
500
1000
1500
2000
2500
3000
AT&T

Application 2:

Modem pool placement for Internet service provider

Modem pool placement for Internet service provider

- Worldnet: AT&T's Internet Service Provider
- Dial-up: hundreds of points of presence (PoPs)
  - Telephone numbers customers must call when making an Internet connection.
- Current footprint:
  - 1305 PoPs;
  - 77.66% of the telephone numbers in the U.S. can make local calls to Worldnet.

AT&T

Footprint Optimization

- In general: more PoPs, better coverage.
- For a fixed coverage, we don't want more PoPs than necessary.
- Not all PoPs are the same:
  - Each has an associated network cost:
    - Hourly rate paid by Worldnet to network company.
    - Between $0.04 and $0.14 in the continental US.
    - Up to $0.42 in Hawaii and Alaska.
  - No setup cost.

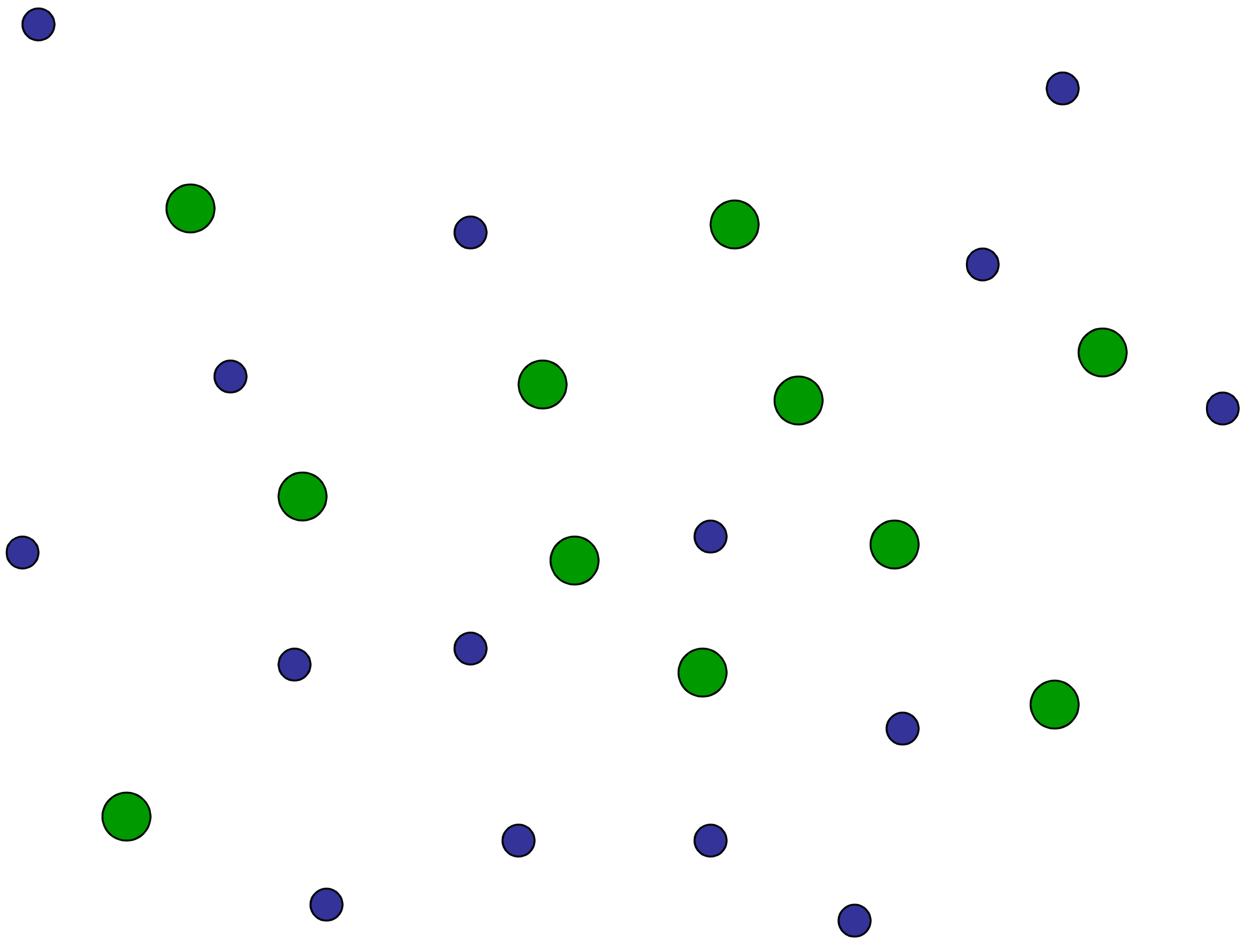
Worldnet

- When is a call local ("free")?
  - Not simply "within same area code".
  - Telephone system divided into exchanges:
    - Area code + first three digits (973360, for example).
- Each PoP has a coordinate.
- We know which exchanges can make local calls to each coordinate (the coverage).
  - Just a big table;
  - 69,534 exchanges covered by current footprint.
- Goal: keep only cheaper PoPs, preserve coverage.

Footprint Optimization

- 270 PoPs could be eliminated by inspection:
  - Dominated by cheaper PoPs
- 335 additional PoPs could be eliminated:
  - Only 700 PoPs left;
  - New footprint covers all exchanges currently covered;
  - No exchange has to make a more expensive call.
- How did we do it?
  - We solved this as a p-median problem.

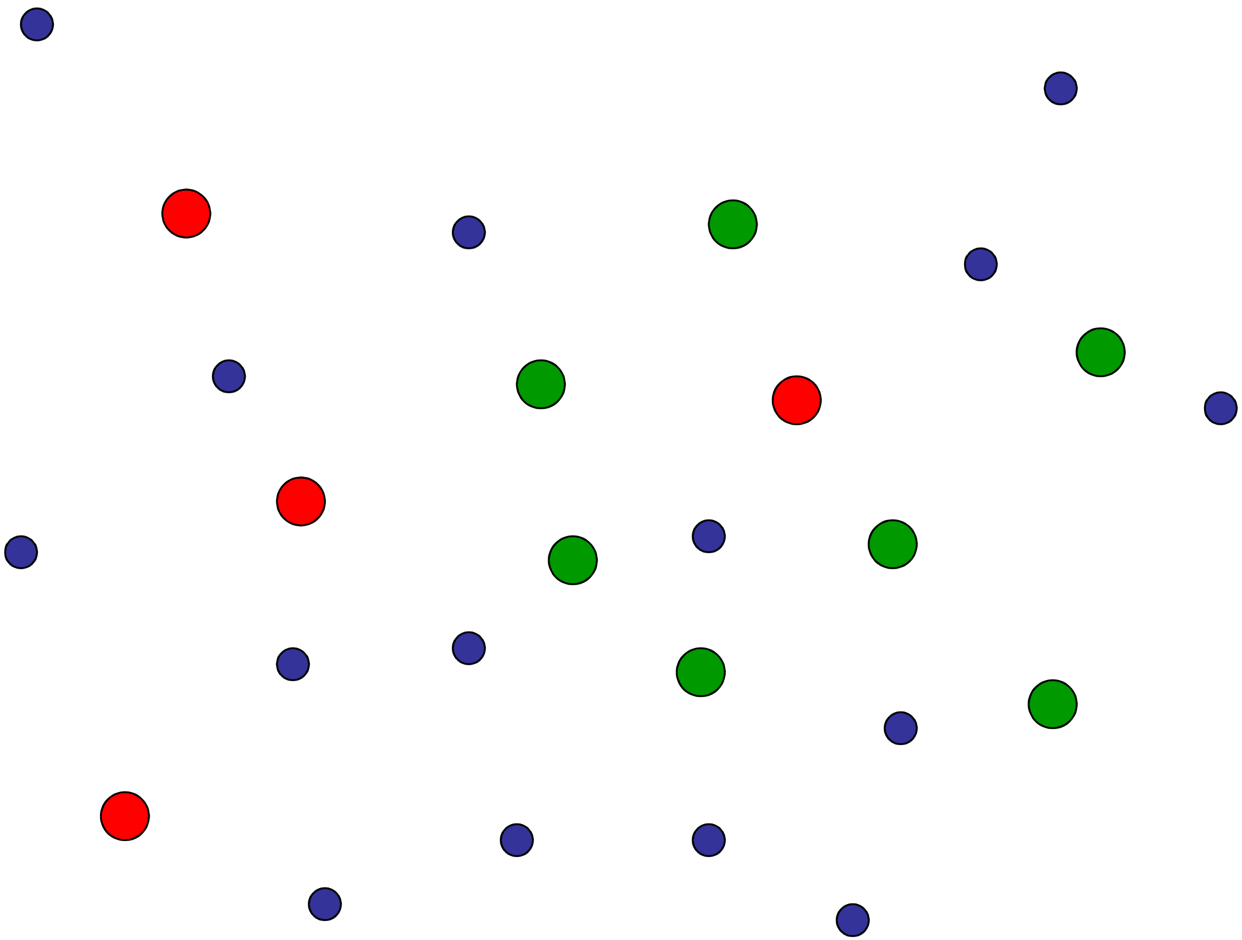
p-median problem



n (=11) potential facility locations

m (=15) users

p-median problem

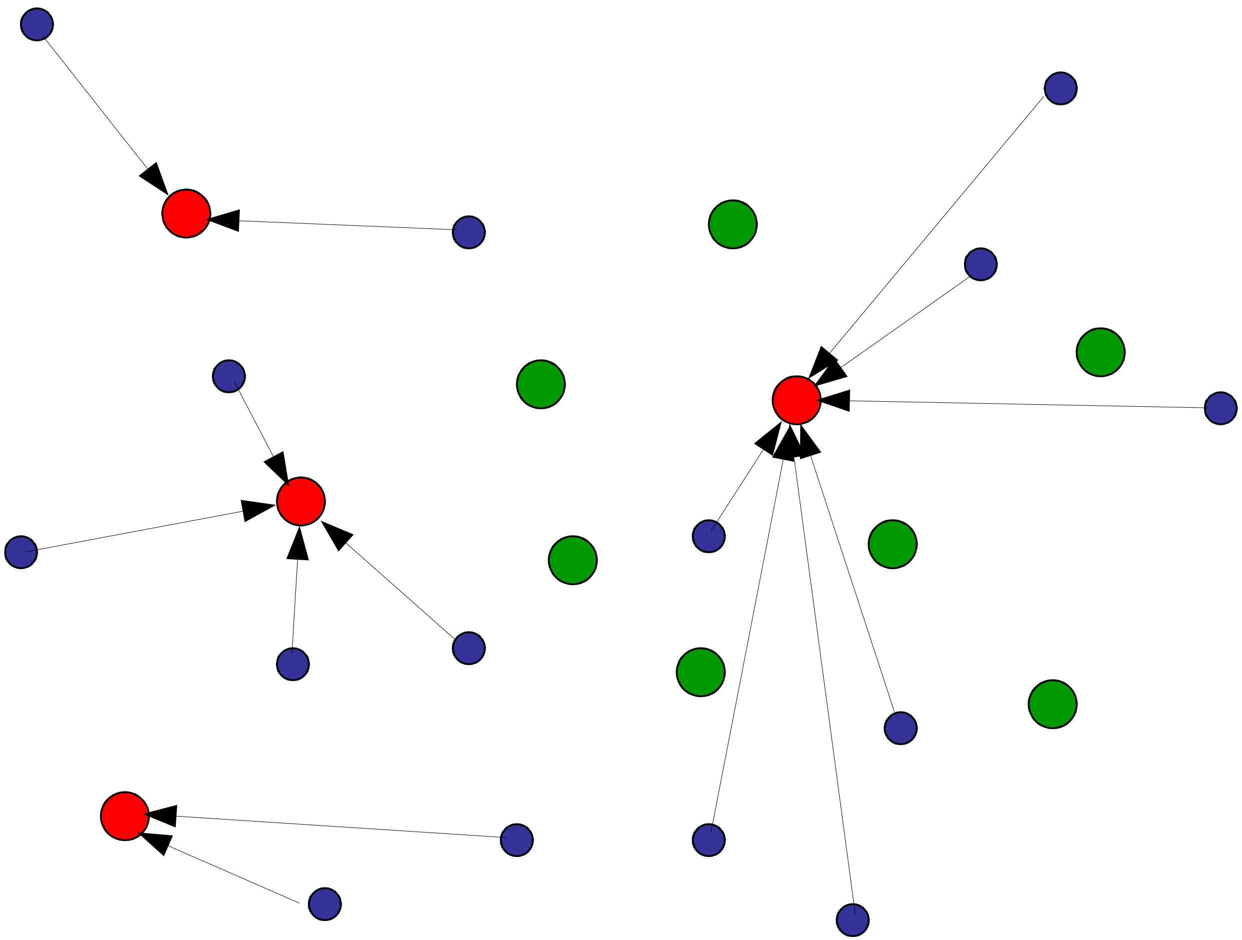


p = 4 facilities to be opened

n (=11) potential facility locations

m (=15) users

p-median problem



Users home into nearest open facility.

n (=11) potential service locations

m (=15) customers

d(u,f) = cost of servicing user u by facility f

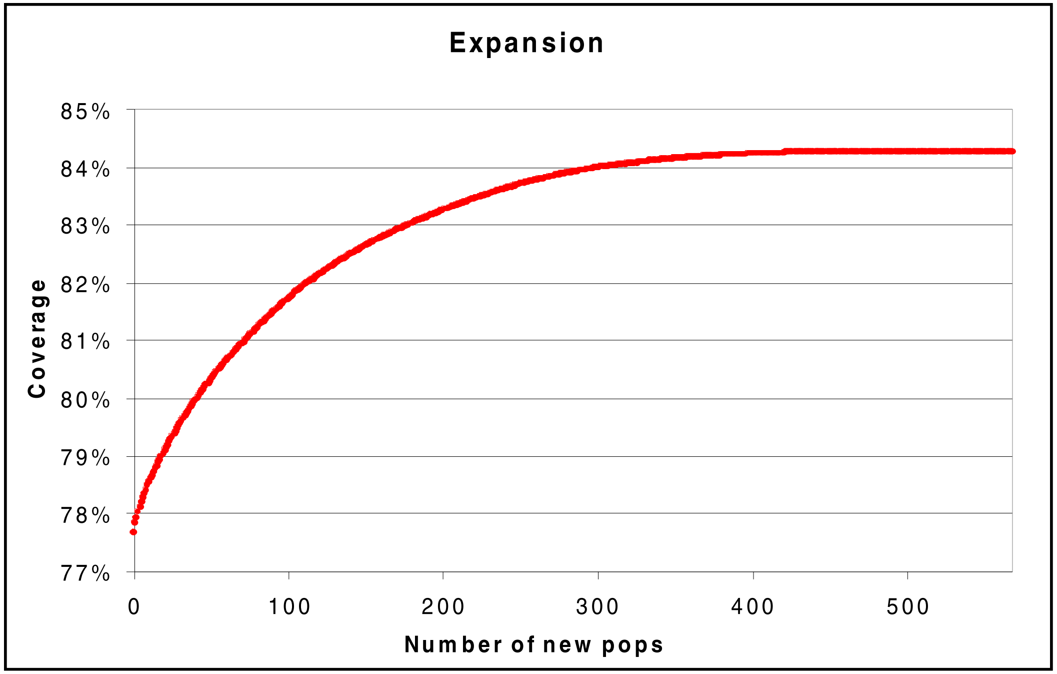
Footprint Optimization

- In our case:
  - each exchange is a p-median user:
    - 69,534 in total (all currently covered).
  - each coordinate is a p-median facility:
    - 1035 in total (all currently open).
  - Distances: network cost.
    - (PoP rate) · (hours used by exchange)
- With p=1035, we get the current network cost.
- We want the smallest p that preserves that cost.
  - Solve the p-median problem for various values of p to find best.
  - 700 was the value we found.

Expanding the Footprint

- Second problem:
  - Increase coverage beyond 77.66%.
- AT&T can use UUNet PoPs:
  - 1,498 candidate PoPs.
  - 568 of those cover at least one new exchange.
- Main question:
  - If we want to open p new PoPs, which PoPs do we open?
    - Goal: maximize coverage.
- This is the maximum cover problem:
  - It can be solved as a p-median problem.

Expansion



Coverage	Footprint
77.66%	current
78%	current+3
79%	current+19
80%	current+41
81%	current+72
82%	current+113
83%	current+177
84%	current+301
84.27%	current+464

References

- M.G.C. Resende, "Computing approximate solutions of the maximum covering problem using GRASP," J. of Heuristics, vol. 4, pp. 161-171, 1998.
- M.G.C. Resende & R.F. Werneck, "A hybrid heuristic for the p-median problem," J. of Heuristics, vol. 10, pp. 59-88, 2004.
- M.G.C. Resende & R.F. Werneck, "A fast swap-based local search procedure for location problems," to appear in Annals of Operations Research, 2005.

Application 3:
Local access network design

Local access network design

- We wish to roll out broadband service in different markets.
- We need to determine which markets we should go for.
- For each candidate market, estimate profit (or loss) associated with rolling out service.

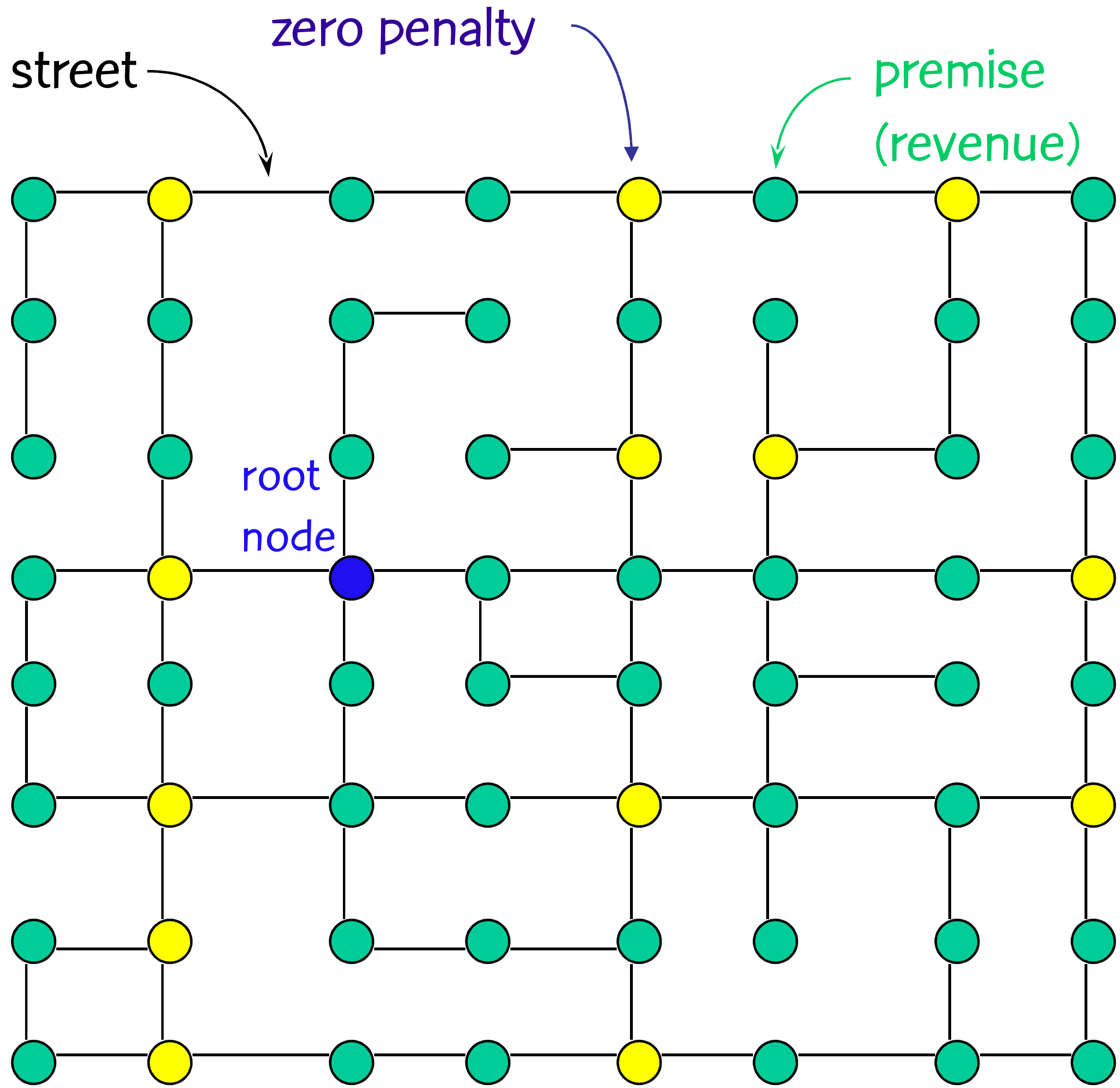
Local access network design

- Build a fiber-optic network for providing broadband connections to business and residential customers.
- Design a local access network taking into account trade-off between:
  - cost of network
  - revenue potential of network

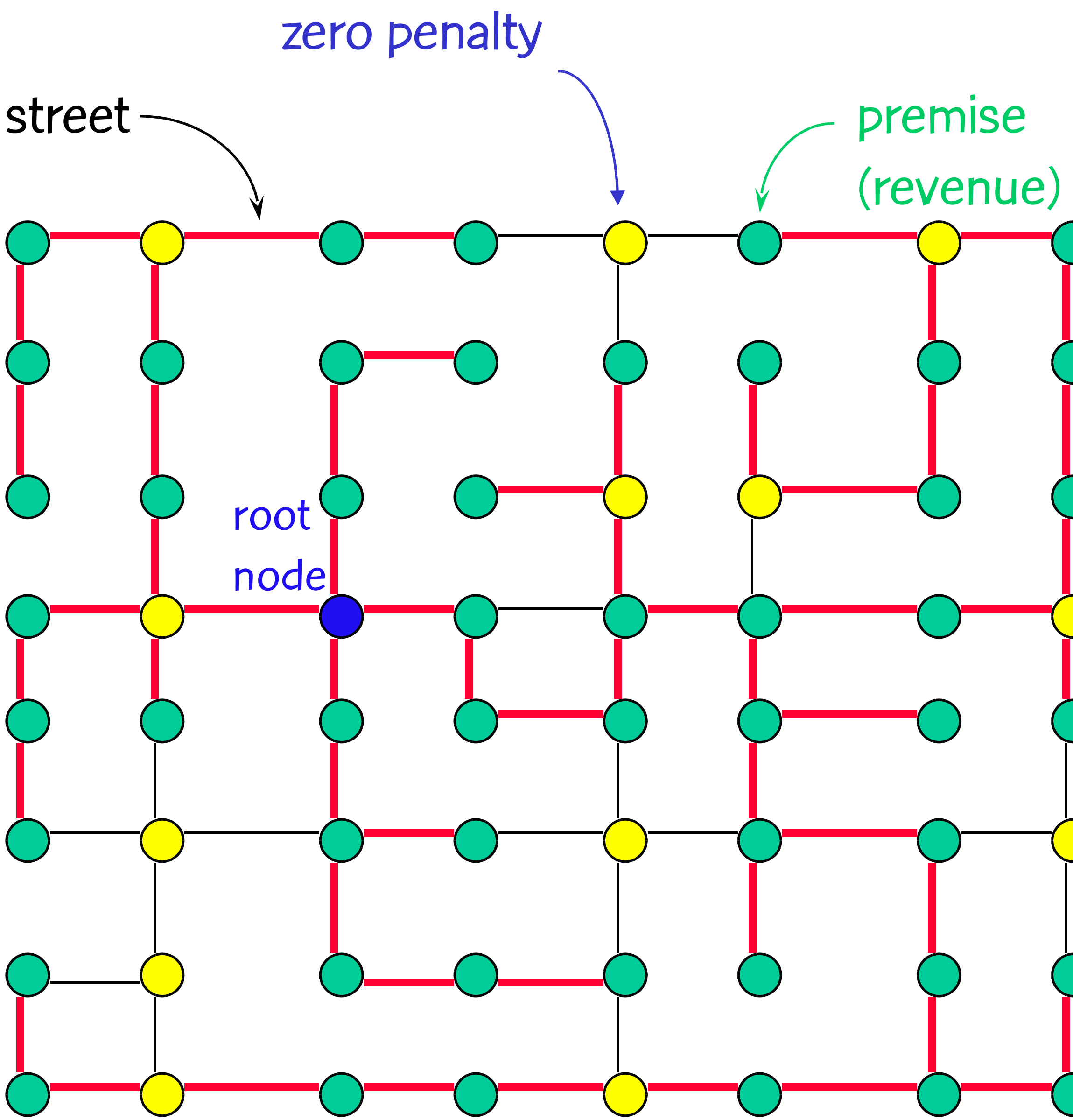
Local access network design

- Graph corresponds to local street map
  - Edges: street segments
    - Edge cost: cost of laying the fiber on the corresponding street segment
  - Vertices: street intersections and potential customer premises
    - Vertex penalty: estimate of potential loss of revenue if the customer were not to be serviced (intersection nodes have no penalty)

Local access network design

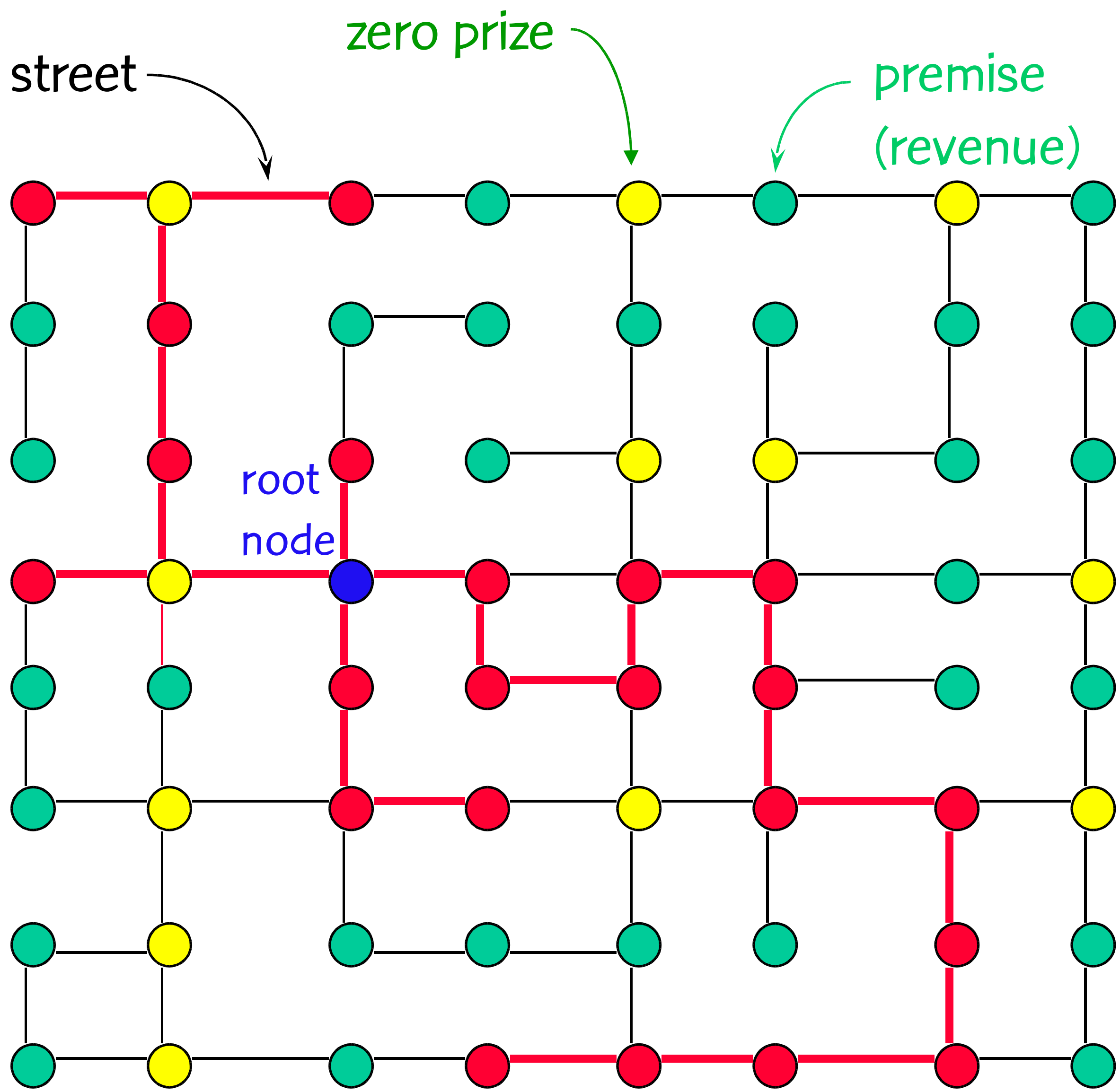


Collect all prizes
(Steiner problem in graphs)



Collect some prizes

(Prize collecting Steiner Problem in Graphs)



Multi-start heuristic

S. Canuto, M.G.C. Resende, & C.C. Ribeiro, "Local search with perturbations for the prize-collecting Steiner tree problem in graphs," Networks, vol. 38, pp. 50-58, 2001

- Repeat:
  - Perturb problem data and solve using approximation algorithm of Goemans and Williamson (1996);
  - If solution is new, perform swap-based local search;
  - Attempt to insert solution into POOL;
  - Select solution at random from POOL and explore path from current iterate and POOL solution using path-relinking;
- Starting from best POOL solution, apply variable neighborhood search;

A cutting planes algorithm: Lower bound

A. Lucena & M.G.C. Resende, "Strong lower bounds for the prize collecting Steiner tree problem in graphs," Discrete Applied Mathematics, vol. 141, pp. 277-294, 2004.

- Integer programming (IP) formulation
- Cutting planes algorithm to solve linear programming relaxation of IP

Application 4:

Traffic routing on a virtual private network

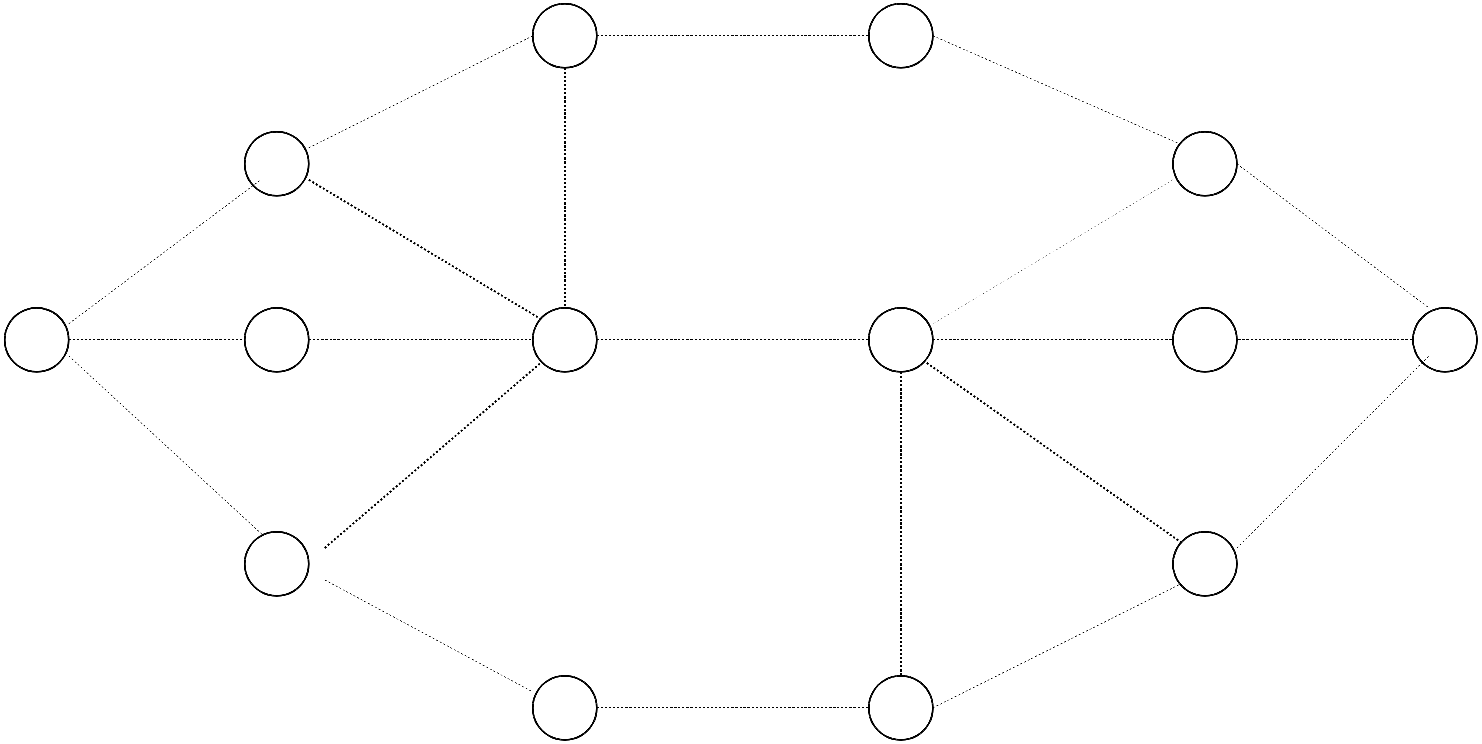
AT&T

Traffic routing on a virtual private network

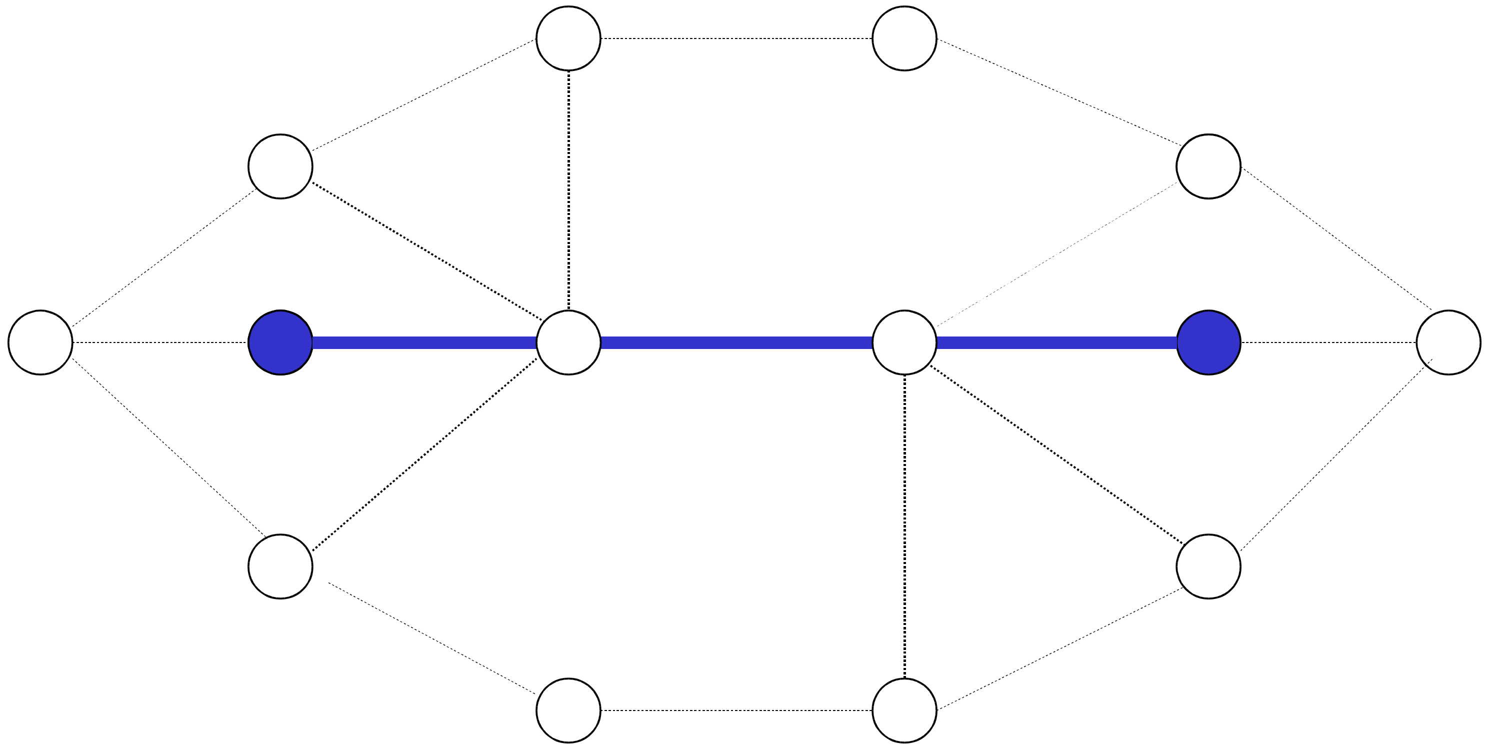
- Frame relay service offers virtual private networks to customers by providing long-term private virtual circuits (PVCs) between customer endpoints on a backbone network.
- Routing is done either automatically by switch or by the network designer without any knowledge of future requests.
- Over time, these decisions cause inefficiencies in the network and occasionally offline rerouting (grooming) of the PVCs is needed:
  - integer multicommodity network flow problem: Resende & Ribeiro (2003)

AT&T

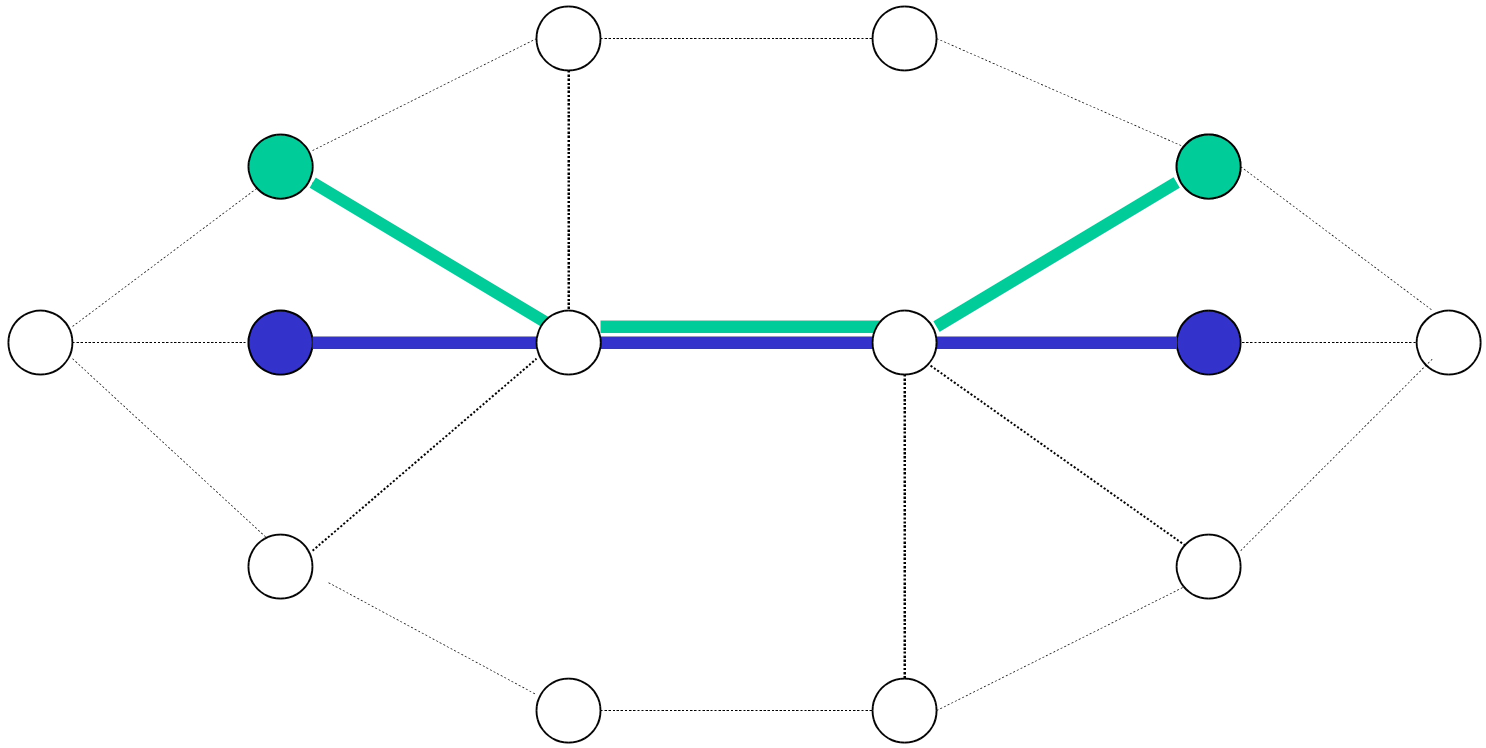
Traffic routing on a virtual private network



Traffic routing on a virtual private network



Traffic routing on a virtual private network



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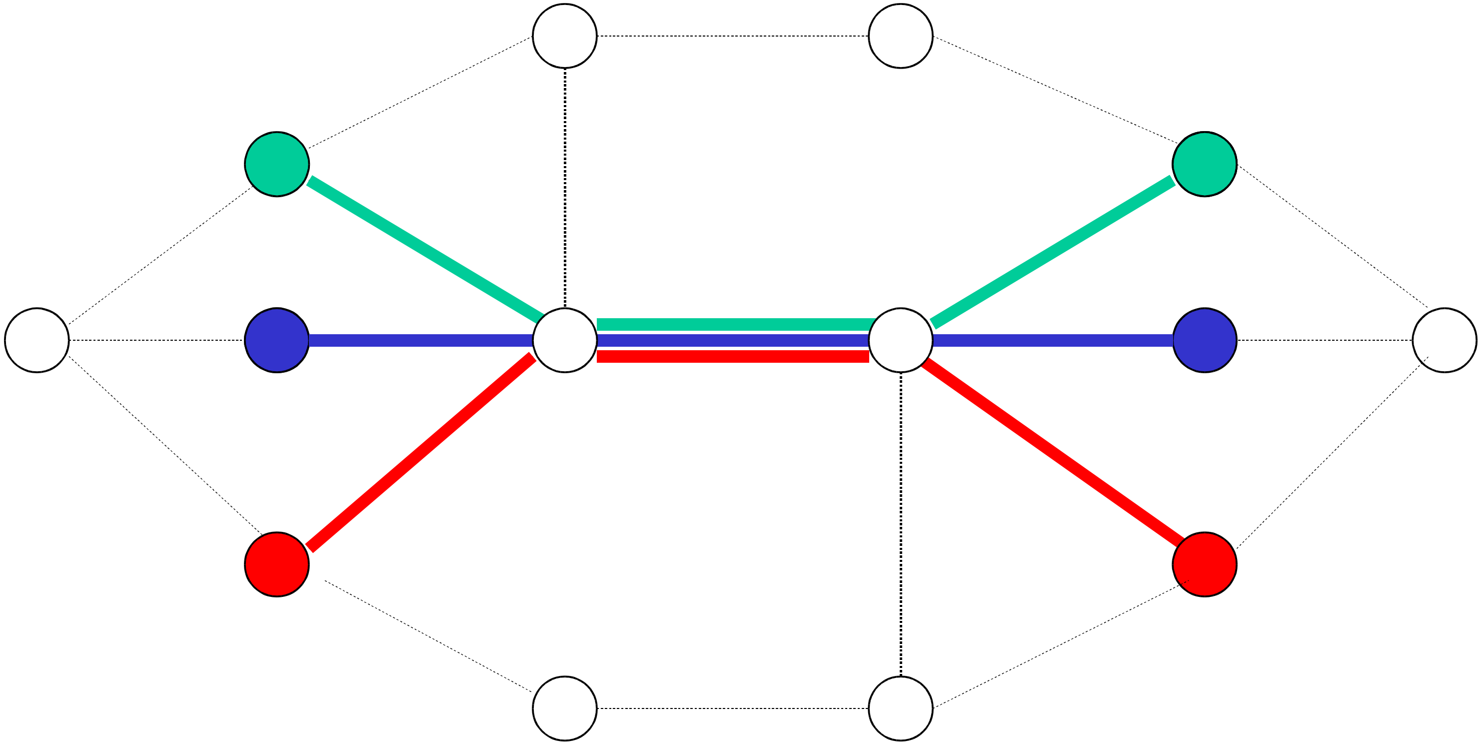
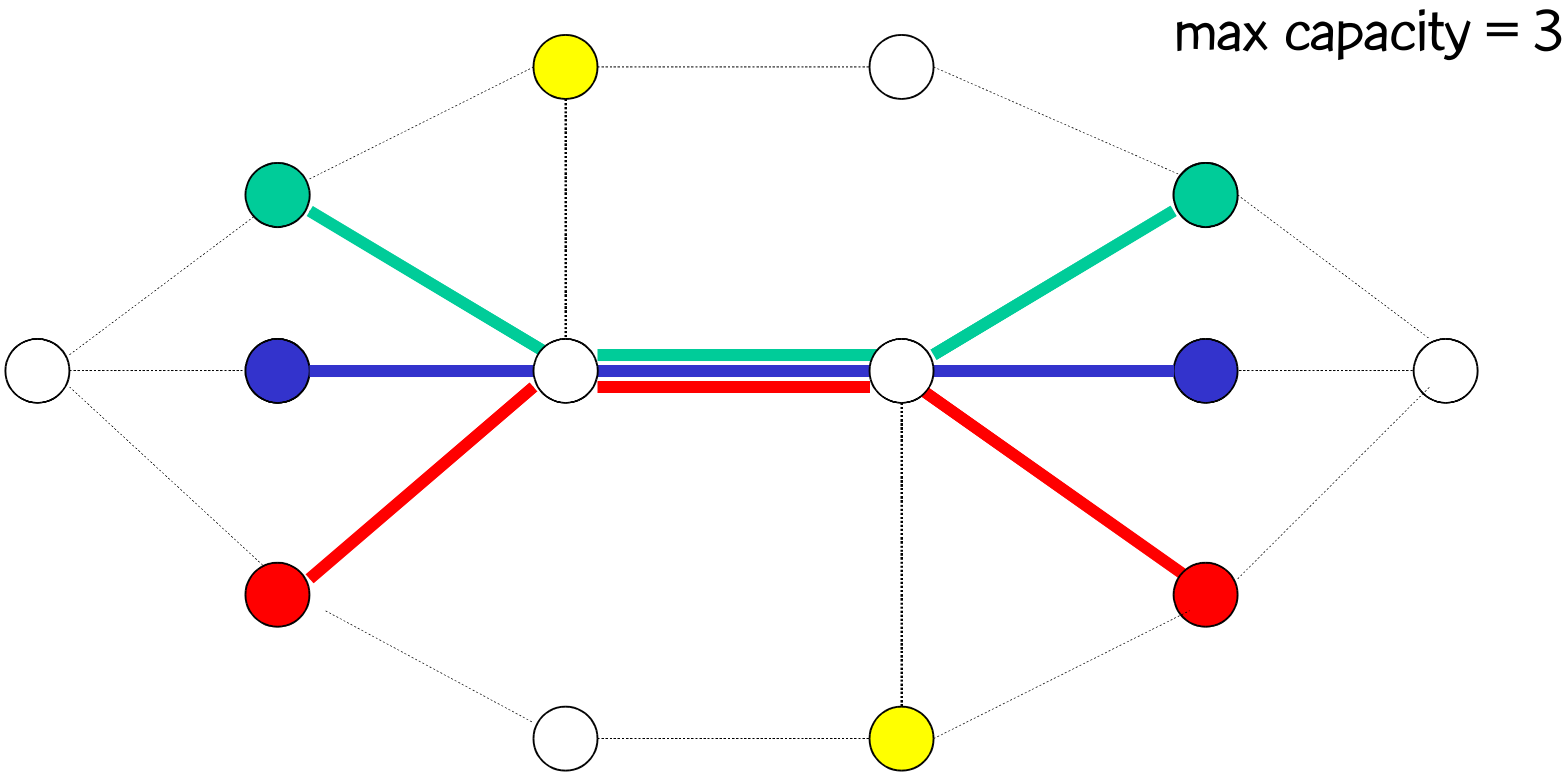
Traffic routing on a virtual private network



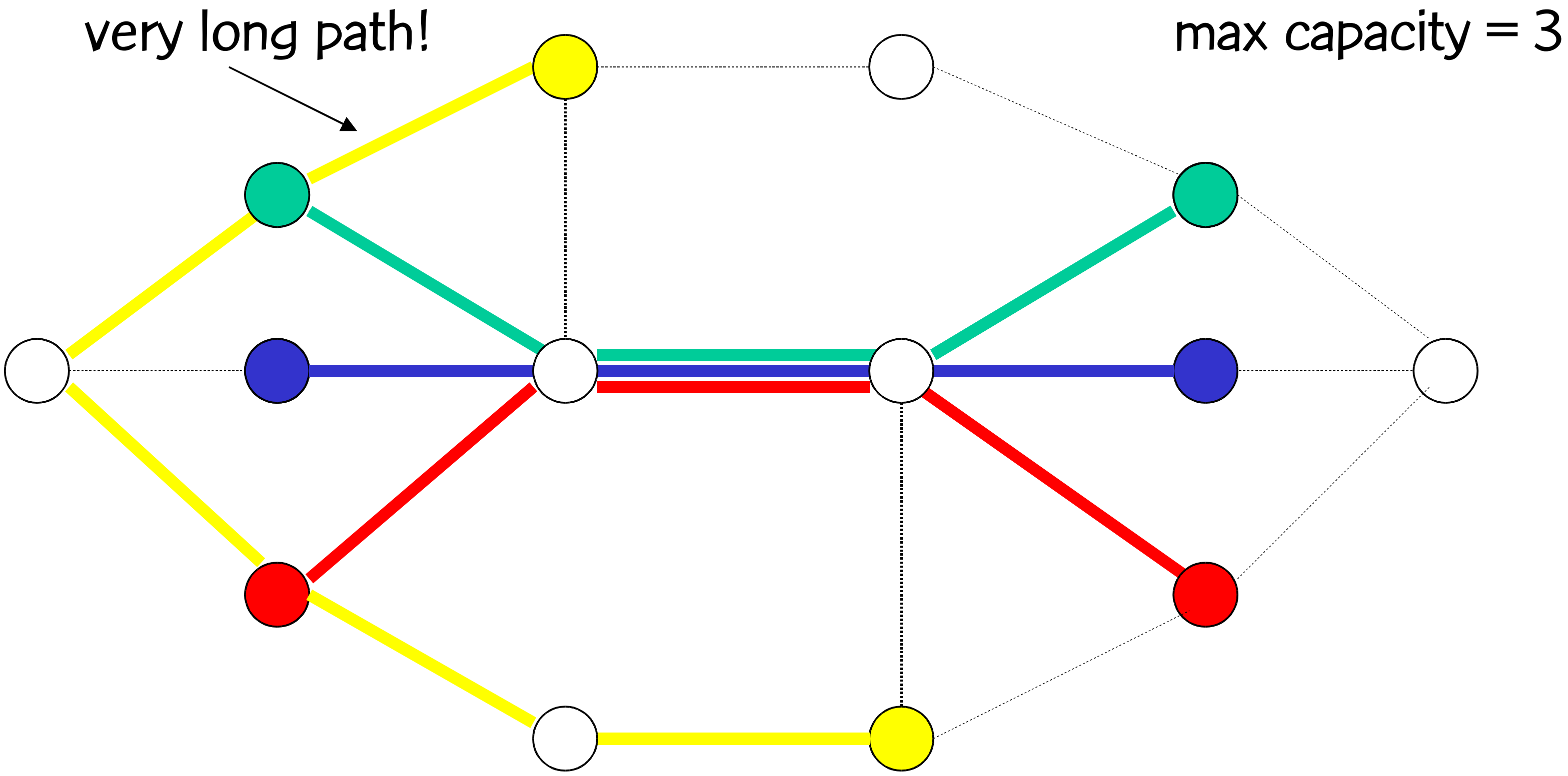
AT&T

Traffic routing on a virtual private network

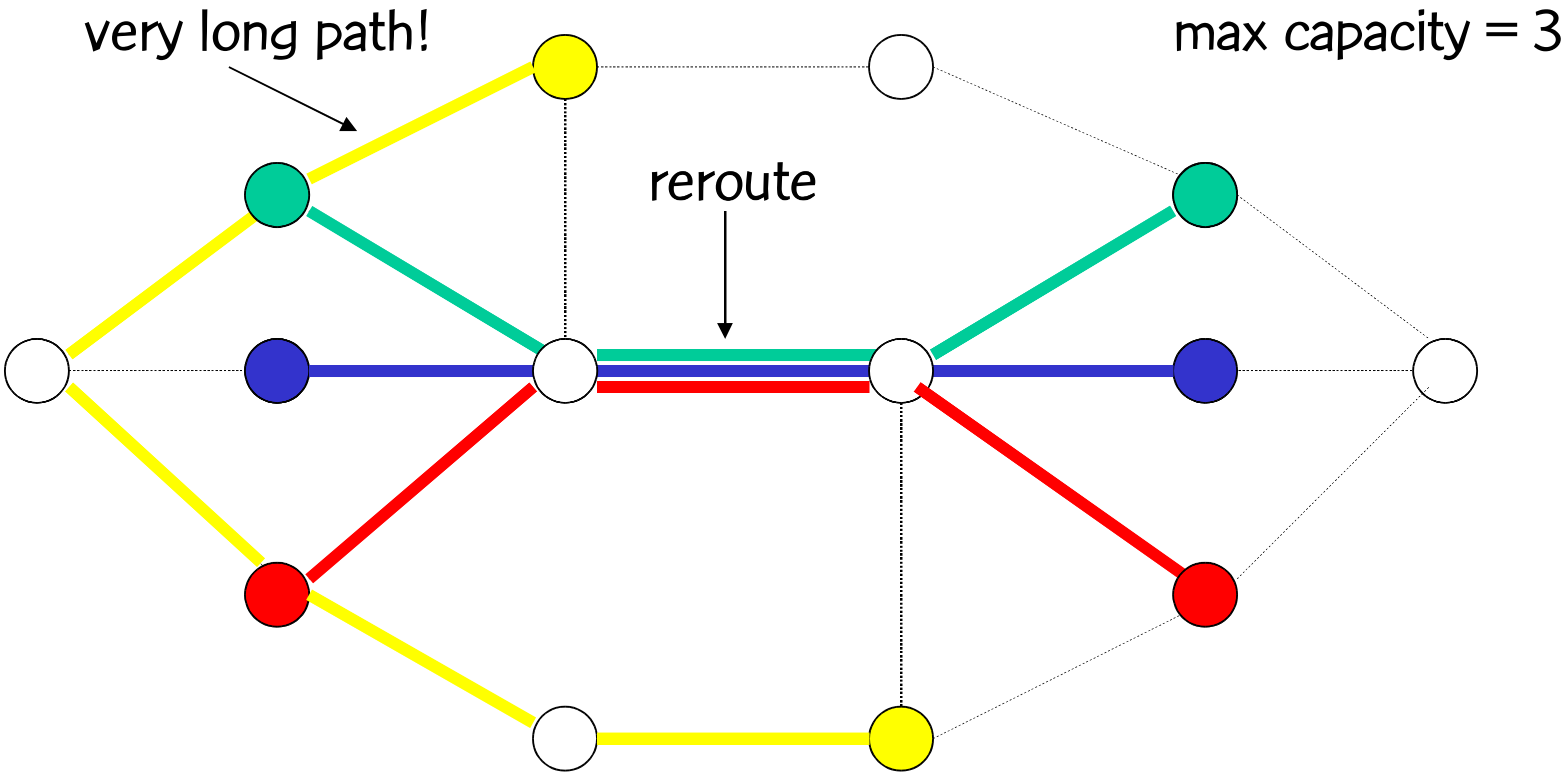


AT&T

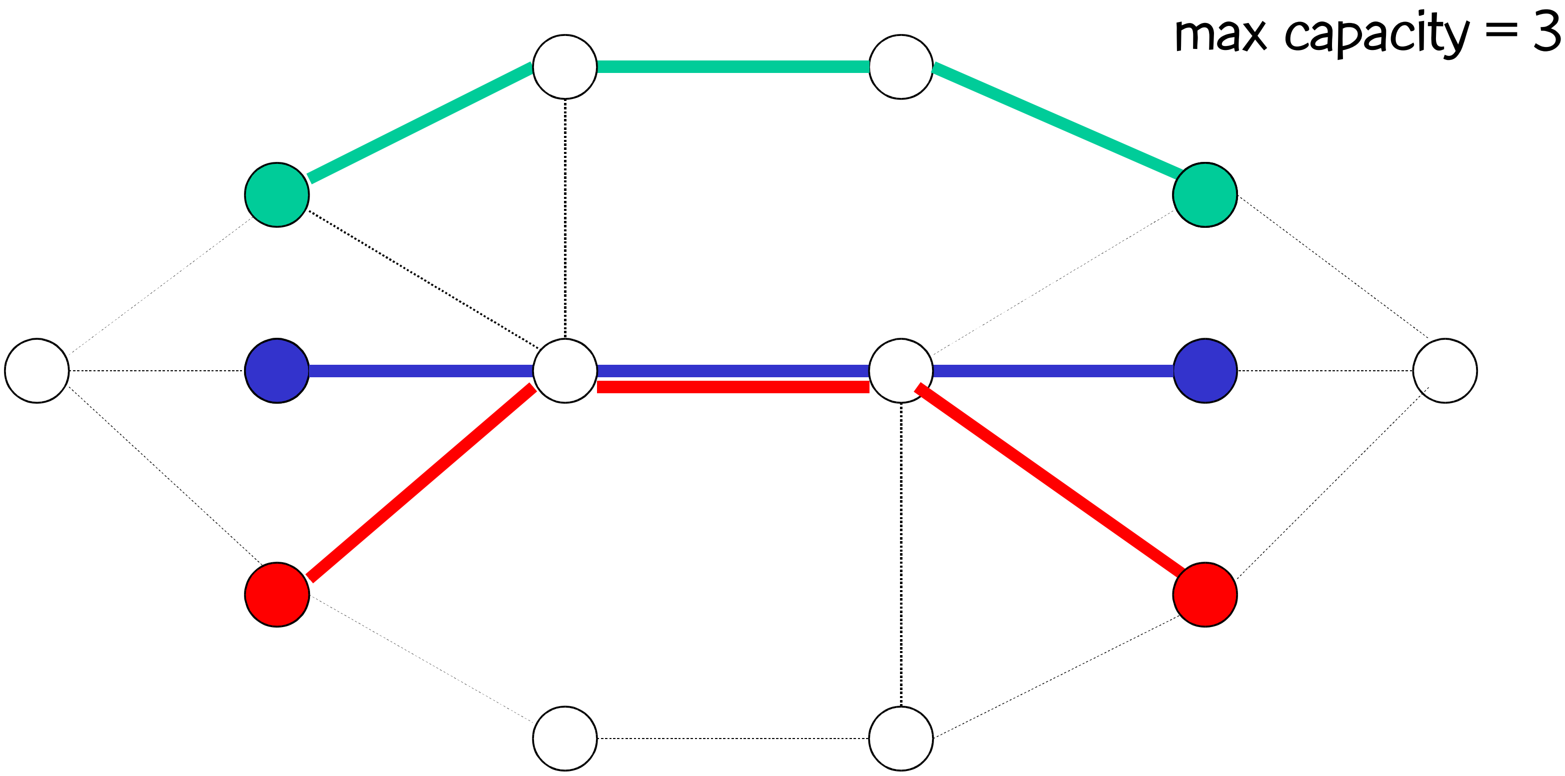
Traffic routing on a virtual private network



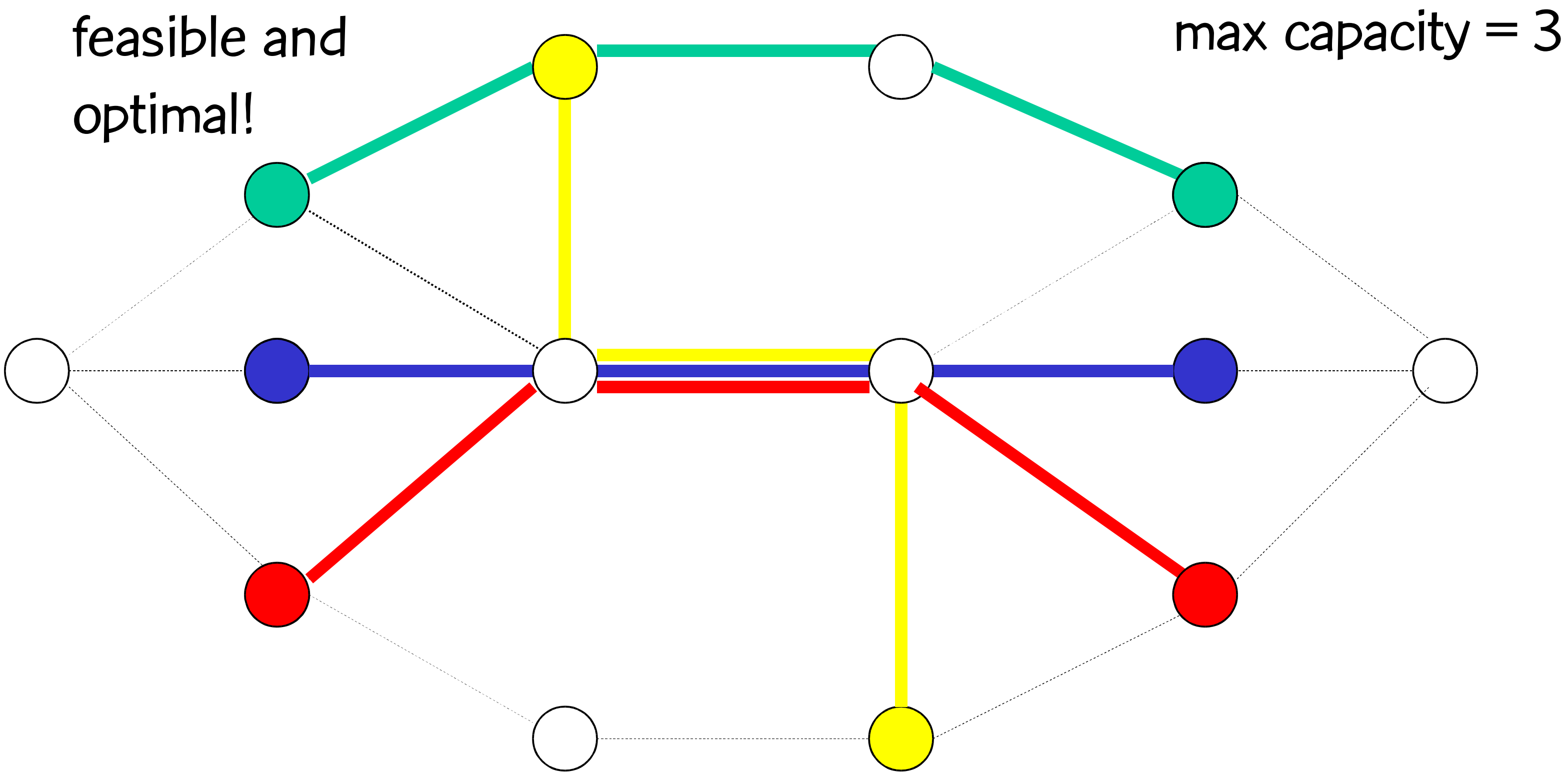
Traffic routing on a virtual private network



Traffic routing on a virtual private network



Traffic routing on a virtual private network



Reference

- M.G.C. Resende & C.C. Ribeiro, "A GRASP with path-relinking for private virtual circuit routing," Networks, vol. 41, pp. 104-114, 2003.

Application 5:
Internet traffic engineering

Internet traffic engineering

- Internet traffic has been doubling each year [Coffman & Odlyzko, 2001]
- In the1995-96 period, there was a doubling of traffic each three months!
  - Web browsers were introduced.
- Increasingly heavy traffic (due to video, voice, etc.) will raise the requirements of the Internet of tomorrow.

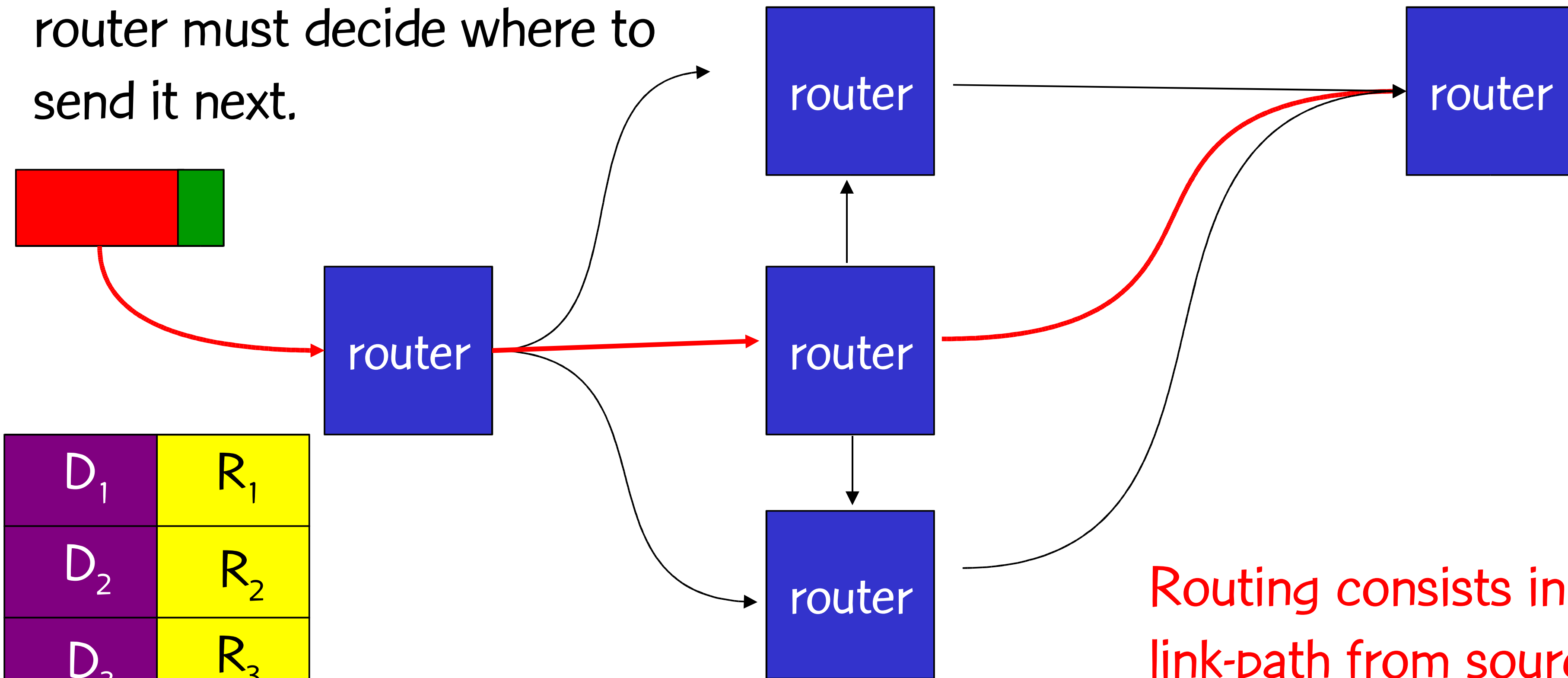
Internet traffic engineering

- Objective: make more efficient use of existing network resources.
- Routing of traffic can have a major impact on efficiency of network resource utilization.

Packet routing

When packet arrives at router, router must decide where to send it next.

Packet's final destination.



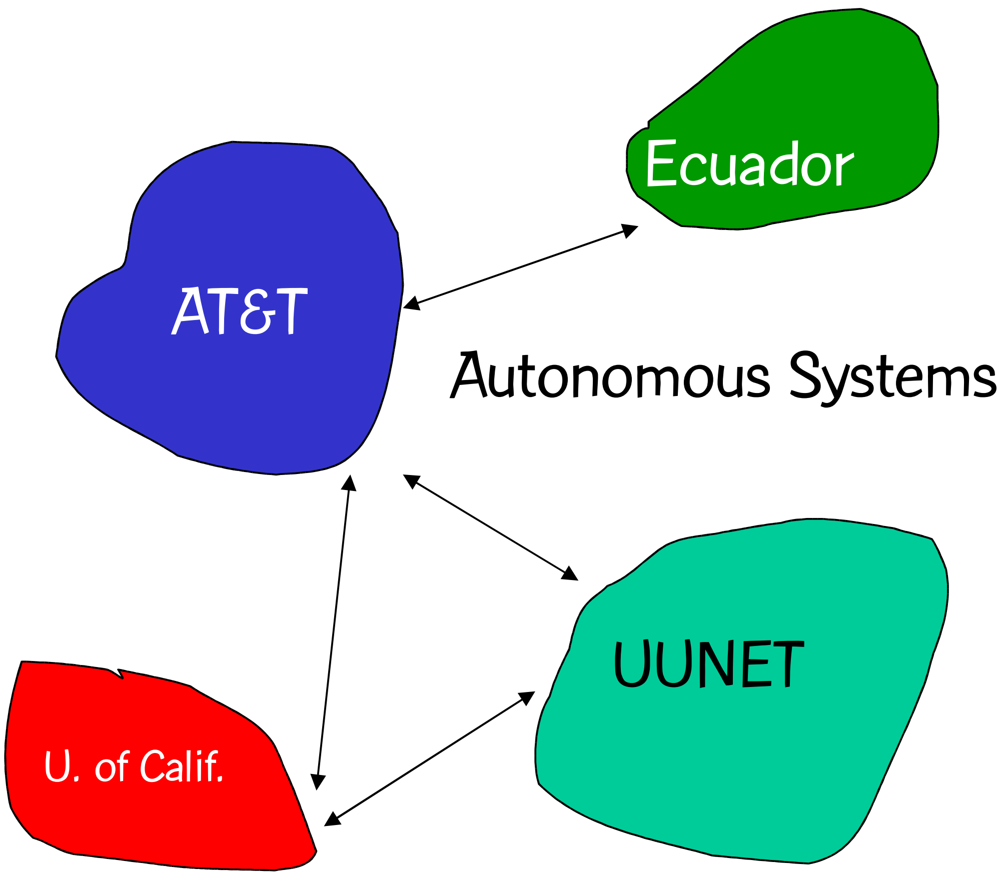
D_1	R_1
D_2	R_2
D_3	R_3
D_4	R_4

Routing table

Routing consists in finding a link-path from source to destination.

OSPF (Open Shortest Path First)

- OSPF is a commonly used intra-domain routing protocol (IGP).
- Routers exchange routing information with all other routers in the autonomous system (AS).
  - Complete network topology knowledge is available to all routers, i.e. state of all routers and links in the AS.



OSPF routing

- Assign an integer weight $\in [1, w_{max}]$ to each link in AS.

  In general, $w_{max} = 65535 = 2^{16} - 1$.

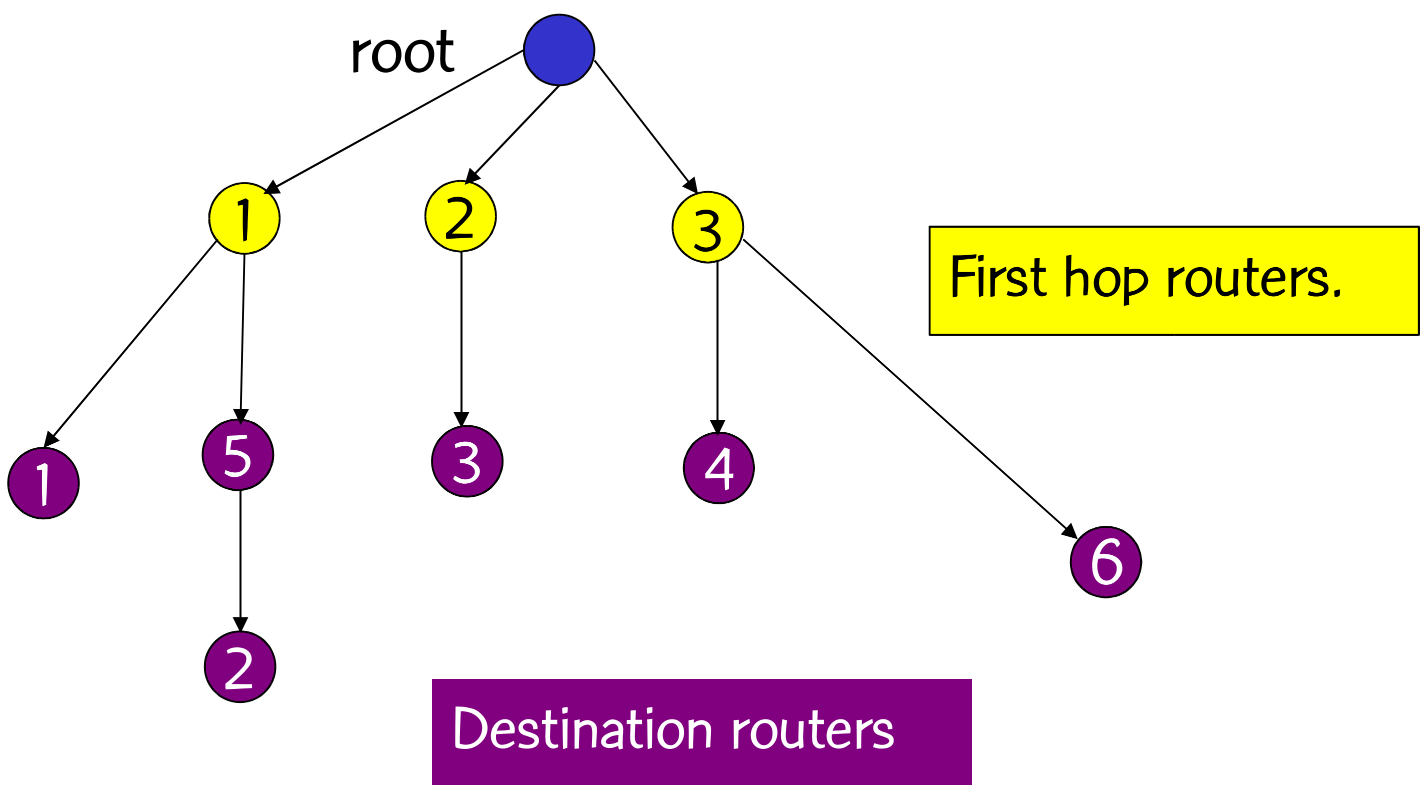
- Each router computes tree of shortest weight paths to all other routers in the AS, with itself as the root, using Dijkstra's algorithm.

OSPF routing

Routing table is filled
with first hop routers
for each possible destination.

Routing table

D_1	R_1
D_2	R_1
D_3	R_2
D_4	R_3
D_5	R_1
D_6	R_3

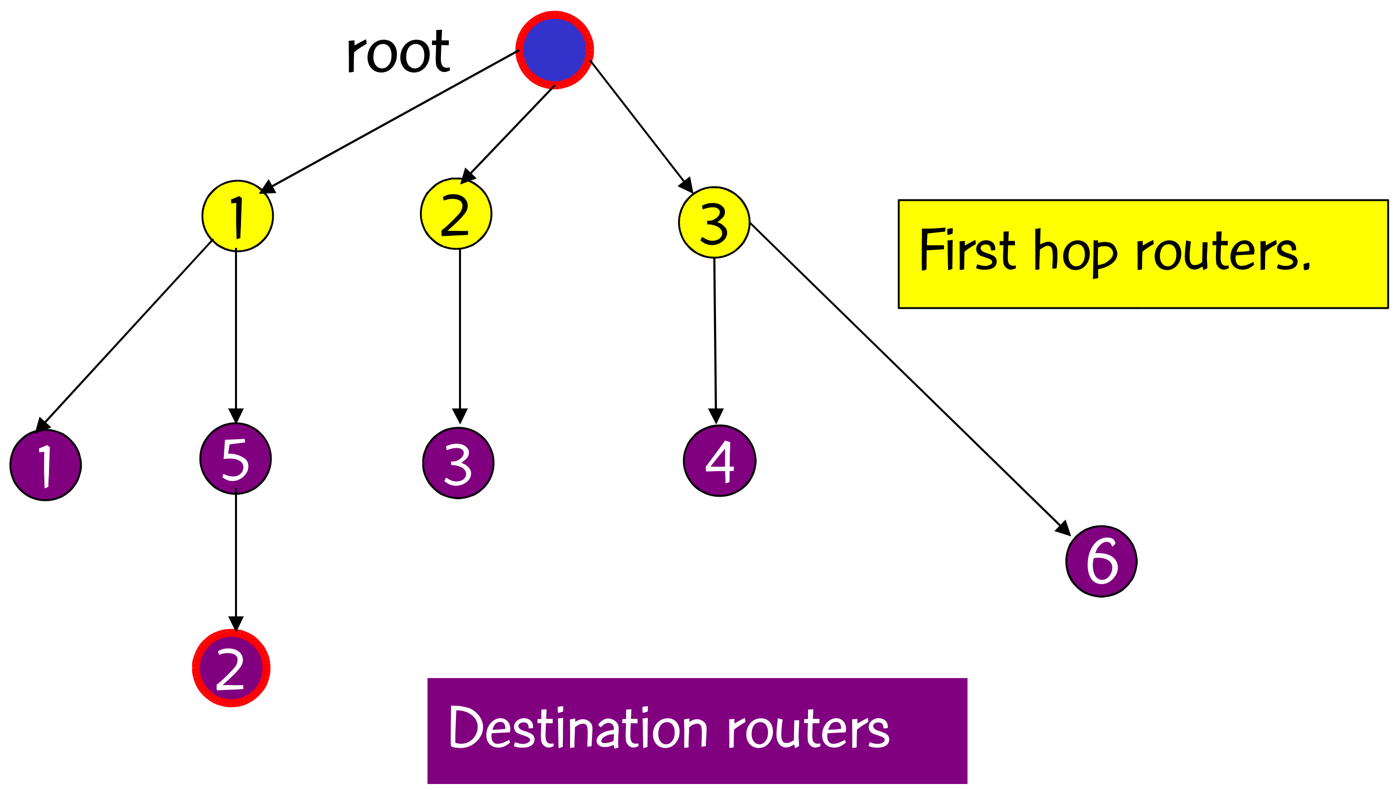


OSPF routing

Routing table is filled with first hop routers for each possible destination.

Routing table

D_1	R_1
D_2	R_1
D_3	R_2
D_4	R_3
D_5	R_1
D_6	R_3

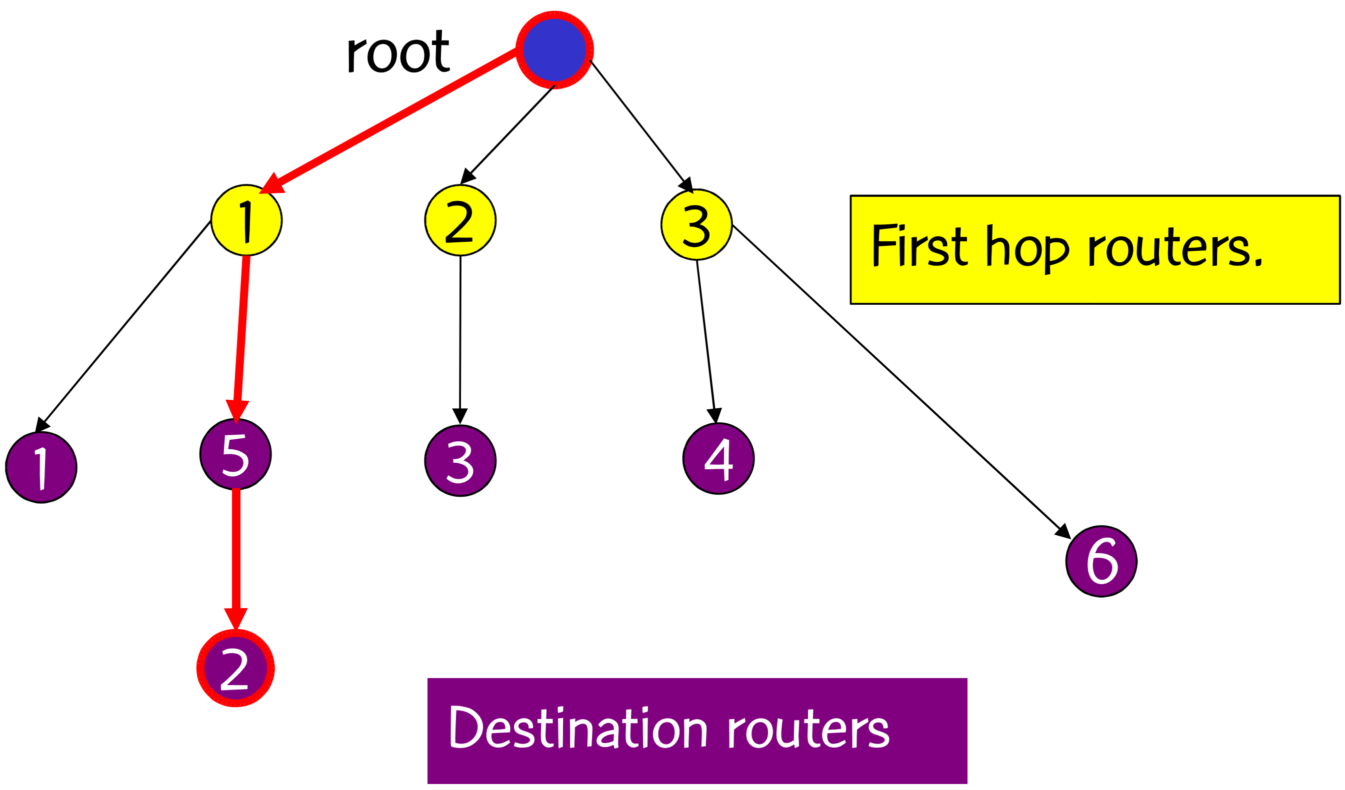


OSPF routing

Routing table is filled
with first hop routers
for each possible destination.

Routing table

D_1	R_1
D_2	R_1
D_3	R_2
D_4	R_3
D_5	R_1
D_6	R_3

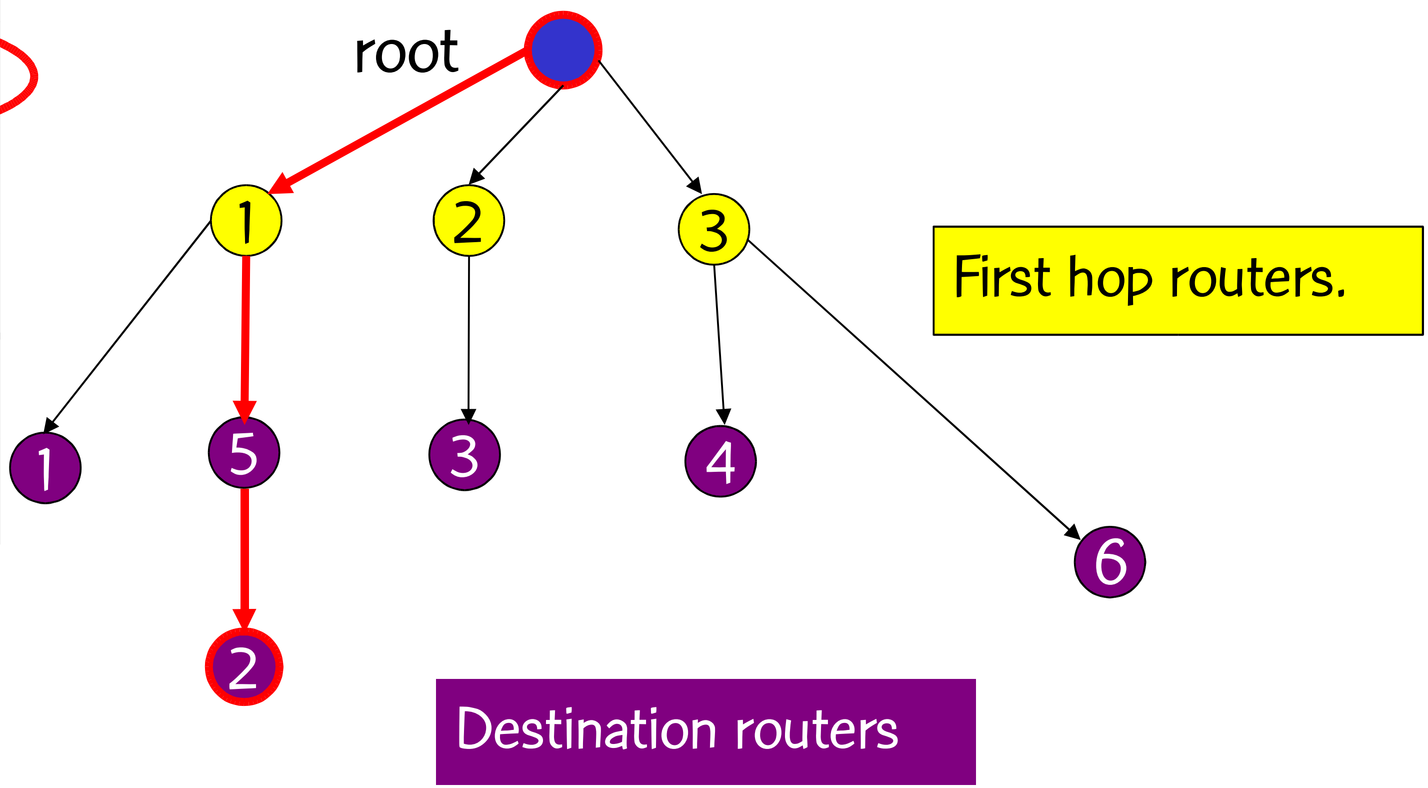


OSPF routing

Routing table is filled
with first hop routers
for each possible destination.

Routing table

D_1	R_1
D_2	R_1
D_3	R_2
D_4	R_3
D_5	R_1
D_6	R_3

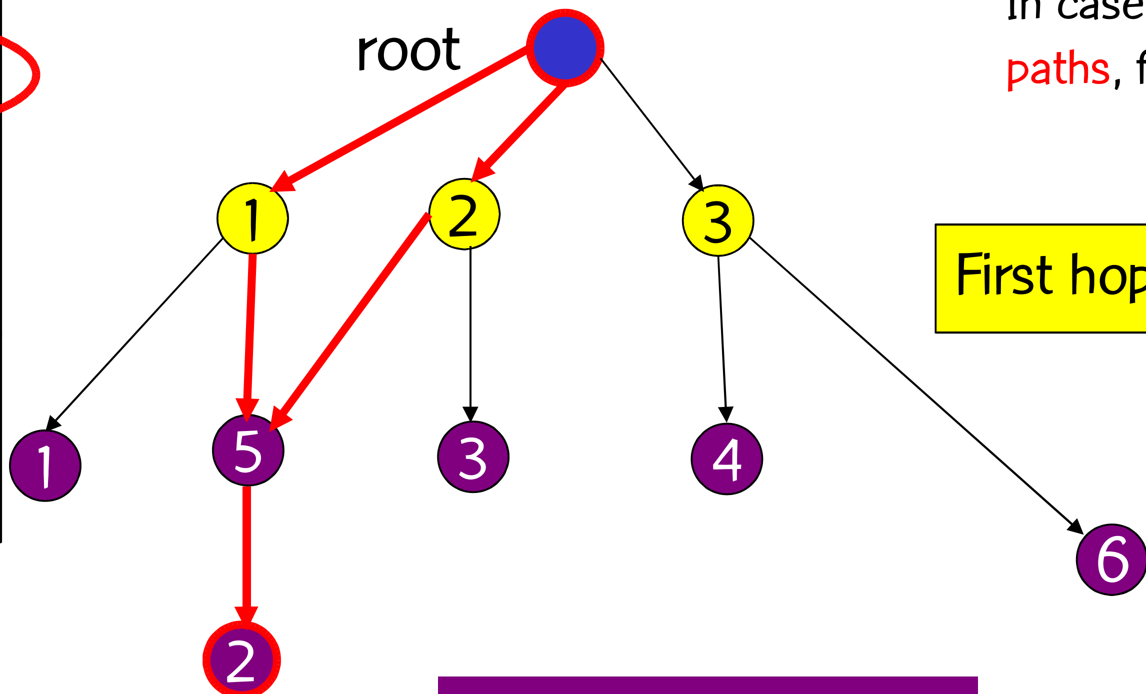


OSPF routing

Routing table

D_1	R_1
D_2	R_1, R_2
D_3	R_2
D_4	R_3
D_5	R_1
D_6	R_3

Routing table is filled with first hop routers for each possible destination. In case of multiple shortest paths, flow is evenly split.



First hop routers.

Destination routers

OSPF weight setting

- OSPF weights are assigned by network operator.
  - CISCO assigns, by default, a weight proportional to the inverse of the link bandwidth (Inv Cap).
  - If all weights are unit, the weight of a path is the number of hops in the path.
- We propose a hybrid genetic algorithm to find good OSPF weights.
  - Memetic algorithm
  - Genetic algorithm with optimized crossover

Minimization of congestion

- Consider the directed capacitated network $G = (N,A,c)$, where N are routers, A are links, and c_a is the capacity of link $a \in A$.
- We use the measure of Fortz & Thorup (2000) to compute congestion:

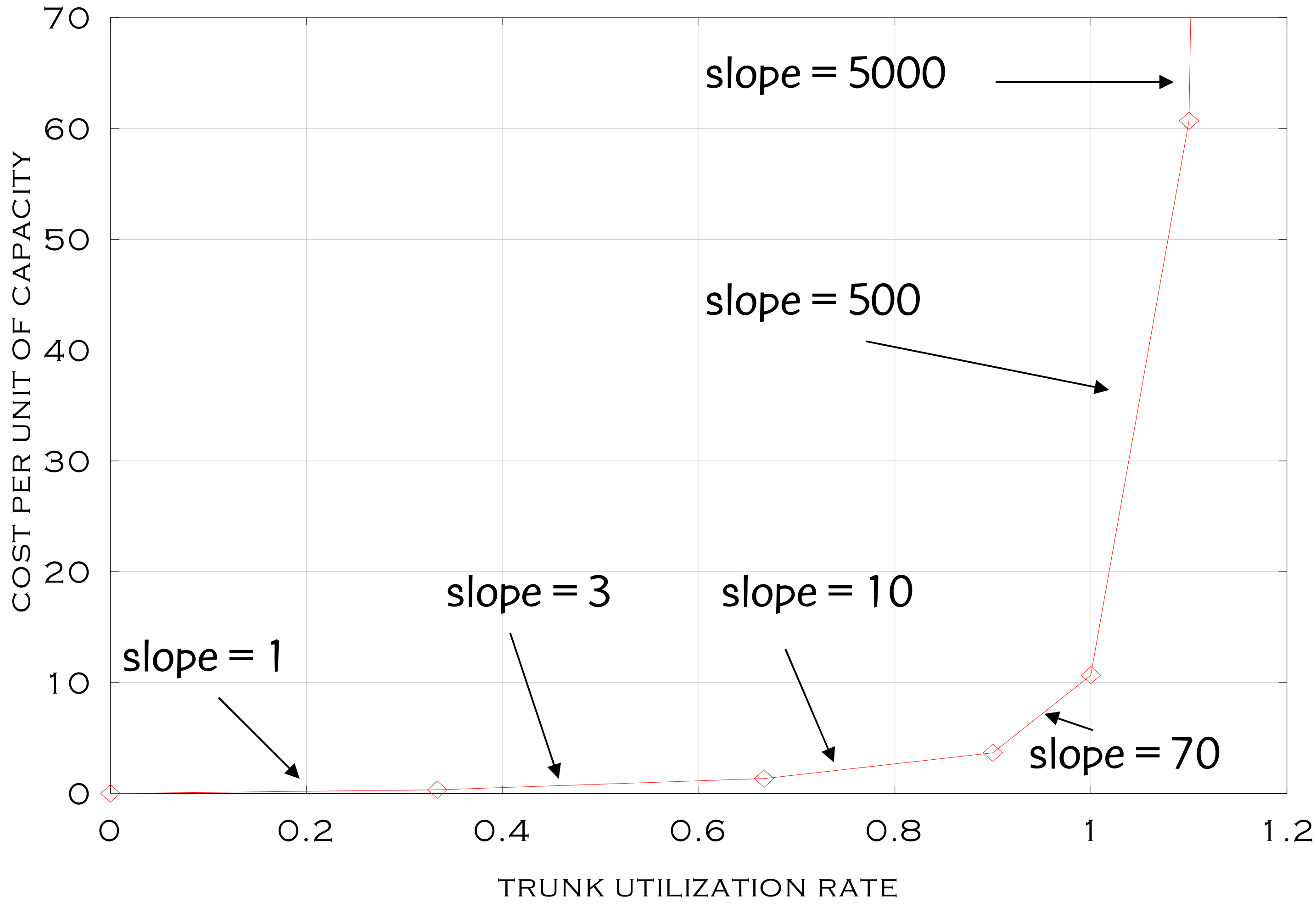
$$\Phi = \Phi_1(l_1) + \Phi_2(l_2) + \ldots + \Phi_{|A|}(l_{|A|})$$

where l_a is the load on link $a \in A$,

$\Phi_a(l_a)$ is piecewise linear and convex,

$\Phi_a(0) = 0$, for all $a \in A$.

Piecewise linear and convex $\Phi_a(l_a)$ link congestion measure

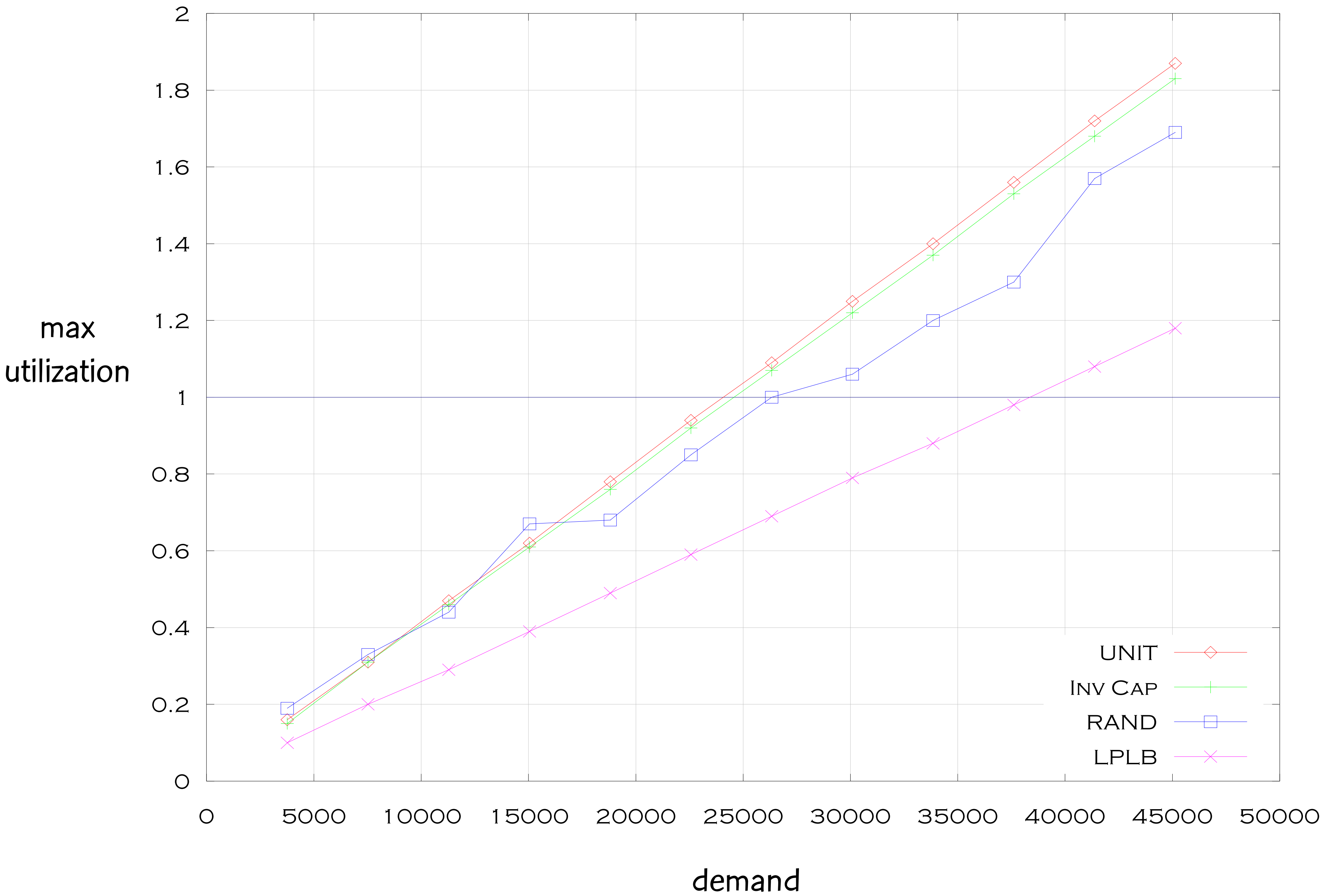


$(l_a \mid c_a)$

OSPF weight setting problem

- Given a directed network $G = (N, A)$ with link capacities $c_a \in A$ and demand matrix $D = (d_{s,t})$ specifying a demand to be sent from node s to node t :
  - Assign weights $w_a \in [1, w_{max}]$ to each link $a \in A$, such that the objective function Φ is minimized when demand is routed according to the OSPF protocol.

AT&T Worldnet backbone network (90 routers, 274 links)



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Genetic and hybrid genetic algorithms for OSPF weight setting problem

- Genetic
  - M. Ericsson, M.G.C. Resende, & P.M. Pardalos, " A genetic algorithm for the weight setting problem in OSPF routing, J. of Combinatorial Optimization, vol. 6, pp. 299-333, 2002.
- Hybrid genetic
  - L.S. Buriol, M.G.C. Resende, C.C. Ribeiro, & M. Thorup, "A hybrid genetic algorithm for the weight setting problem in OSPF/IS-IS routing," Networks, vol. 46, pp. 36-56, 2005.

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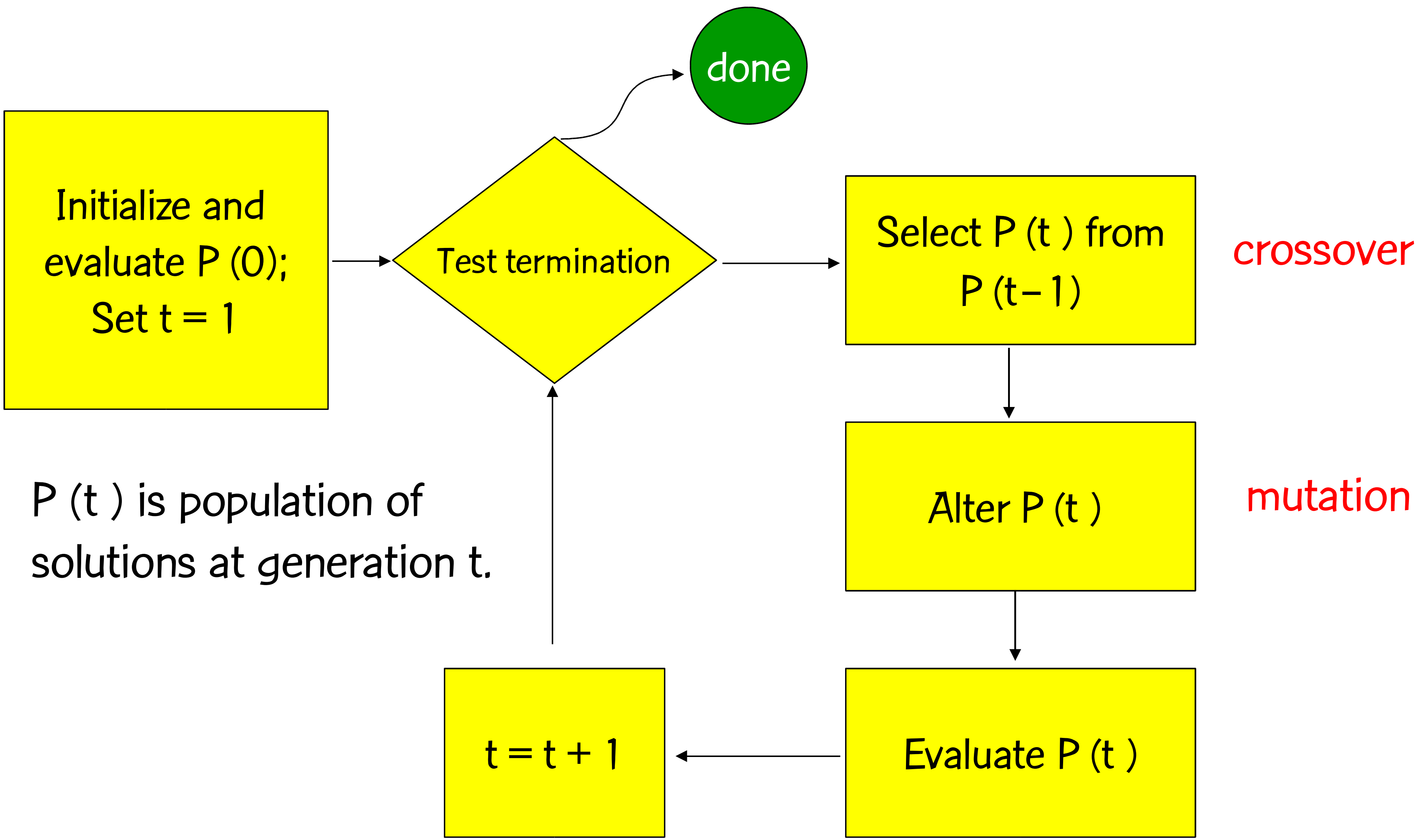
Genetic algorithms



P (t) is population of solutions at generation t.

Solution encoding

- A population consists of nPop = 50 integer weight arrays: $w = (w_1, w_2, \ldots, w_{|A|})$,

  where $w_a \in [1, w_{max} = 20]$

- All possible weight arrays correspond to feasible solutions.

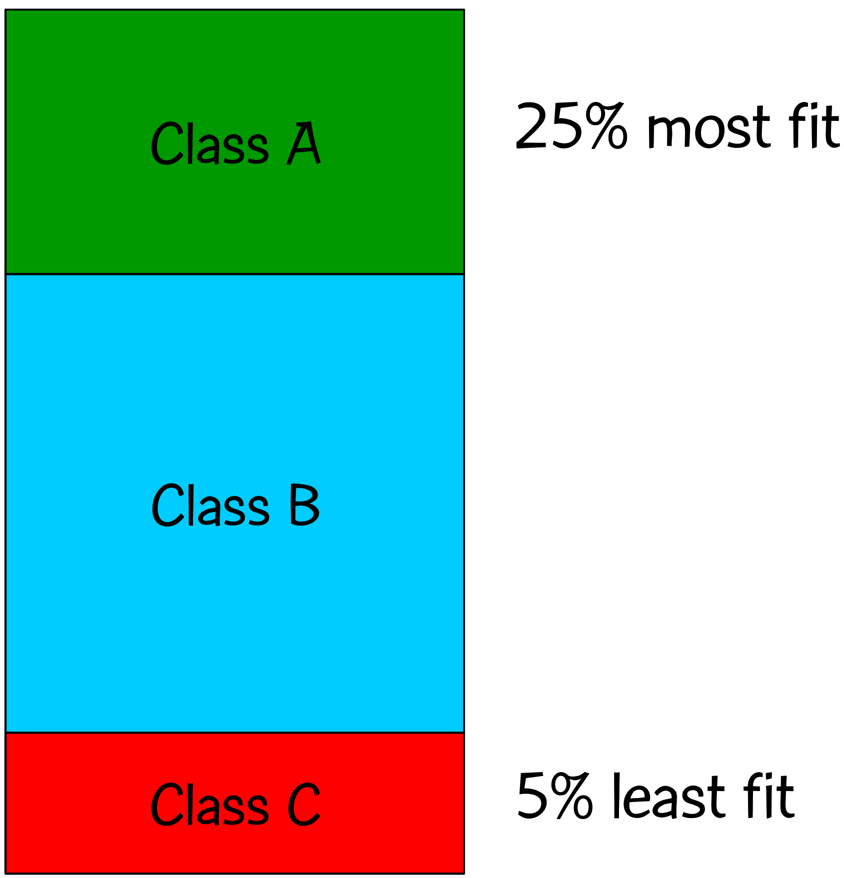
Initial population

- nPop solutions, with each weight randomly generated, uniformly in the interval [1, w_{max} /3].

Solution evaluation

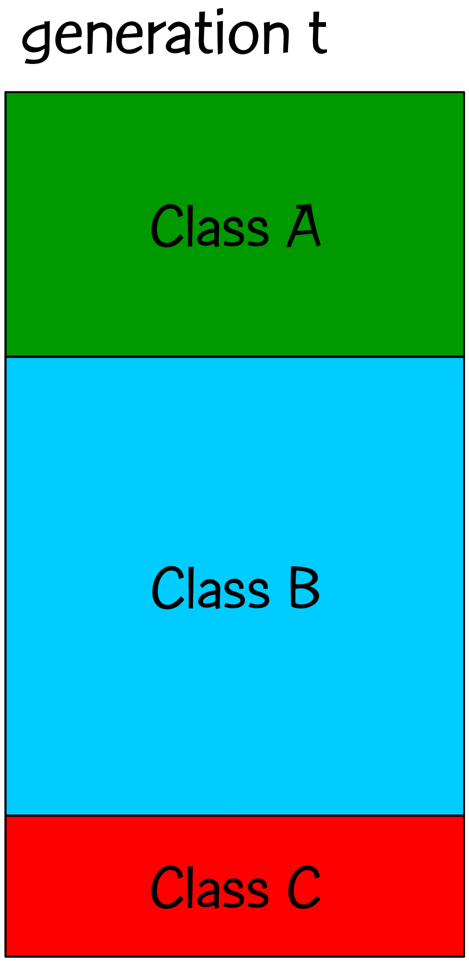
- For each demand pair (s,t), route using OSPF, computing demand pair loads $l_a^{s,t}$ on each link $a \in A$.
- Add up demand pair loads on each link $a \in A$, yielding total load l_a on link.
- Compute link congestion cost $\Phi_a(l_a)$ for each link $a \in A$.
- Add up costs: $\Phi = \Phi_1(l_1) + \Phi_2(l_2) + \ldots + \Phi_{|A|}(l_{|A|})$

Population partitioning

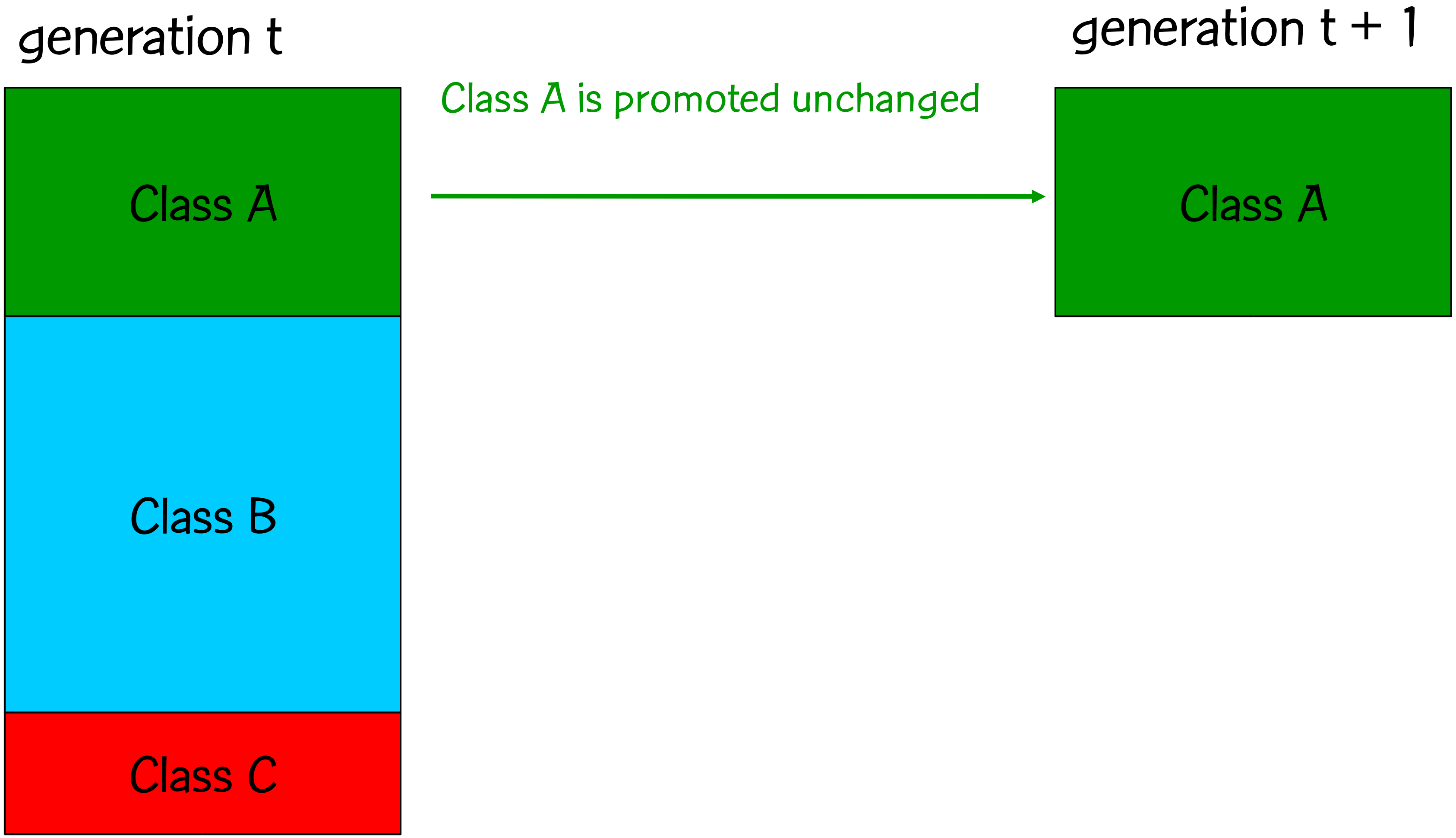


Population is sorted according to solution value Φ and solutions are classified into three categories.

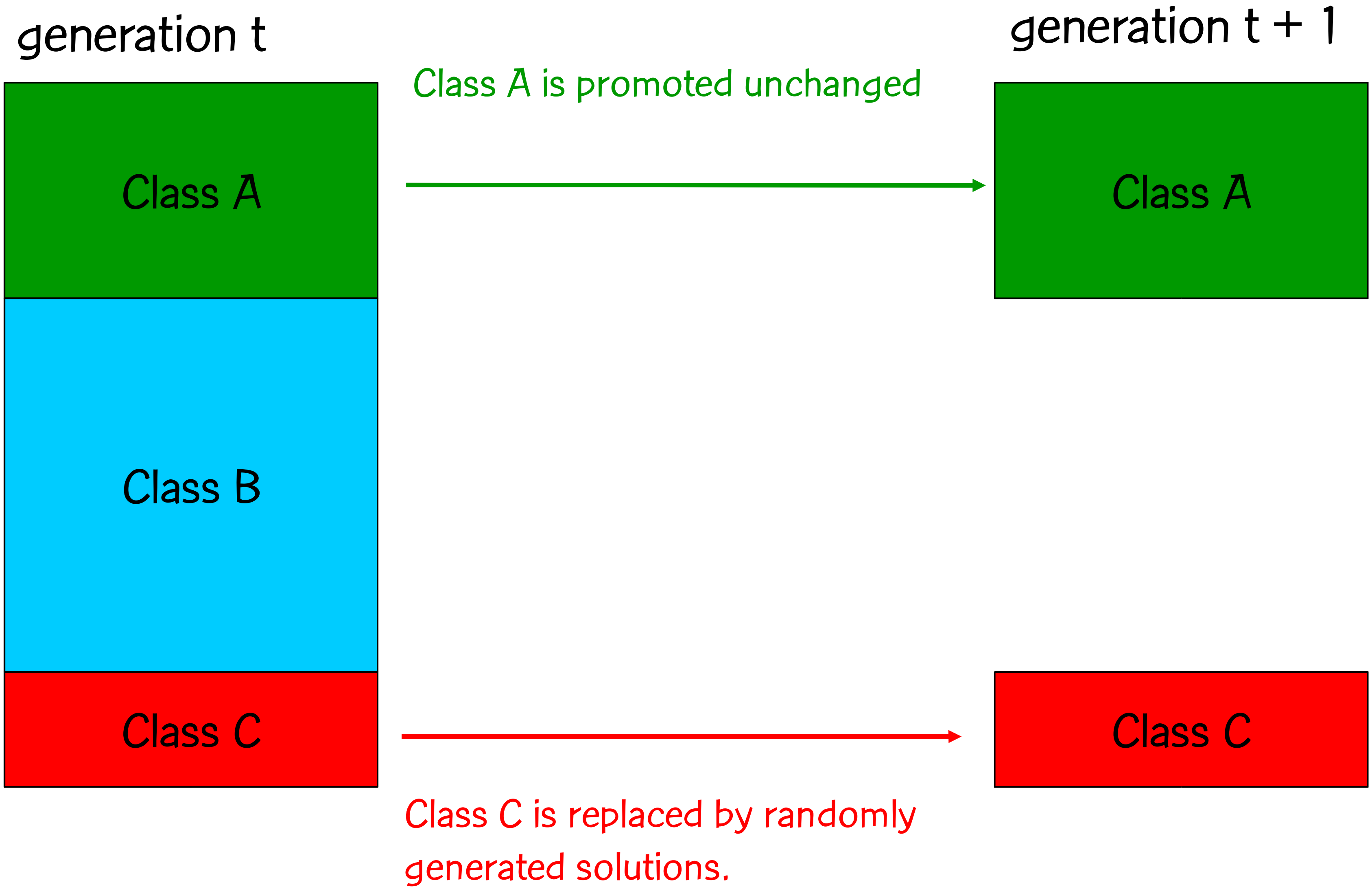
Population dynamics



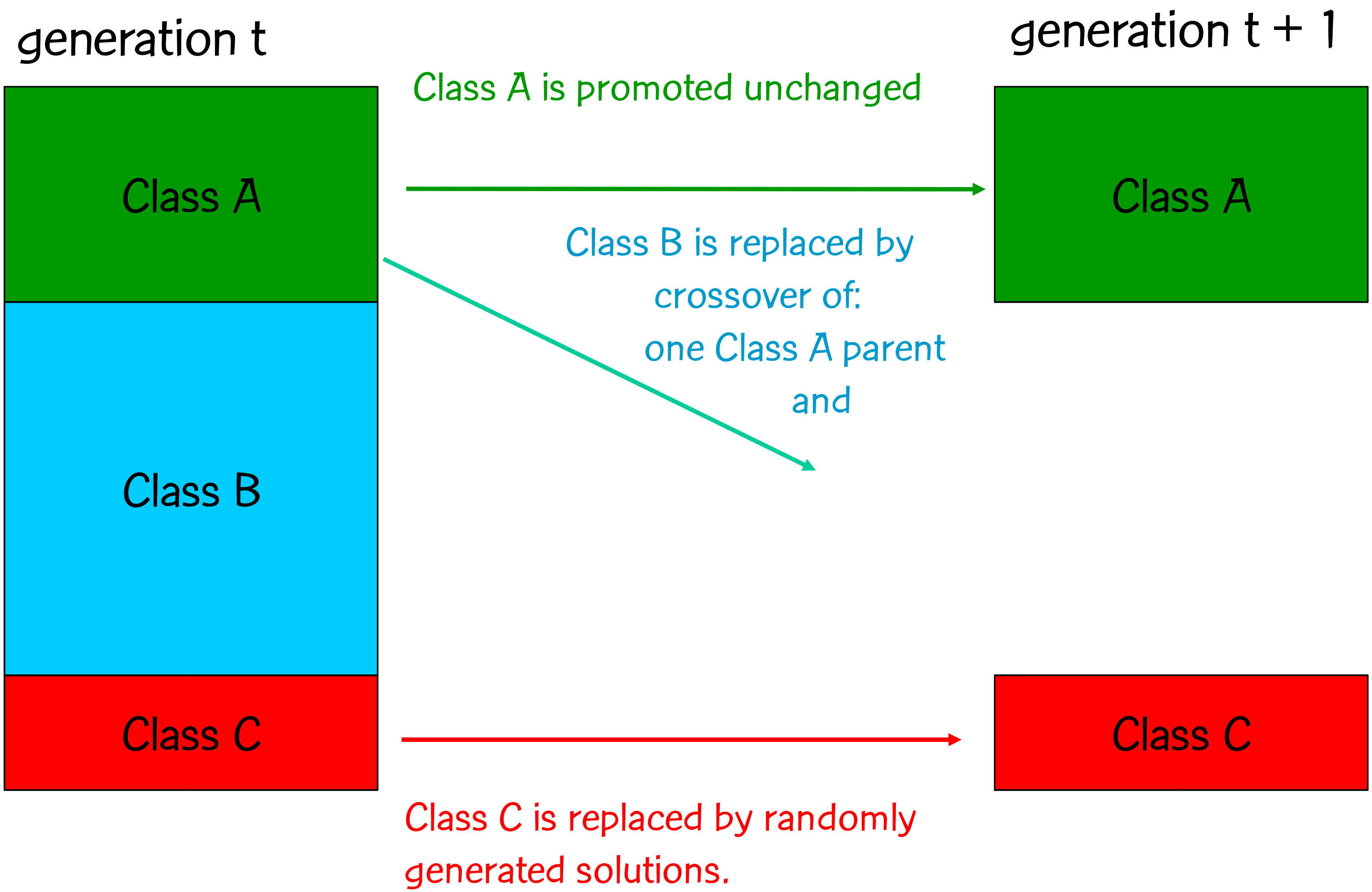
Population dynamics



Population dynamics



Population dynamics



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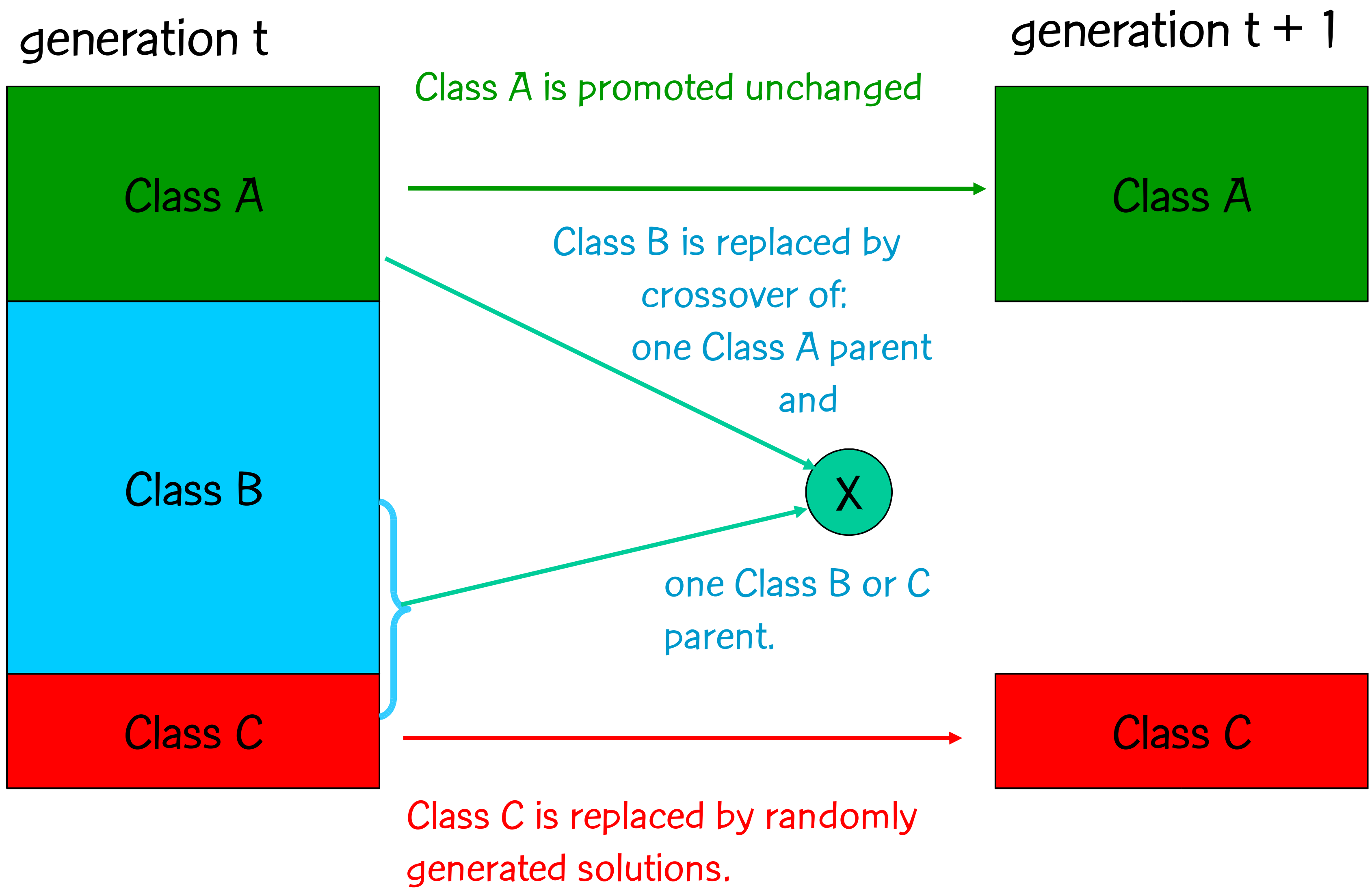
Population dynamics



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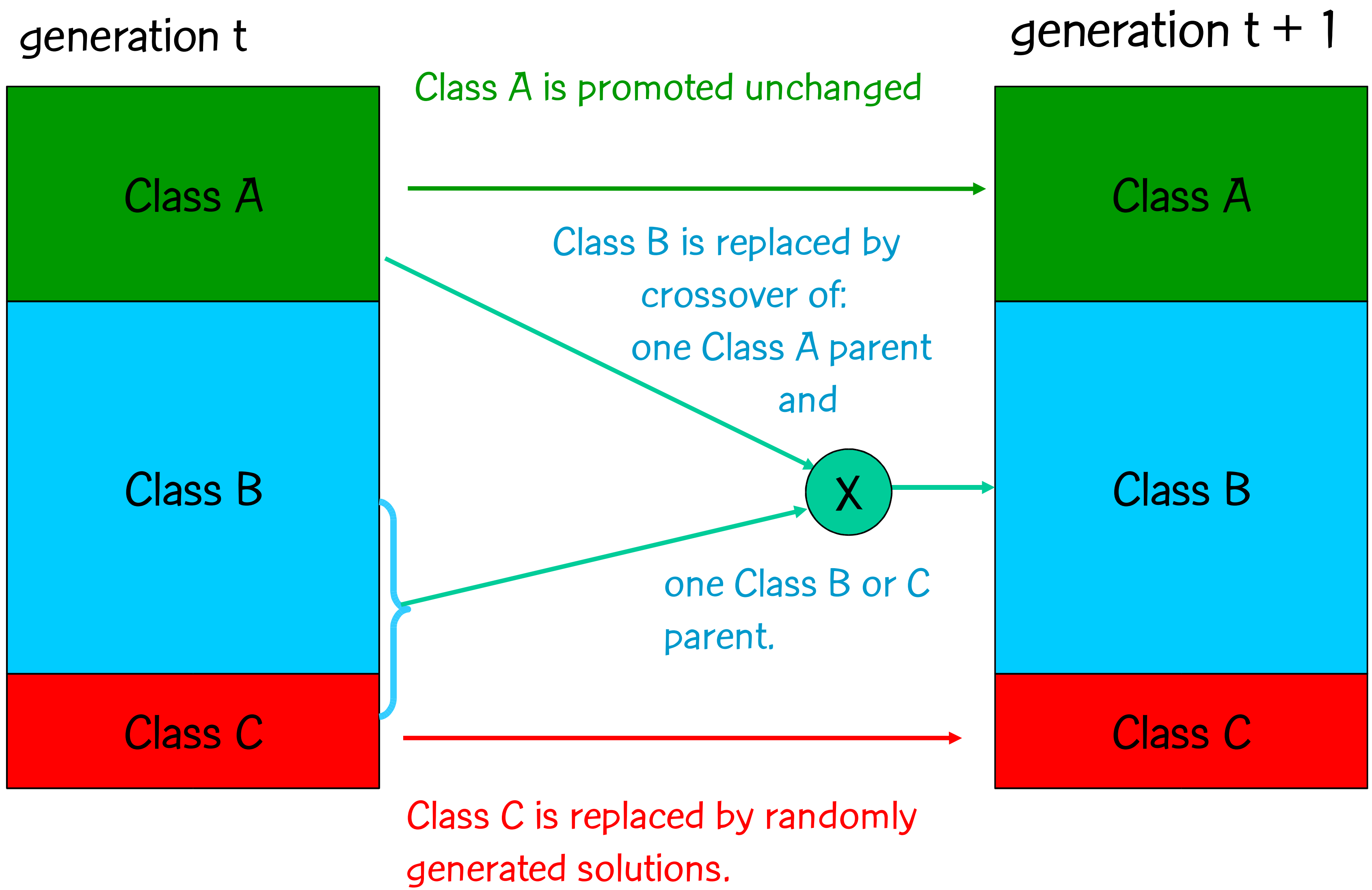
Population dynamics



Parent selection

- Parents are chosen at random:
  - one parent from Class A (elite).
  - one parent from Class B or C (non-elite).
- Reselection is allowed, i.e. parents can breed more than once per generation.
- Better individuals are more likely to reproduce.

Crossover with random keys

Bean (1994)

Crossover combines elite parent p_1 with non-elite parent p_2 to produce child c :

With small probability child has single gene mutation.

```
for all genes i = 1,2,...,|A| do
    if rrandom[0,1] < 0.01 then
        c[i] = irandom[1, w_max]
    else if rrandom[0,1] < 0.7 then
        c[i] = p_1[i]
    else c[i] = p_2[i]
end
```

Child is more likely to inherit gene of elite parent.

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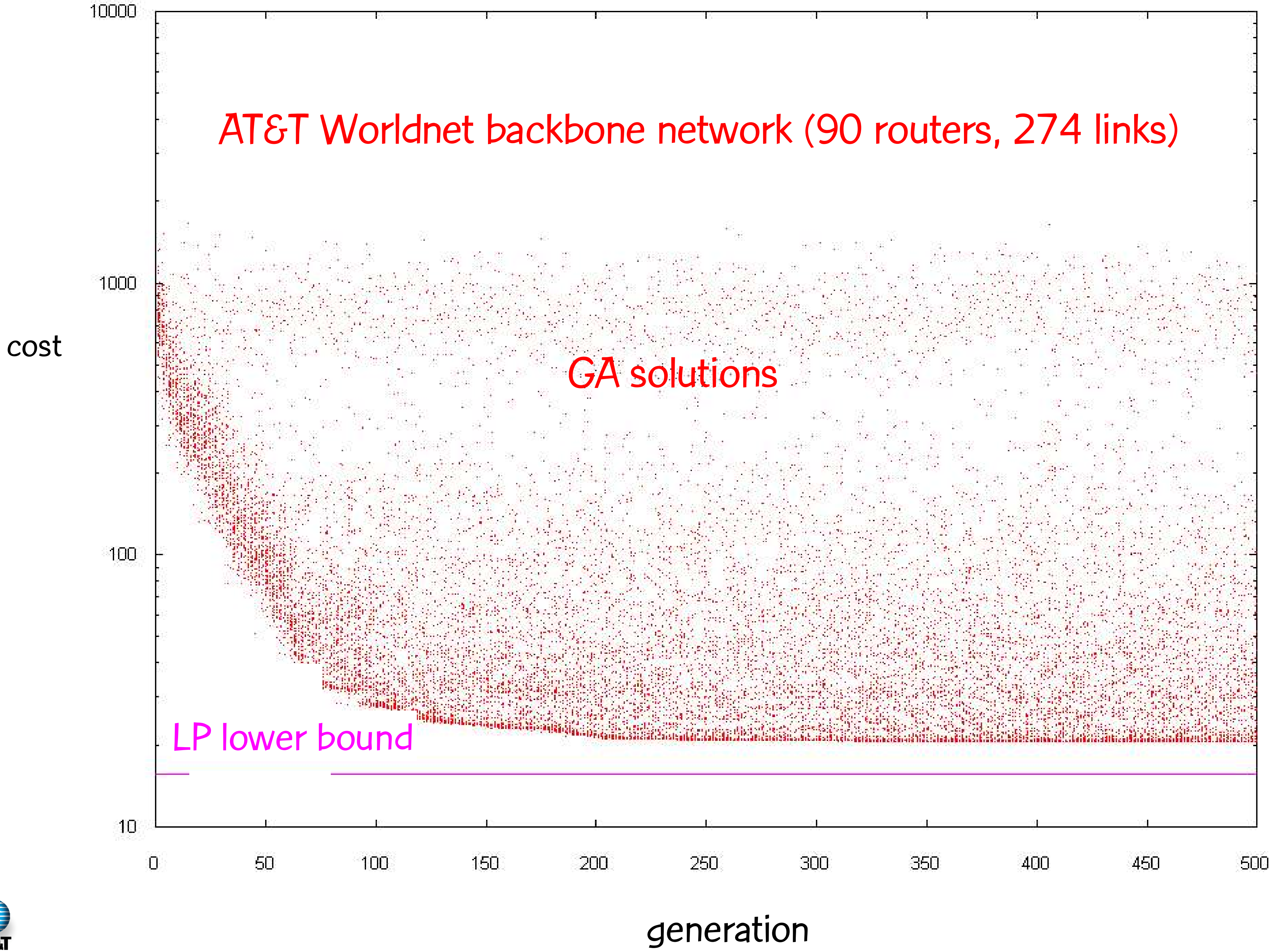
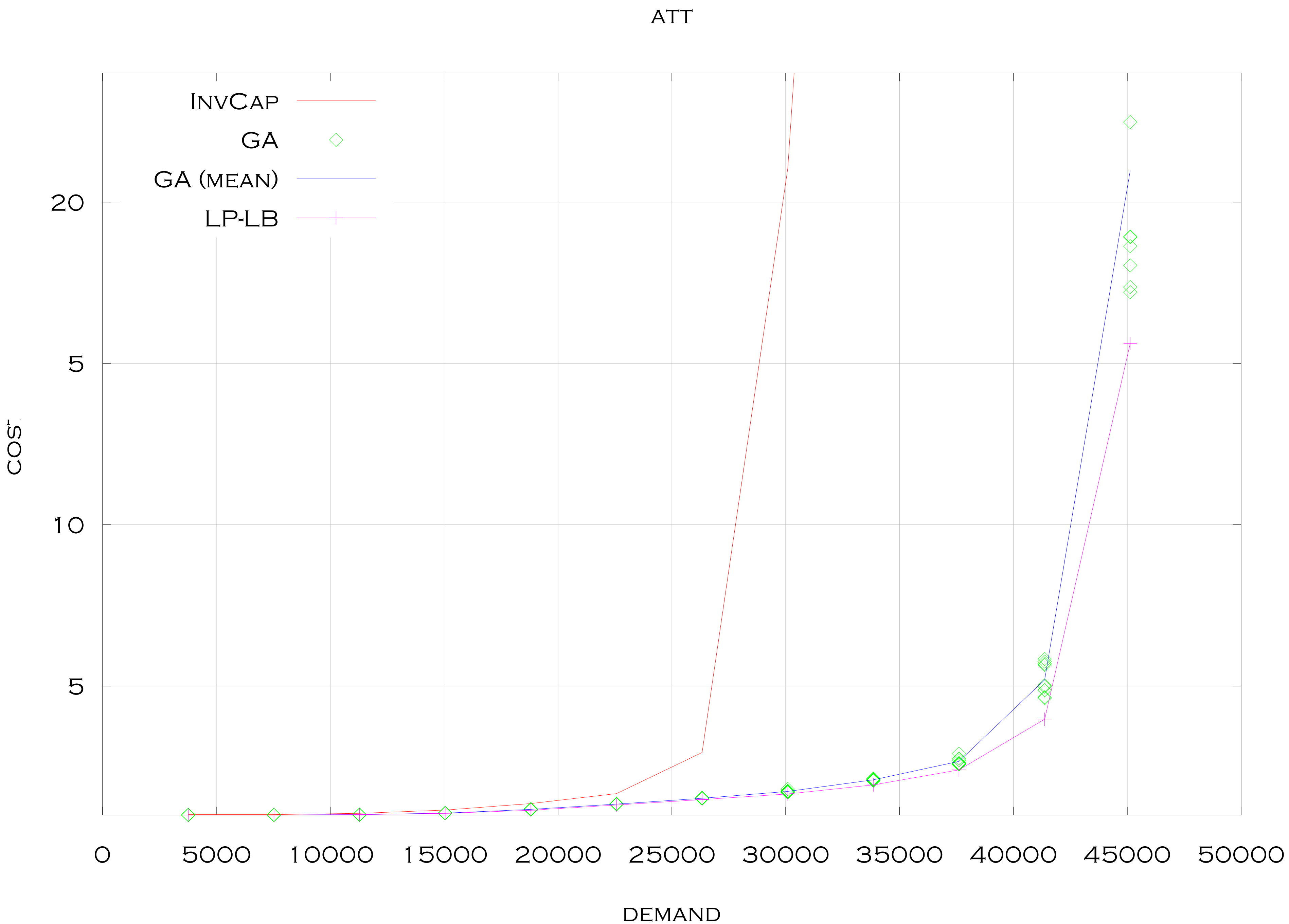
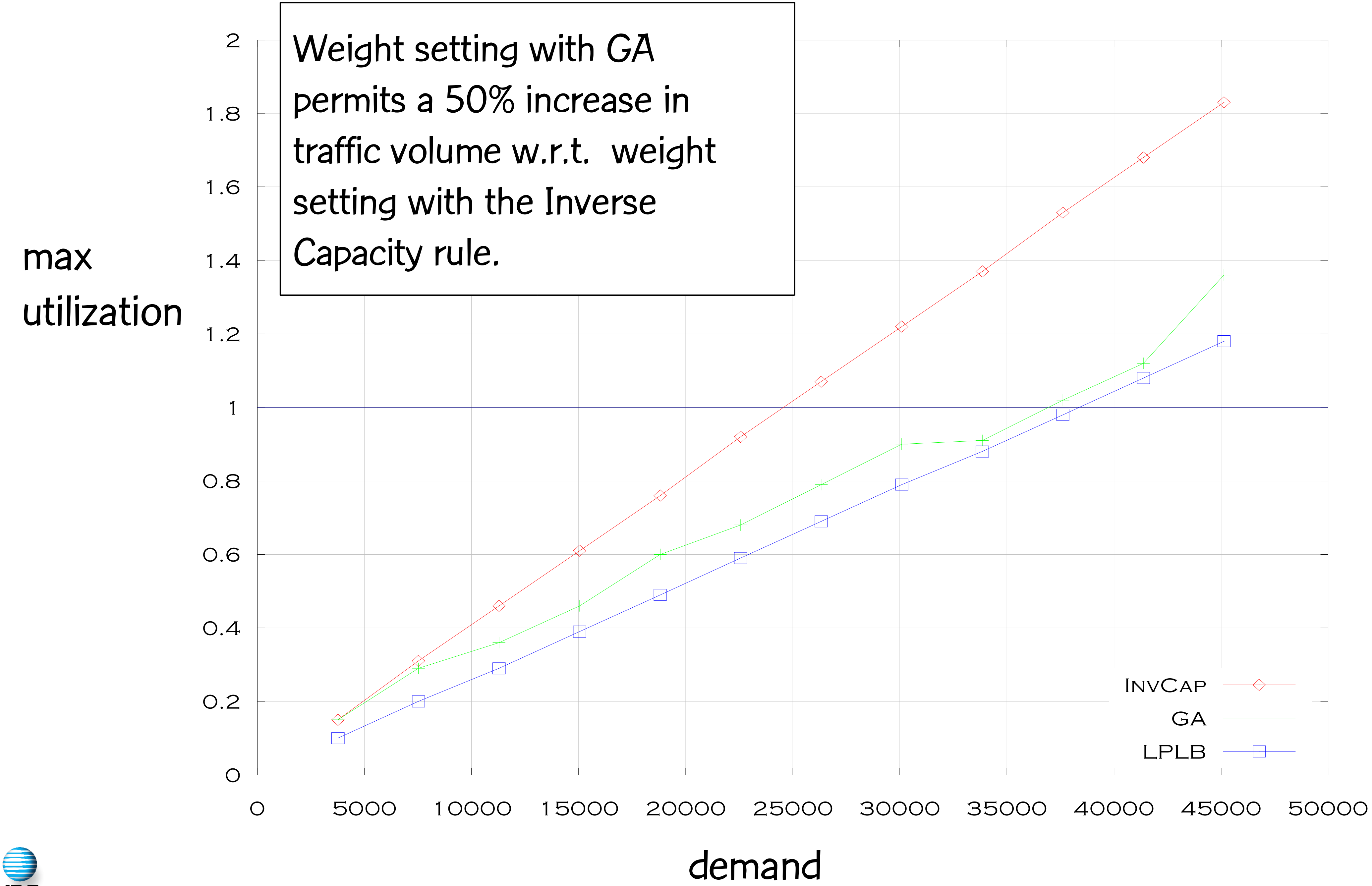

AT&T Worldnet backbone network (90 routers, 274 links)
GA solutions
LP lower bound
cost
generation
10000
1000
100
10
0
50
100
150
200
250
300
350
400
450
500

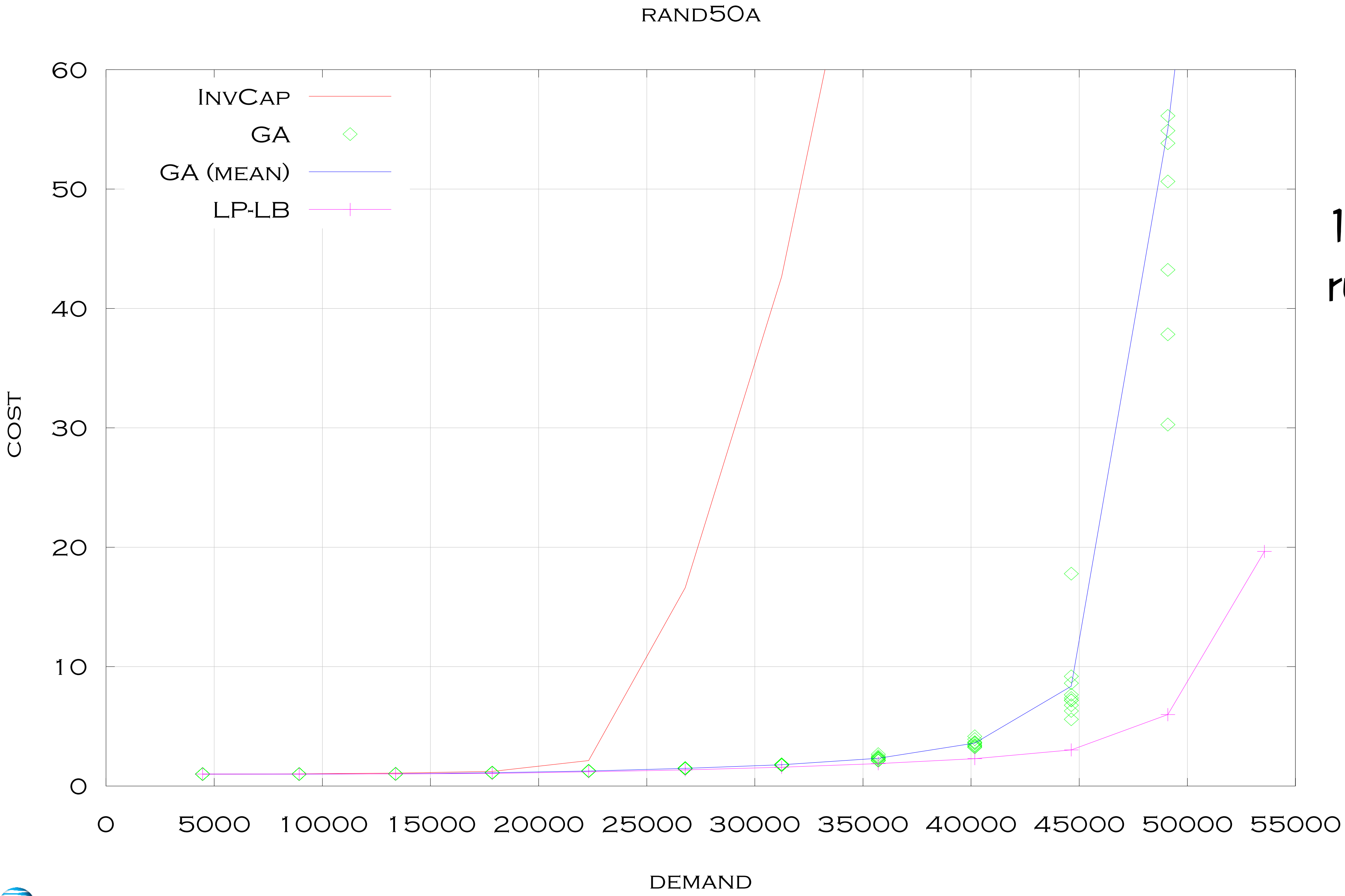
AT&T Worldnet backbone network (90 routers, 274 links)



AT&T Worldnet backbone network (90 routers, 274 links)

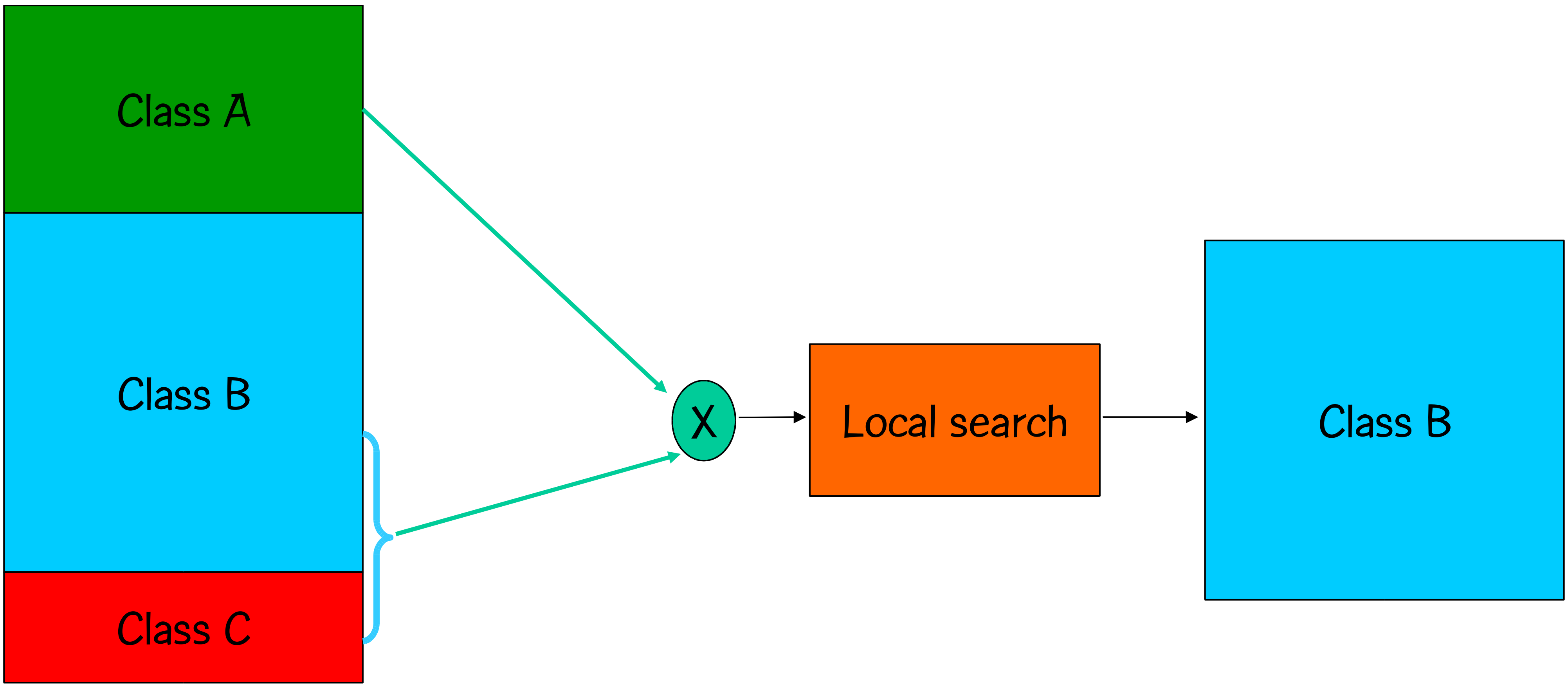


Rand50a: random graph with 50 nodes and 245 arcs.



1 hour run

Optimized crossover = crossover + local search



Fast local search

- Let A^* be the set of five arcs $a \in A$ having largest Φ_a values.
- Scan arcs $a \in A^*$ from largest to smallest Φ_a:
  - Increase arc weight, one unit at a time, in the range $[w_a, w_a + \lceil (w_{max} - w_a)/4 \rceil]$
  - If total cost Φ is reduced, restart local search.

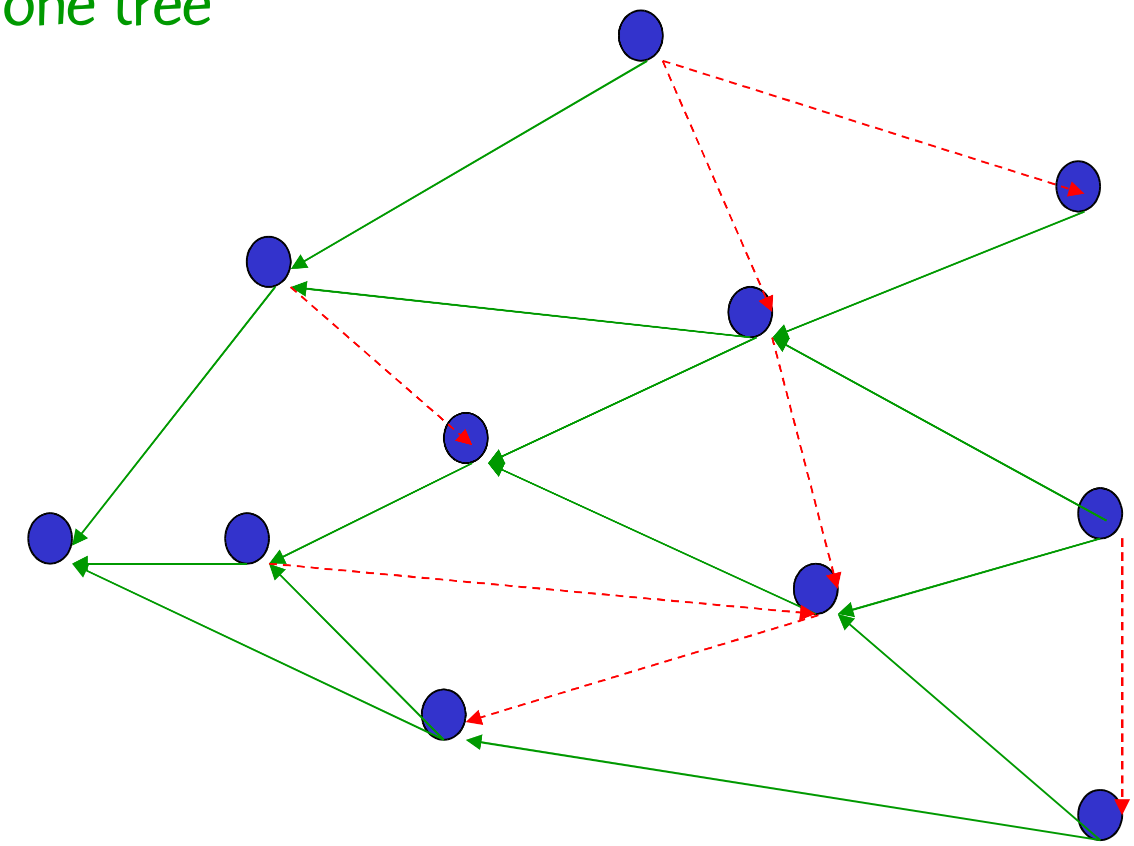
Dynamic shortest path

- In local search, when arc weight increases, shortest path trees:
  - may change completely (rarely do)
  - may remain unchanged (e.g. arc not in a tree)
  - may change partially
    - Few trees change
    - Small portion of tree changes

} Does not make sense to recompute trees from scratch.

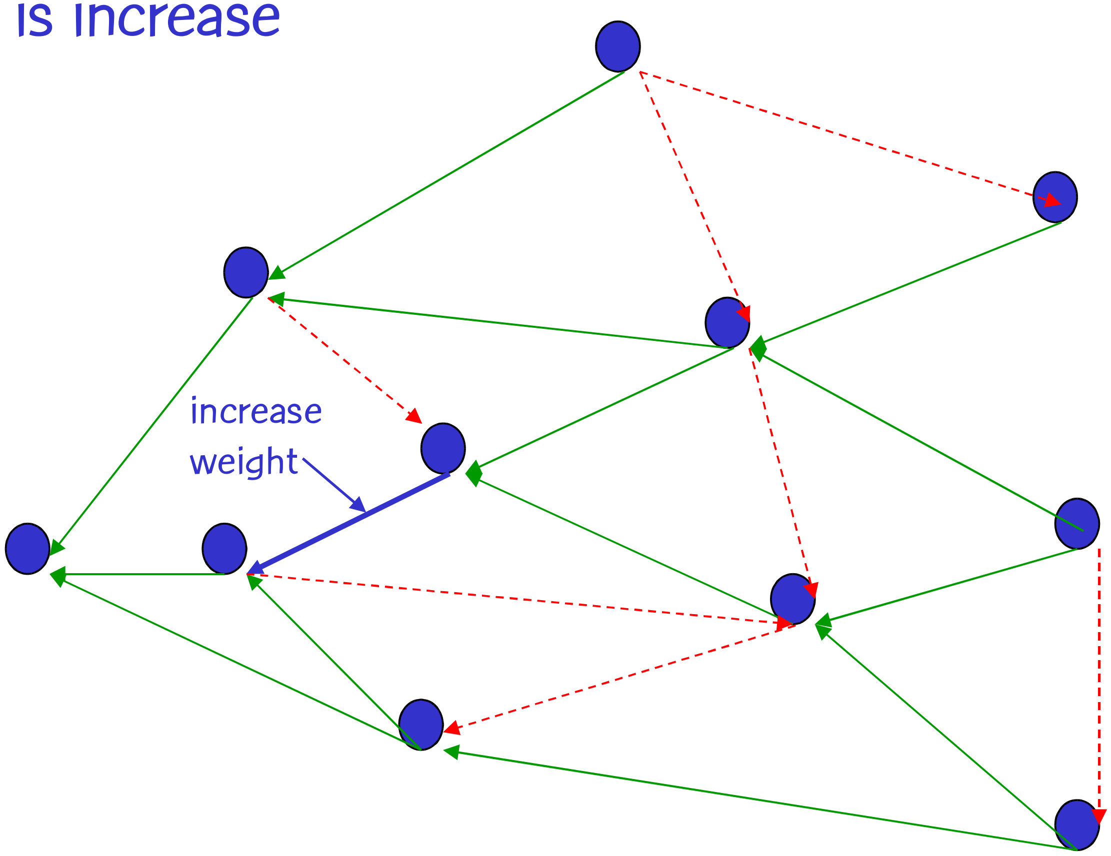
Dynamic shortest path

Consider one tree at a time.



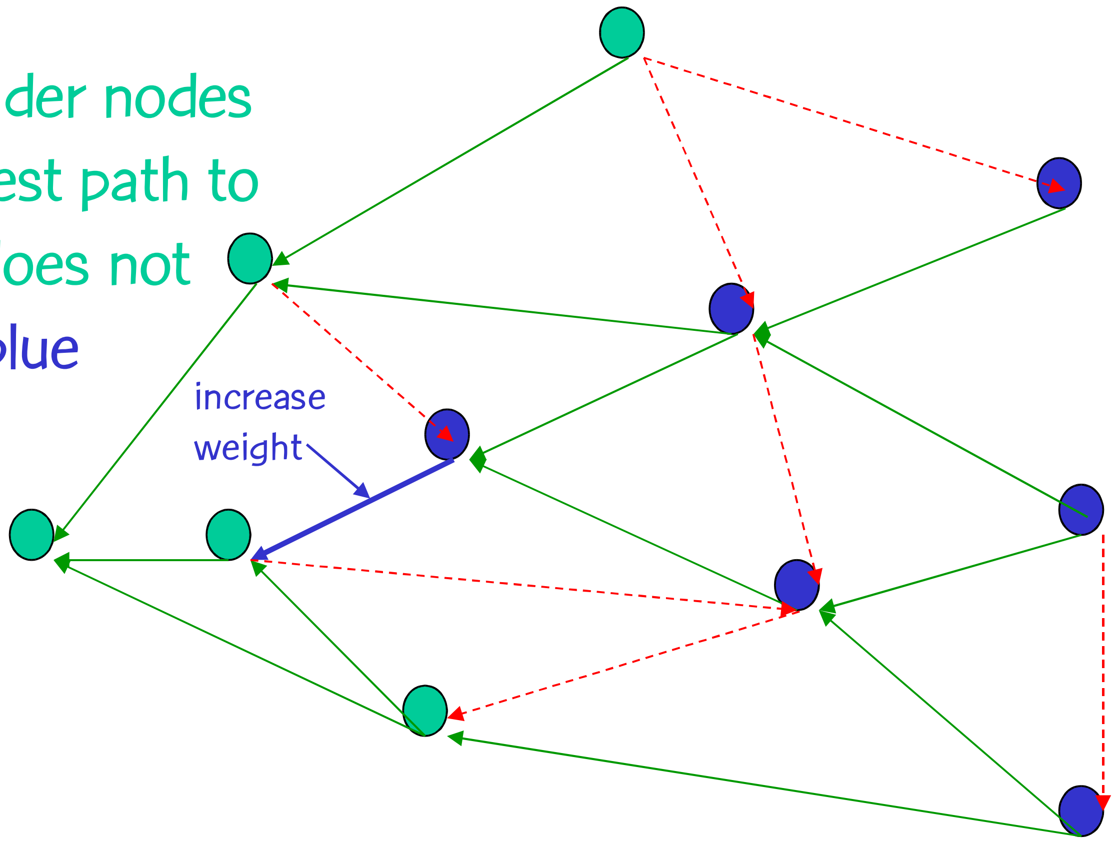
Dynamic shortest path

Arc weight is increase by 1.

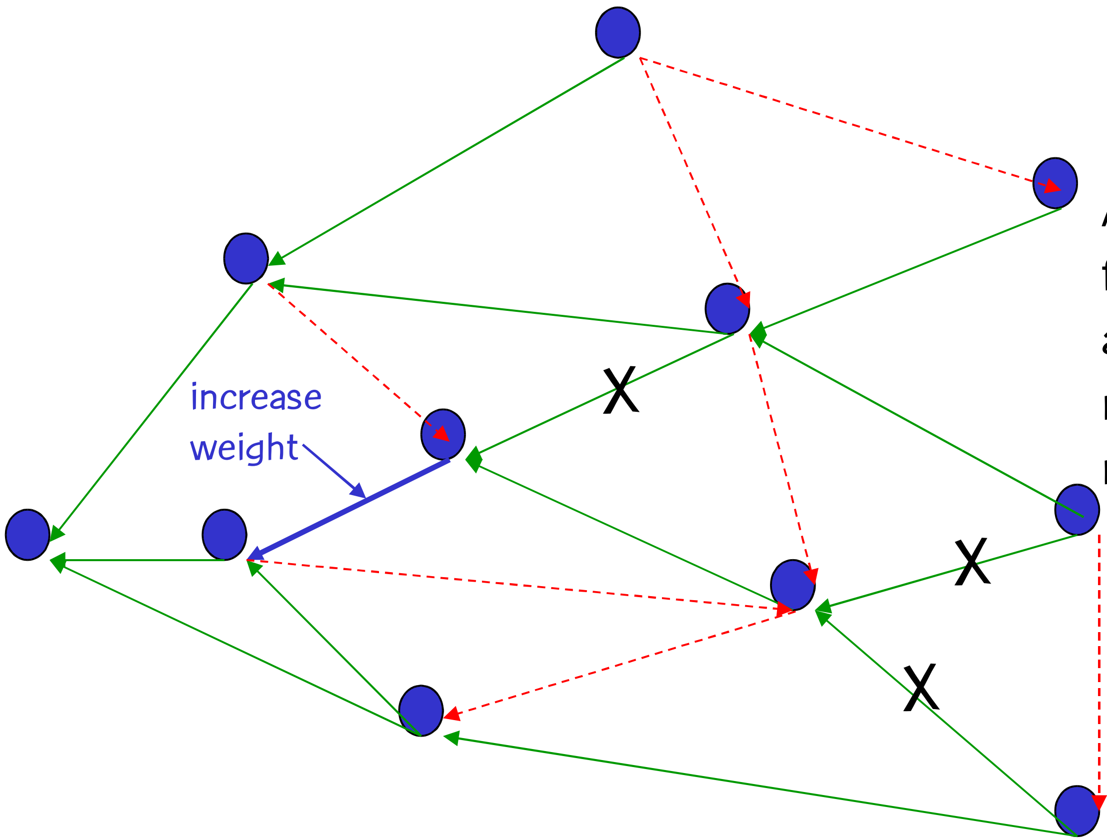


Dynamic shortest path

Do not consider nodes whose shortest path to destination does not go through blue arc.

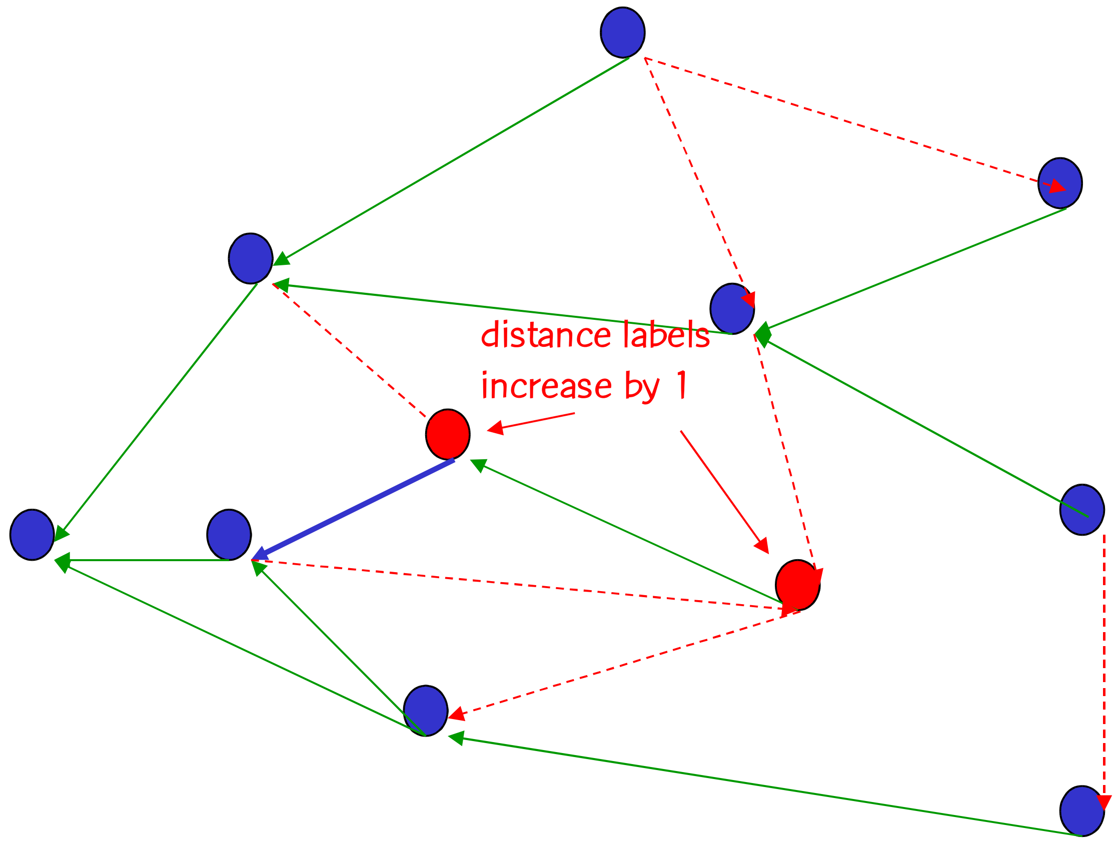


Dynamic shortest path



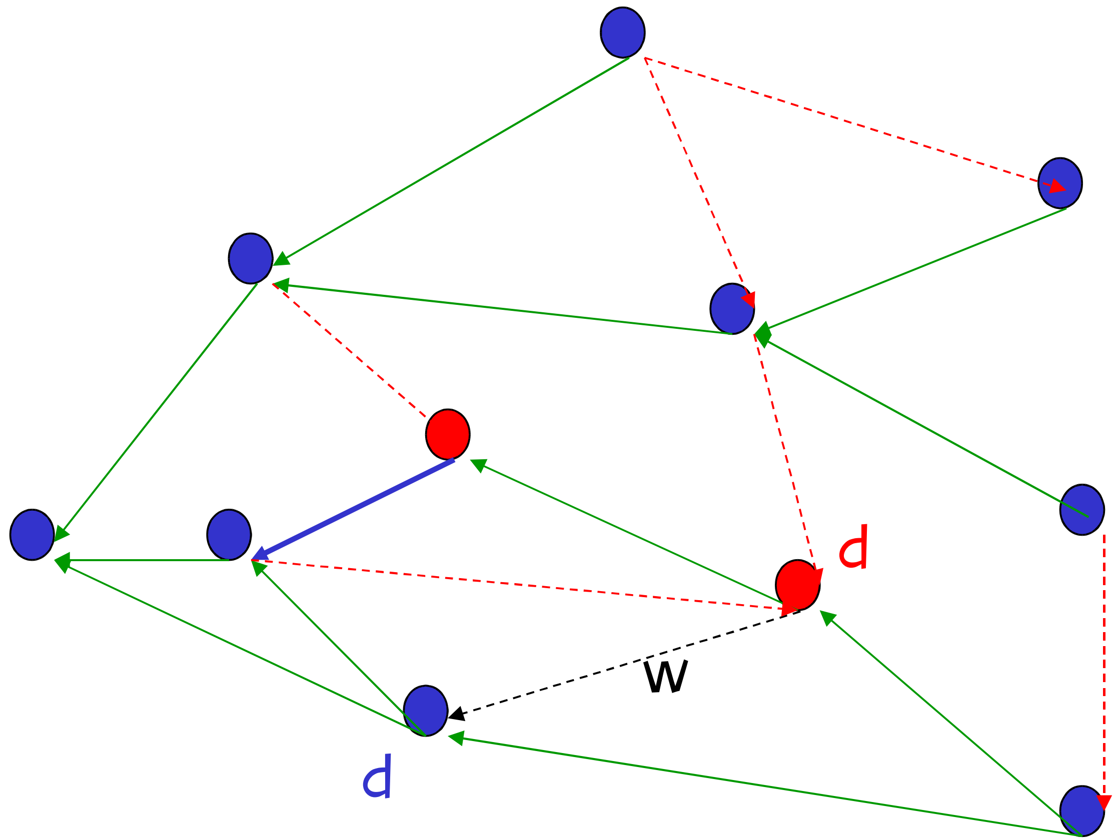
Arc (u,v) is removed from tree since alternative paths from node u to the destination node exist.

Dynamic shortest path

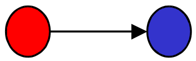


Shortest paths from red nodes must traverse blue arc.

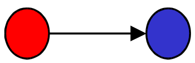
Dynamic shortest path



Test all arcs of type

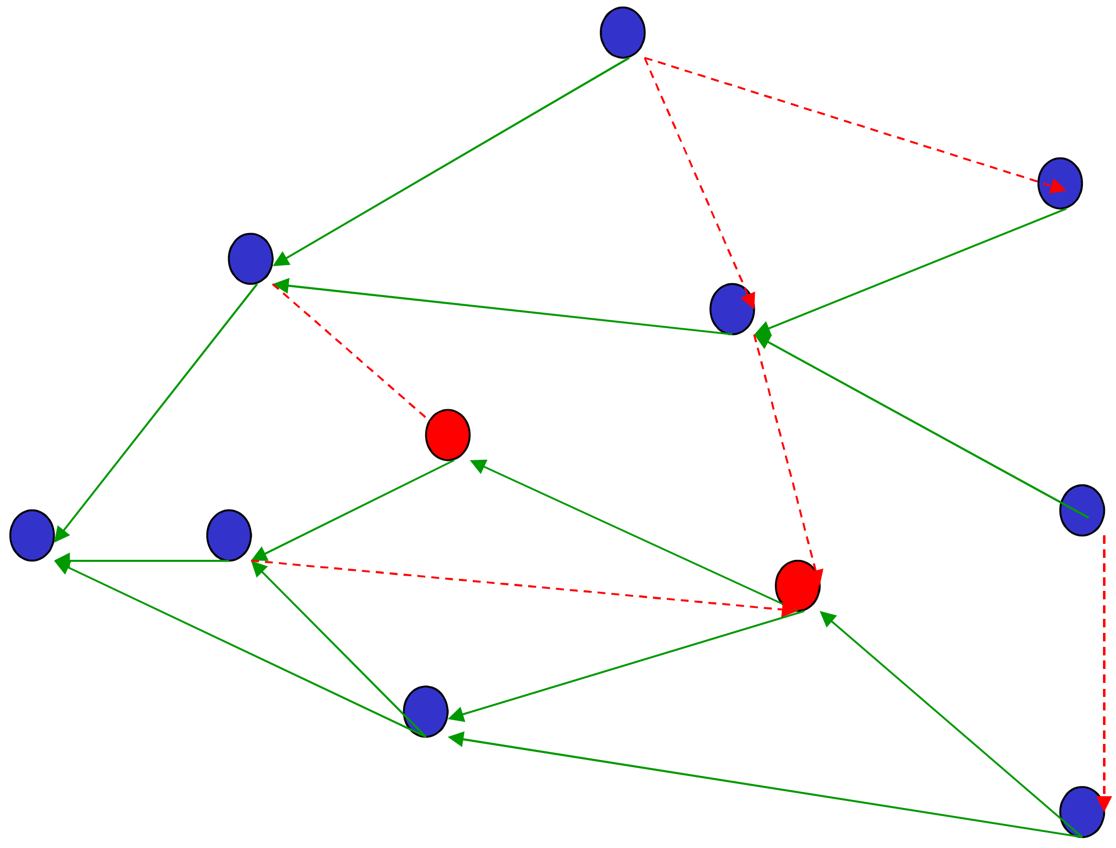


If d − d = w , then



enters tree.

Dynamic shortest path



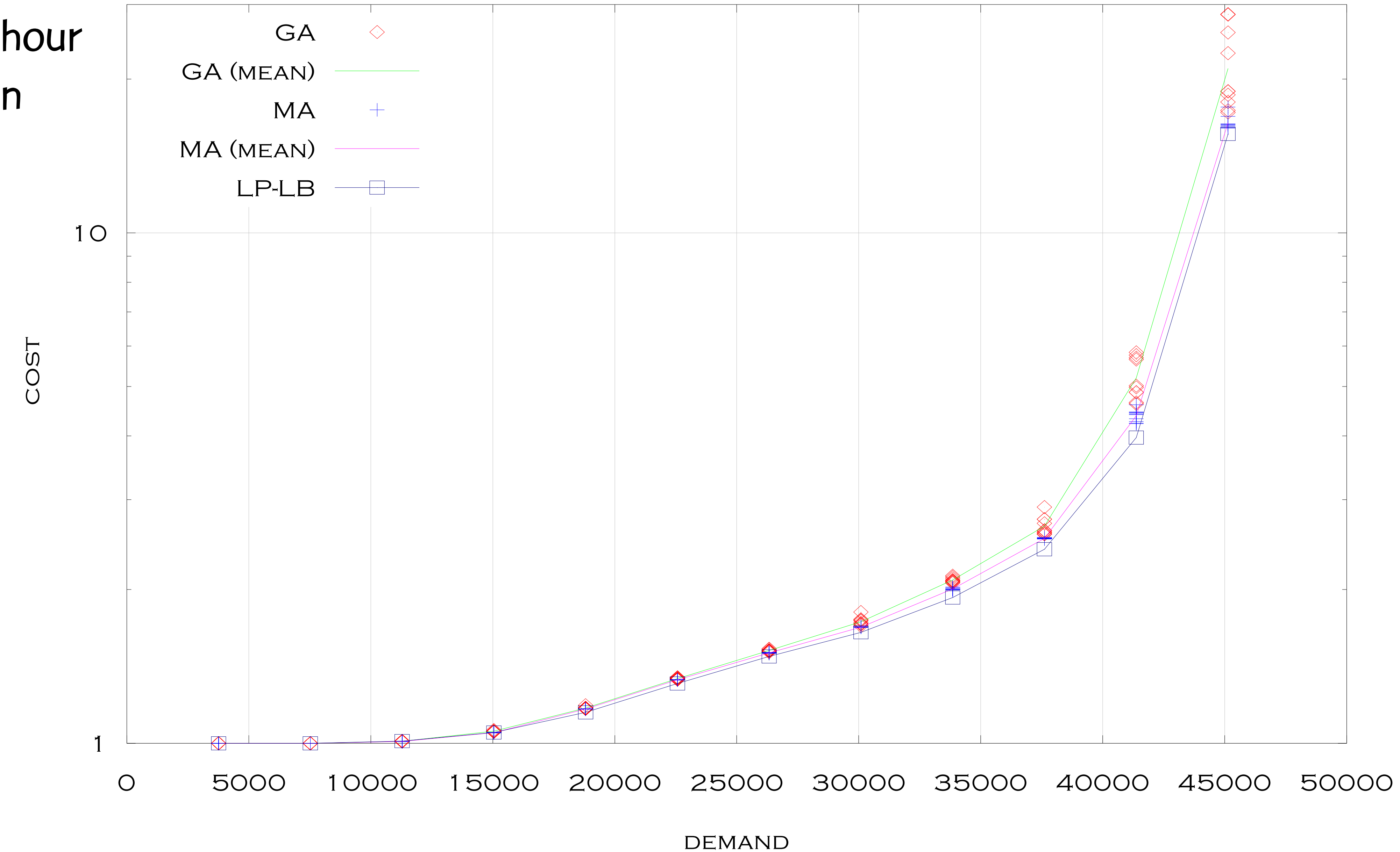
Dynamic shortest path

L.S. Buriol, M.G.C. Resende, & M. Thorup, "Speeding up dynamic shortest path algorithms," AT&T Labs Research Report, 2003.

- Ramalingam & Reps (1996) allow arbitrary arc weight change.
- We specialized the Ramalingam & Reps algorithm for unit arc weight change.
  - Avoid use of heaps
  - Achieve a factor of 2~5 speedup w.r.t. Ramalingam & Reps on these test problems

AT&T Worldnet backbone network (90 routers, 274 links)

1 hour run



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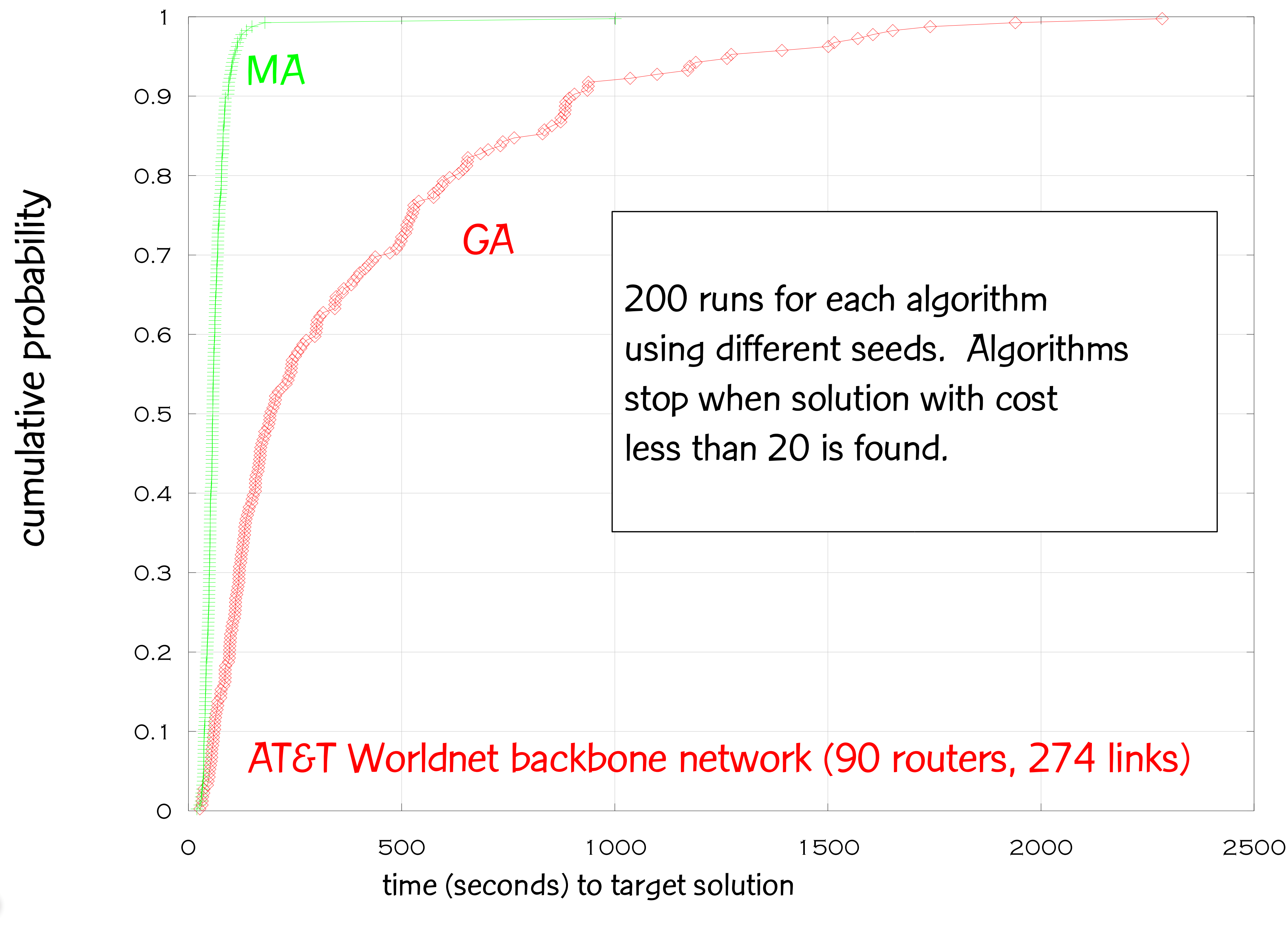
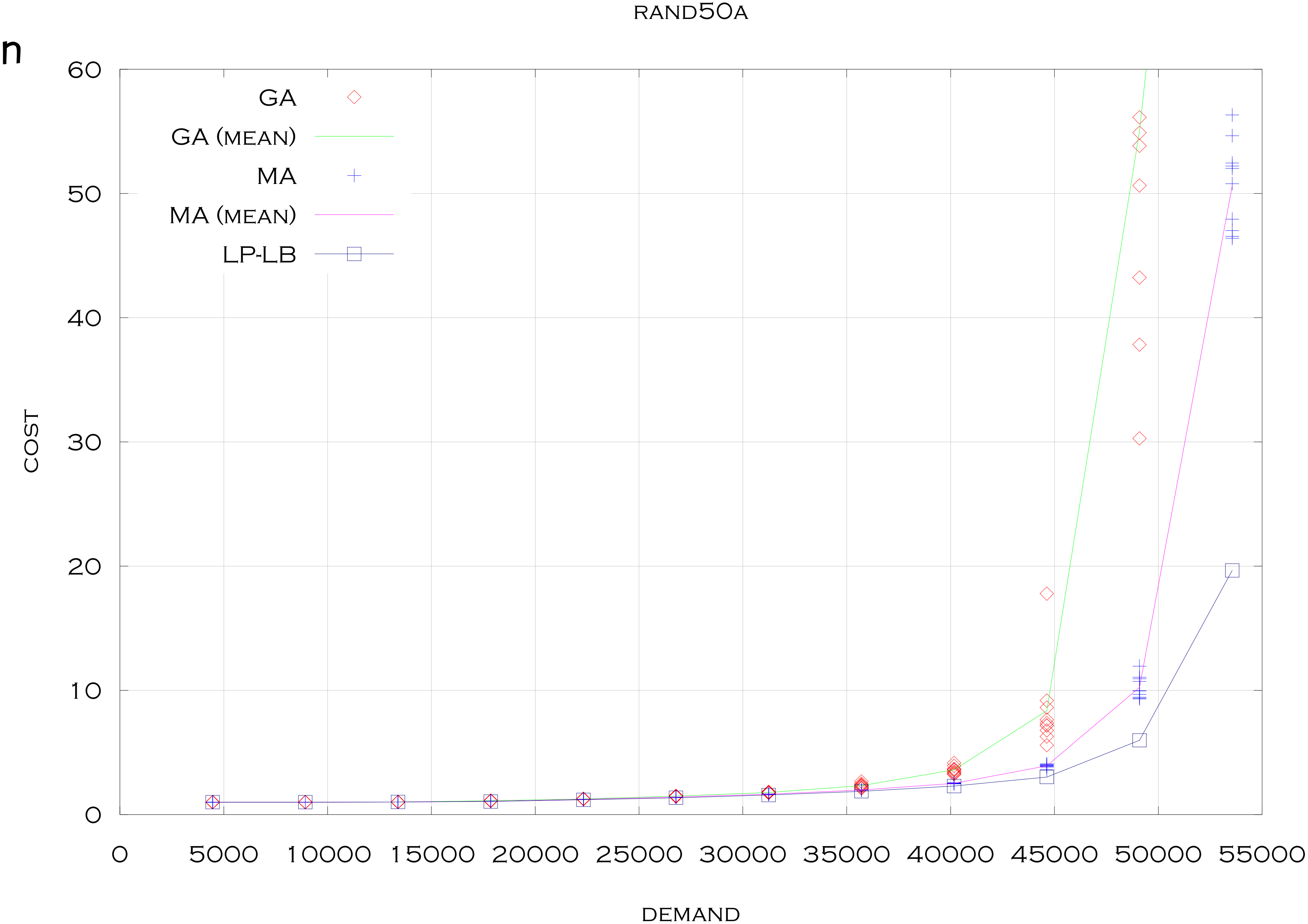

cumulative probability
time (seconds) to target solution
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
500
1000
1500
2000
2500
MA
GA
200 runs for each algorithm using different seeds. Algorithms stop when solution with cost less than 20 is found.
AT&T Worldnet backbone network (90 routers, 274 links)
AT&T

Rand50a: random graph with 50 nodes and 245 arcs.

1 hour run



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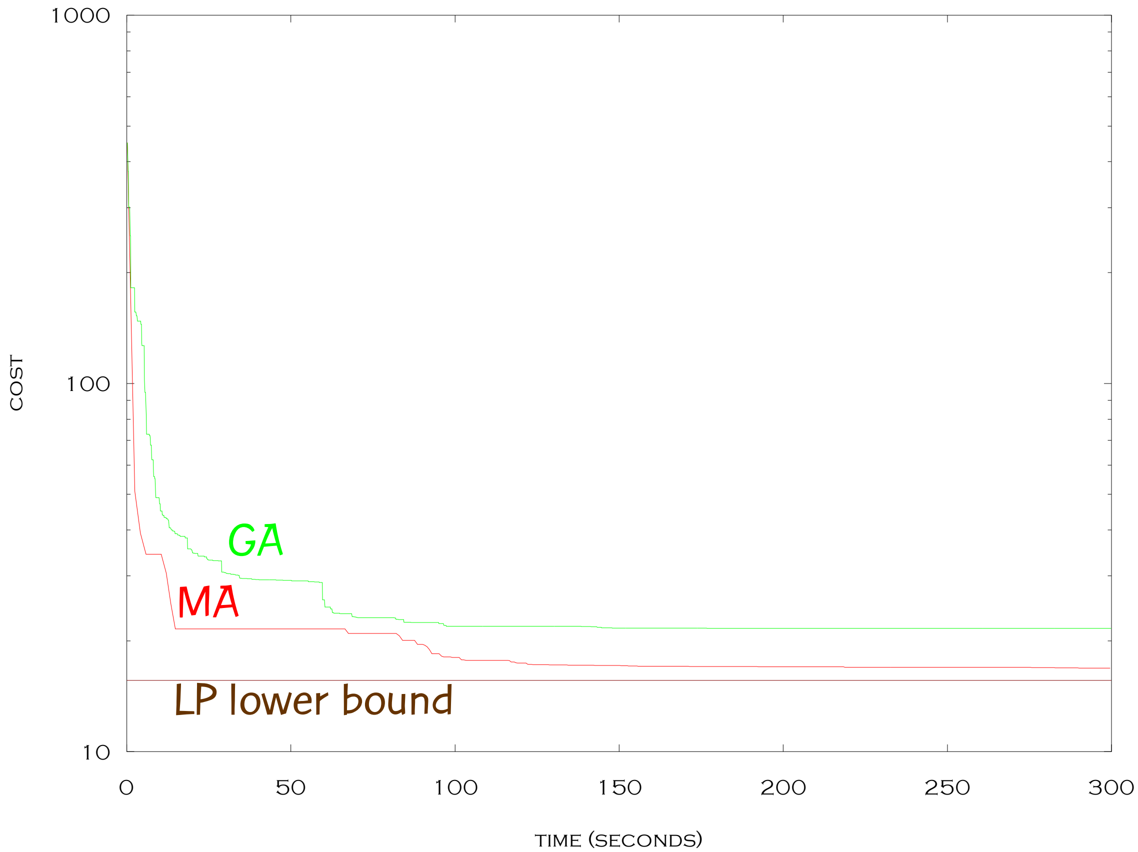
Remark

- Memetic algorithm (MA) improves over pure genetic algorithm (GA) in two ways:
  - Finds solutions faster
  - Finds better solutions



Application 6:

Survivable IP network design

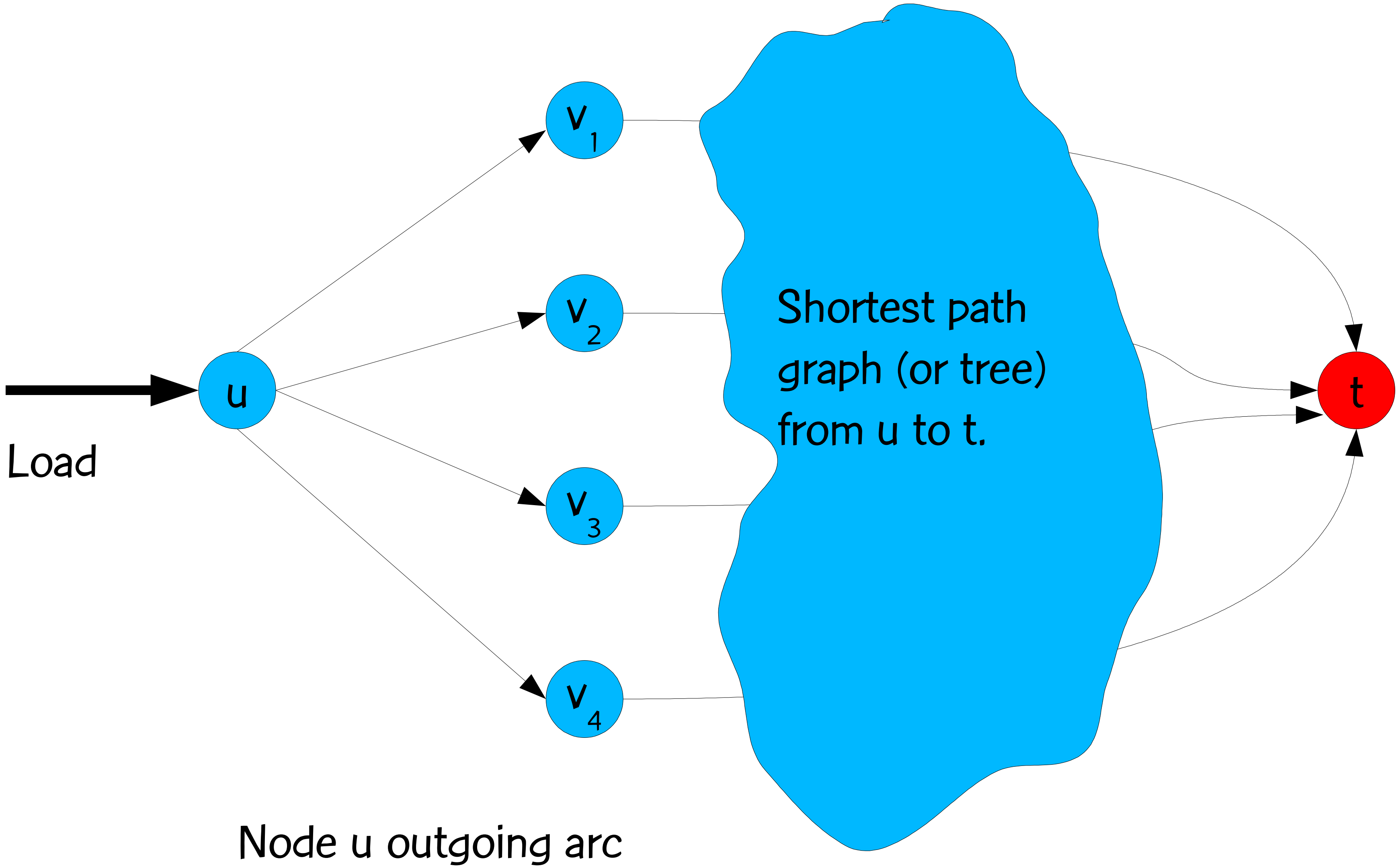
Survivable IP network design

- Given
  - $G = (N,A)$, where:
    - N is the set of routers
    - A is the set of potential arcs where capacity can be installed.
  - Demand matrix $D = [d]$, such that for each $(u,v) \in N \times N$
    - $d(u,v)$ is the traffic demand from router u to router v.
  - Single link capacity M

Survivable IP network design

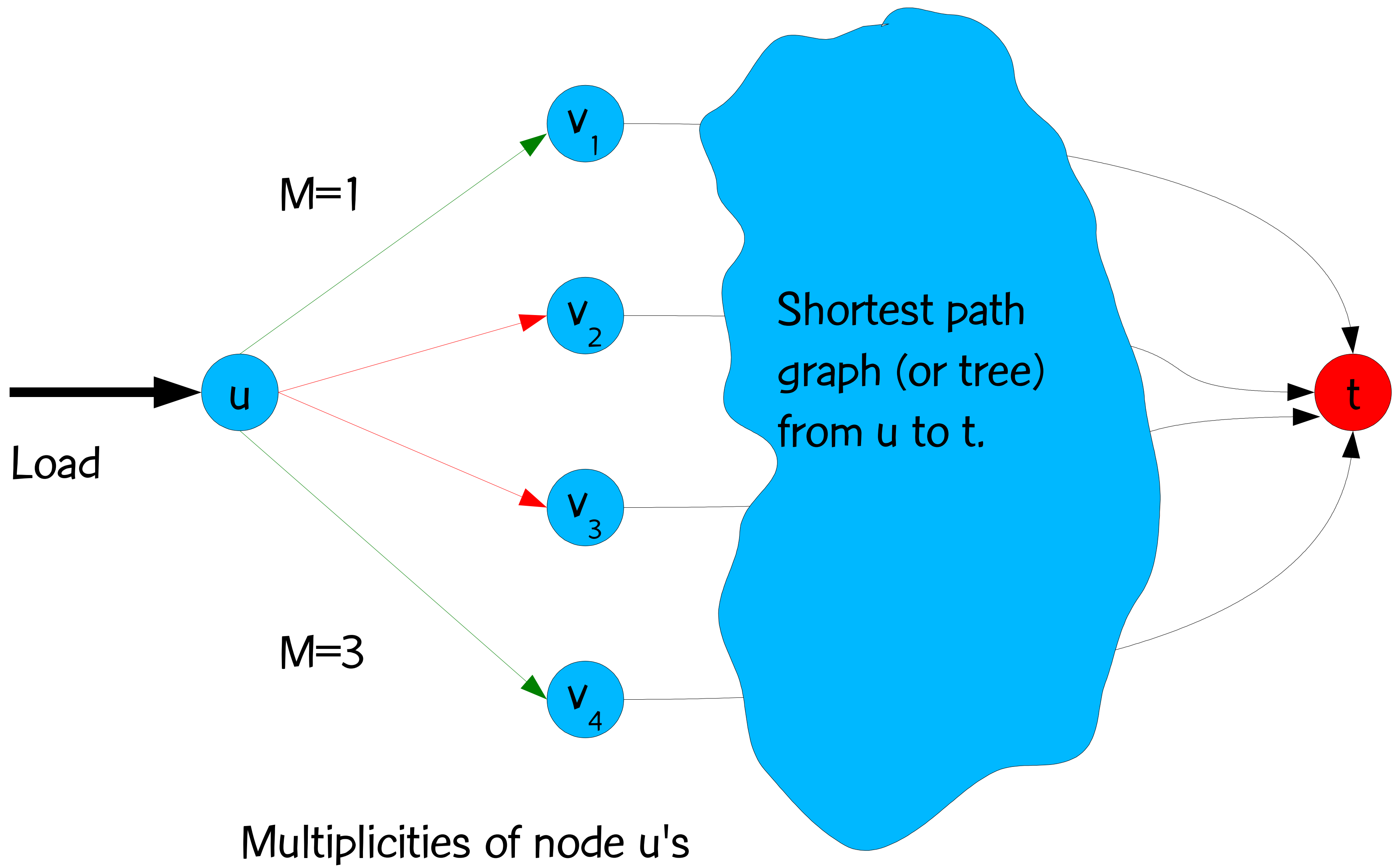
- Determine, for each arc a
  - OSPF weight $w_a \in [1, w_{max}]$
  - Number of links of capacity M installed in arc a (arc multiplicity)
- Such that
  - There is sufficient capacity to route all of the demand
  - Using OSPF routing with traffic splitting
  - Subject to single router or single arc failure

Traffic splitting



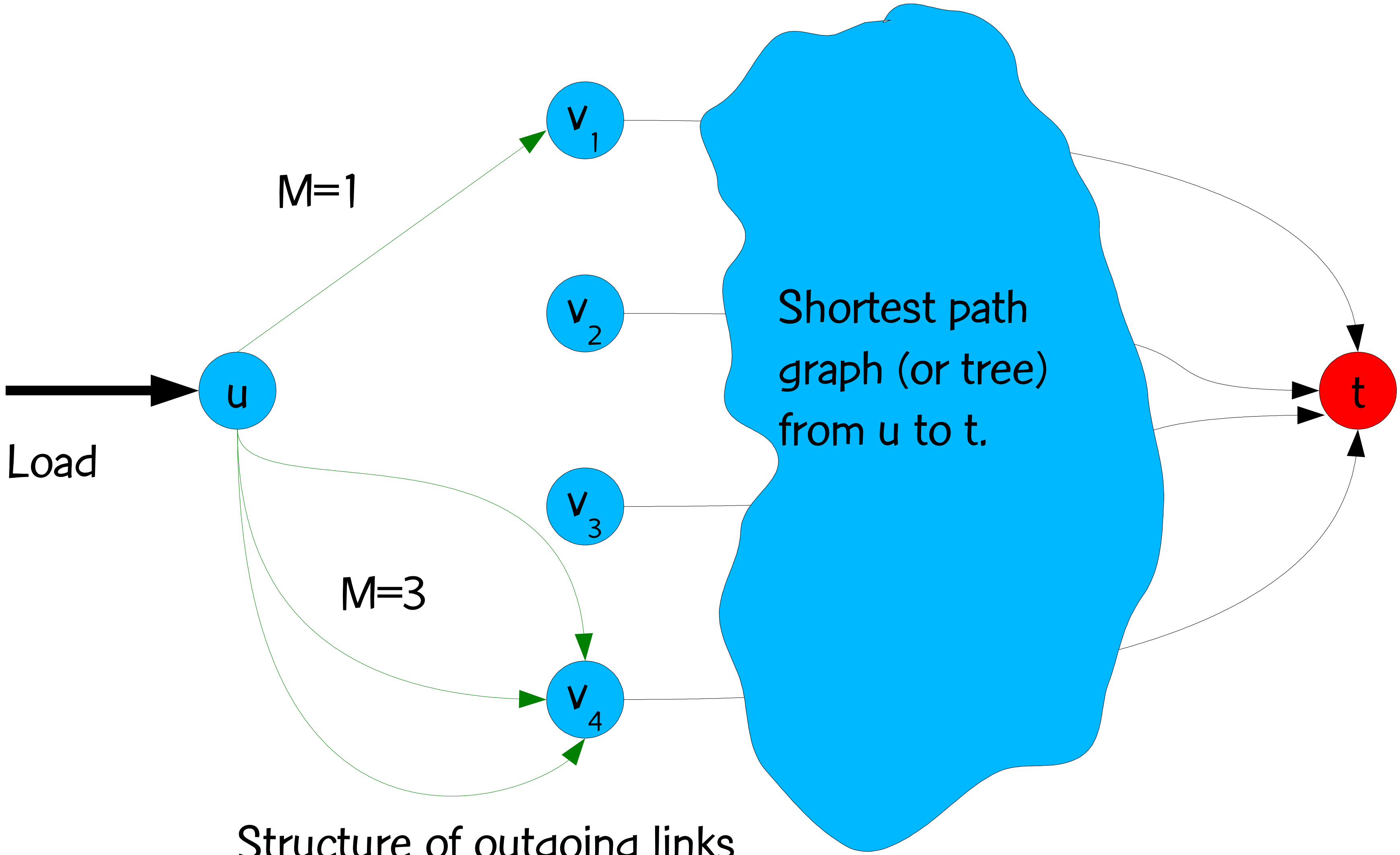
Node u outgoing arc
structure

Traffic splitting



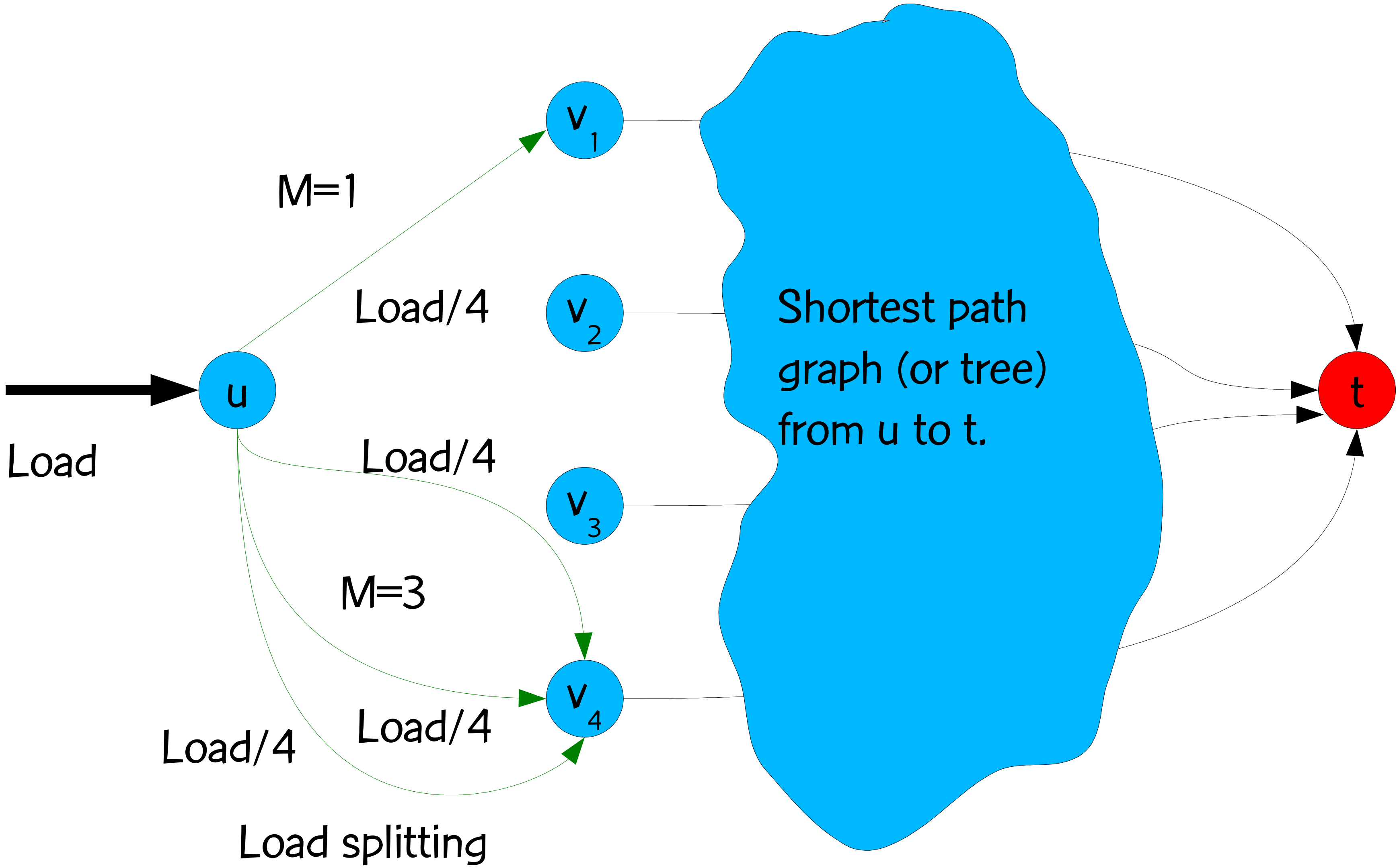
Multiplicities of node u's outgoing arcs

Traffic splitting



Structure of outgoing links
of node u

Traffic splitting



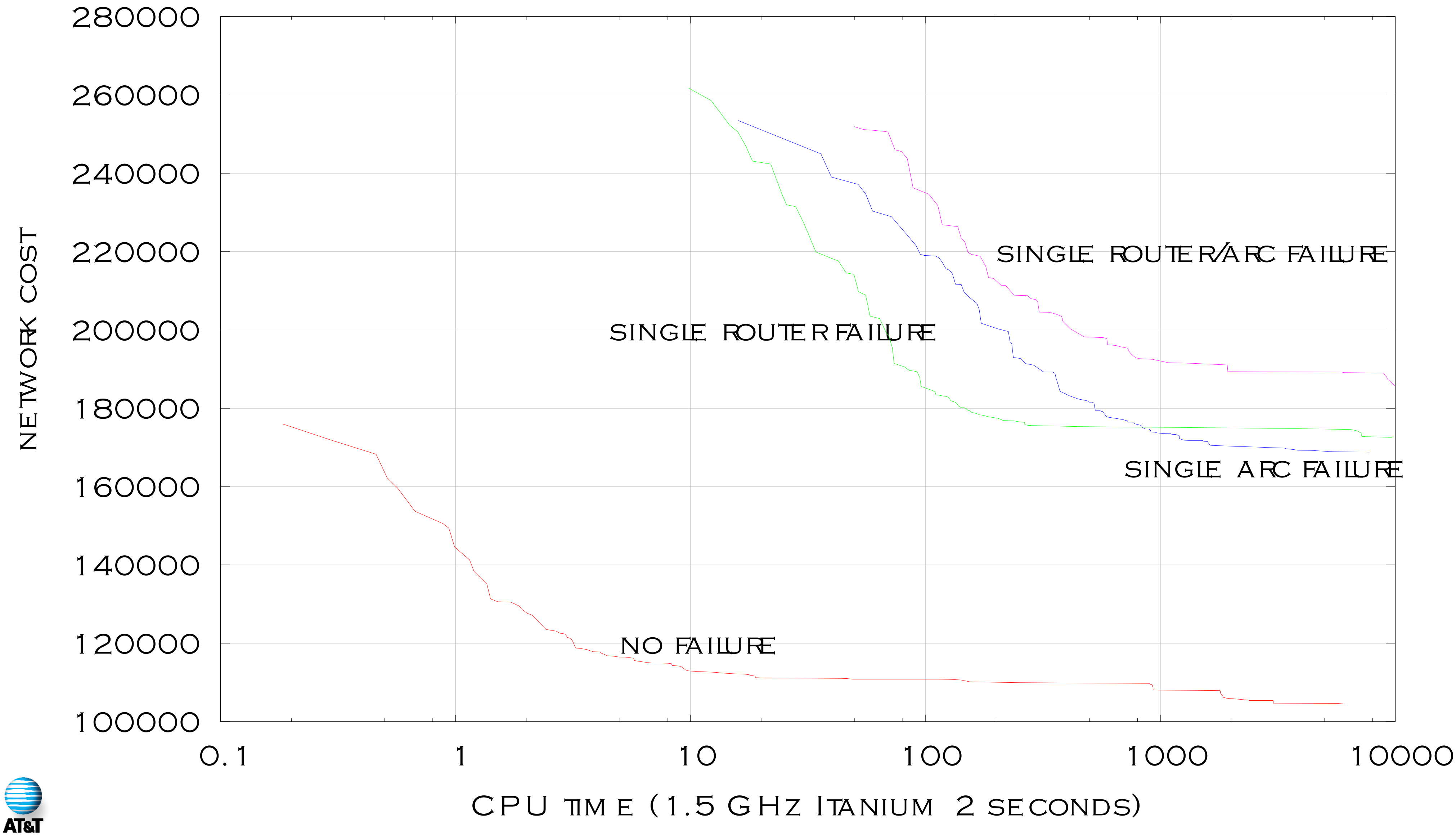
Genetic algorithm for no-failure case

- Solutions are OSPF weight vectors.
- A OSPF weight vector defines shortest path graphs on which routing is done.
- Assume each arc has unit multiplicity.
- Repeat until feasible capacity/load is achieved:
  - Route demand and determine loads on arcs.
  - Determine arc multiplicities to insure minimum arc capacities required to flow loads on arcs. Multiplicities are never decreased.

Genetic algorithm for single-failure case

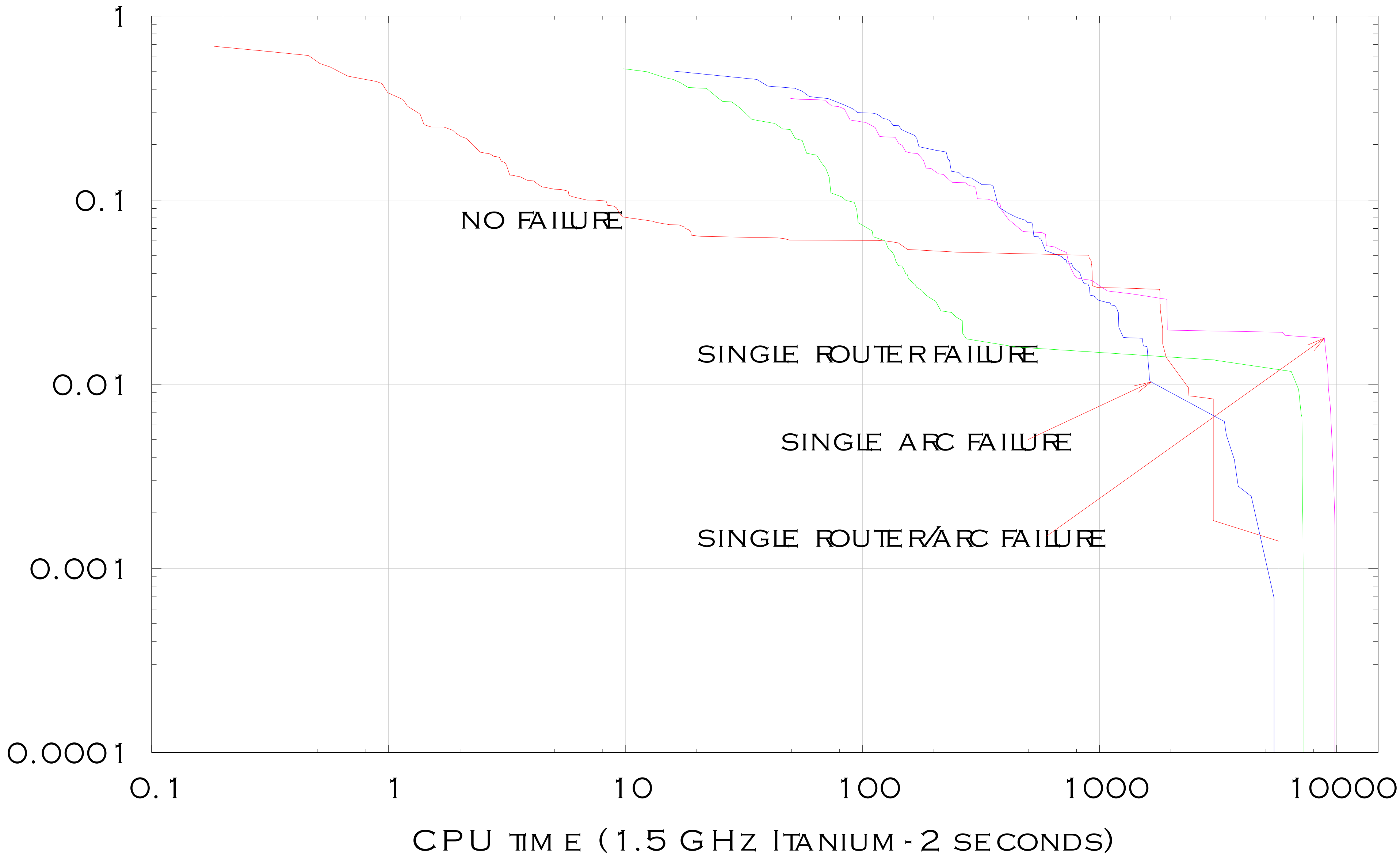
- Algorithm similar to no-failure case.
- Compute multiplicities for no-failure configuration and for each single-failure configuration.
- For each arc, set its multiplicity to be the maximum multiplicity over all simulated configurations.

Network cost: 74-router, 278-arc, 18-terminal nodes, 306 demand pairs
No router or arc failure, single-router failure, single-arc failure, and single-router or single-arc failure.



Relative error of network cost: 74-router, 278-arc, 18-terminal nodes, 306 demand pairs.

No router or arc failure, single-router failure, single-arc failure, and single-router or single-arc failure.



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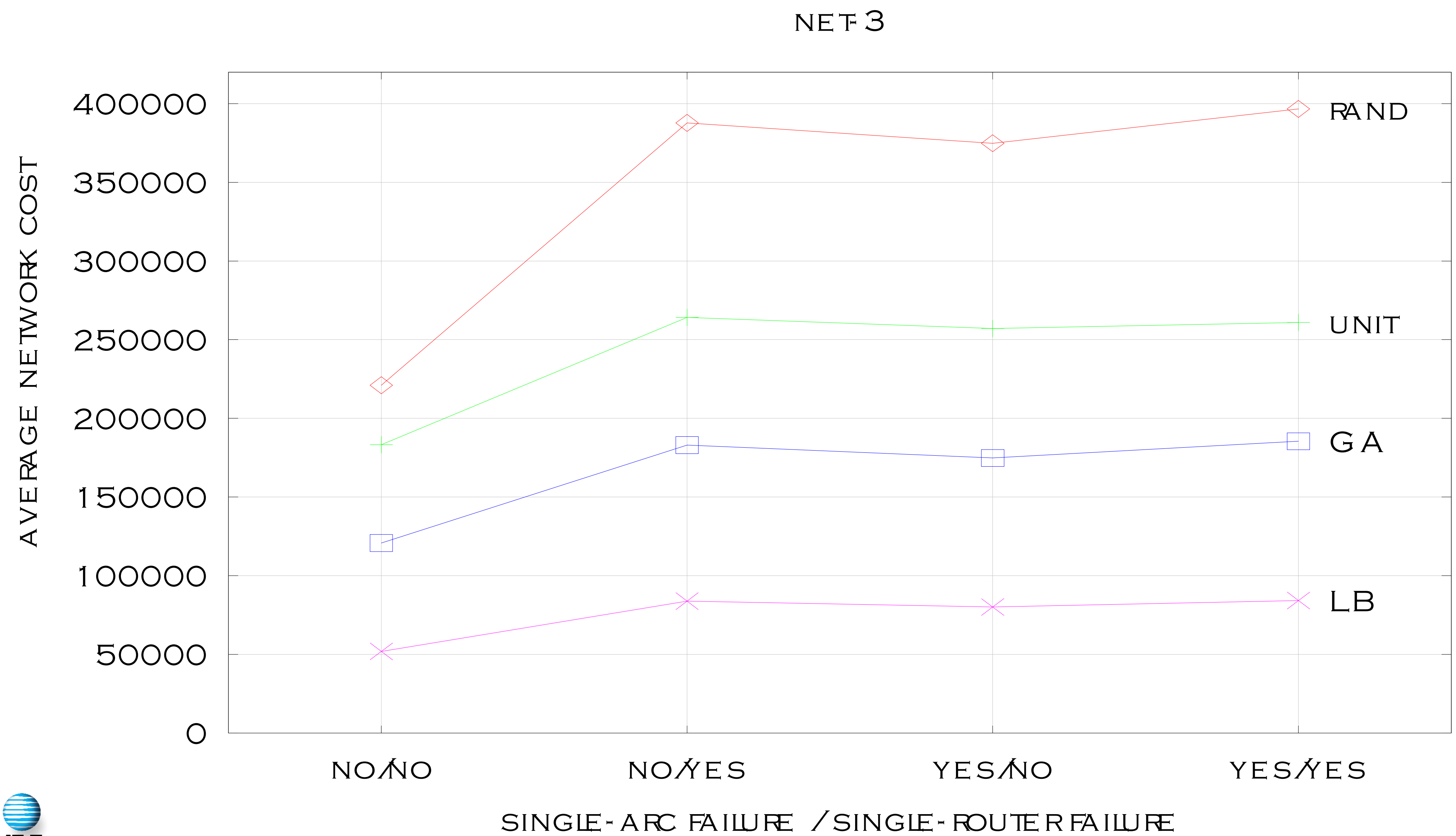
Average network costs for random weights, unit weights, GA weights compared to lower bound. Network has 74 routers, 278 arcs, 18 terminal nodes, and 306 demand pairs.



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Refence

L.S. Buriol, M.G.C. Resende, and M. Thorup, "Survivable IP network design with OSPF routing," AT&T Labs Technical Report TD-64KUAW, September 2004. To appear in Networks.

Concluding Remarks

- we have seen a small sample of applications of optimization in telecommunications
- opportunities for optimization arise in practice all the time
- our profession call have a major impact in telecommunications

Concluding remarks

- These slides, and papers about GRASP, path-relinking, and their telecom applications available at:
  http://www.research.att.com/~mgcr
  http://graspheuristic.org

Handbook of Optimization in Telecommunications (HOT), M.G.C. Resende and P.M. Pardalos, eds. Springer, forthcoming in 2006.

37 chapters
79 authors
1162 pages

- Part I: Optimization algorithms
- Part II: Planning and design
- Part III: Routing
- Part IV: Reliability, restoration, and grooming
- Part V: Wireless
- Part VI: The web and beyond

Part I: Optimization algorithms

- Interior point methods for large scale linear programming
- Nonlinear programming in telecommunications
- Integer programming for telecommunications
- Metaheuristics and applications to problems in telecommunications
- Minimum cost network flow algorithms
- Multicommodity network flow models and algorithms
- Shortest path algorithms

Part II: Planning and design

- Network planning
- Multicommodity flow problems and decomposition in telecom
- Telecom network design
- Ring network design
- Telecom access network design
- Optimization in distribution network design
- Design of survivable networks
- Design of survivable networks based on p-cycles
- Optimization issues in quality of service
- Steiner tree problems in telecom
- Formulations and methods for hop-constrained min spanning tree problem
- Location problems in telecom
- Pricing and equilibrium in communication networks

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Part III: Routing

- Optimization of dynamic routing networks
- ILP formulations for the routing and wavelength assignment problems: Symmetric systems
- Route optimization in IP networks
- Optimization problems in multicast tree construction

Part IV: Reliability, restoration, and grooming

- Network reliability optimization
- Stochastic optimization in telecom
- Network restoration
- Telecom network grooming

Part V: Wireless

- Graph domination, coloring, and cliques in telecom
- Optimization in wireless networks
- Optimization for planning cellular networks
- Load balancing in cellular wireless networks

Part VI: The web and beyond

- Optimization issues in web search engines
- Optimization in e-commerce
- Optimization issues in combinatorial auctions
- Supernetworks

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The End