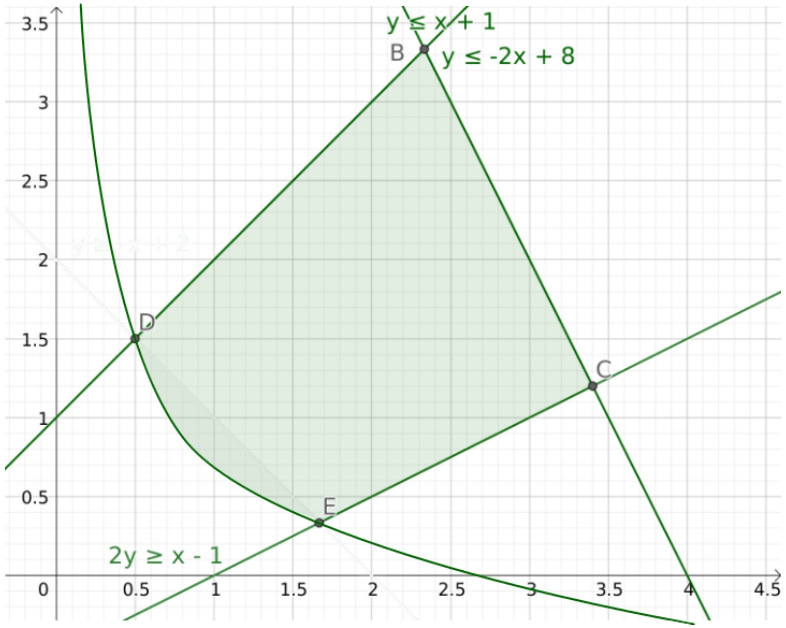
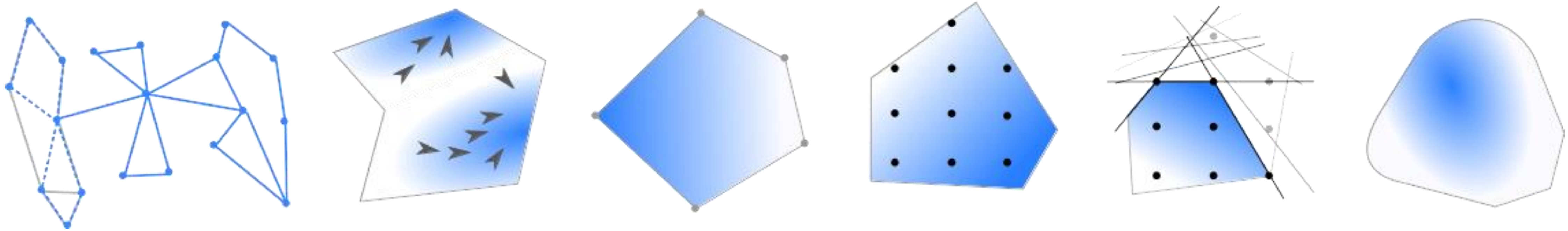
Local Search

COMP4691 / 8691





Previously on COMP4691/8691

Construction

ALG HEUR

- Greedy construction
- Regret
- Bespoke

NOTHING → 1st SOLUTION

ROMANIA PROBLEM FROM AI

SEARCH TO FIND A SOLUTION

↳ OPT (A*

↳ GBFS

$SOLUTION_0 \rightarrow SOL_1 \rightarrow SOL_2$

$SOLUTION_0 \dashrightarrow SOL_A$

Today:

- **Improve – locally**

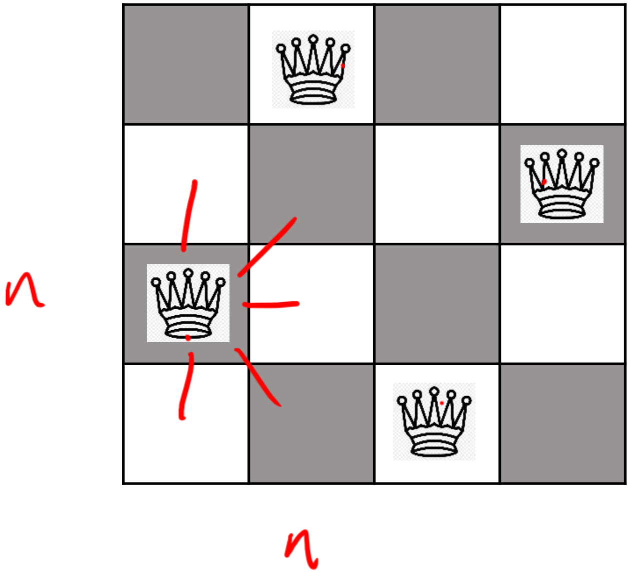
LOCAL SEARCH

HEUR. ALG

META HEURIS HOW TO DEF. THIS SEARCH SPACE

Local Search

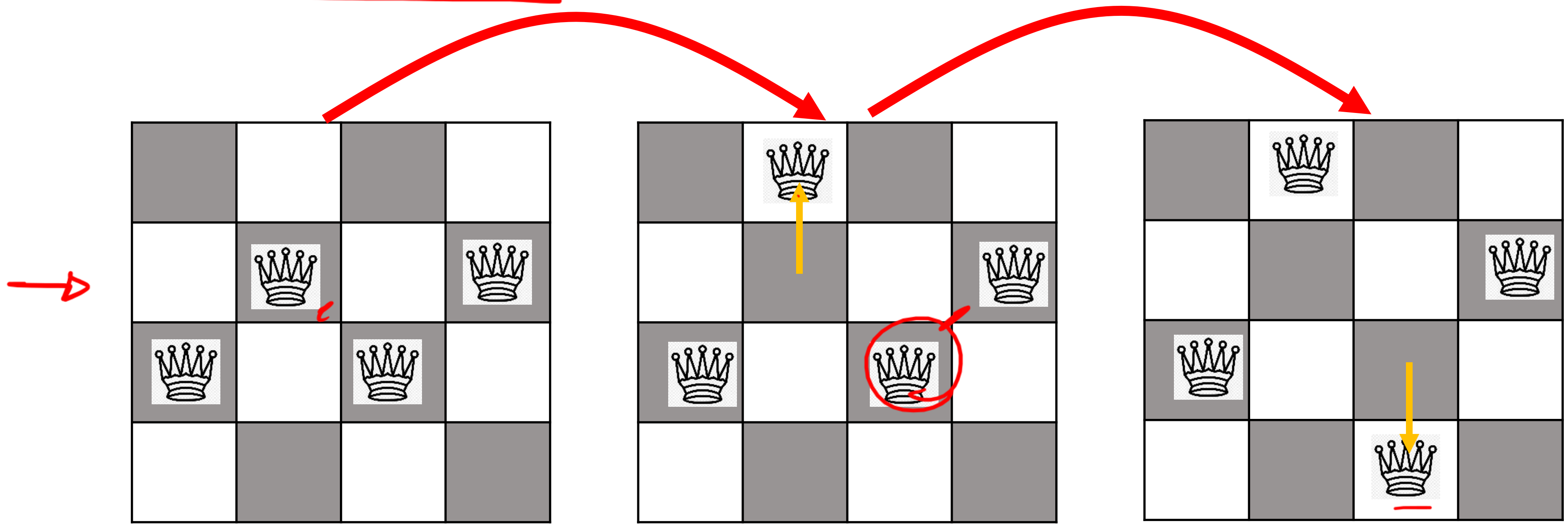
- Move from a solution to its *neighbour* SOLUTION
- Neighbour defined by an operator
- E.g. n-queens problem
  - Place *n* queens on an *n* x *n* board, so that none can attack another (i.e., no two on the same row, column, or diagonal)



n-queens

1-MOVE OP

- Neighbourhood: All solutions that can be achieved by moving one queen to a different row

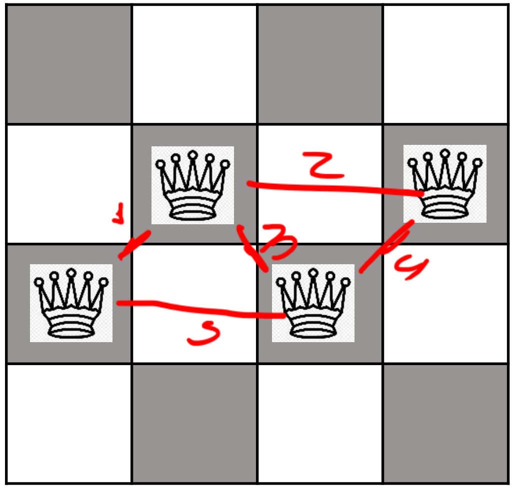


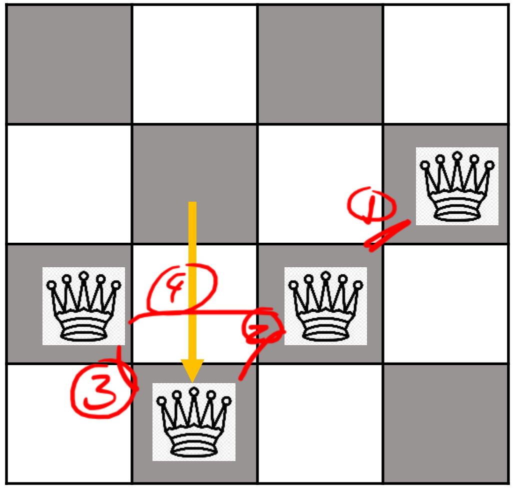
FEAS SOL
OPT

- Solution in 2 moves

n-queens

- Alg 1: Random (random walk)
  - Choose a random move; execute; repeat
  - Asymptotically complete (eventually, you visit every state)

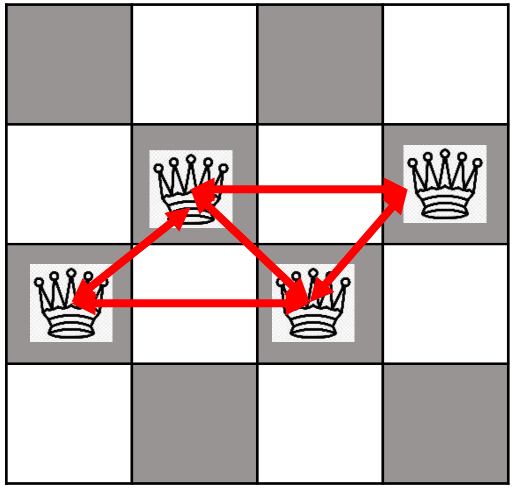




0 ATTACKS

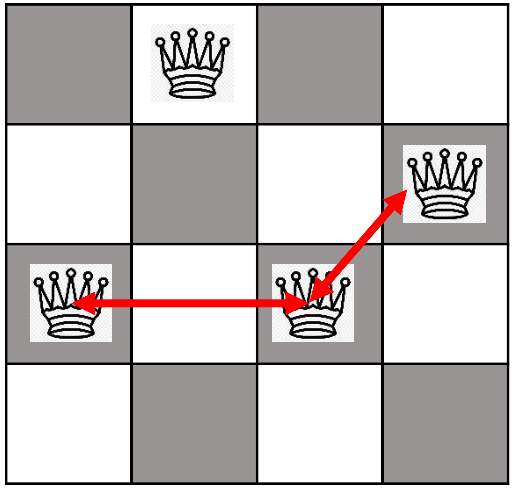
n-queens

- Currently 5 attacks, so give this score 5
- We want score 0



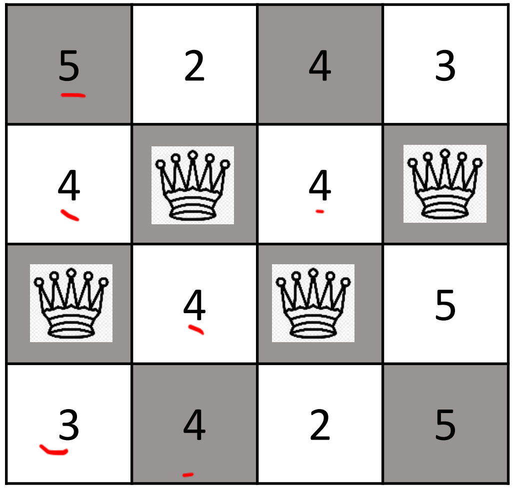
n-queens

- This neighbour has score 2



n-queens

- We can label all squares with their score



n-queens

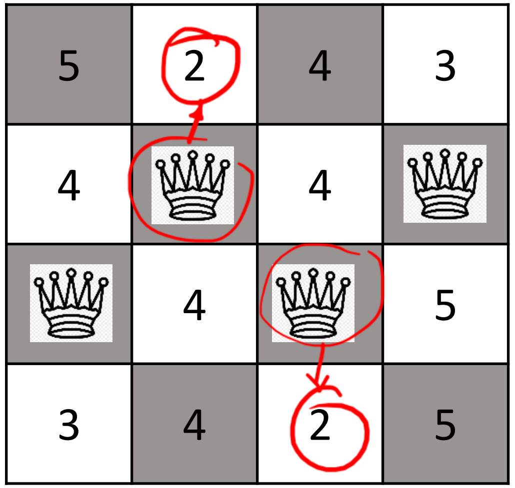
NO QUEUE

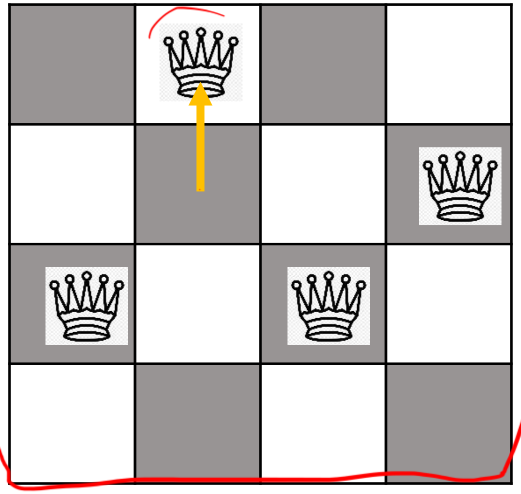
MAX PROB

ON AI: GREEDY BEST FIRST SEARCH (GBFS)

QUEUE

- Alg 2: Greedy (a.k.a Hill Climbing)
  - Choose the best move / one of the best moves
  - Requires us to evaluate the entire Neighbourhood





NEW SOLUTION

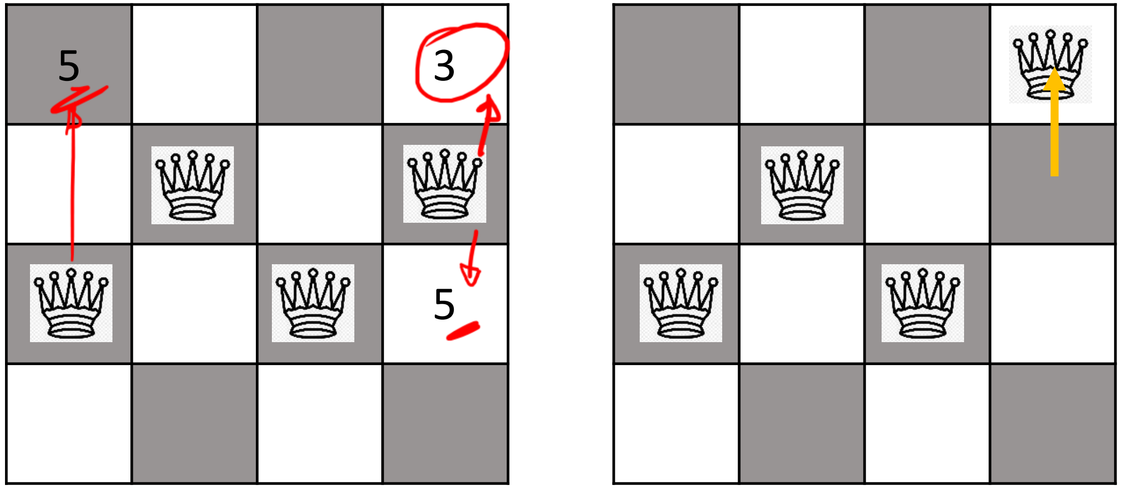
Hill Climbing has been compared to climbing Mt Everest in thick fog

… and while suffering from amnesia.

n-queens

- Alg 3: First found
  - Randomise neighbourhood evaluation
  - Make first improving move

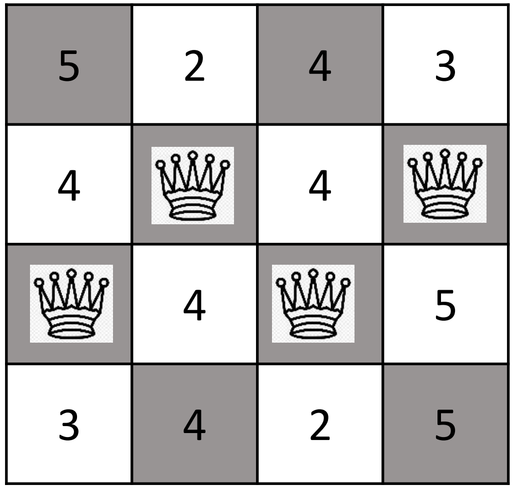
Computational evidence favours first-found over greedy

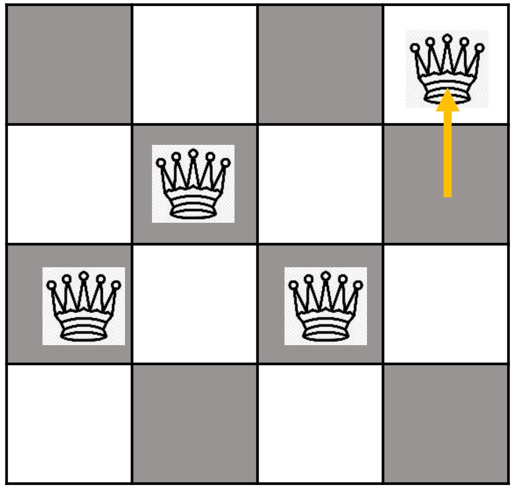


CUR SOL: 5 ATTACKS
SCORE 5

n-queens

- Greedy search is incomplete
- Alg 4: Randomised Greedy
  - With probability p do greedy/first found move
  - With otherwise do a random move
    - Asymptotically complete

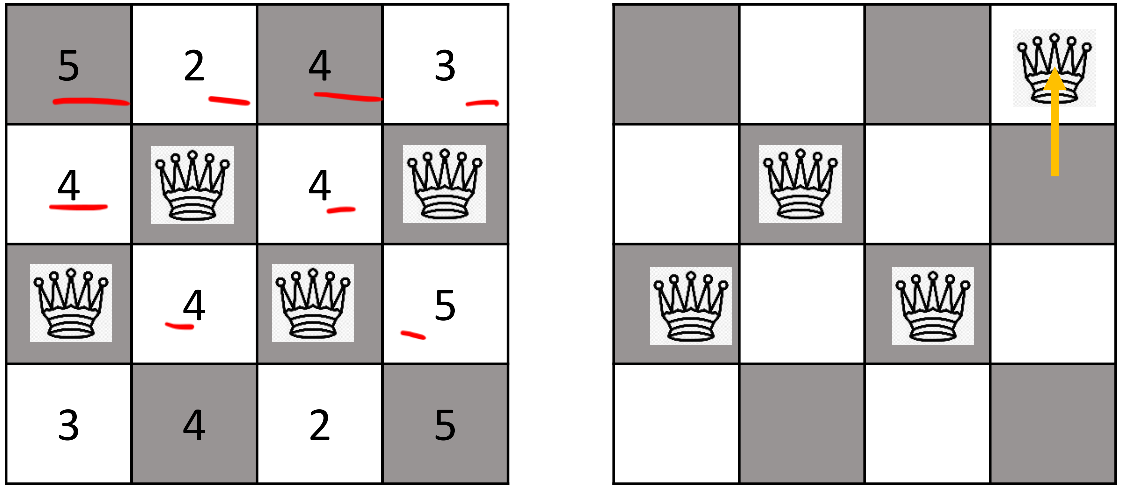




n-queens

MIN PROBLEM

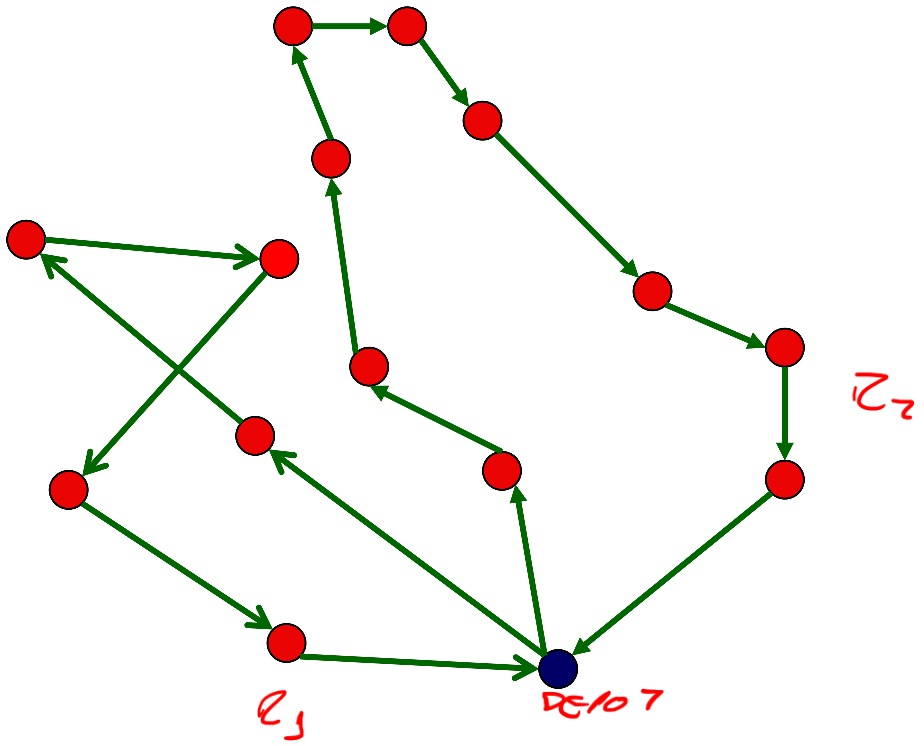
- Alg 5: Biased
  - Choose a move with probability (inversely) proportional to score
  - (Twice as likely to choose a '2' move than a '4')



VRP

Local Search in VRP

- More complex operators



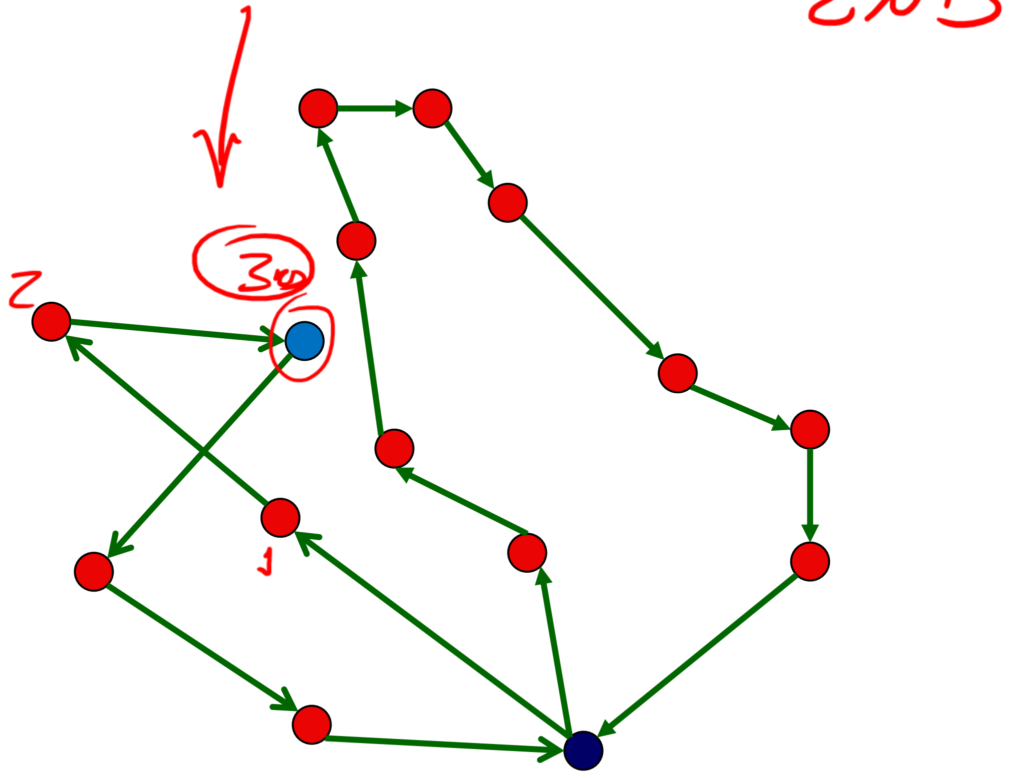
VRP

Local Search in VRP

- More complex operators
  - 1-move

→ Pos in which we visit the client

MOVE FROM 3RD TO 2ND



VRP

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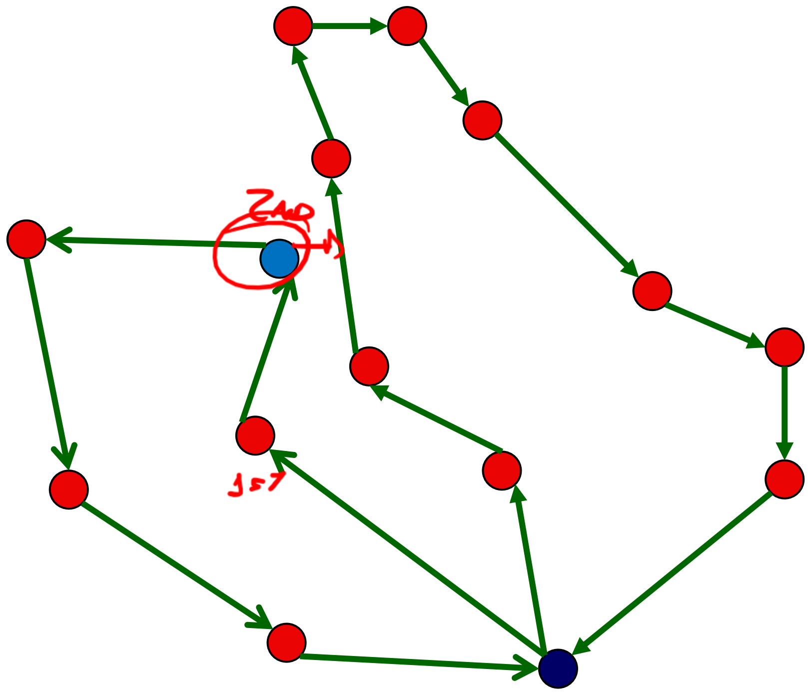

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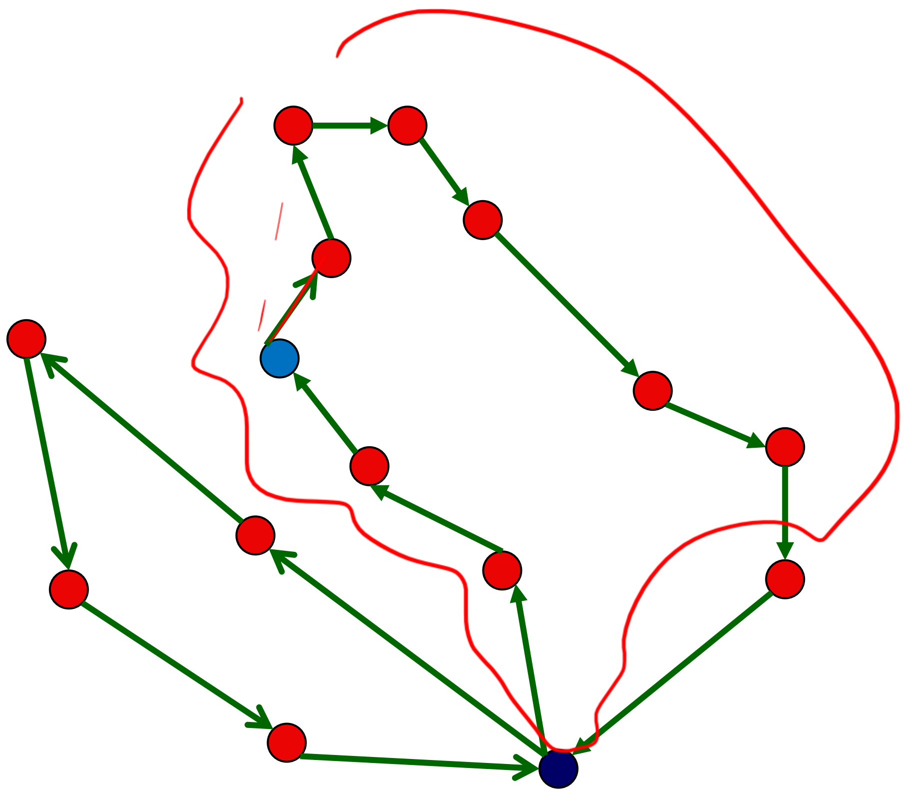

VRP

Local Search in VRP

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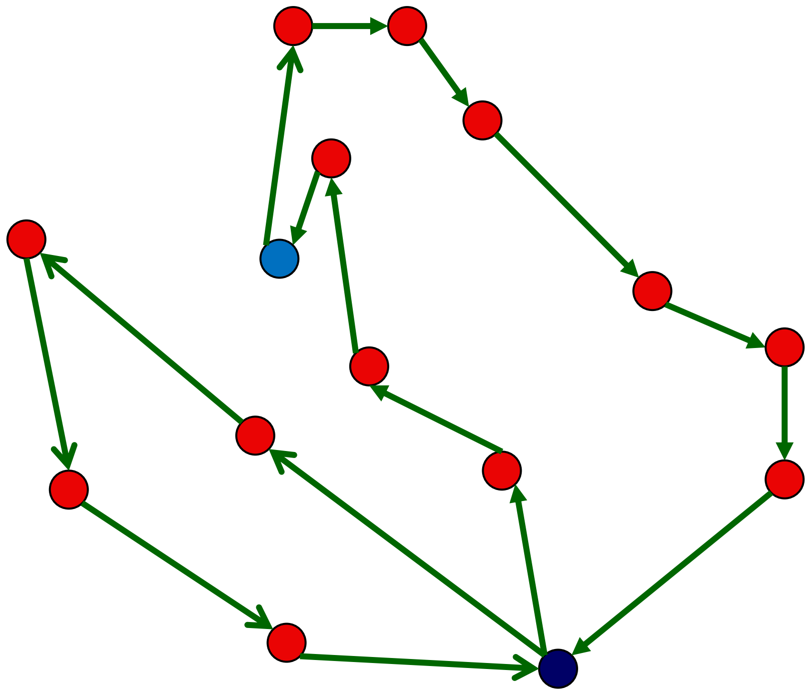

VRP

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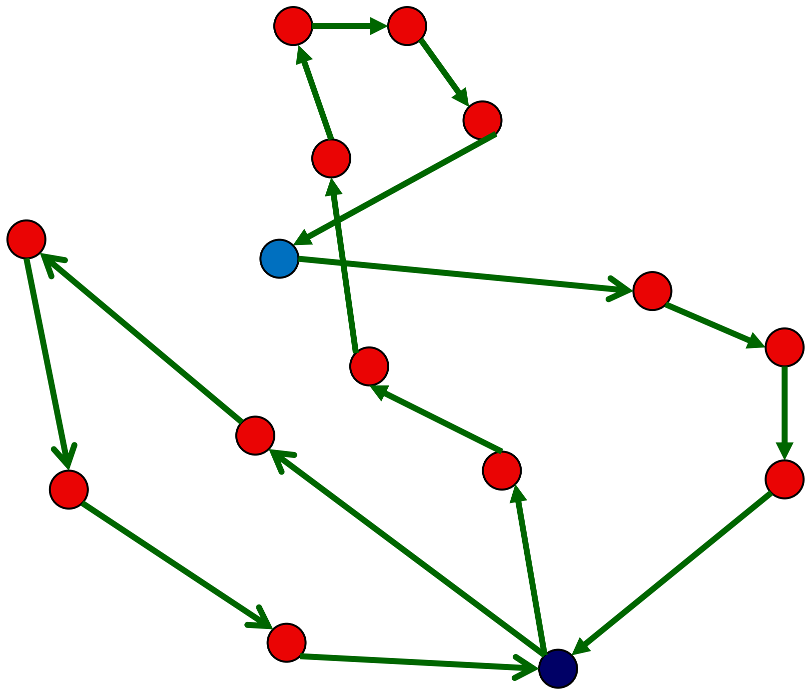
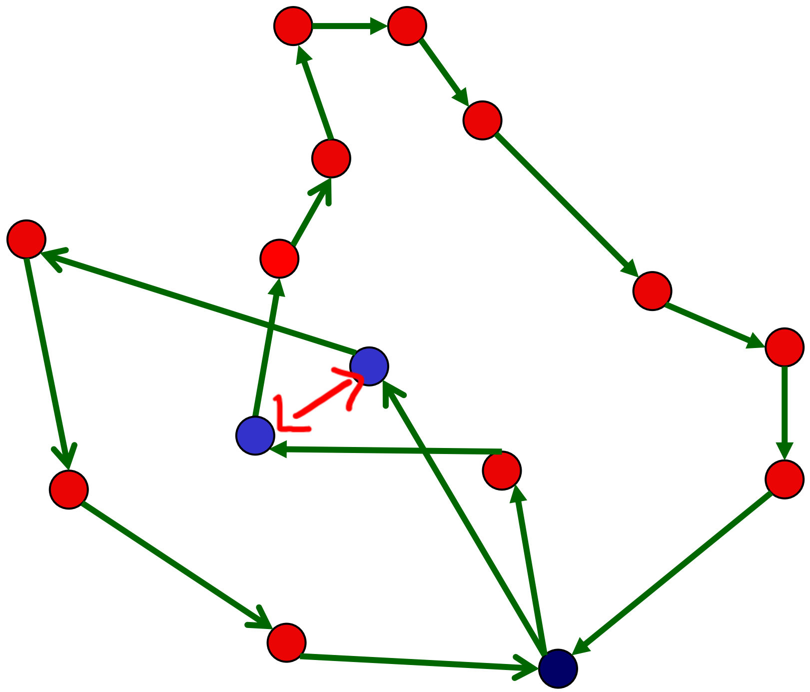


Local Search

Other Neighbourhoods for VRP:

- Swap 1-1



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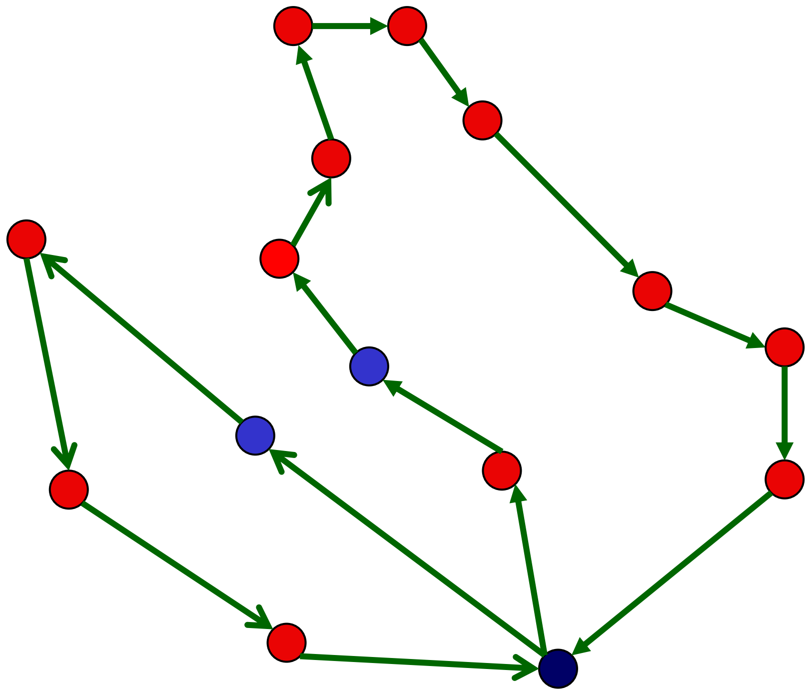
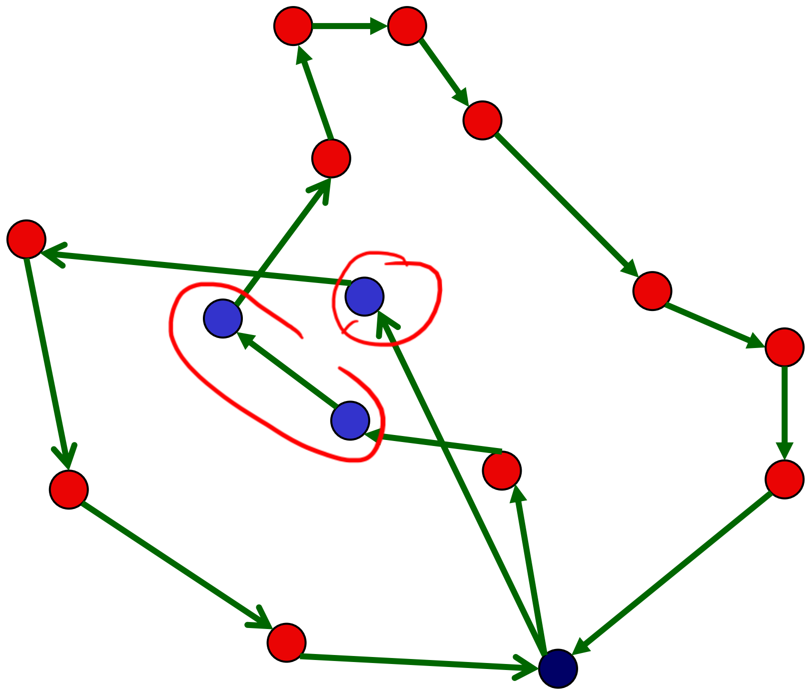


Local Search

Other Neighbourhoods for VRP:

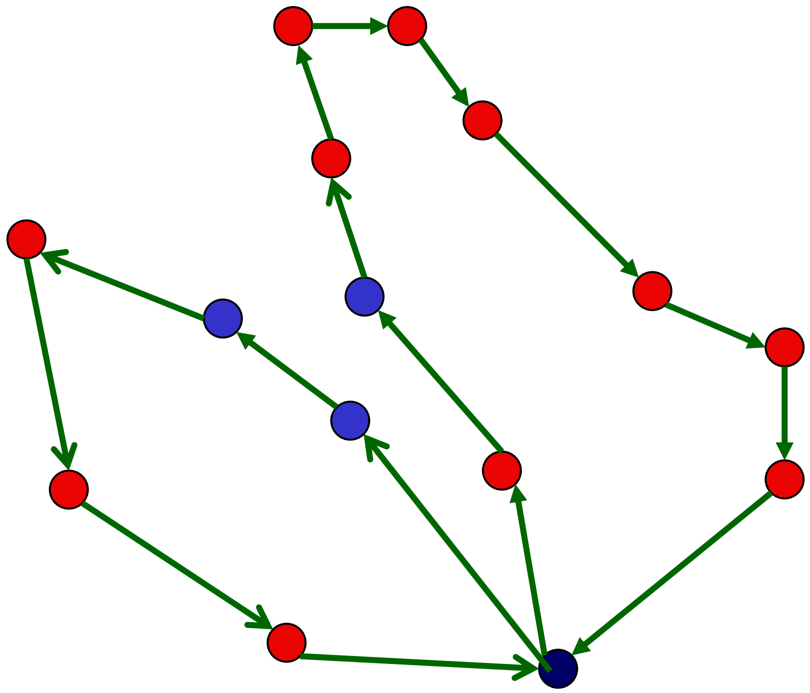
- Swap 2-1



Local Search

Other Neighbourhoods for VRP:

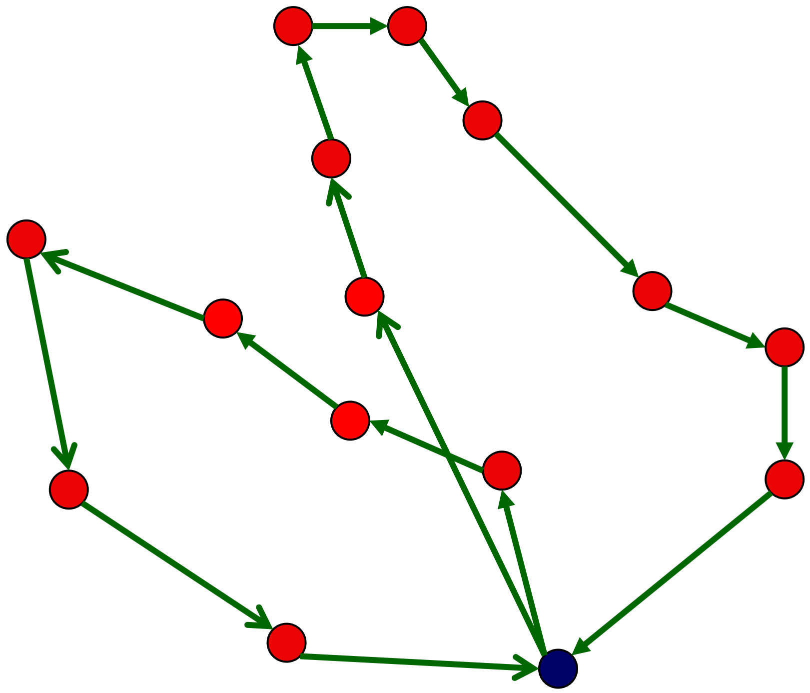
- Swap 2-1



Local Search

Other Neighbourhoods for VRP:

- Swap tails



Local Search

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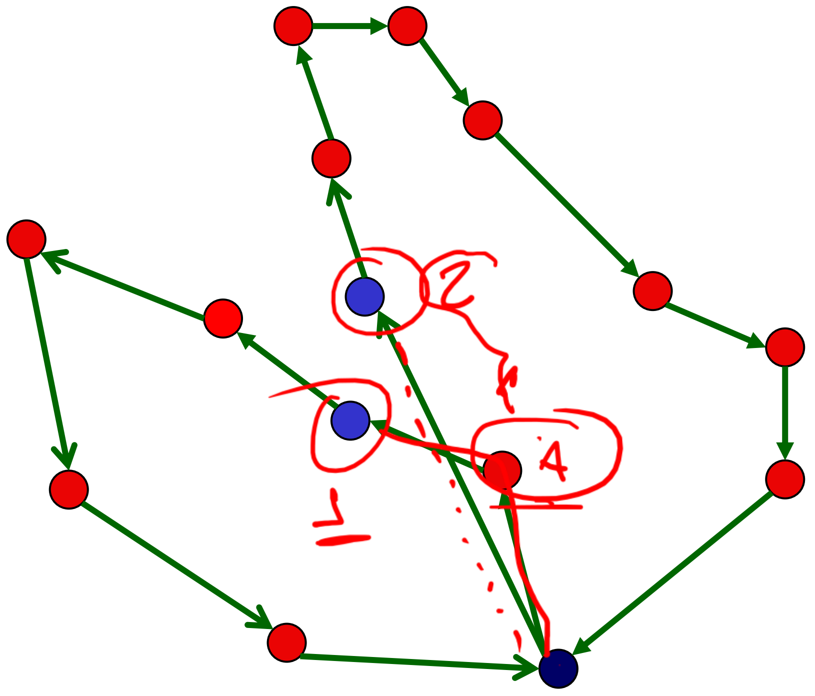

Local Search

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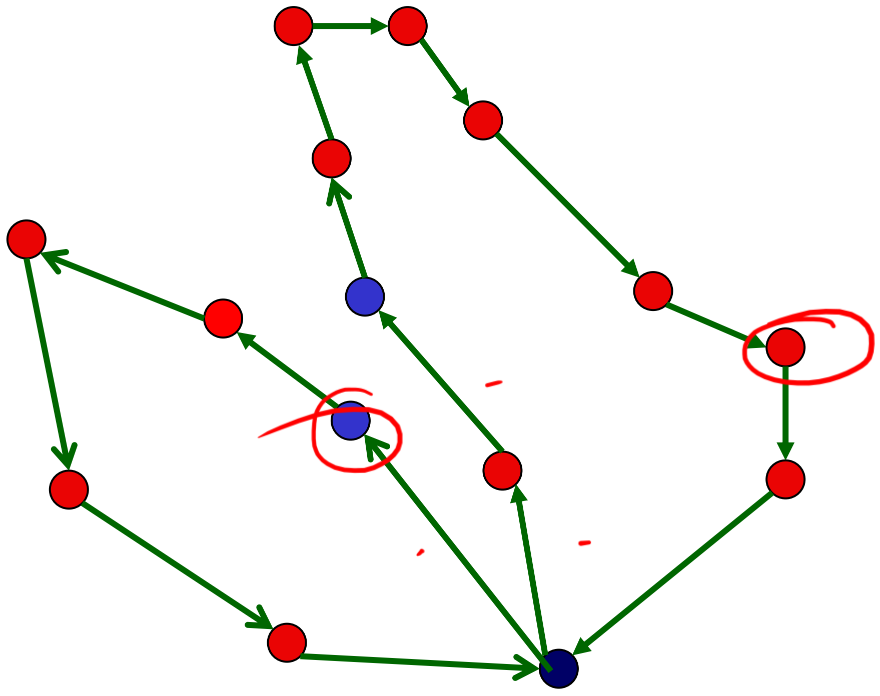
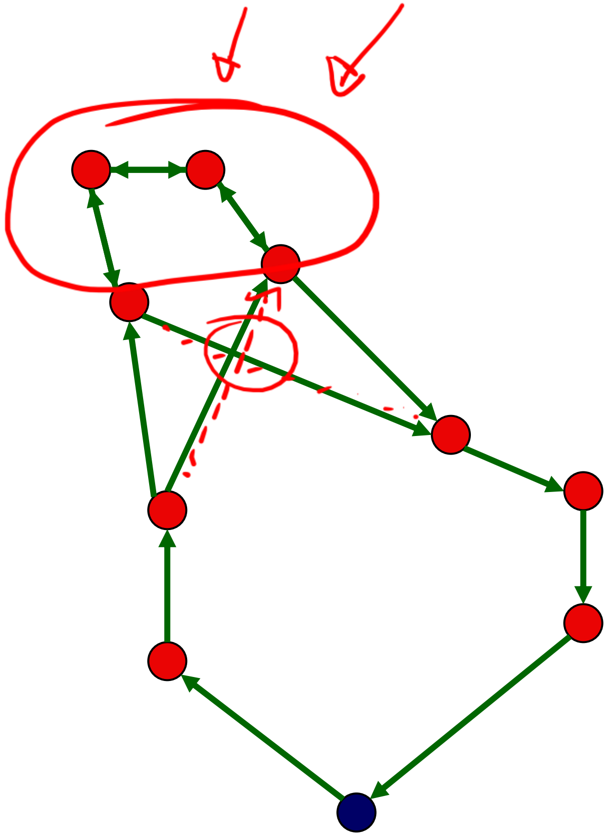


VRP specific operators

2-opt (3-opt, 4-opt…)

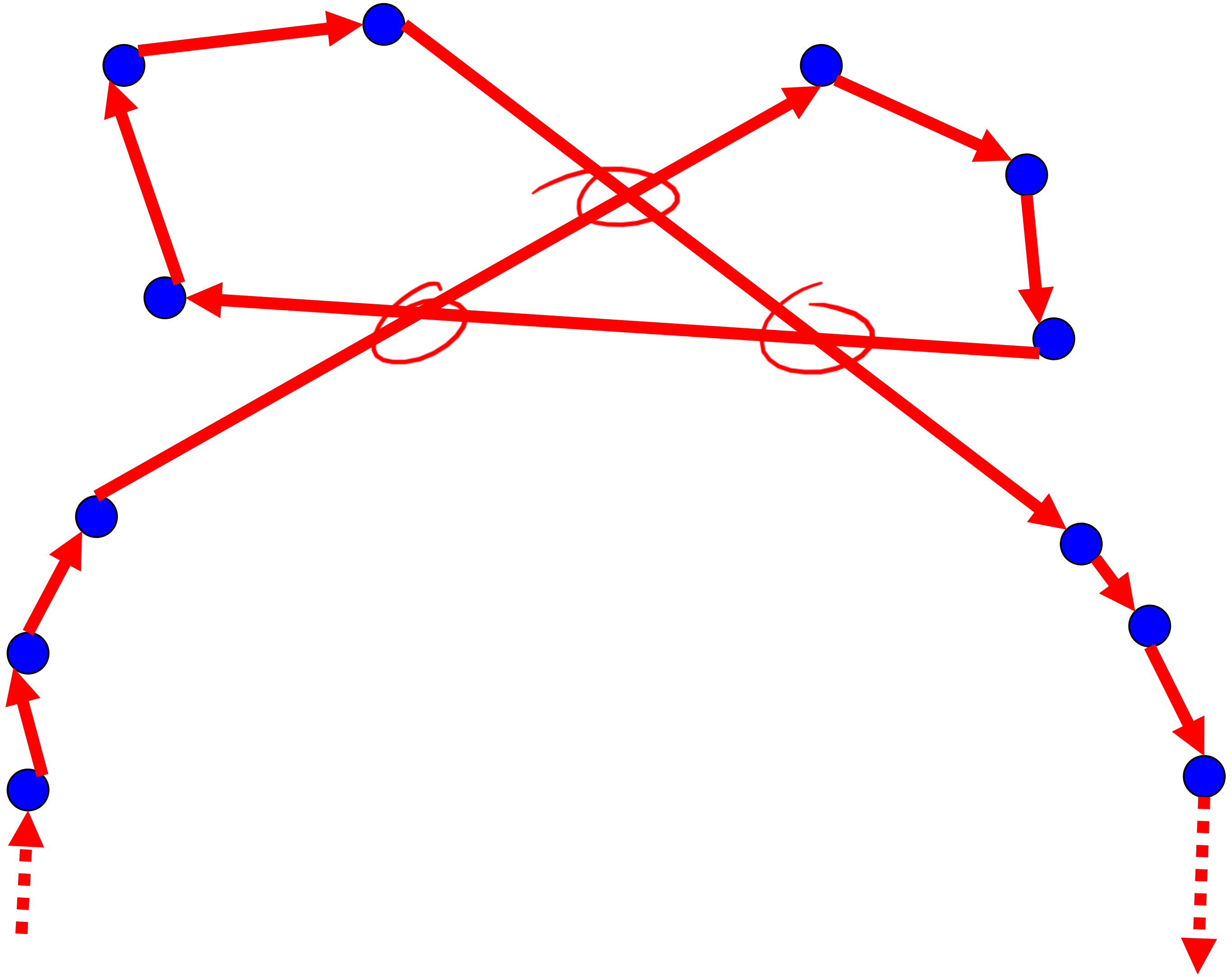
- Remove 2 arcs
- Replace with 2 others



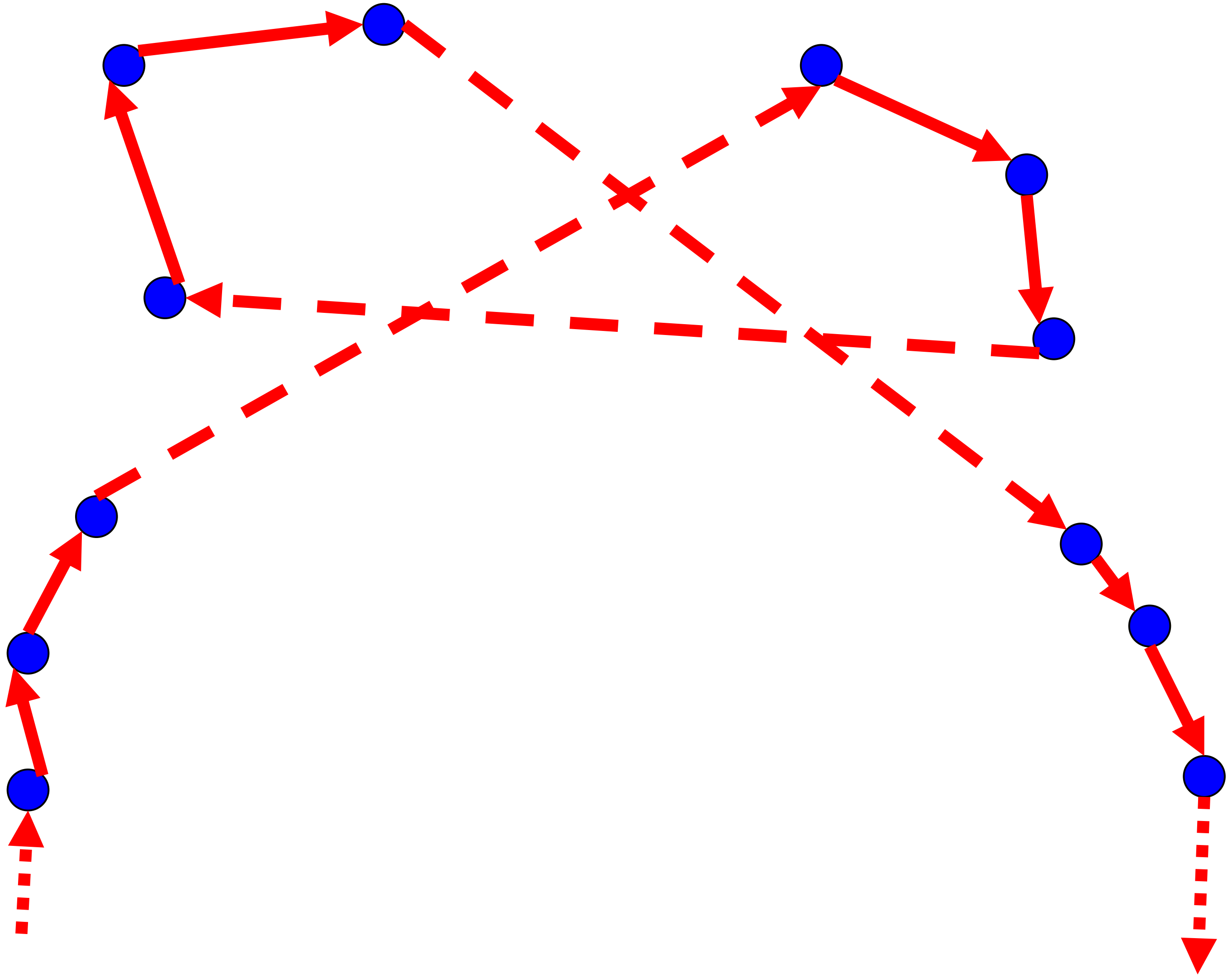
3-opt exchange

- Select three arcs
- Replace with three others
- 2 orientations possible

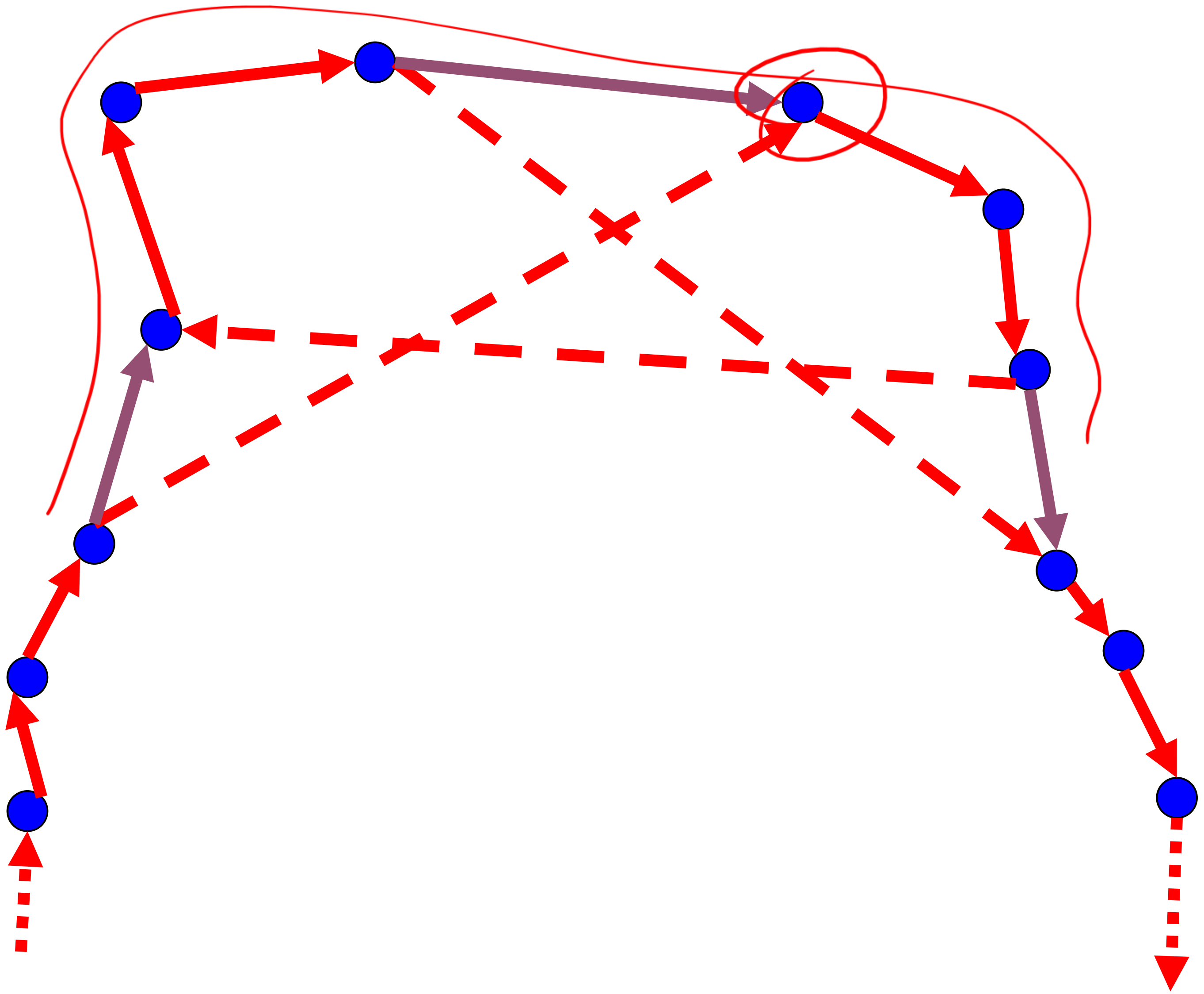
3-opt exchange



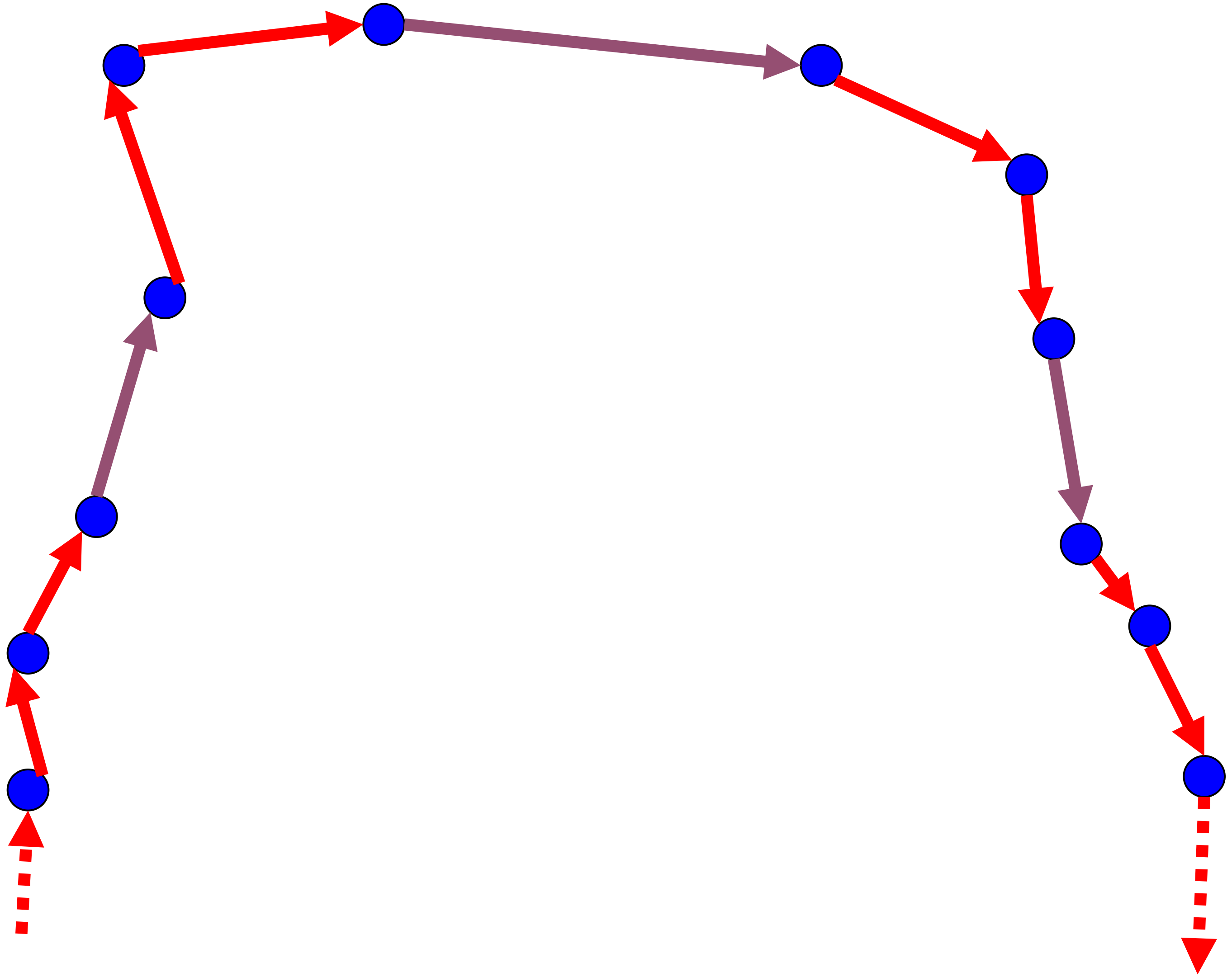
3-opt exchange



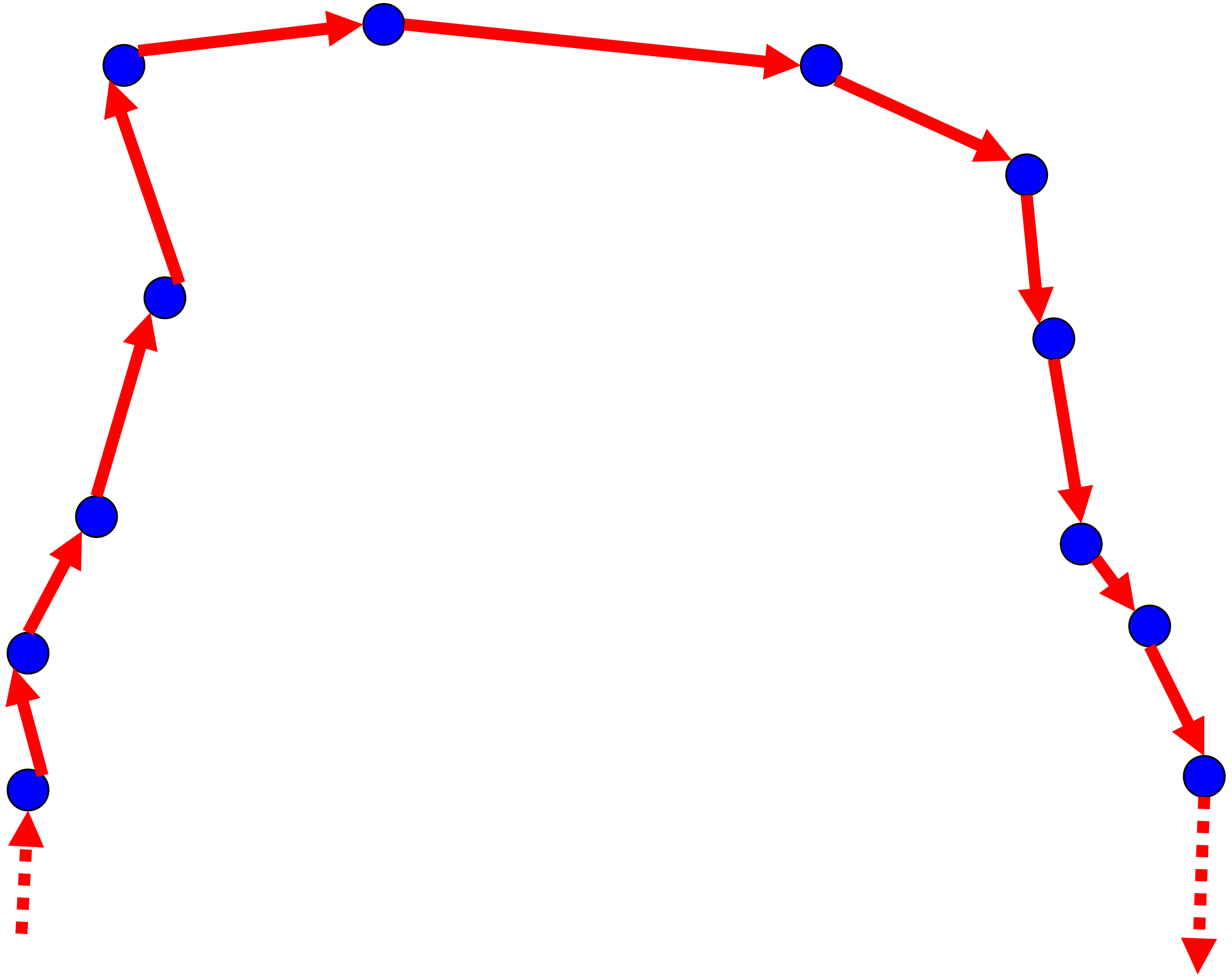
3-opt exchange



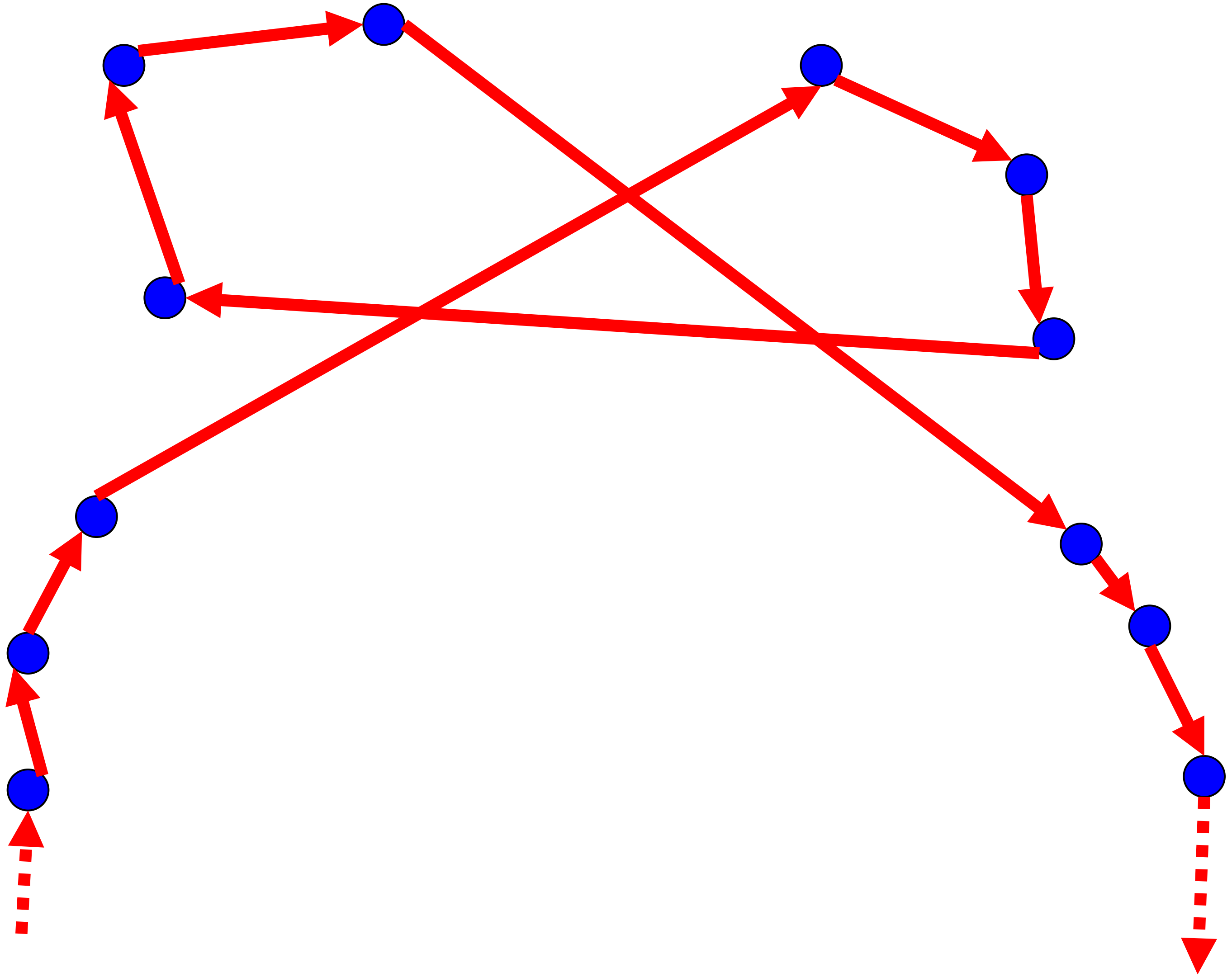
3-opt exchange



3-opt exchange

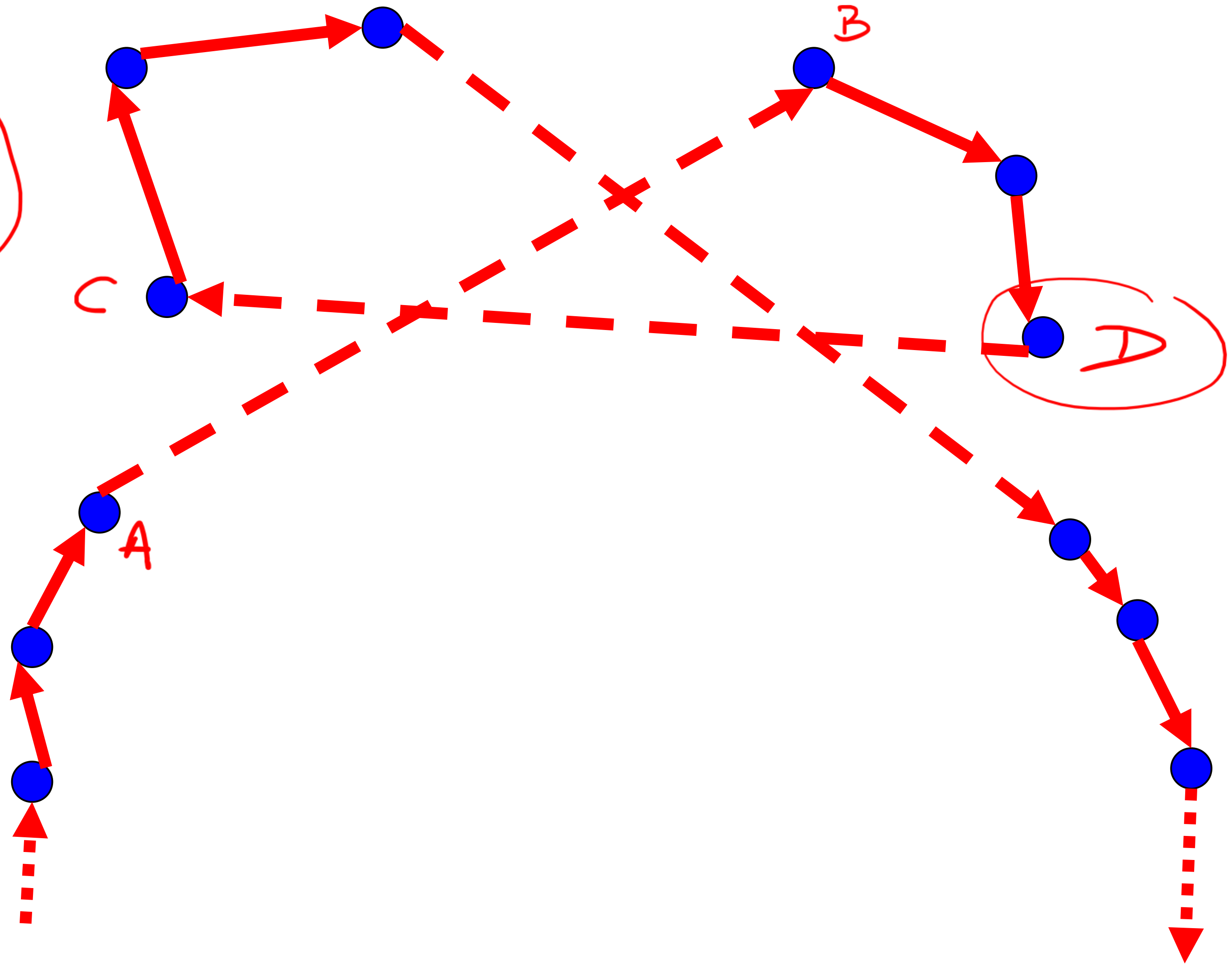


3-opt exchange

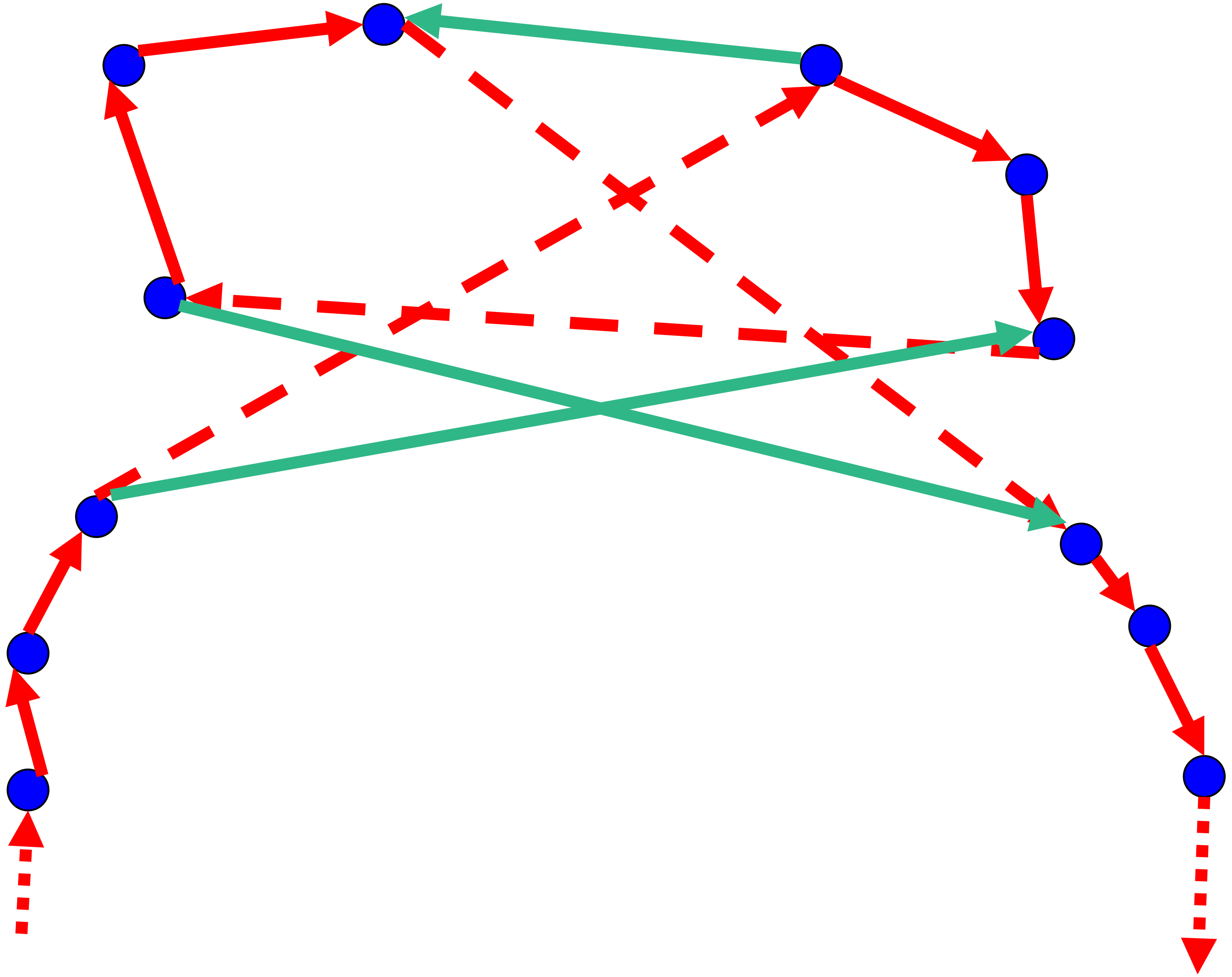


3-opt exchange

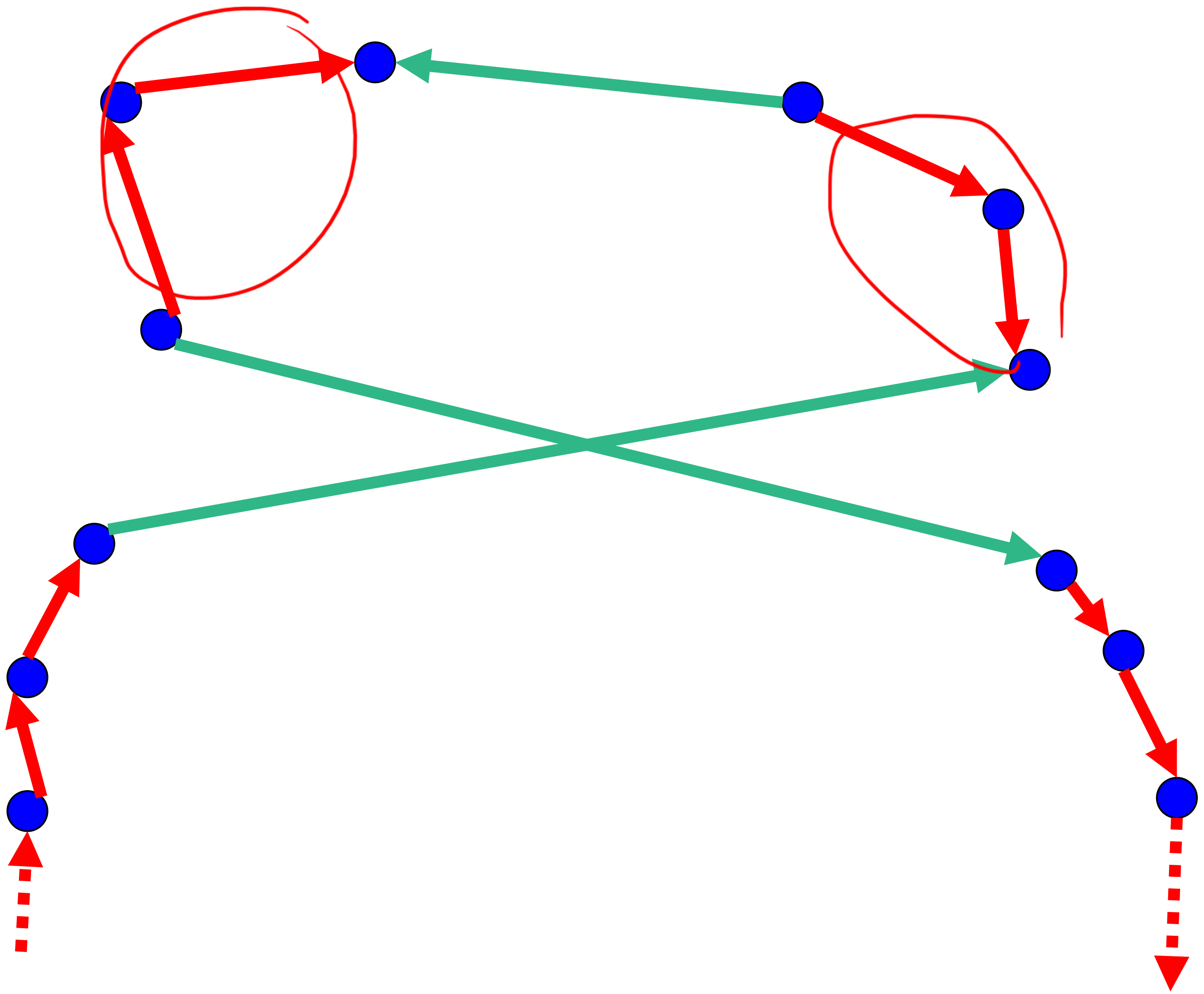
A→B ORIG
A→C 3-OPT-1
A→D 3-OPT-2



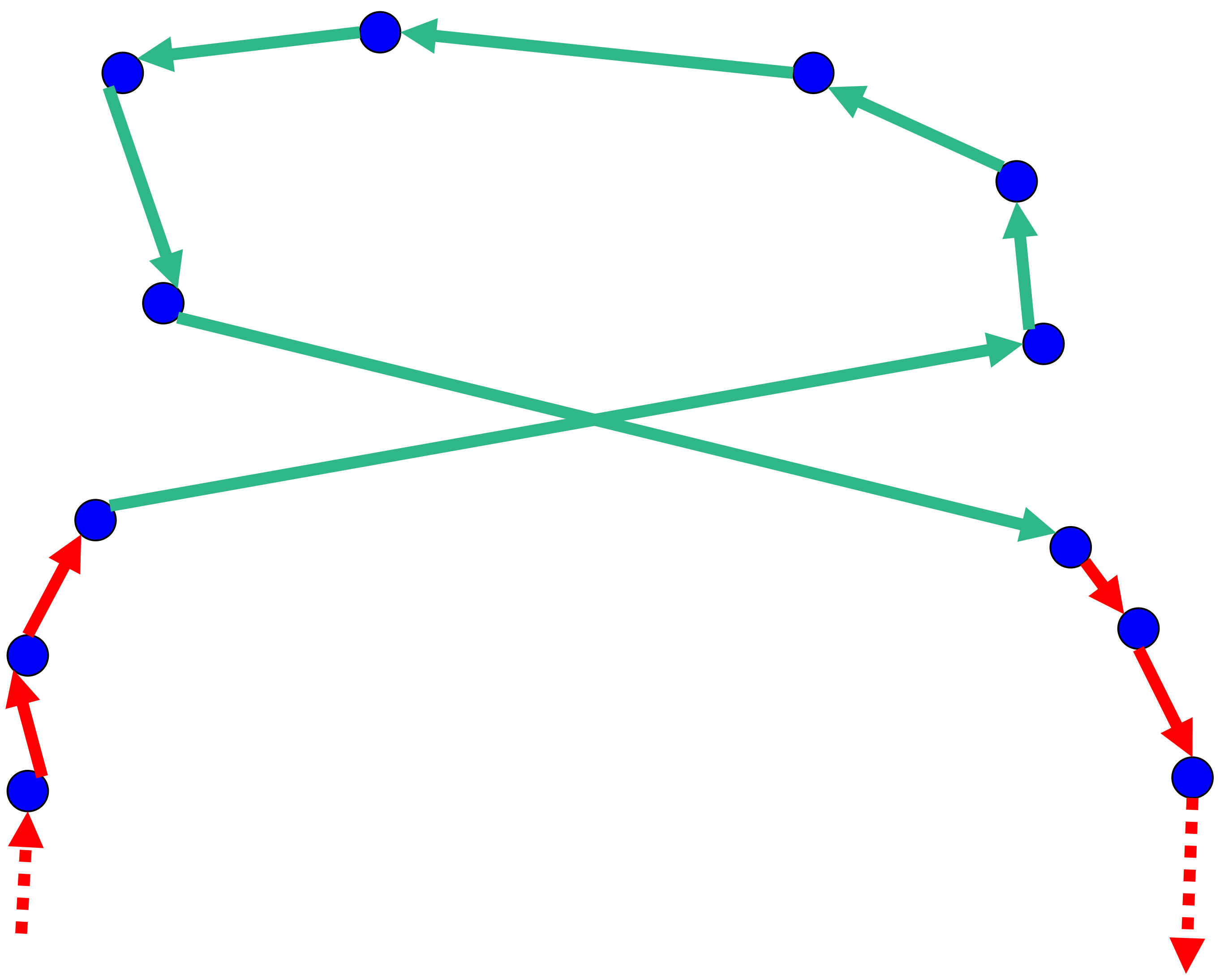
3-opt exchange



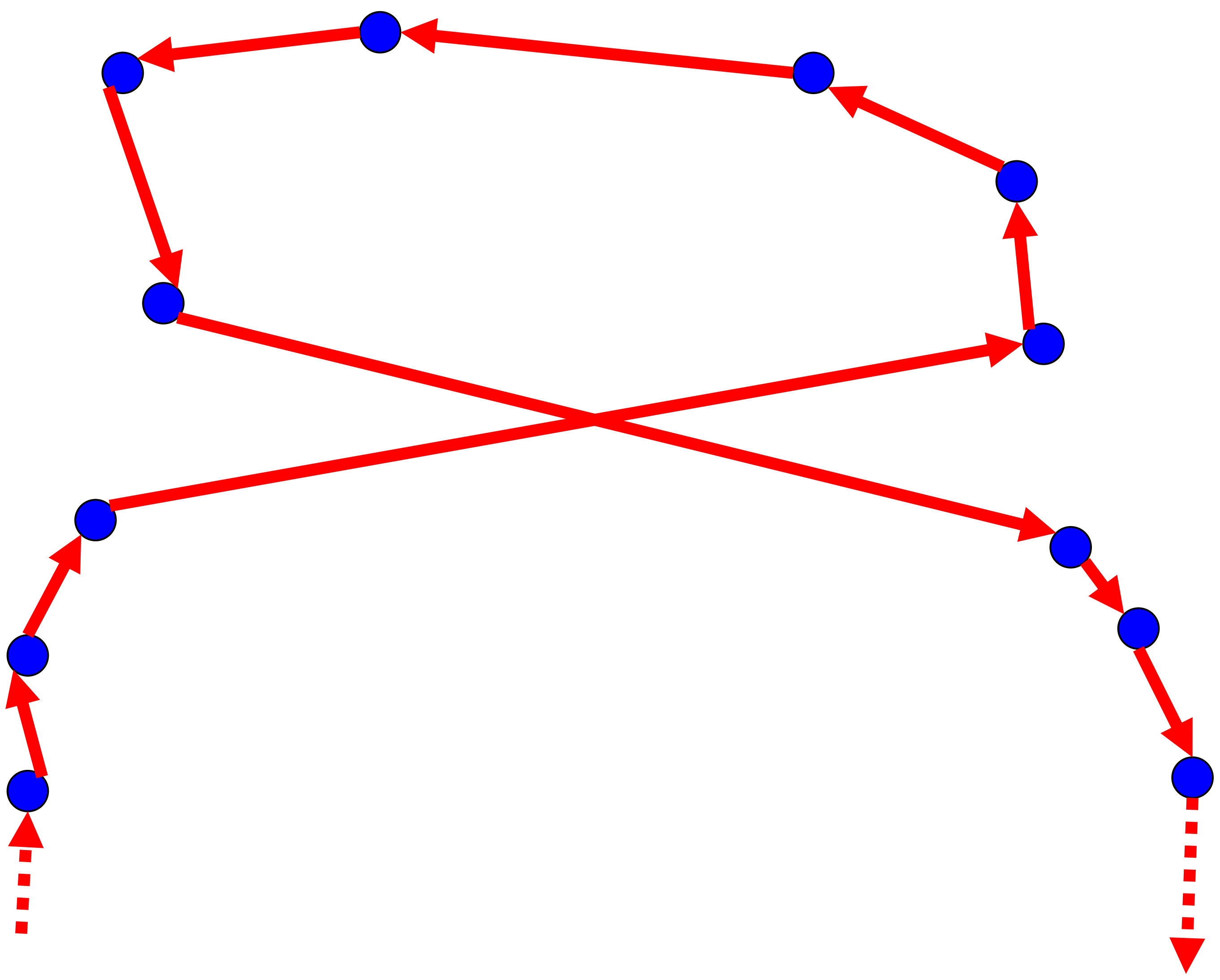
3-opt exchange



3-opt exchange



3-opt exchange



Other problems

Neighbourhoods for other problems

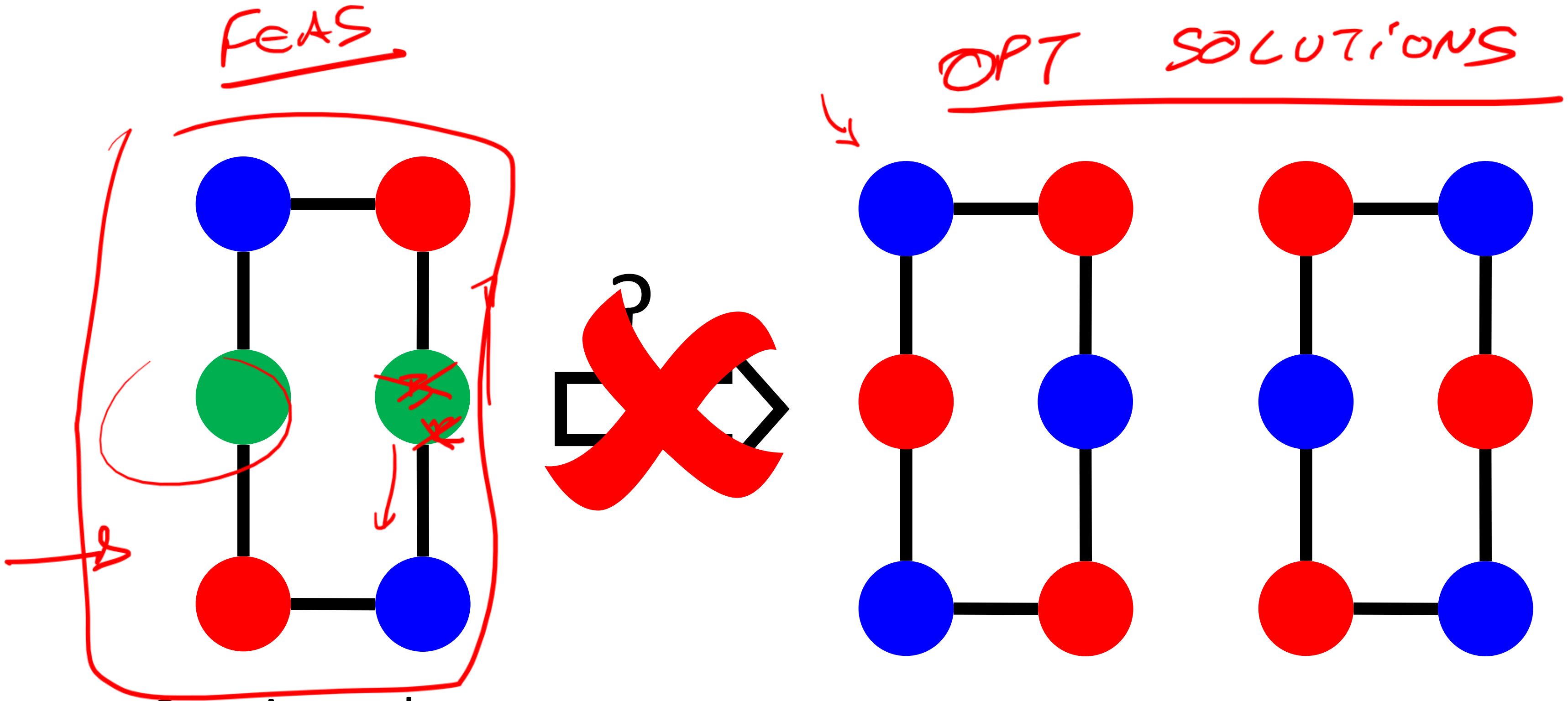
- Knapsack
  - Swap 2 items
  - Swap 1 item with multiple items of equal size

- Scheduling
  - Swap jobs between machines
  - Swap order of jobs

Neighbourhood

- E.g. Map Colouring (k-colouring)
  - Colour a map (graph) so that no two adjacent countries (nodes) are the same colour
  - Either:
    - Use at most k colours
    - Minimize number of colours

Map Colouring



Starting sol

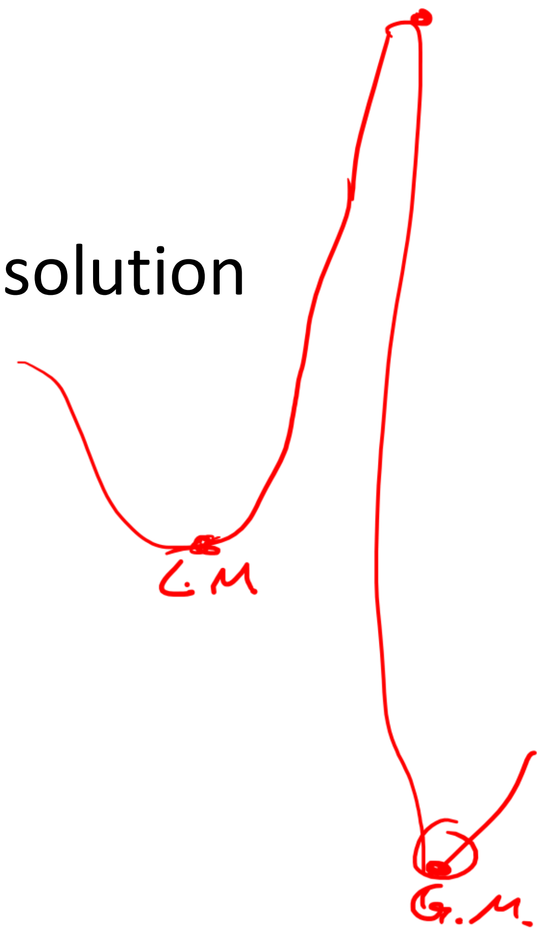
Two optimal solutions

Define neighbourhood as:

Change the colour of at most one vertex

Make k-colour constraint soft fixes this issue

Neighbourhood



- Hard constraints create impenetrable mountain ranges in solution space
- Soft constraints allow passes through the mountains

Strongly connected: MAP W/ 2-WAY STREETS ONLY

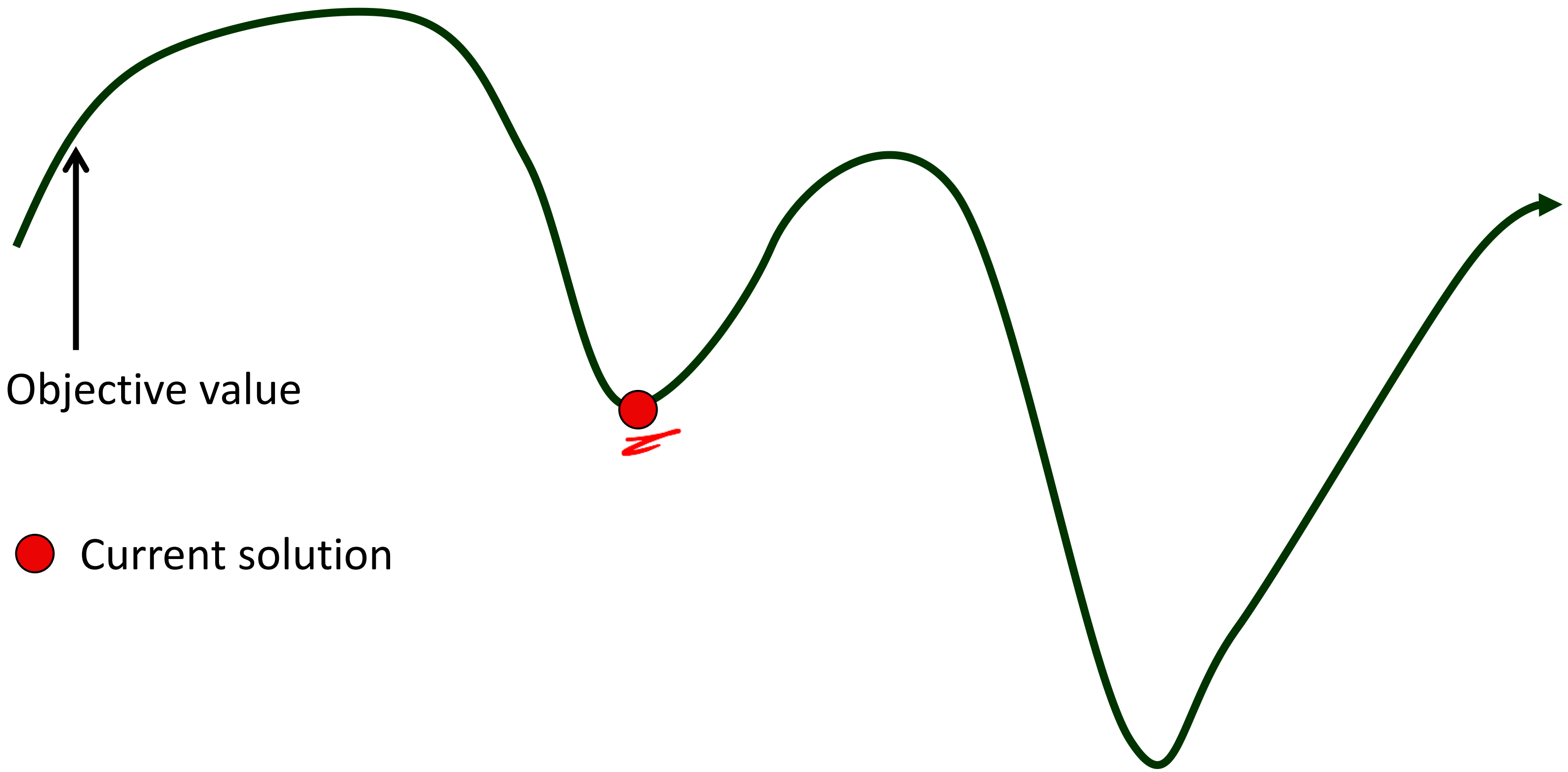
- Any solution can be reached from any other (e.g. 2-opt)

Weakly optimally connected MAP WITH SOME ONE-WAY STREETS

- The optimum can be reached from any starting solution

Problems with Local Search I

Local minima

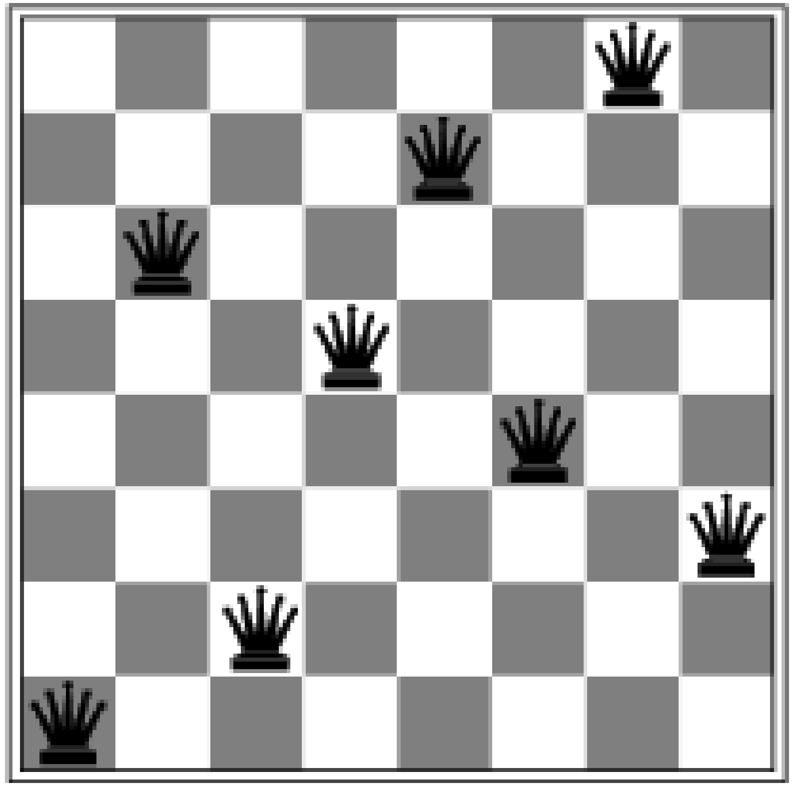


8 Queens

Hill-climbing search for 8-Queens

- Randomly generated 8-queens starting states…
- 14% the time it solves the problem
- 86% of the time it get stuck at a local minimum

- However…
  - Takes only 4 steps on average when it succeeds
  - And 3 on average when it gets stuck
  - (for a state space with 8^8 =~17 million states)



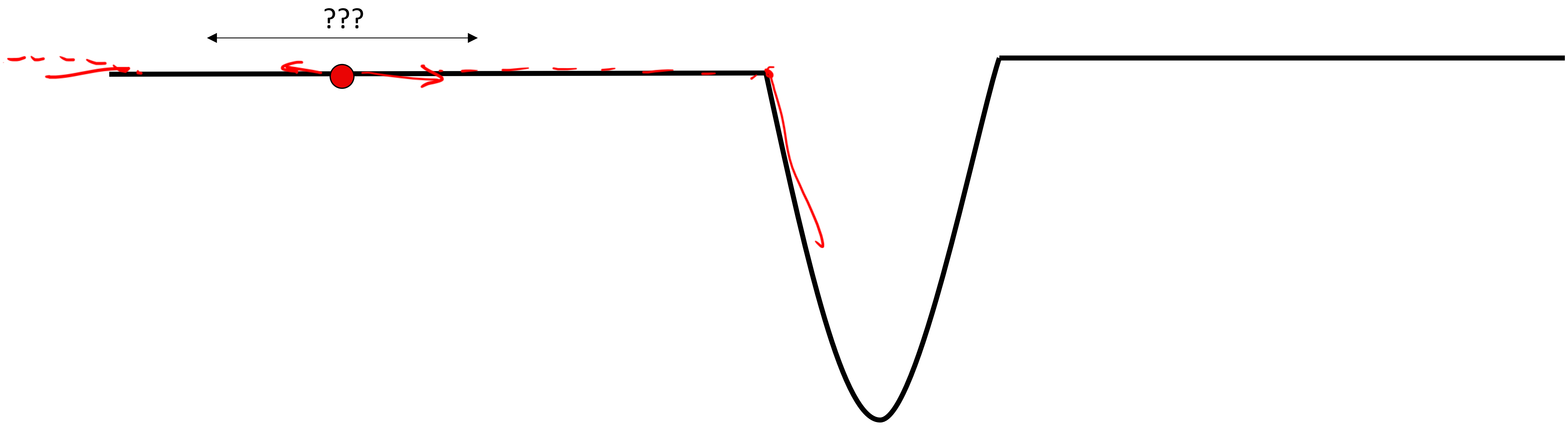
Escaping local minima

- Solution 1: Random Restarts
  - Whenever you hit a local minimum, generate a new {random / randomised} starting solution
  - This has proved very powerful on some problems
  - Particularly powerful is combination of randomised greedy + random restarts

3-SAT

Problems with Local Search II

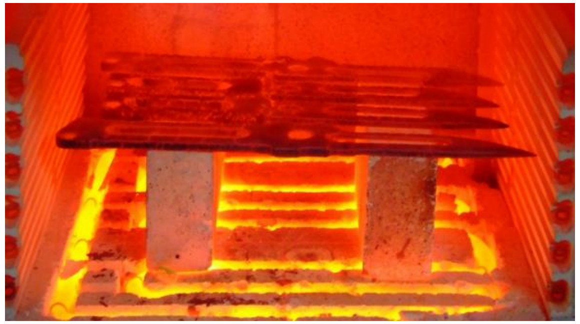
- Plateaux



Escaping Plateaux (Shoulders)

- If no downhill (uphill) moves, allow sideways moves in hope that algorithm can escape
  - Need to place a limit on the possible number of sideways moves to avoid infinite loops
- For 8-queens
  - Now allow sideways moves with a limit of 100
  - Raises percentage of problem instances solved from 14% to 94%
- However....
  - 21 steps on average for every successful solution
  - 64 for each failure 6%

Escaping local minima II



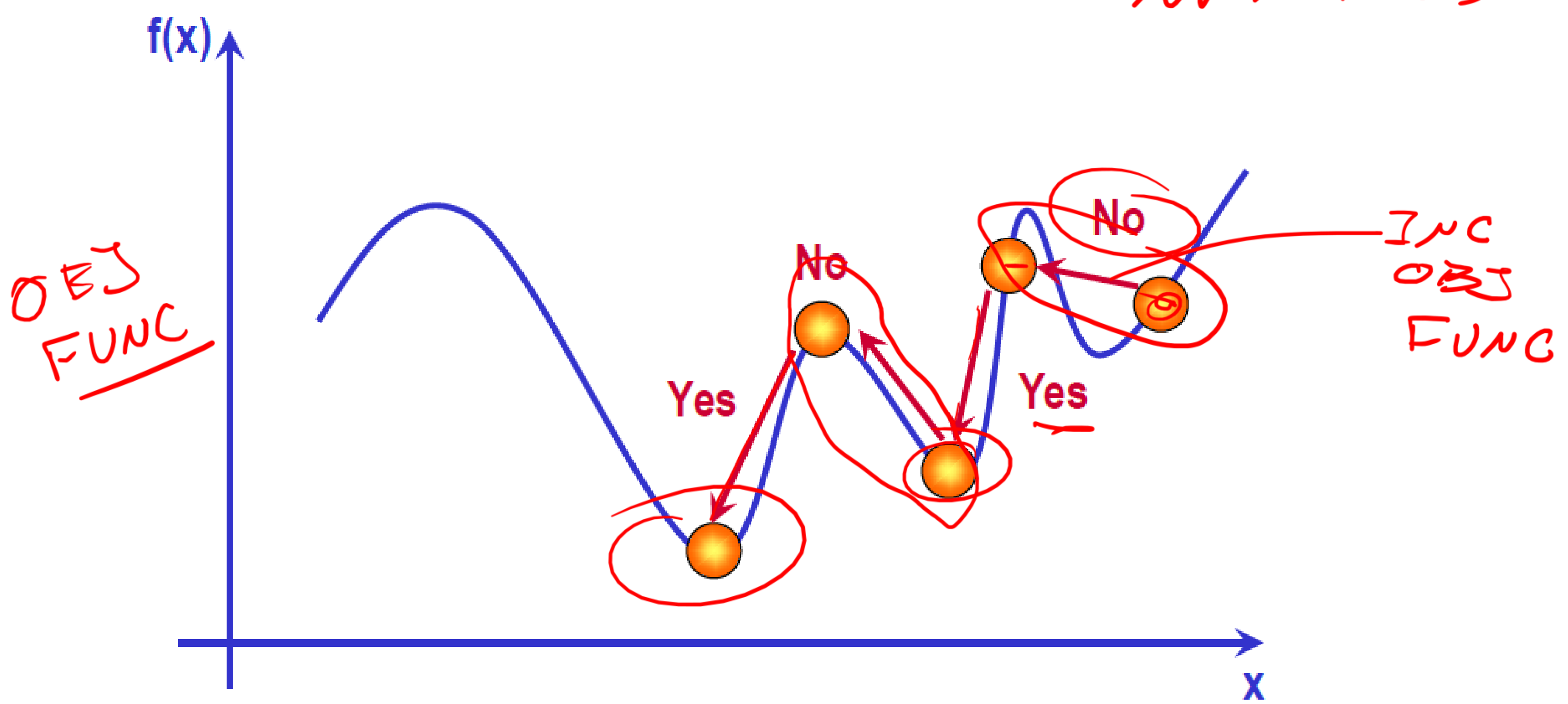
Solution 2: Simulated $\boxed{\text{Annealing}}$

- Based on manner in which crystals are formed
  - At high temperatures, molecules move freely
  - At low temperatures, molecules are "stuck"
- If cooling is slow
  - A low energy, organized crystal lattice formed

- Minimise energy in crystal ⟺ Minimise objective

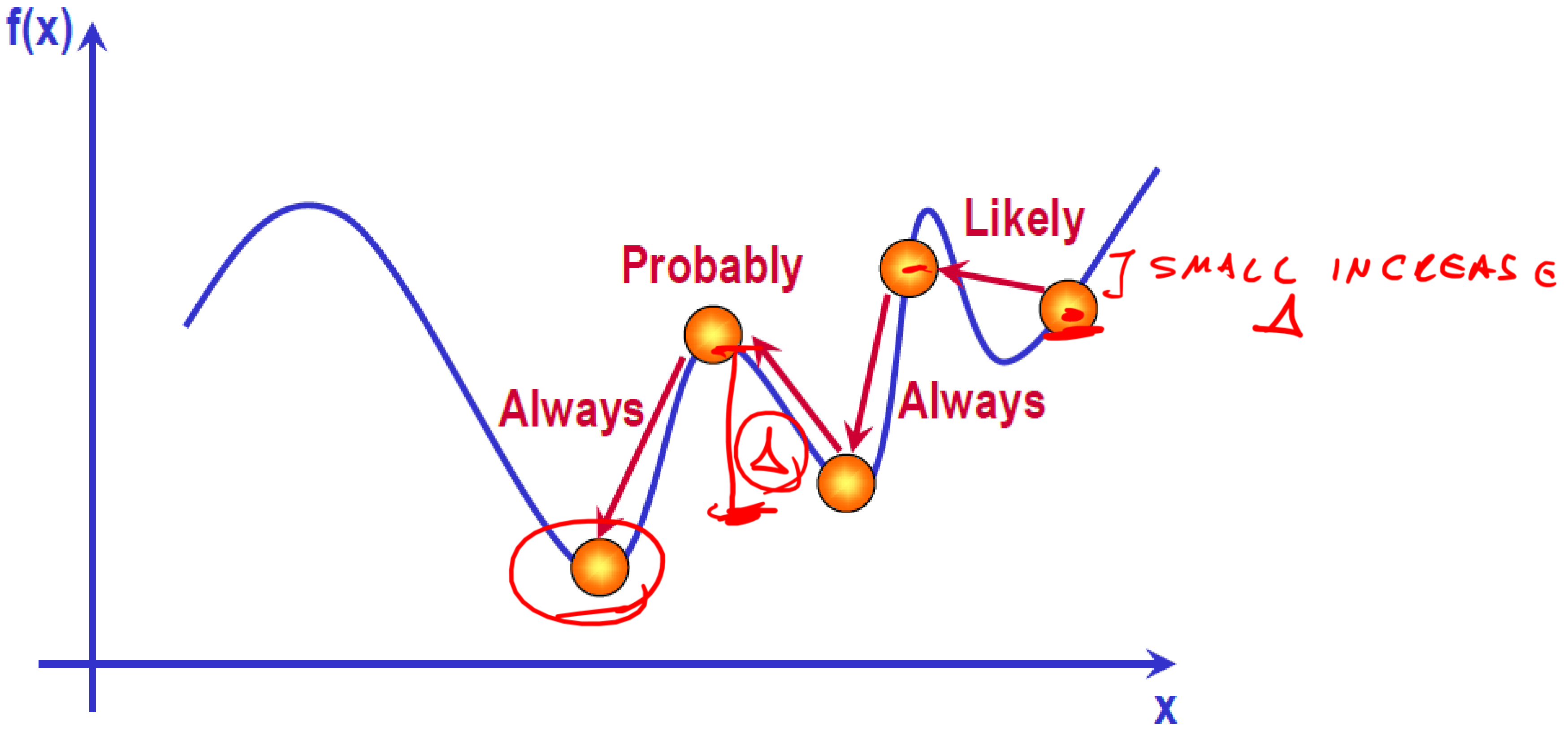
Simulated Annealing

MIN PROB



Greedy local search reduces objective at every iteration

Simulated Annealing



Simulated Annealing accepts/rejects solution candidate based on probability

Simulated Annealing

If candidate solution reduces the objective,

- always accept the change (c.f. first found)

If candidate solution has higher objective,

- system parameter *T* (*"Temperature"*) controls probability of acceptance

$$P(accept\ increase\ of\ \Delta\ in\ objective) = \boxed{e^{-\Delta/T}}$$

- *T* reduces as method proceeds
- As *T* → 0, only improving moves accepted

Simulated Annealing

- Nice theoretical result:

  As number of iters → ∞, probability of finding the optimal solution → 1

- Experimental confirmation: on many problem, long runs yield good results

- Weak optimal connection required ← 7%. OF SEARCH SPACE

Simulated Annealing

Initial T

- Set equal to max [acceptable] Δ

Updating T

- Geometric update: $\boxed{T_{k+1} = \alpha\, T_k}$
- α usually in [0.9, 0.999]

Don't want too many changes at one temperature (too hot):

```
If (numChangesThisT > maxChangesThisT)
    updateT()
```

Simulated Annealing

Updating T

- Many other update schemes

Re-boil (== Restart)

- Re-initialise T

0-cost changes

- Handle randomly

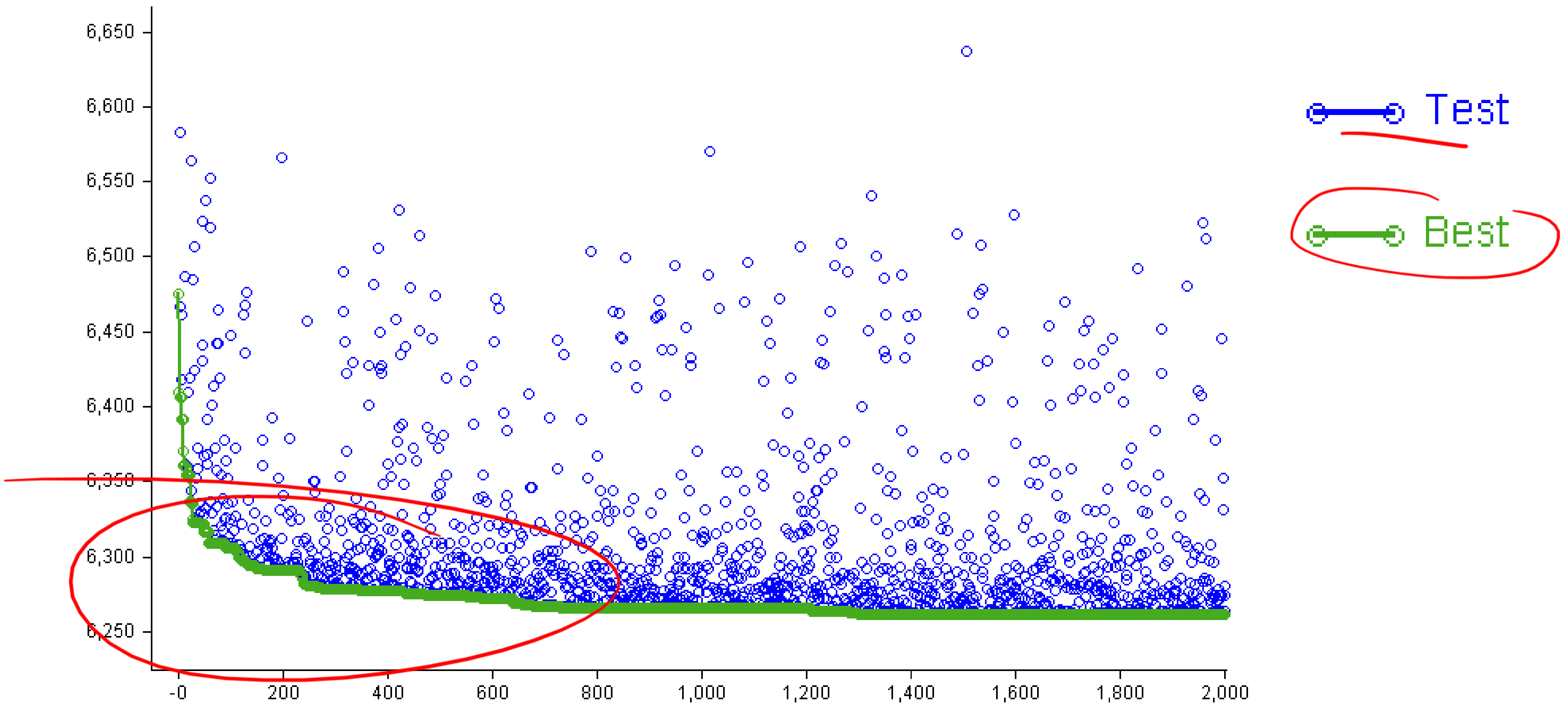
PLATEAU

Adaptive parameters

- If you keep falling into the same local minimum,
  - `maxChangesThisT *= 2, or initialT *= 2`

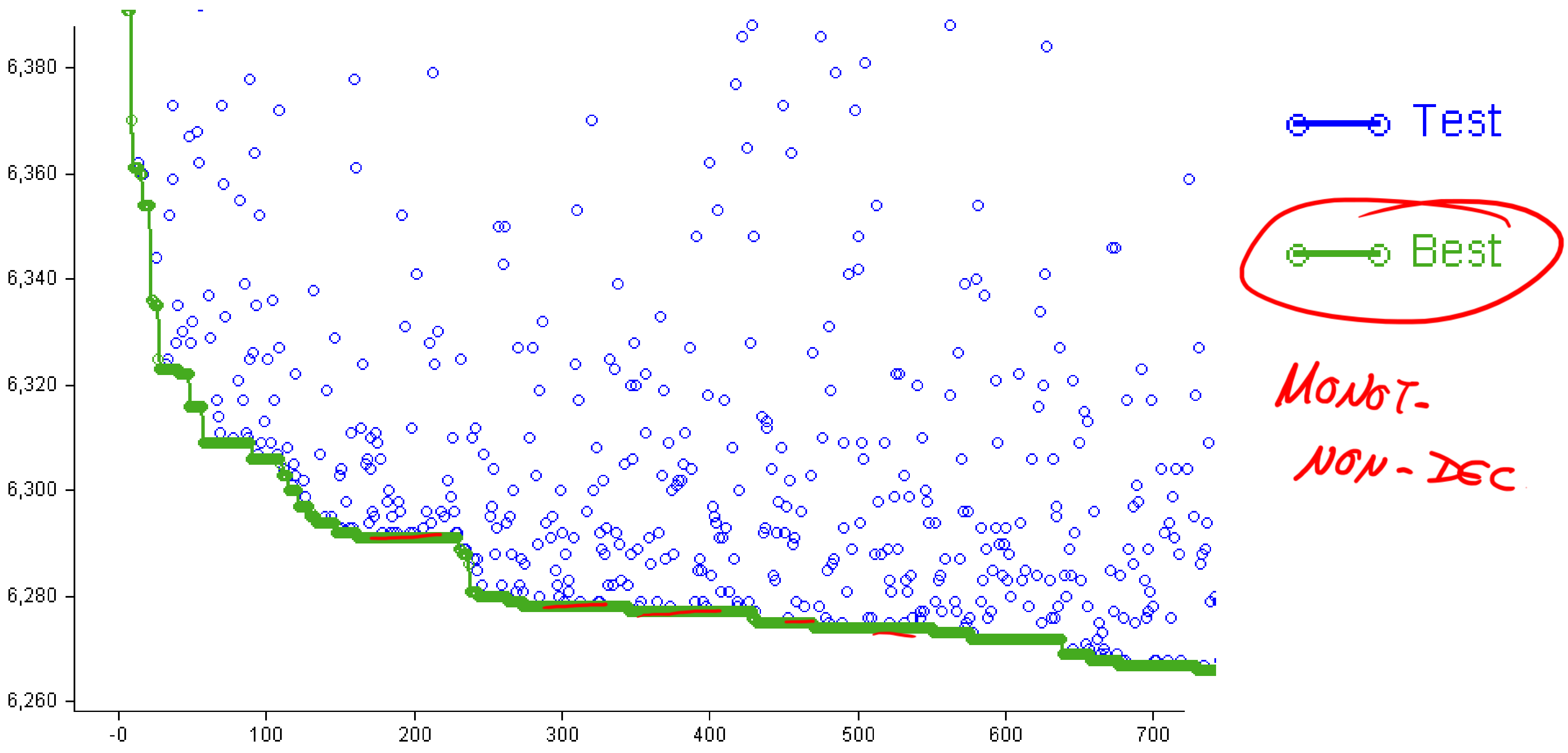
VRP – Greedy Search

Hill Climbing

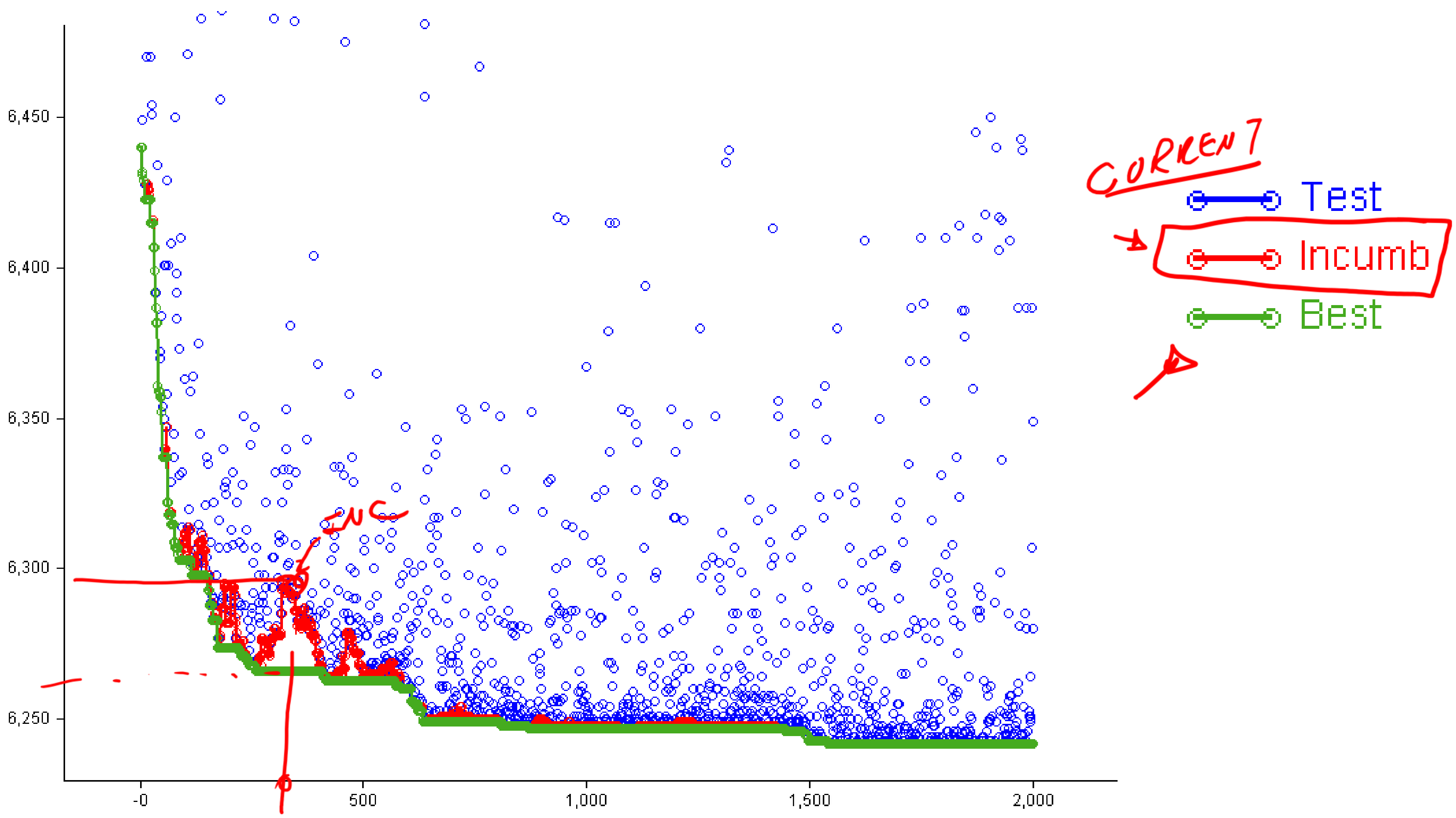


VRP – Greedy Search

Zoom in on the first 700 iterations

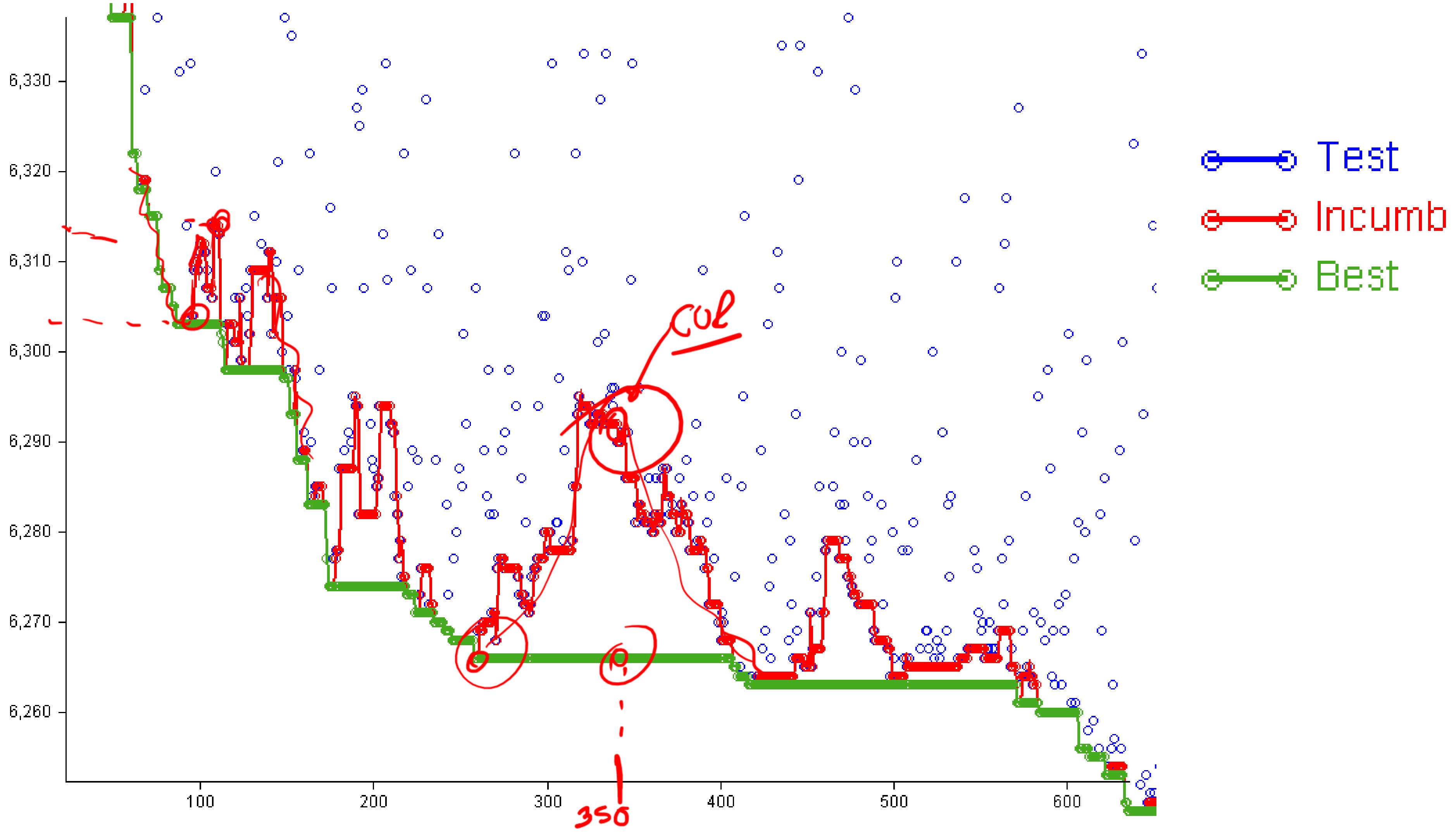


VRP – Simulated Annealing



VRP – Simulated Annealing

Zoom in on the first 600 iterations



Summary

- We have defined Local Search in terms of a *Neighbourhood* defined by an operator
- We have seen several ways of moving through the search space
  - Greedy, Random, Randomised Greedy, …
- We have seen some features of the solution space can mess up local search
  - Disconnected spaces, Plateaux, Local minima, …
- We have seen how to try to alleviate these problems
  - Sideways moves, Restarts, Simulated Annealing, …

Summary

Simulated Annealing is an example of a *meta-heuristic*

CONTROLLING HEURISTIC

- A heuristic that applies to heuristics

Next week

- More meta-heuristics