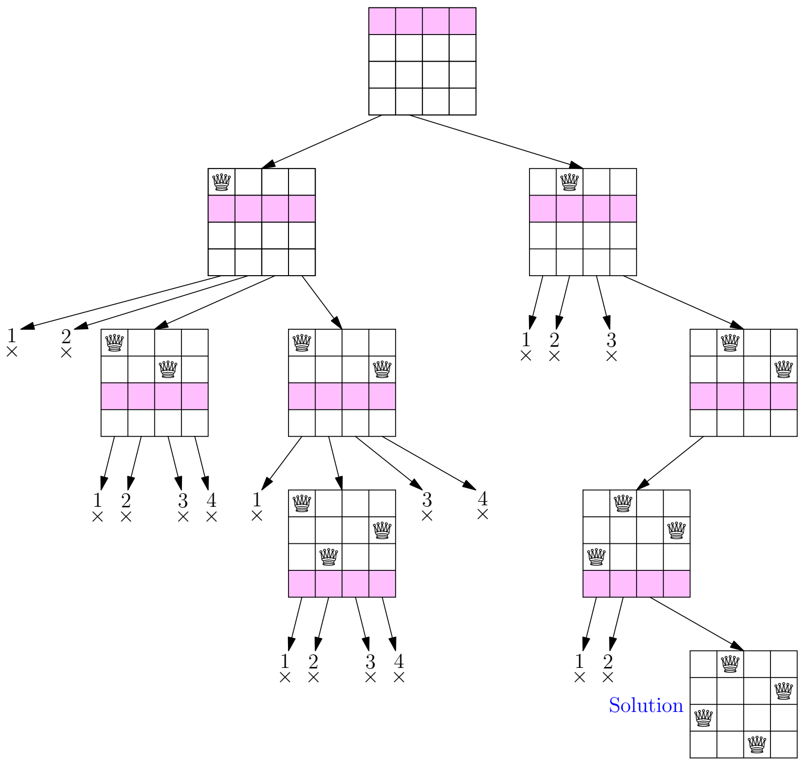
Algorithms and Analysis

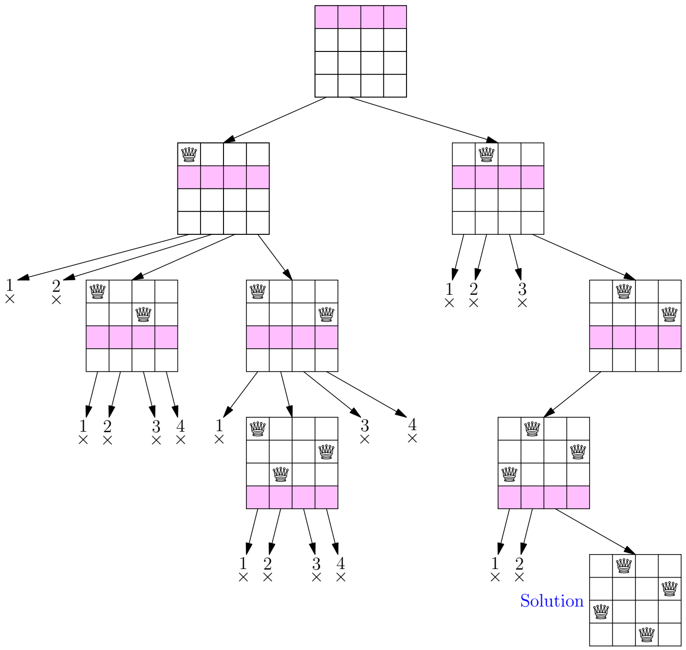
Lesson 22: *Know how to Search*



Backtracking, Branch and Bound

Outline

1. **Search Trees**
2. Backtracking
3. Branch and Bound
4. Search in AI



State Space Representation

- Many real world problems involve taking a series of actions to manipulate the state of the system
- This is the area of planning and search which sits within the domain of artificial intelligence
- One of the key props to help us develop algorithms is to think of the states as nodes of a graph which are linked if there exists an action taking us from one state to another
- This provides a **state space representation** of the problem (we saw this before when we derived a low bound on sorting)

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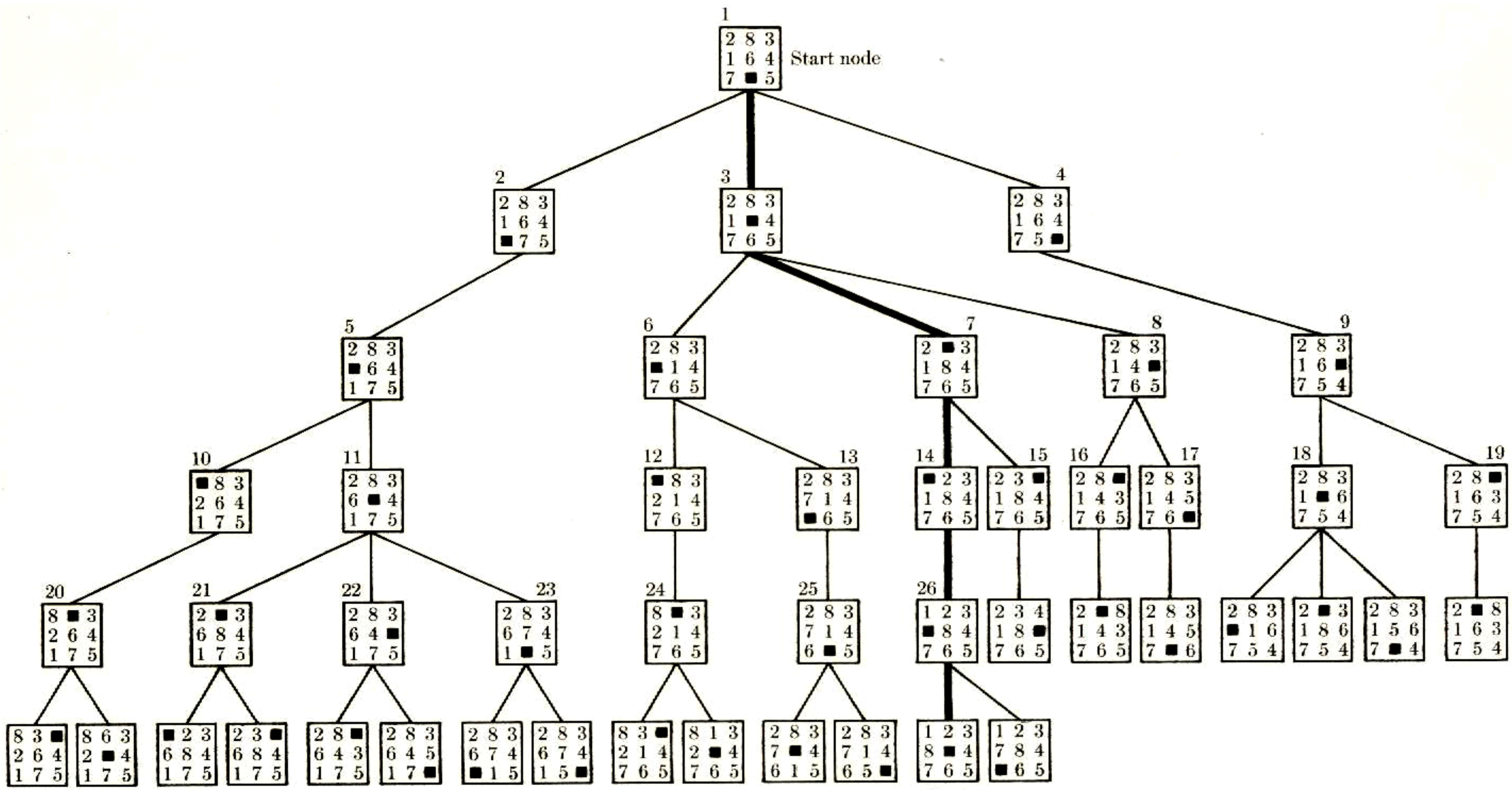
8-Puzzle Example



Large State Spaces

- The search space typically increase exponentially with the problem size
- We can find the quickest solution to the 8-puzzle (and the 15 puzzle) using breadth first search, but larger puzzles soon become intractable
- Nevertheless, a lot of important problems involve very large state spaces and we have to find algorithms to explore them

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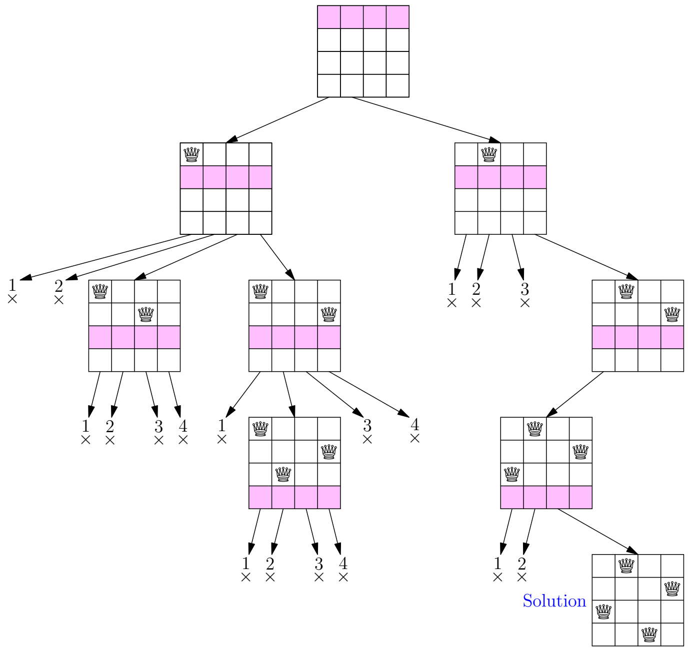

Backtracking

- Backtracking is used to find feasible solutions in large state spaces
- E.g. solving sudoku
- It works by growing partial solutions until either
  - ⋆ a feasible solution is found when we can finish
  - ⋆ no feasible solution is found when we backtrack
- We often search the state space using depth first search

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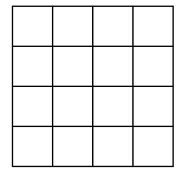

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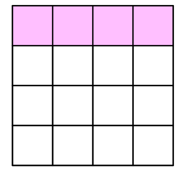

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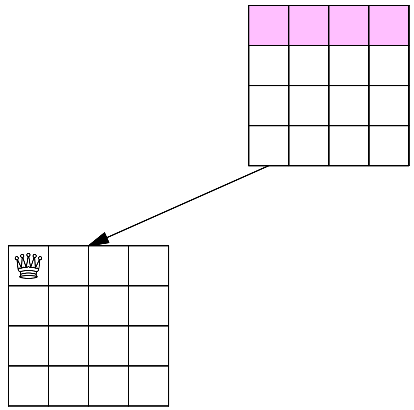

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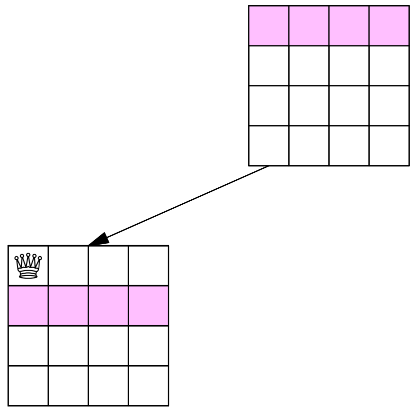

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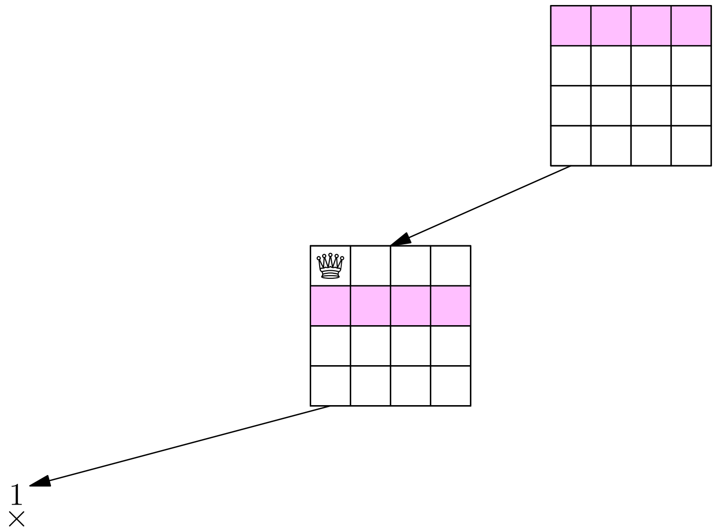

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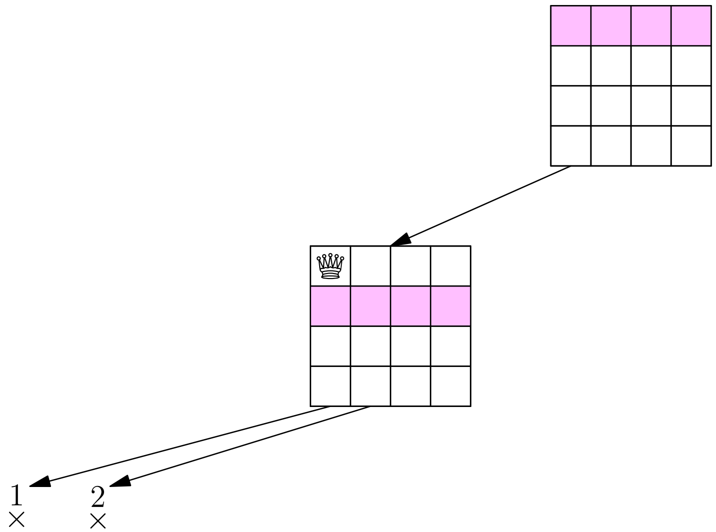

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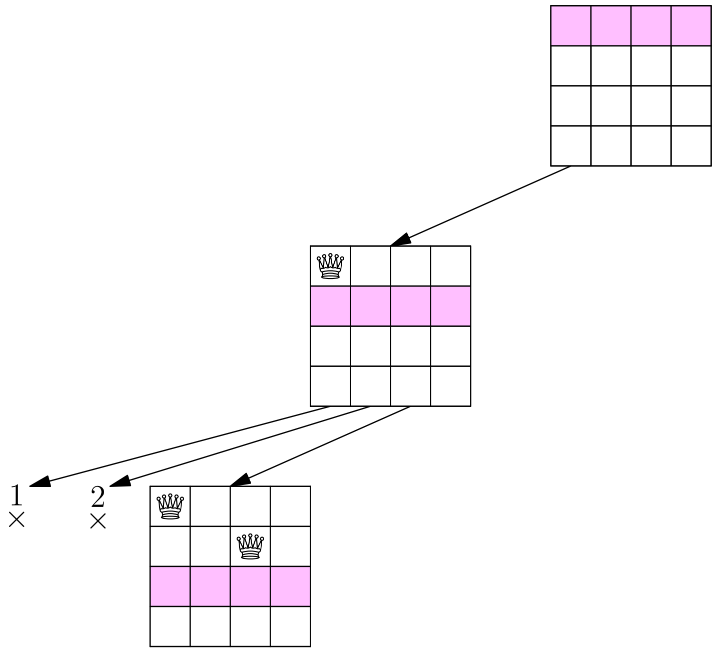

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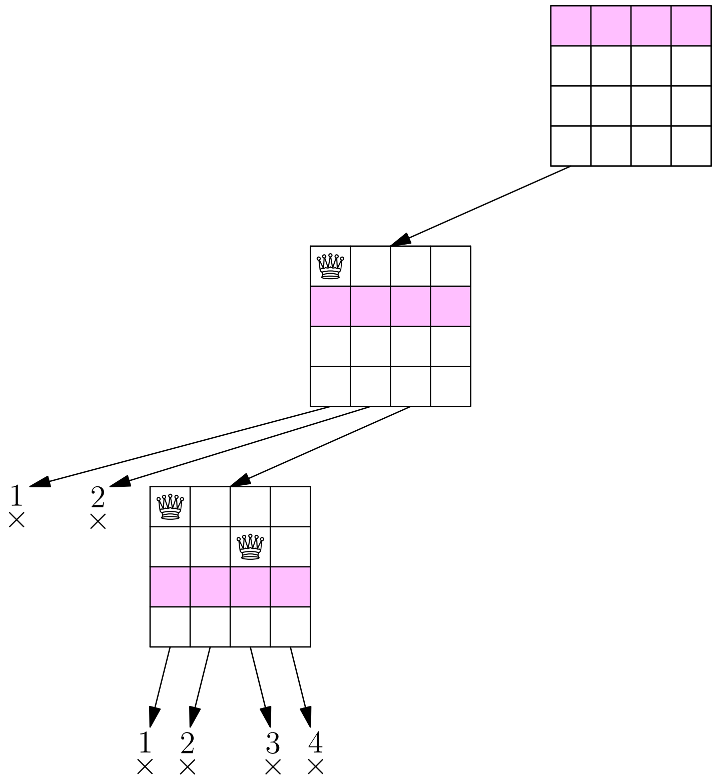

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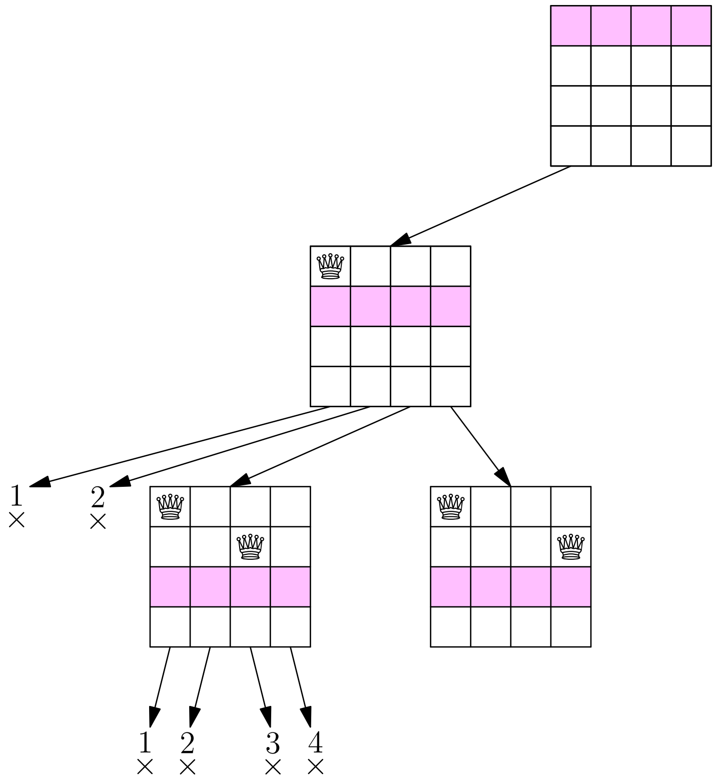

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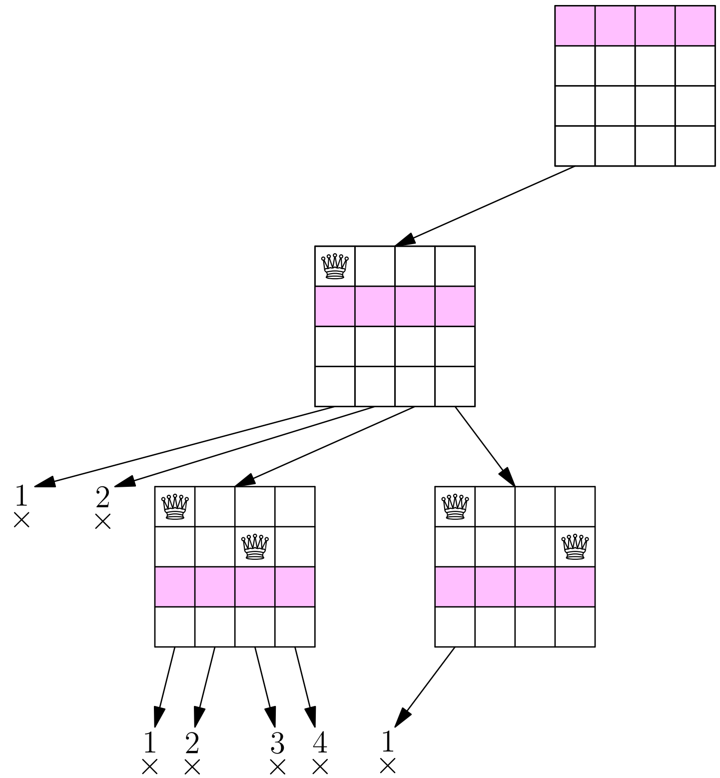

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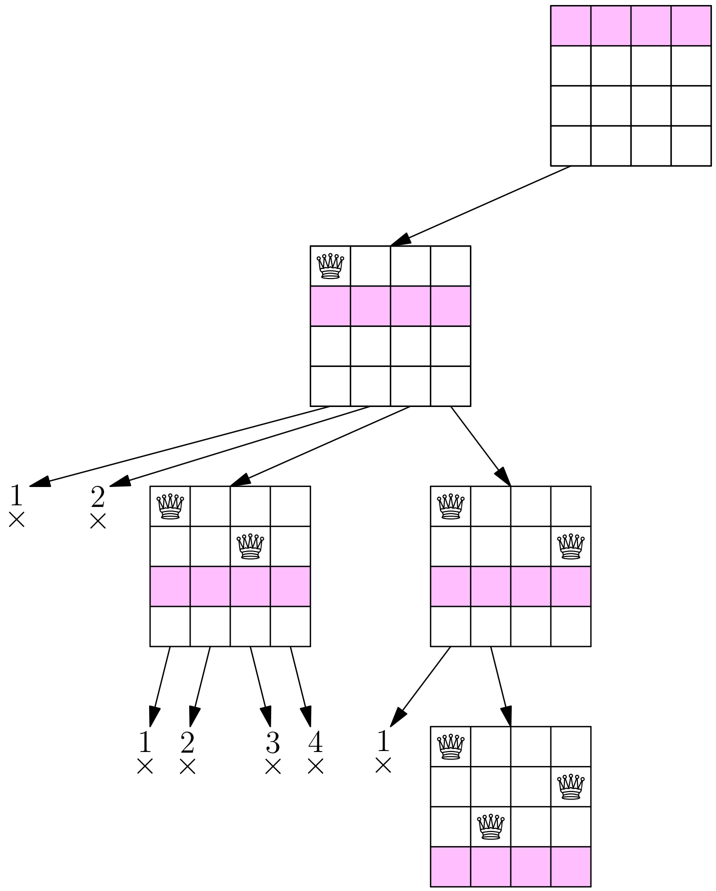

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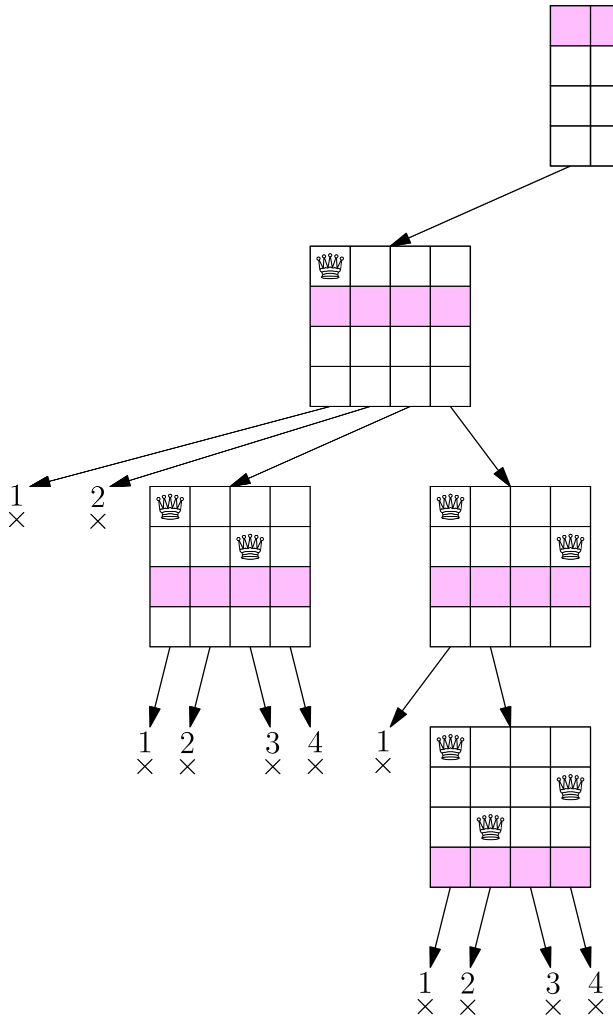

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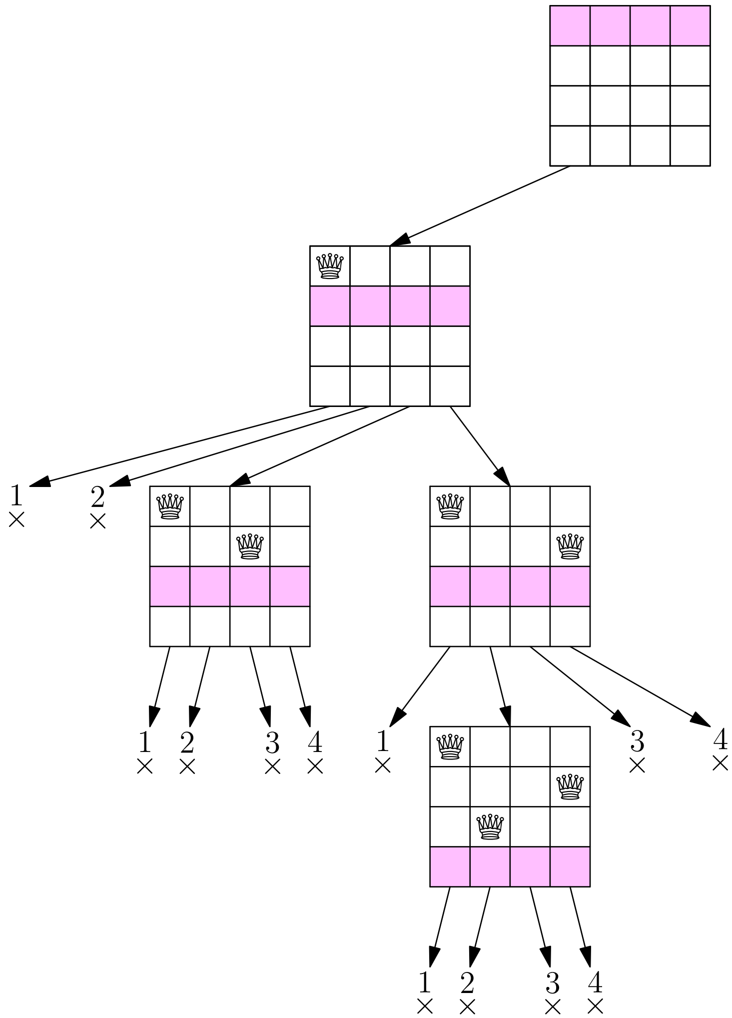

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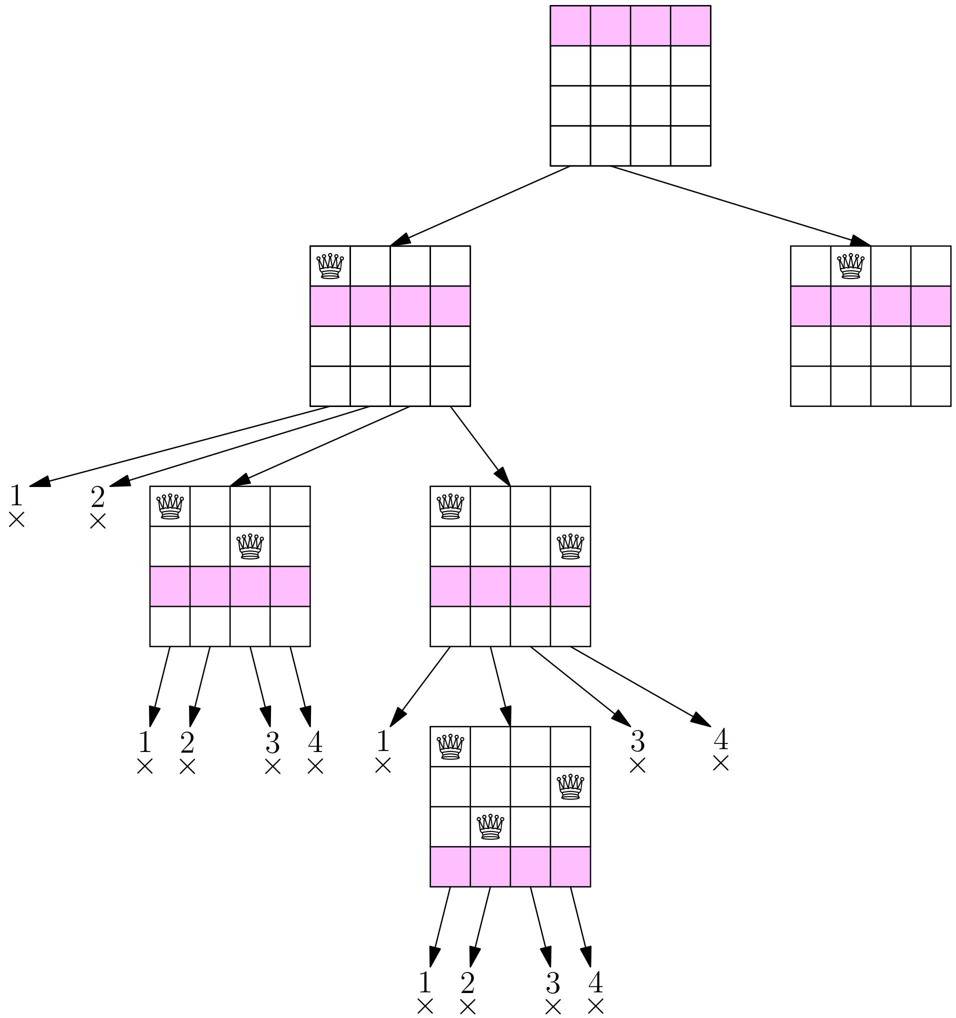

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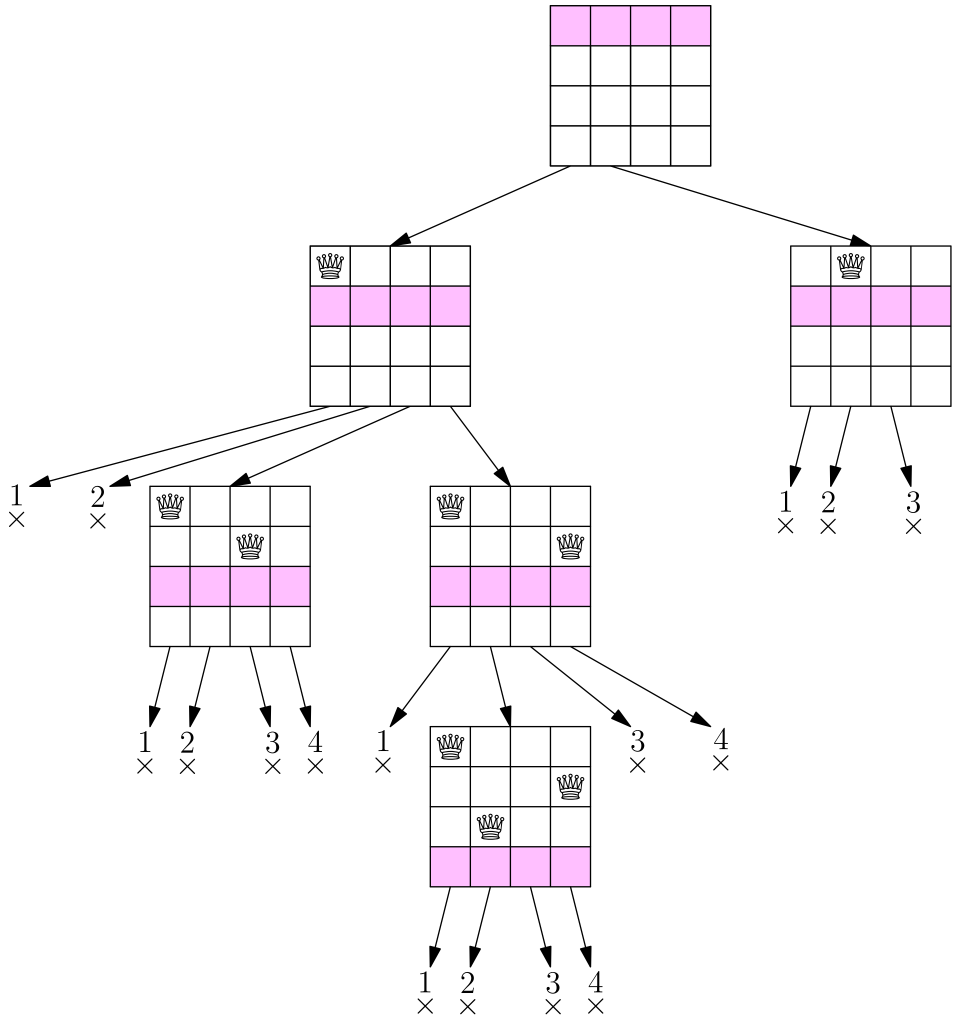

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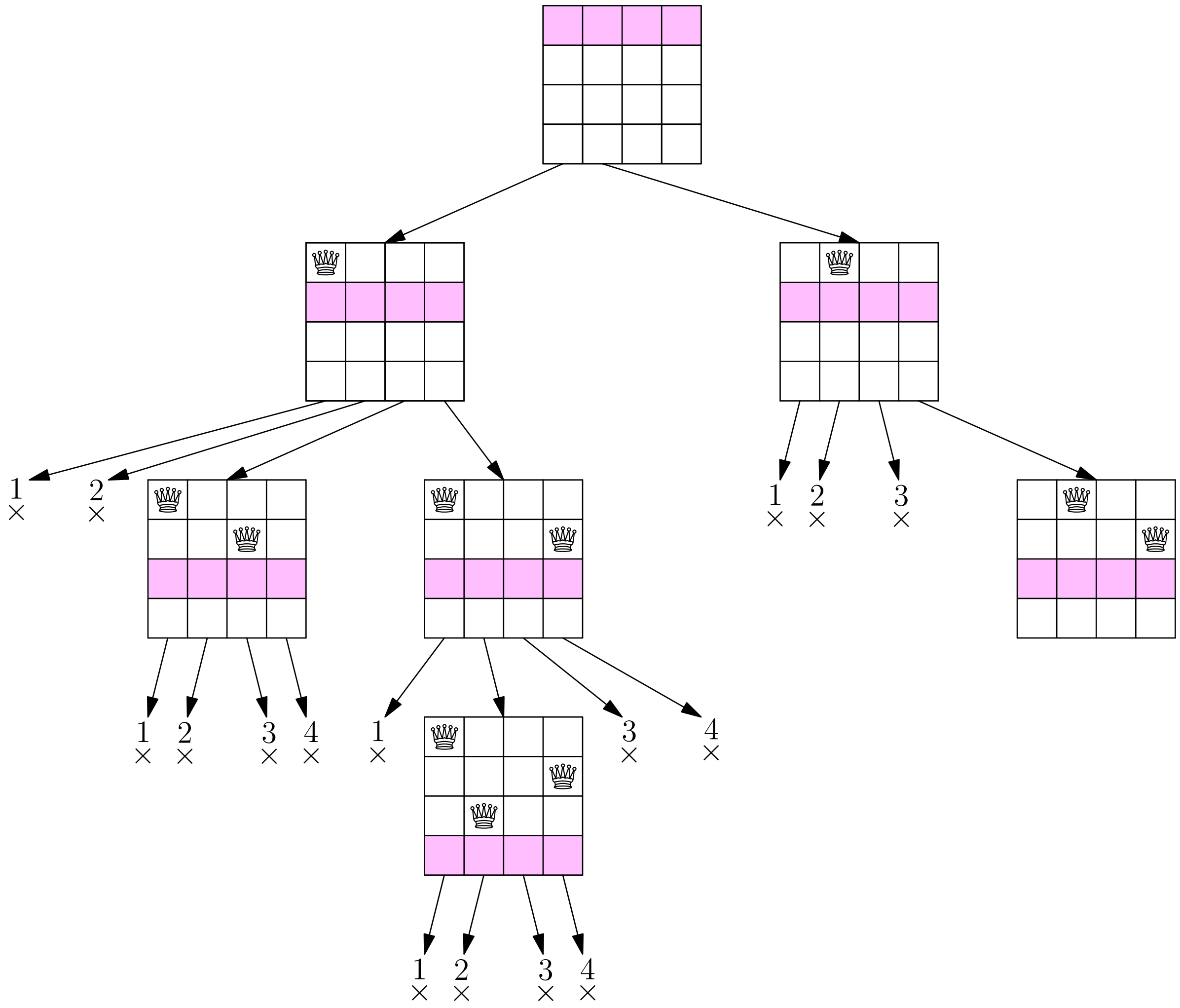

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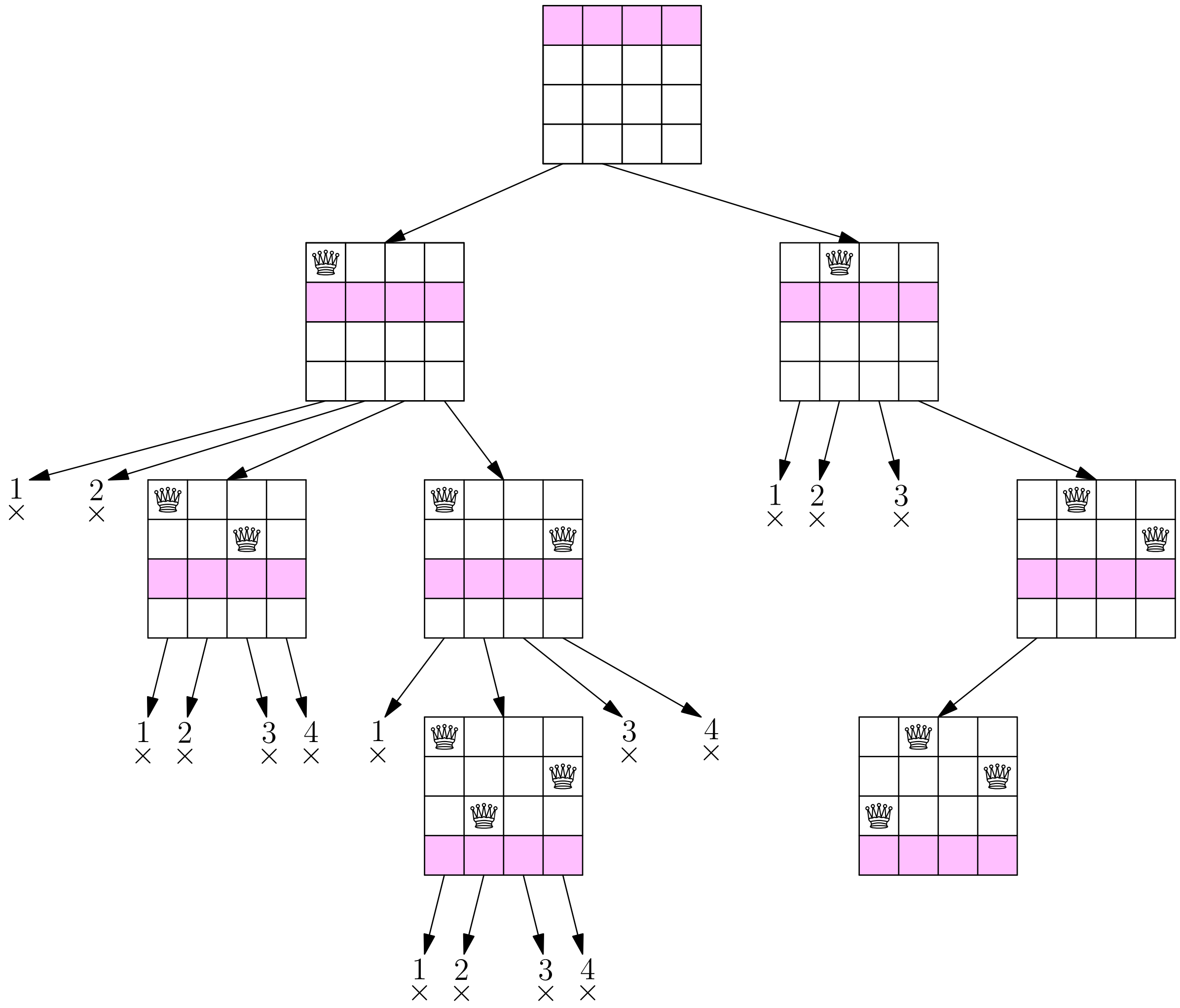

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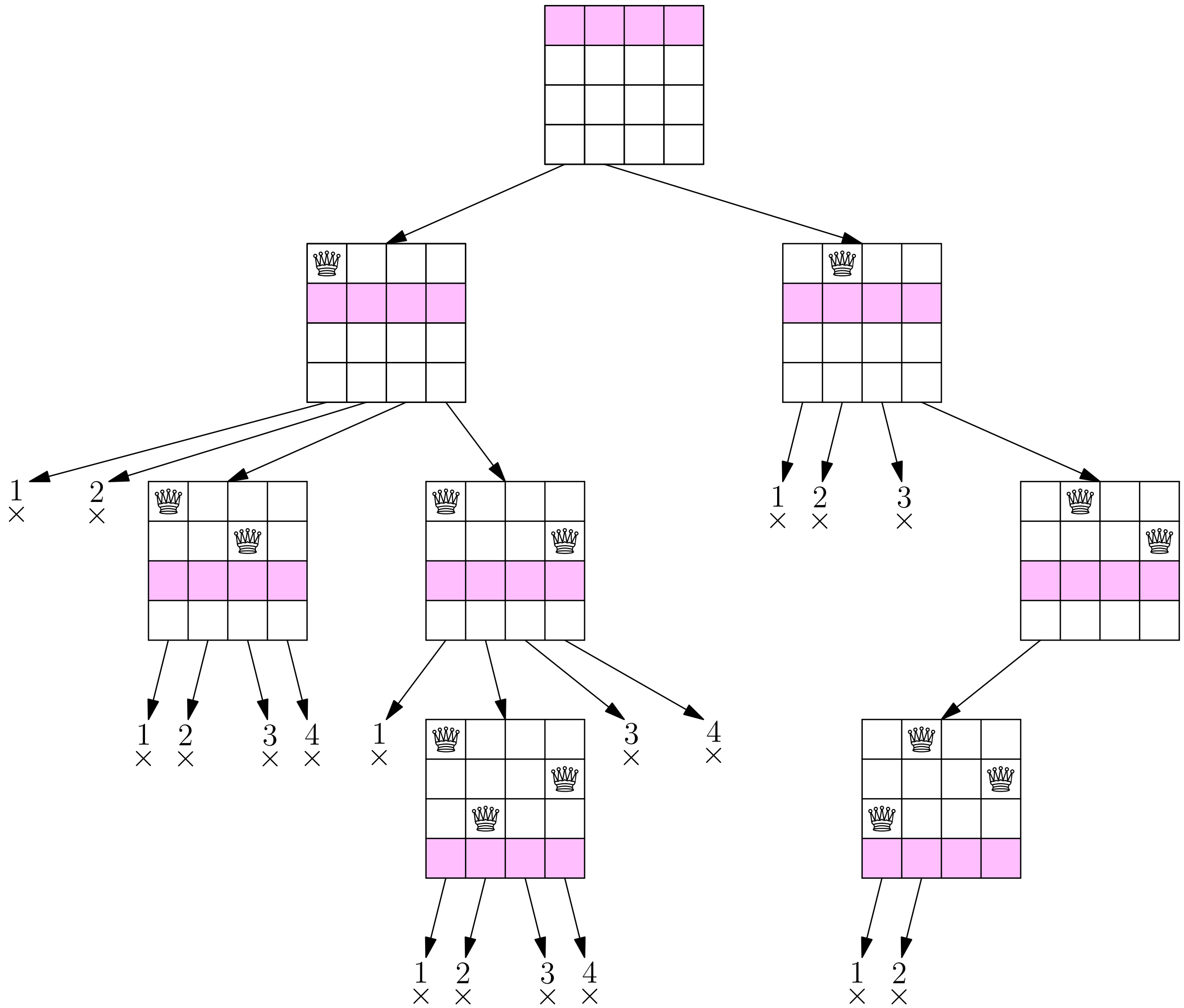

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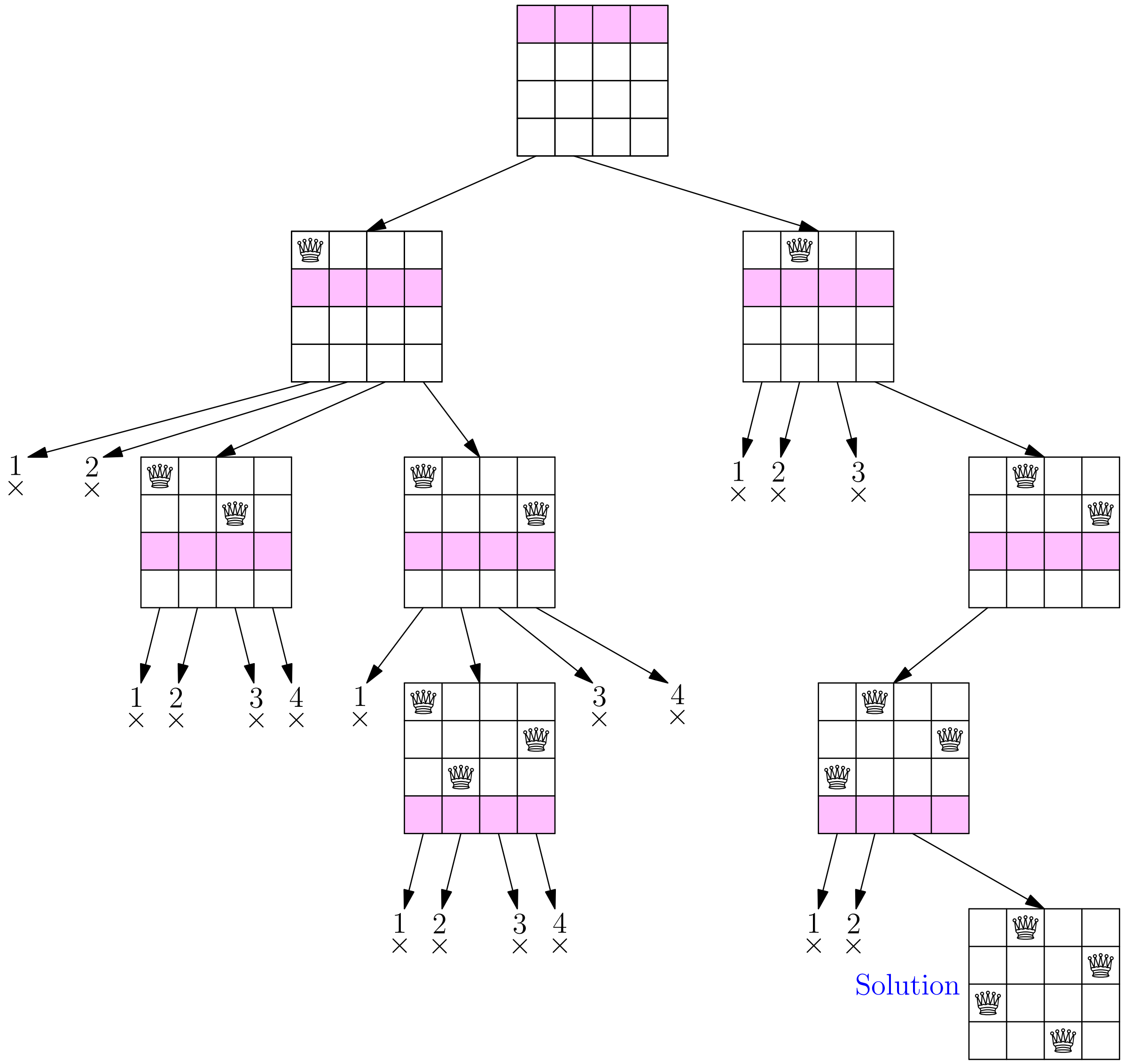

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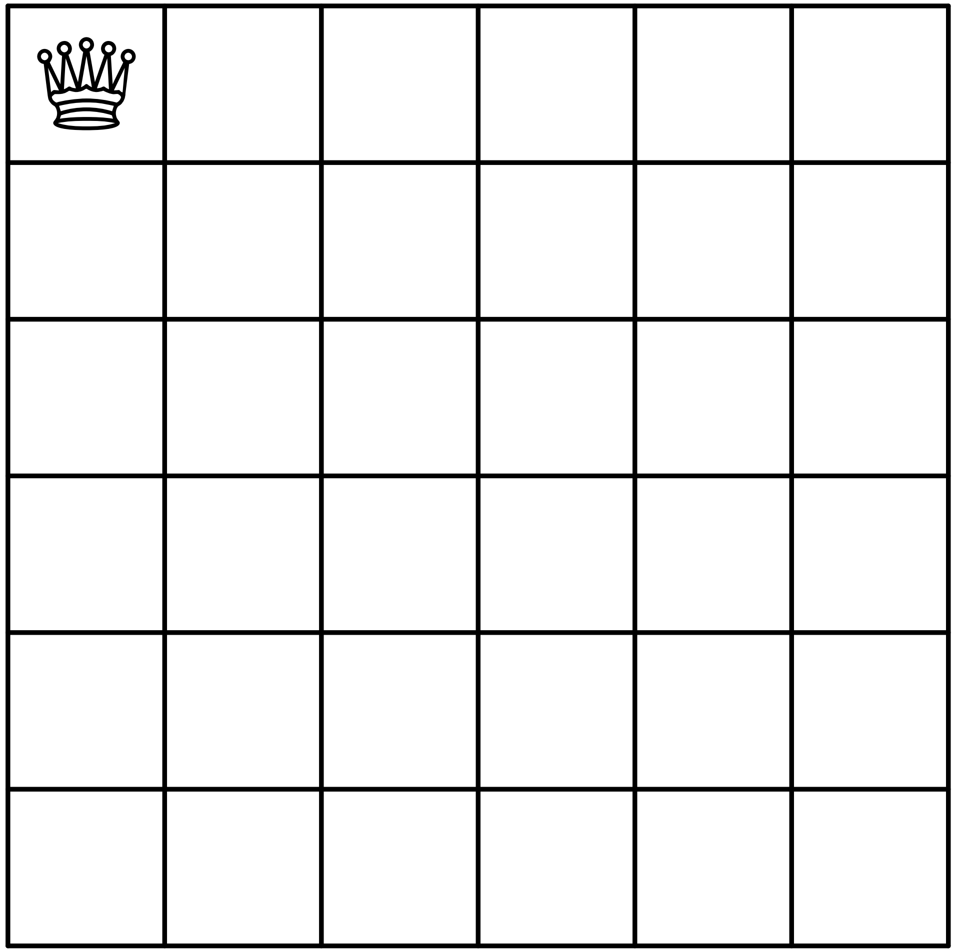

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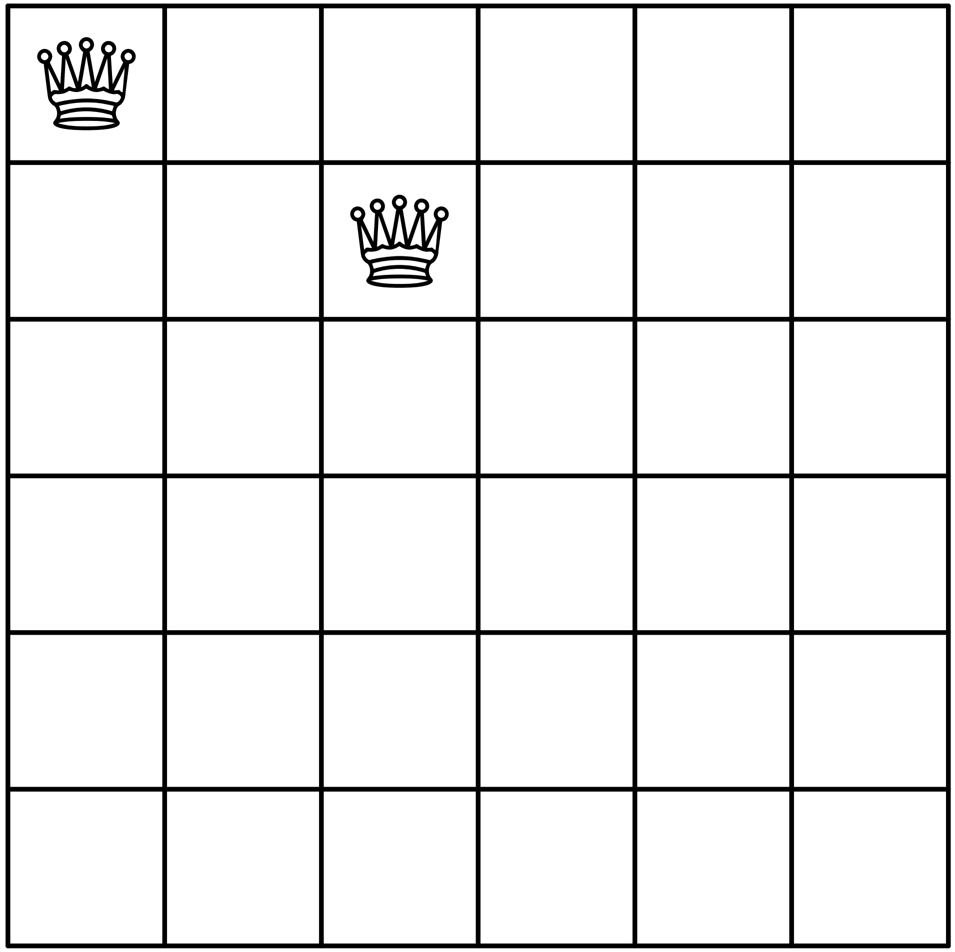

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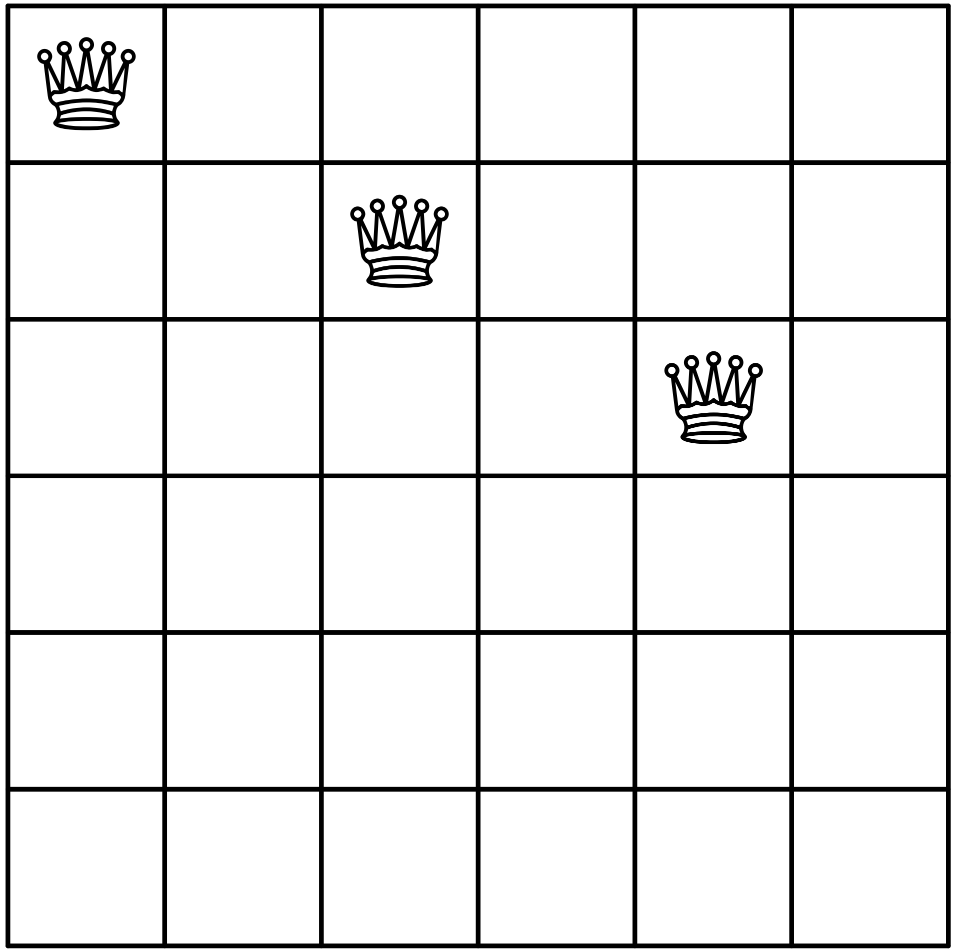

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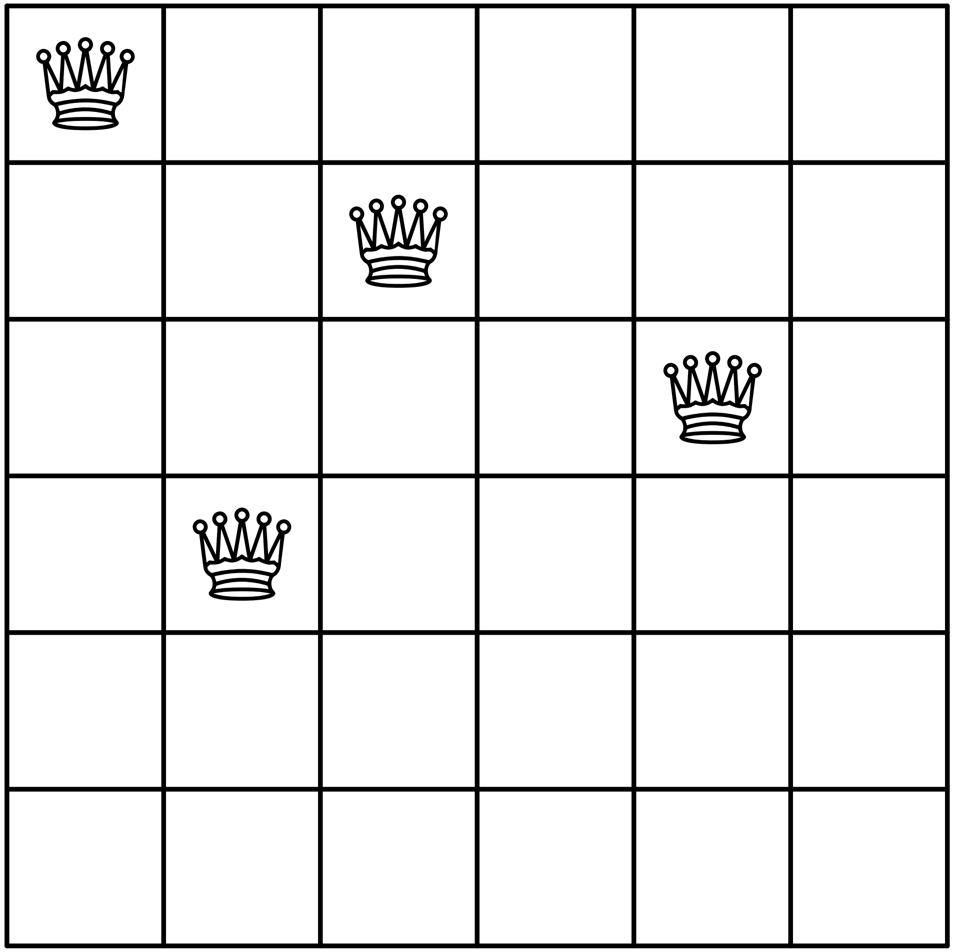

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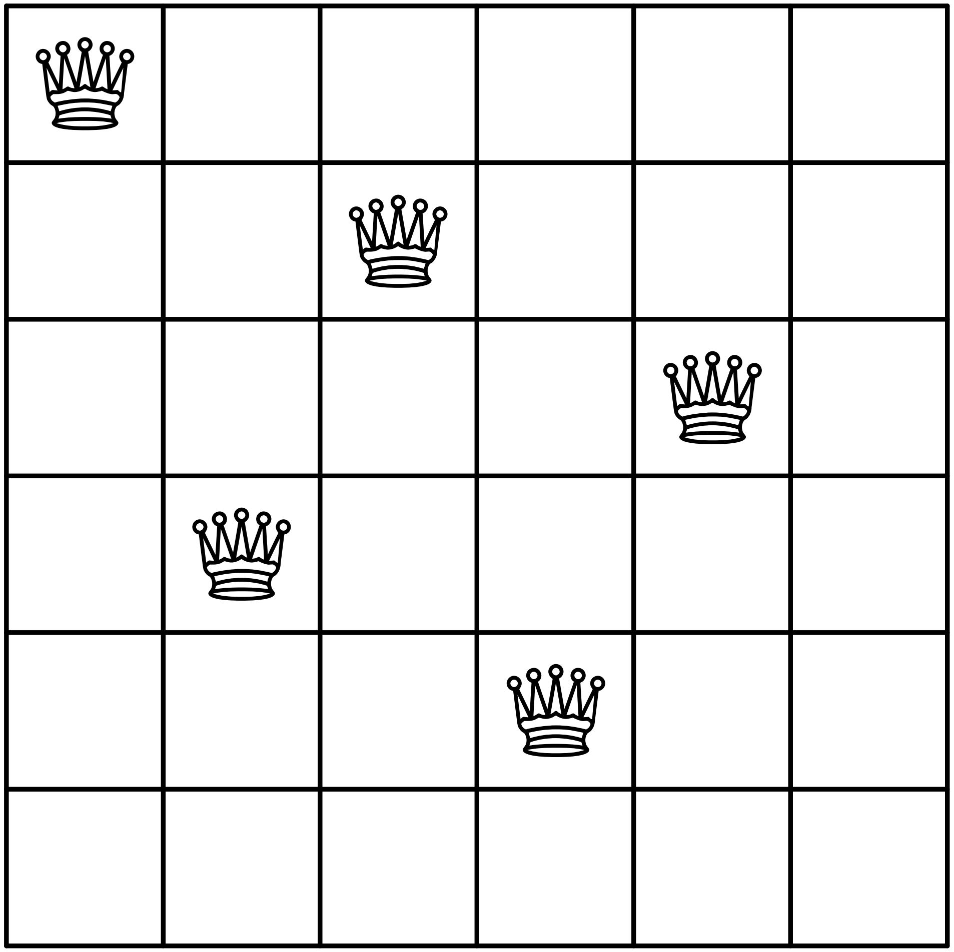

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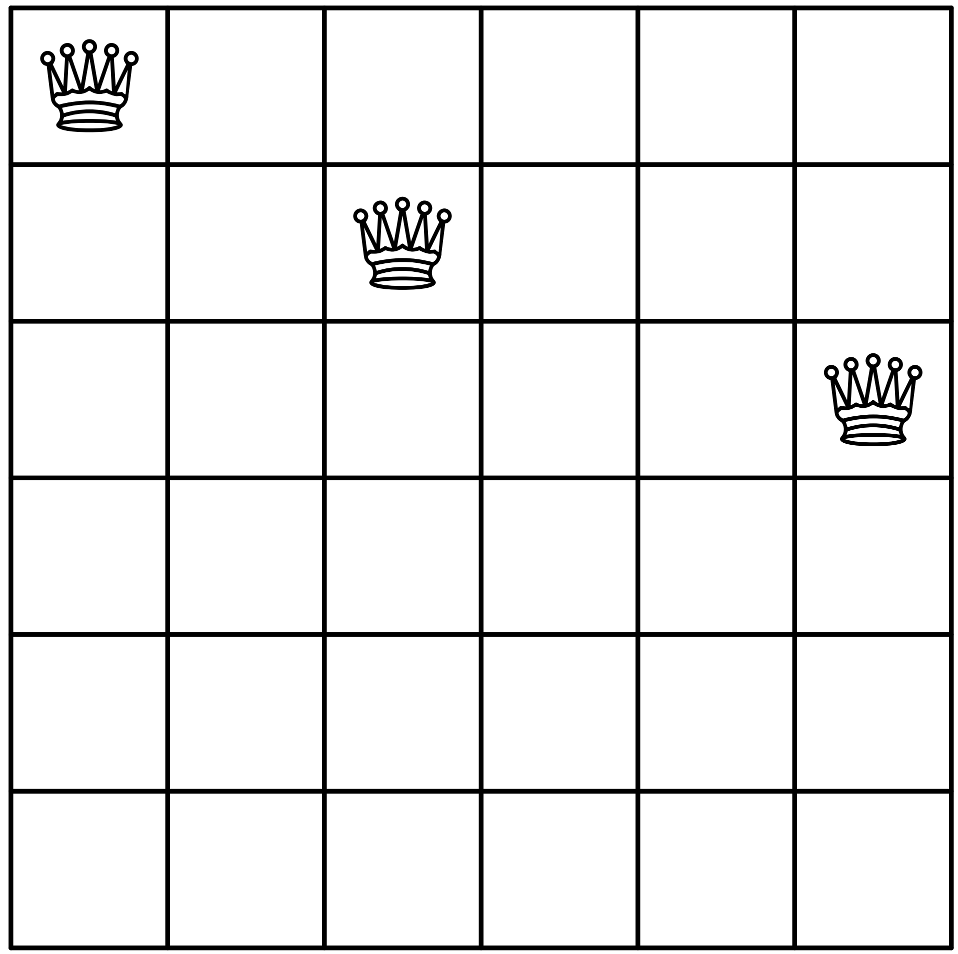

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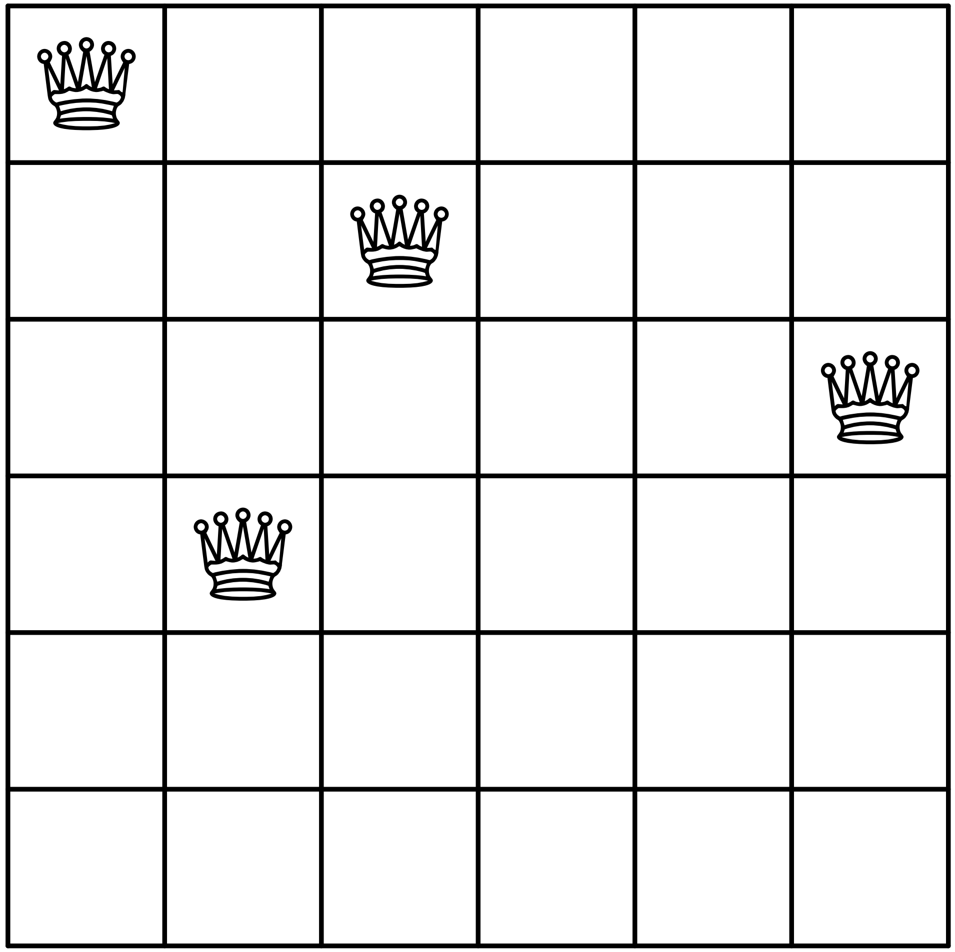

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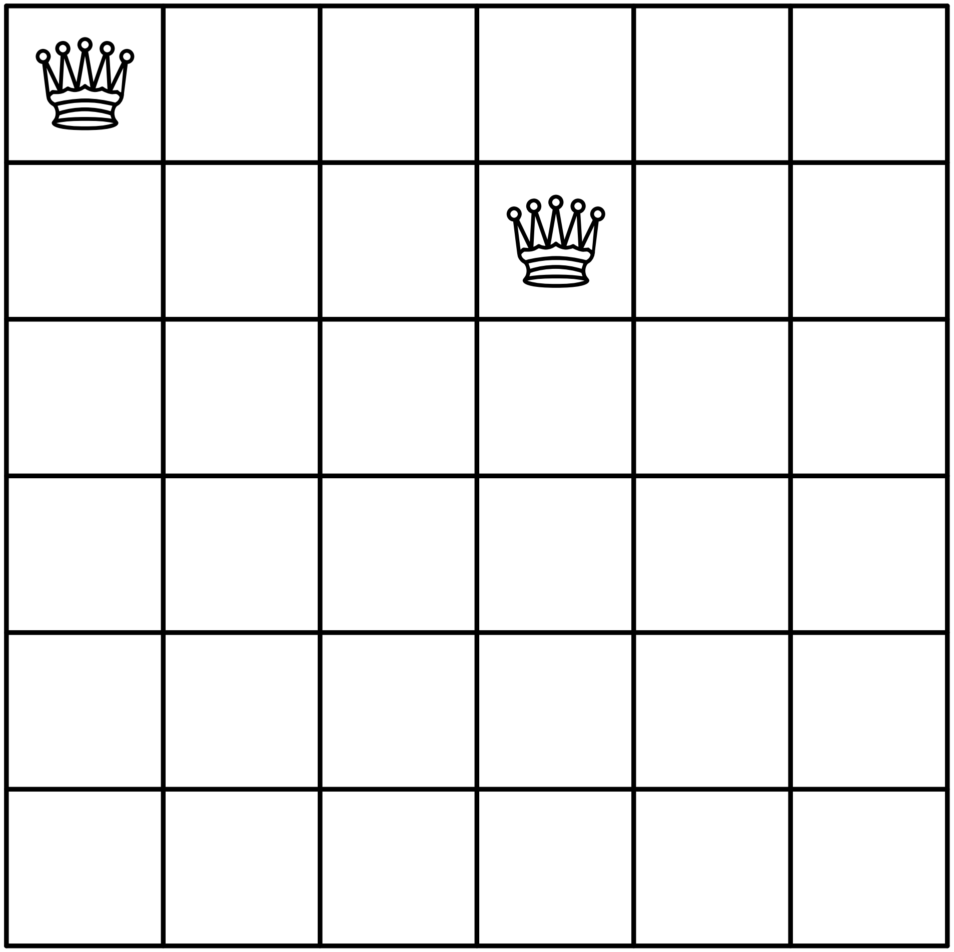

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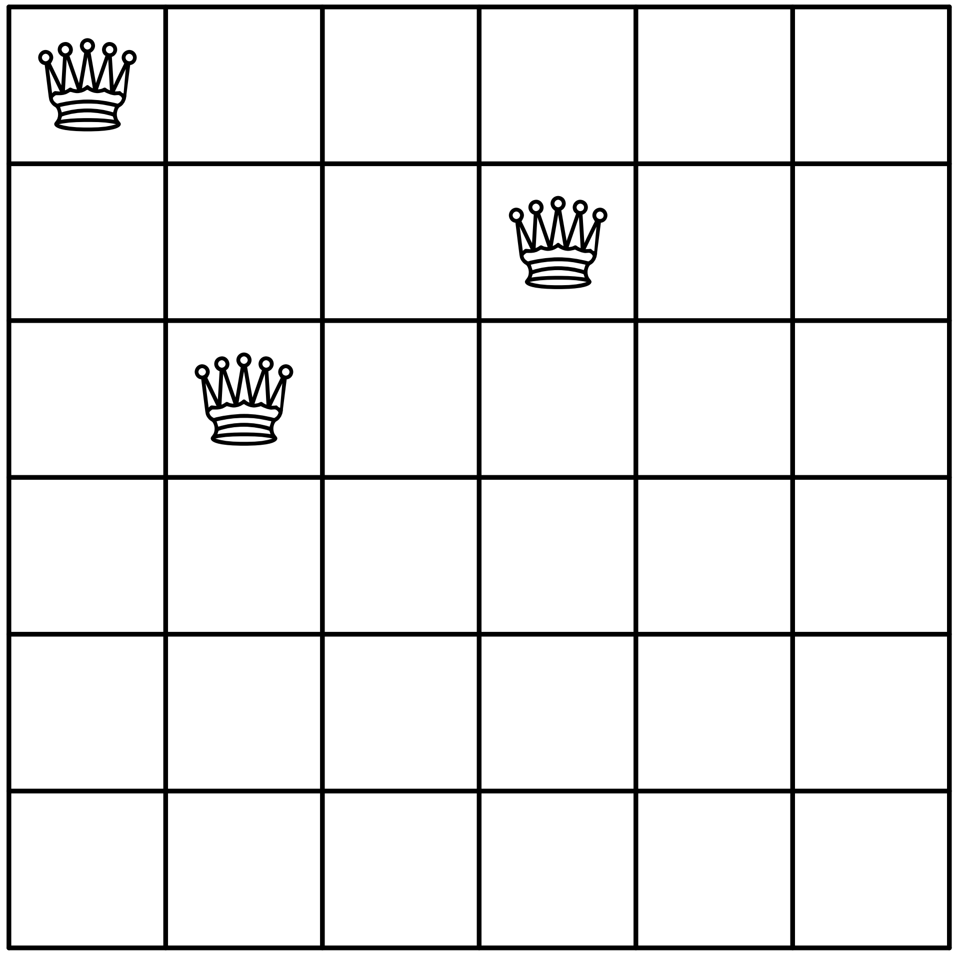

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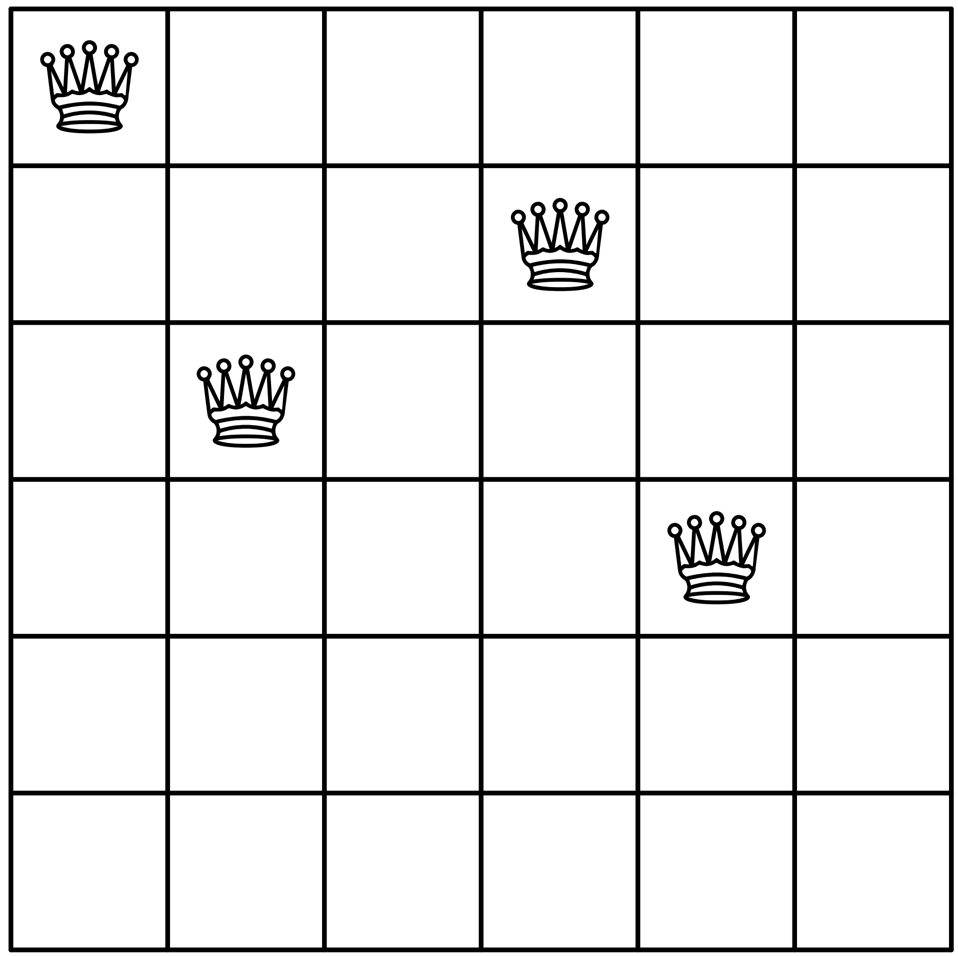

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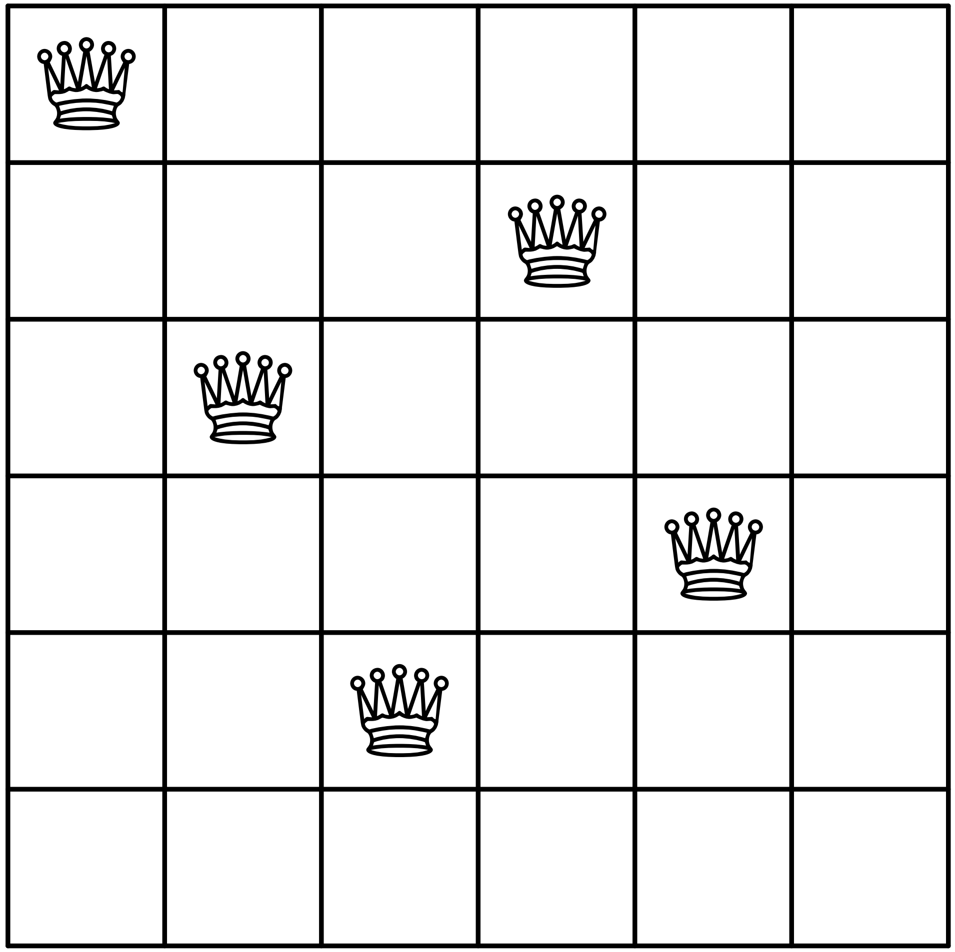

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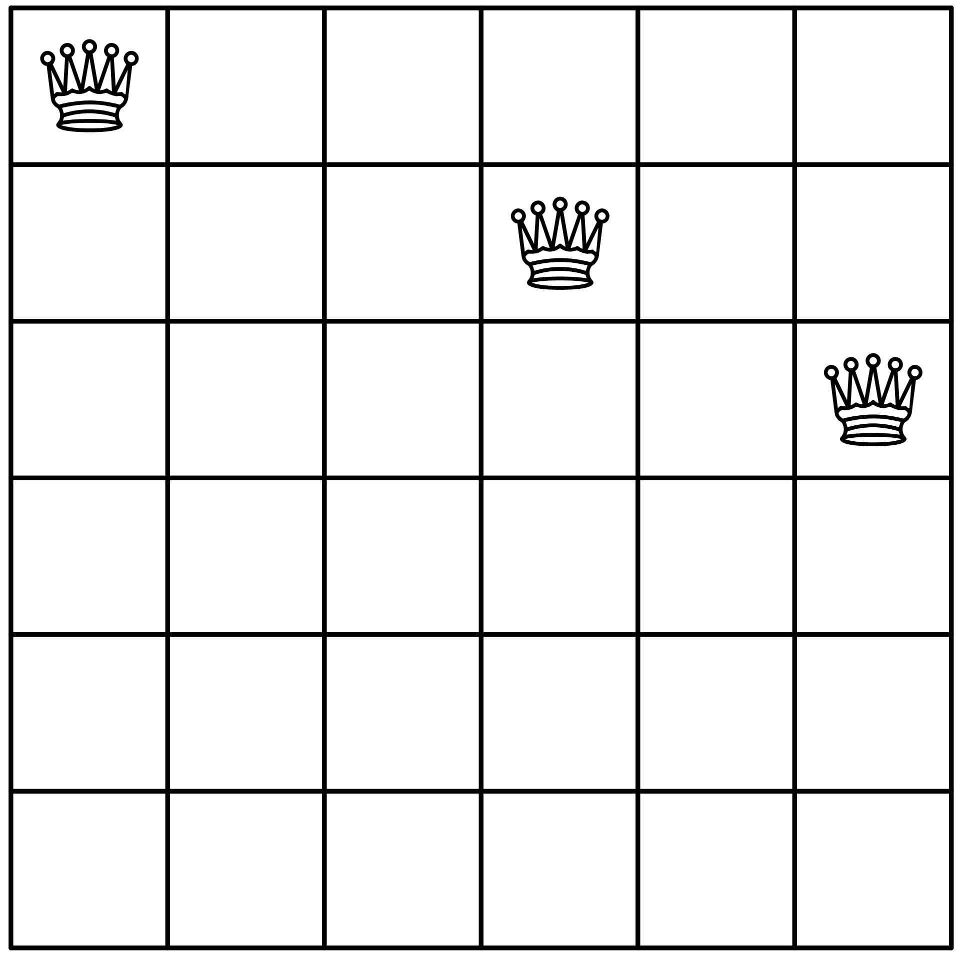

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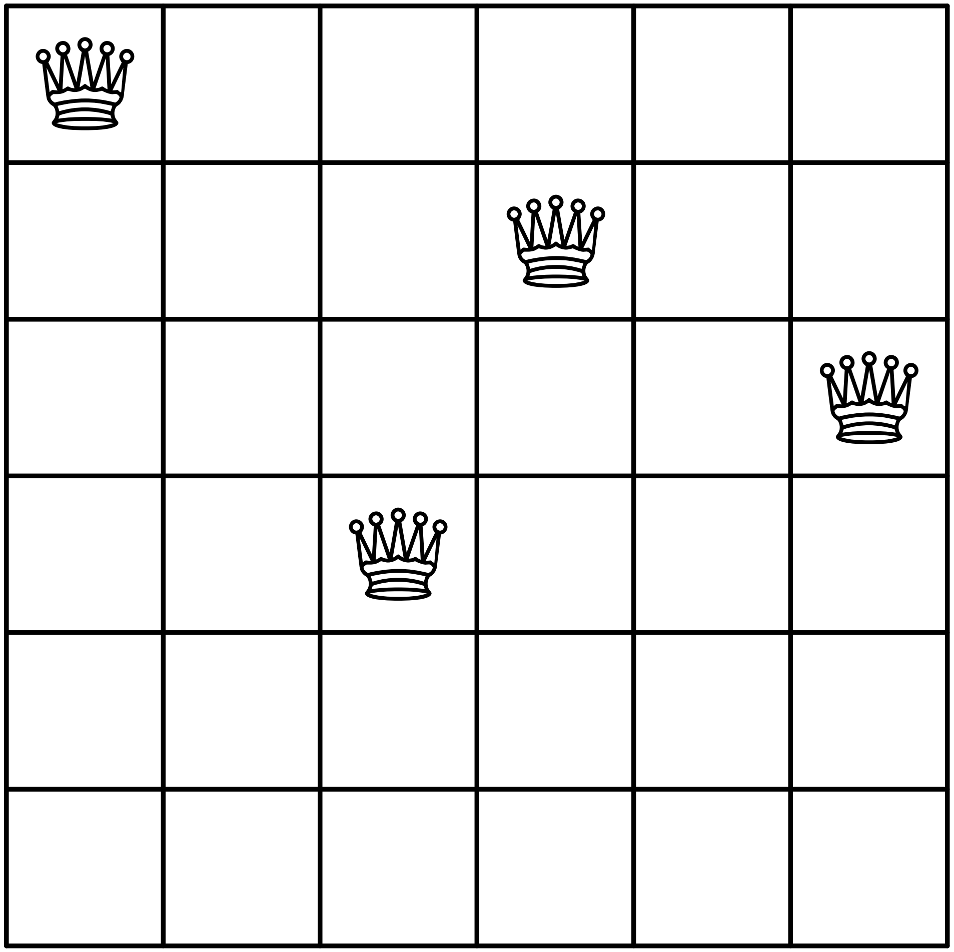

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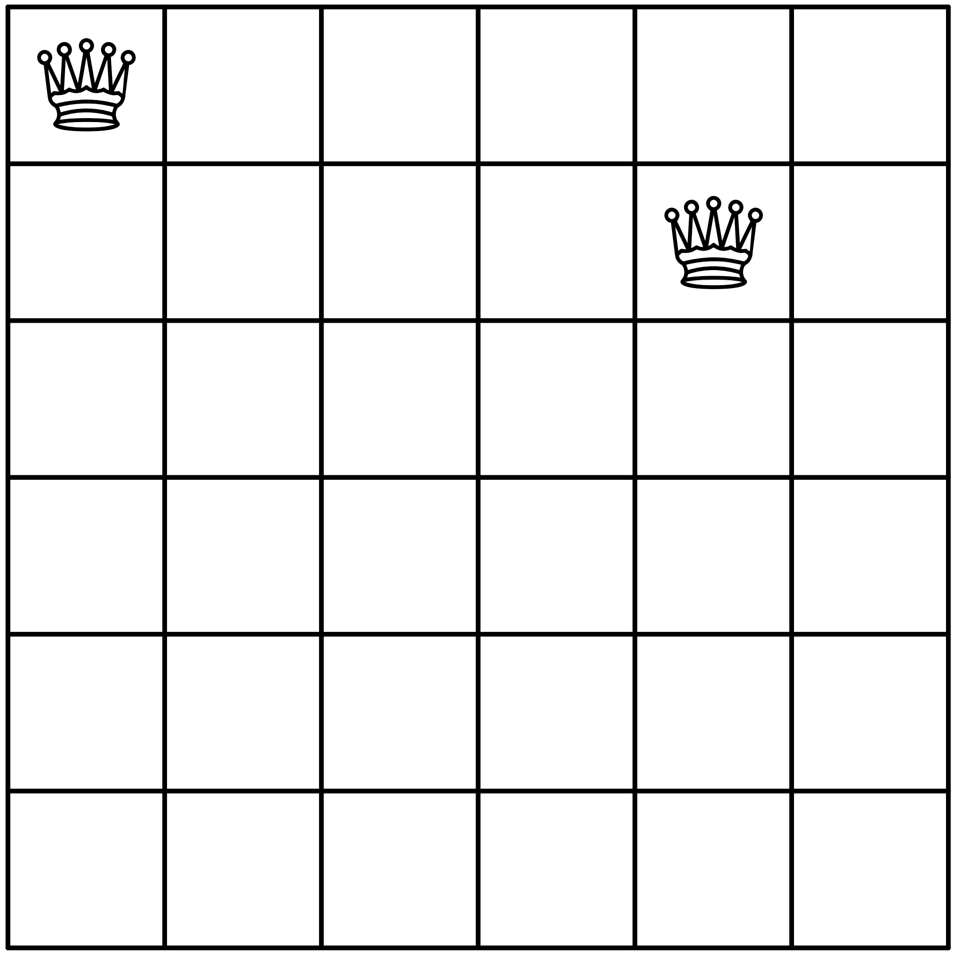

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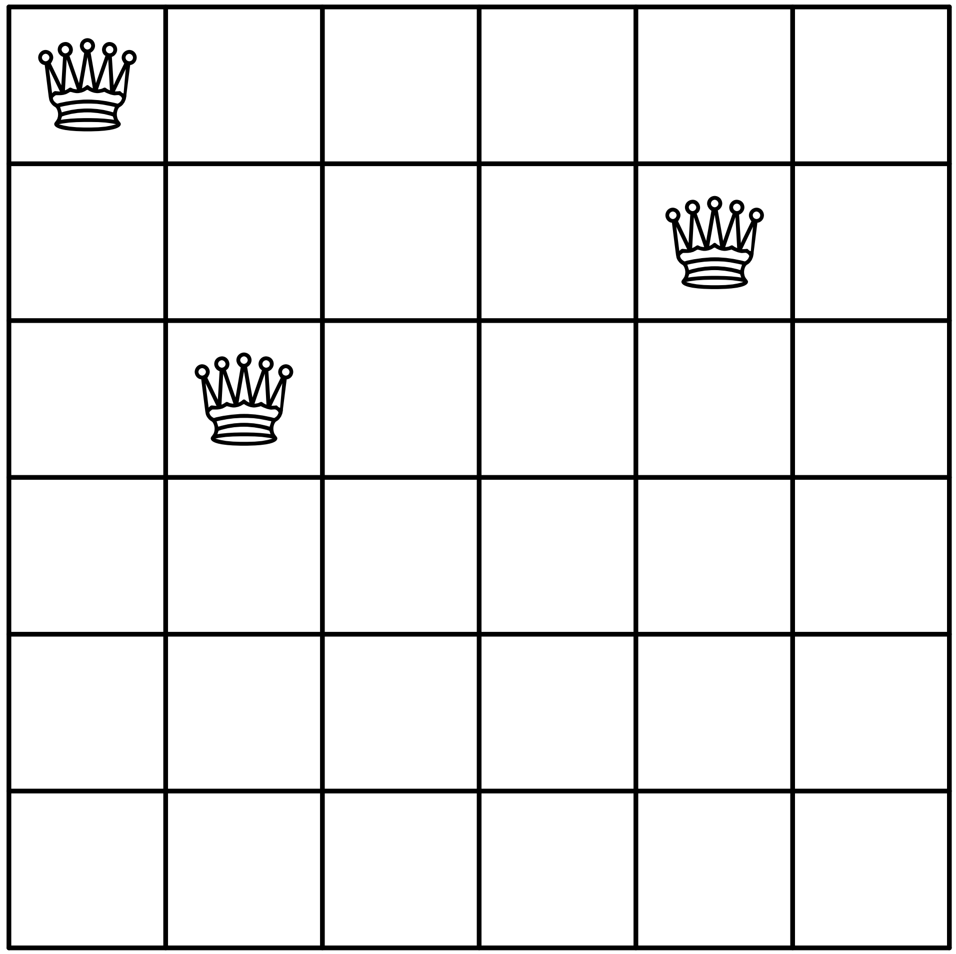

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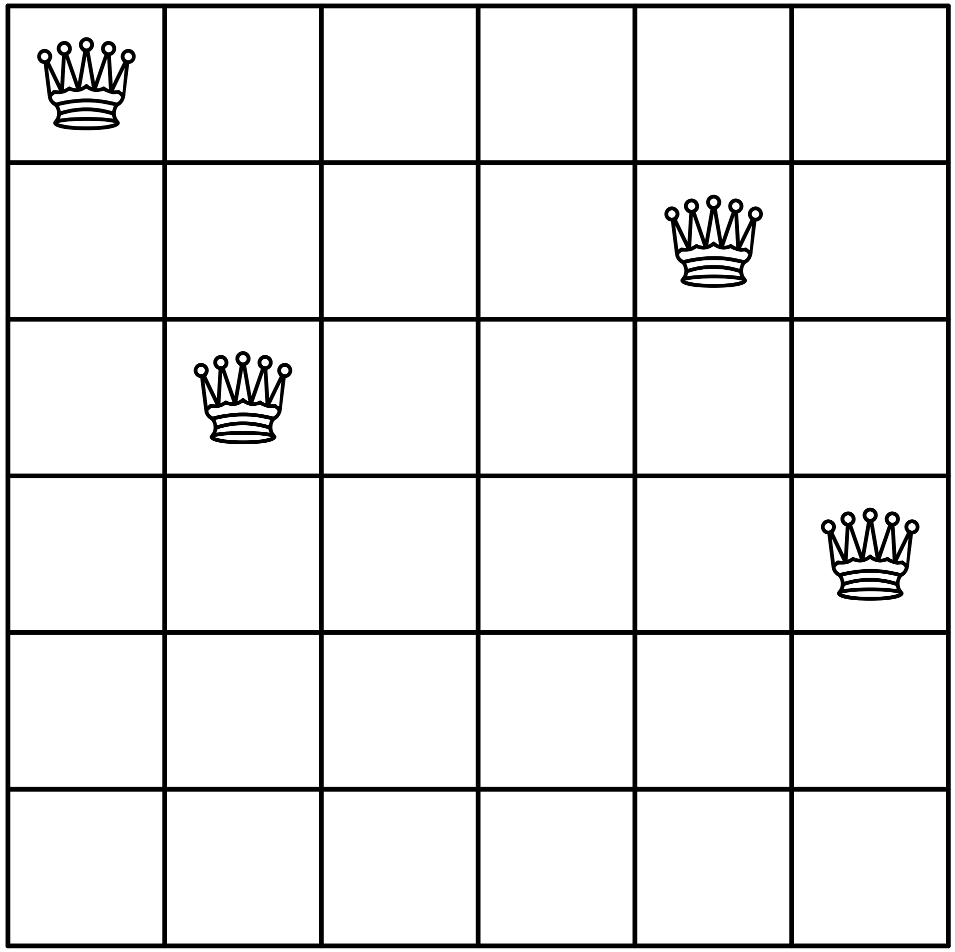

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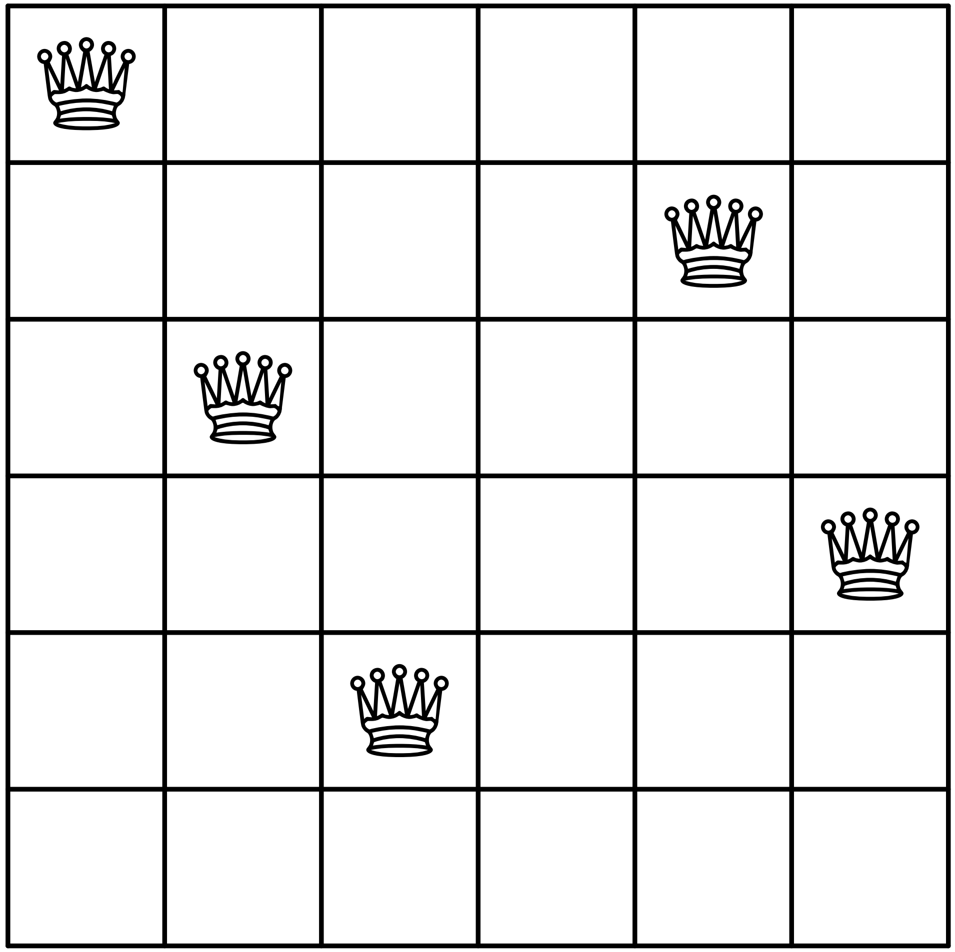

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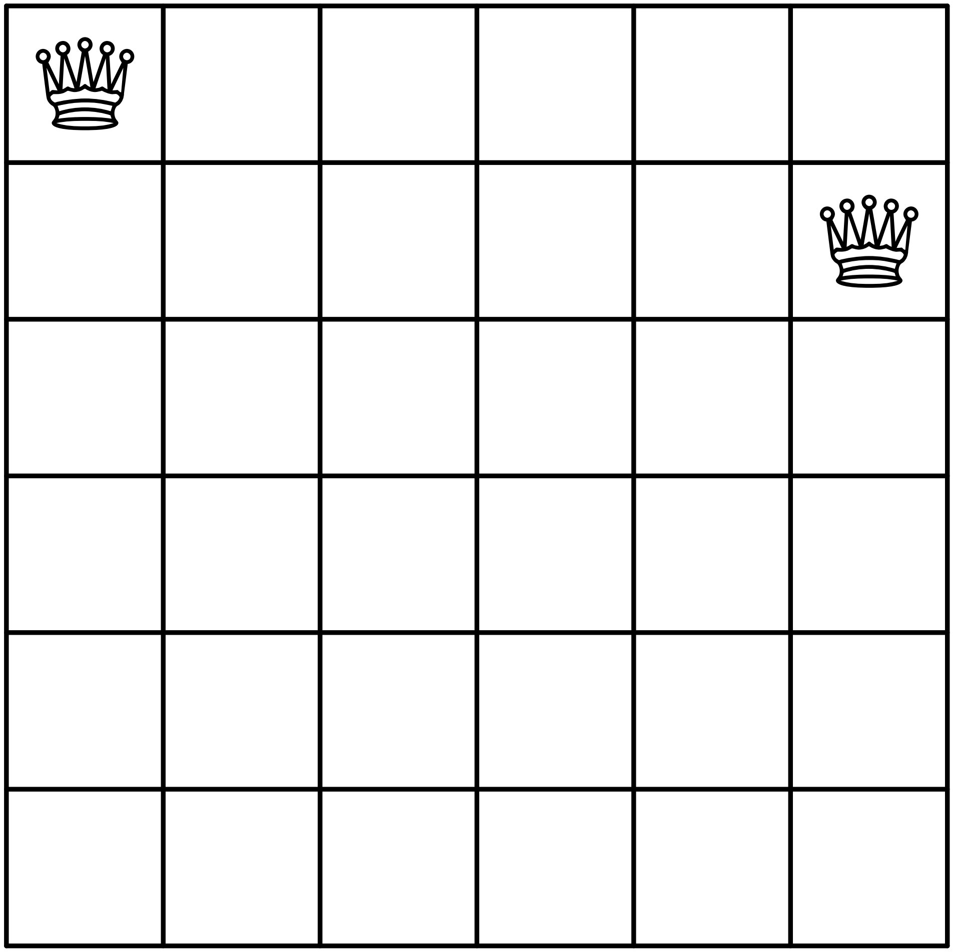

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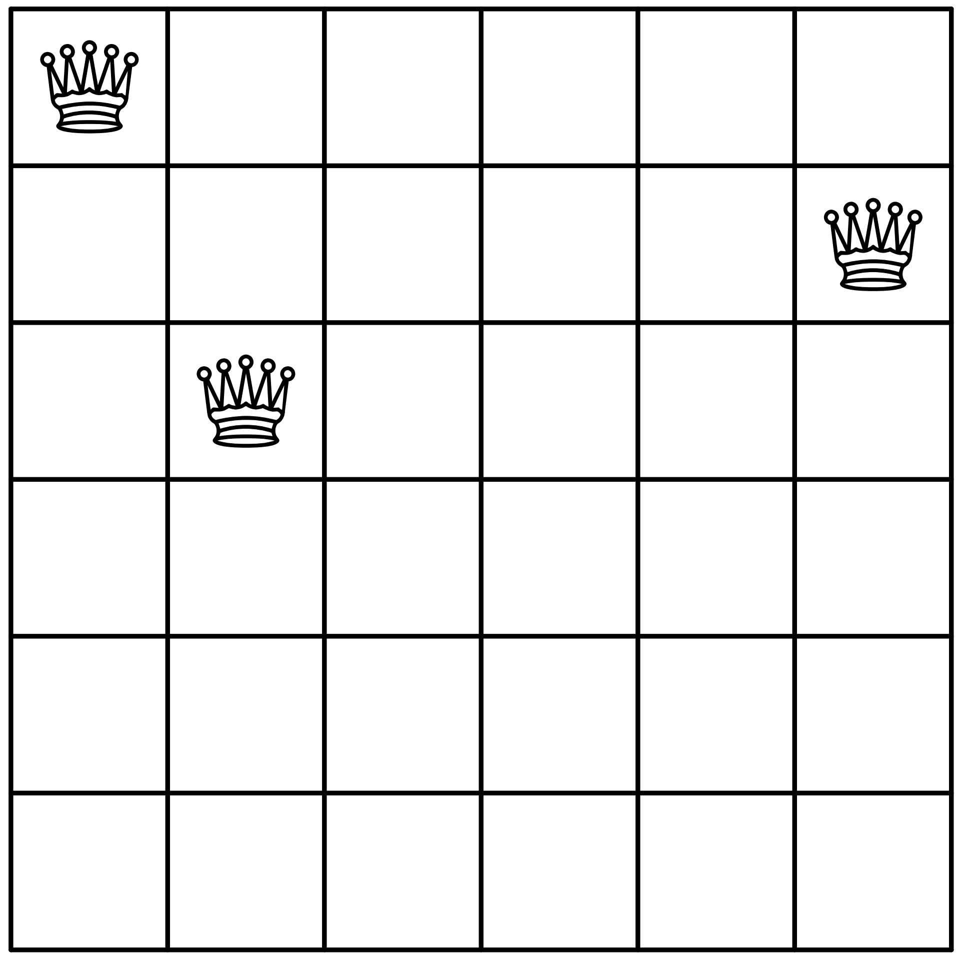

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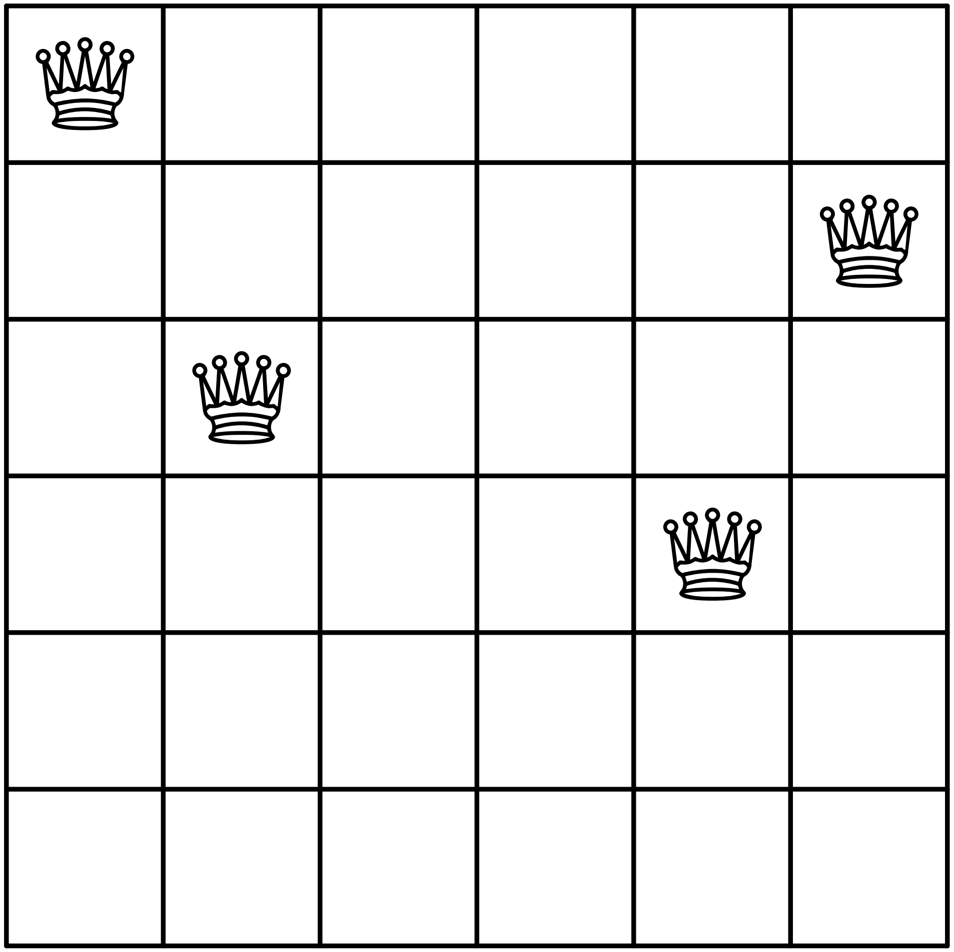

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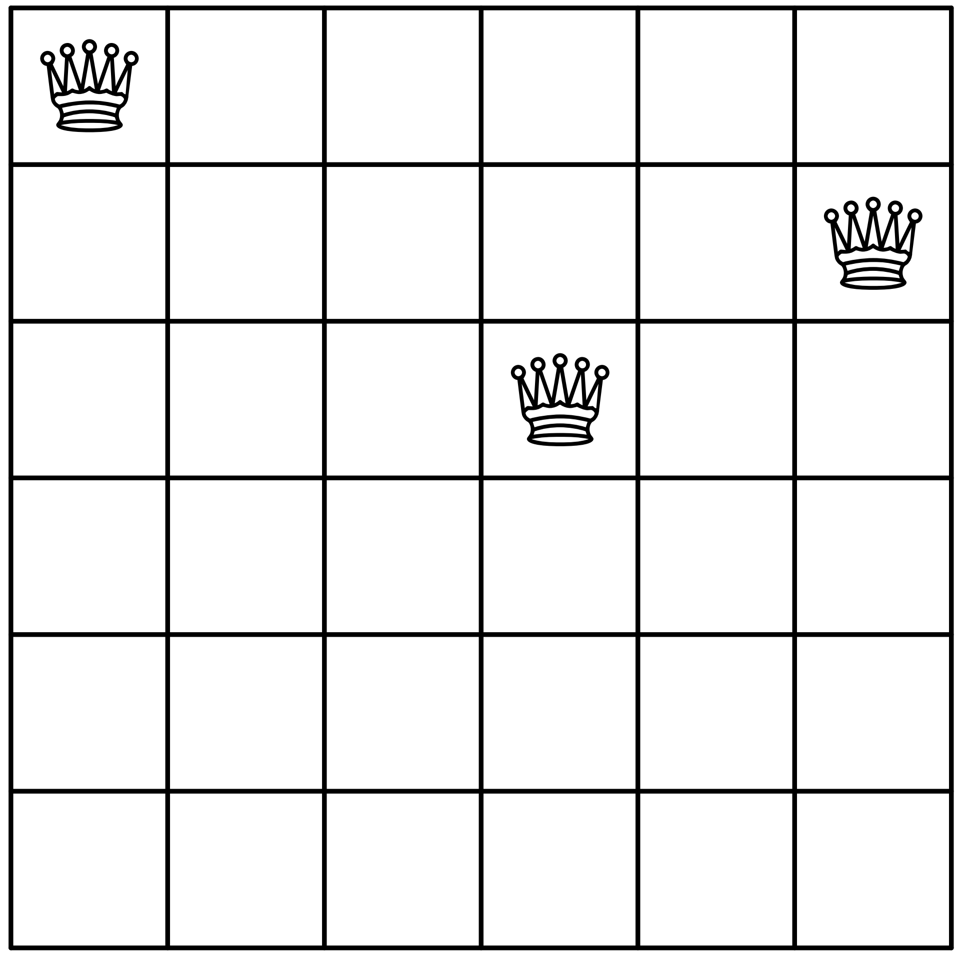

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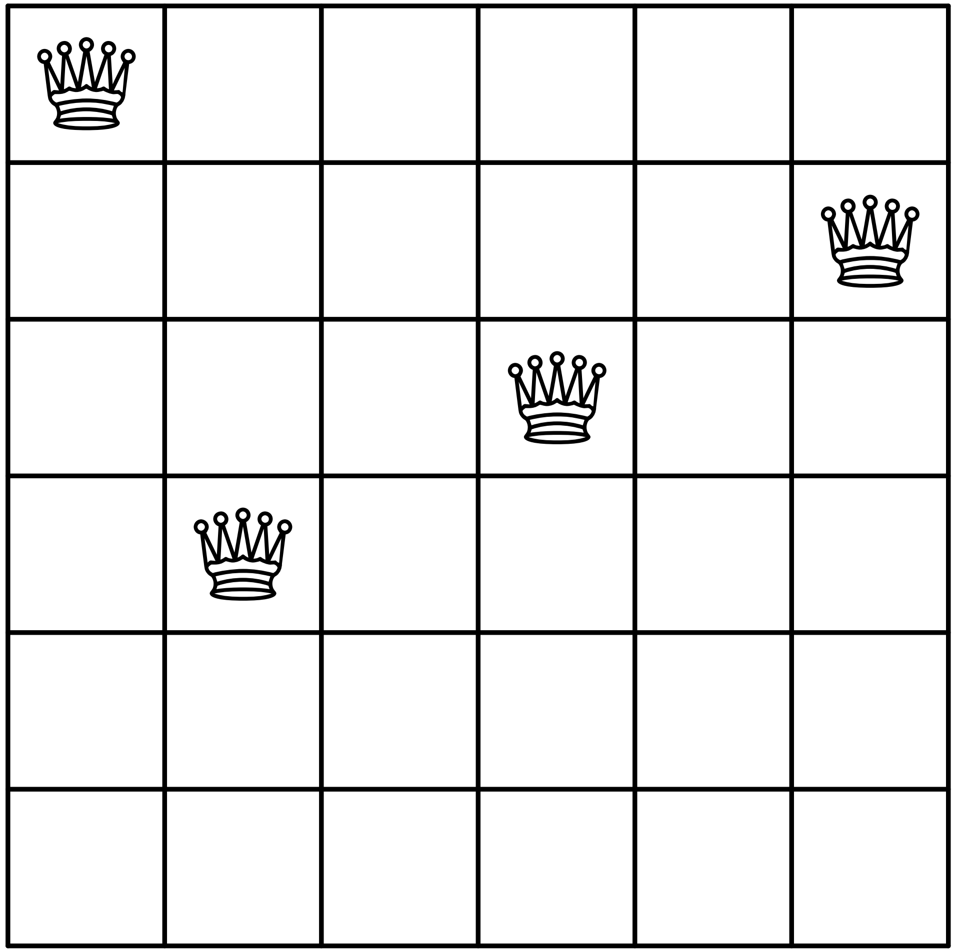

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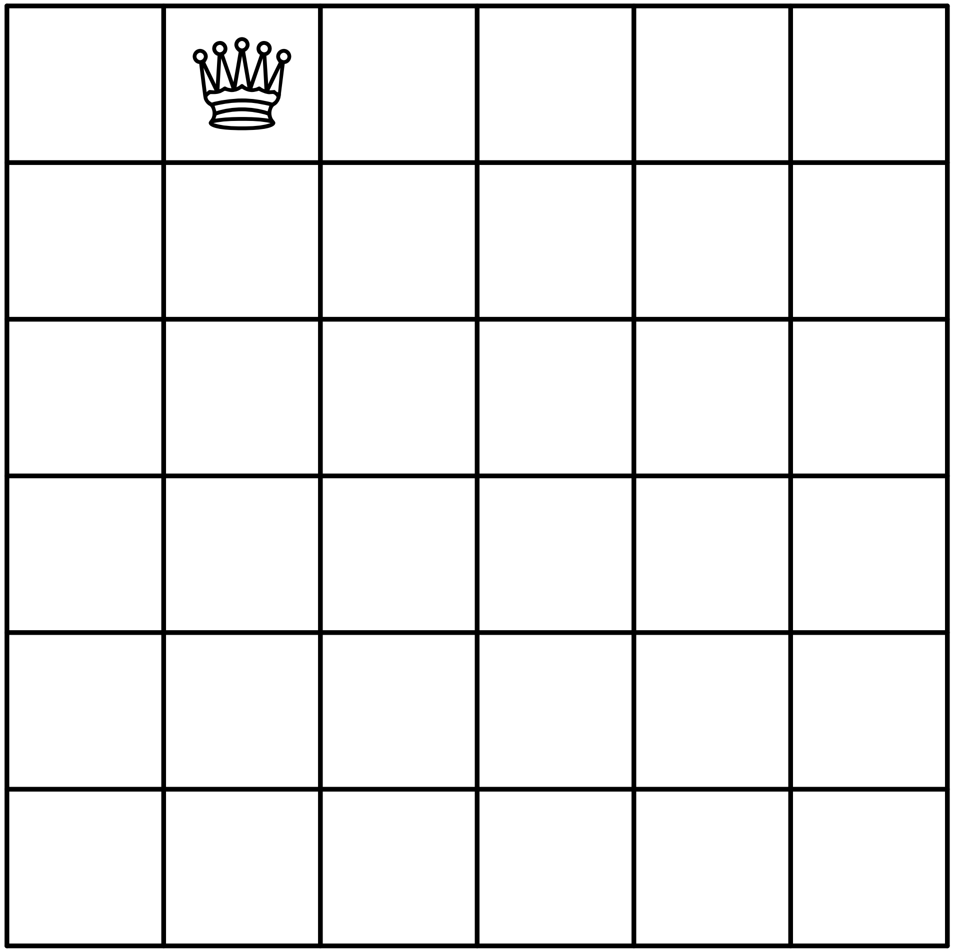

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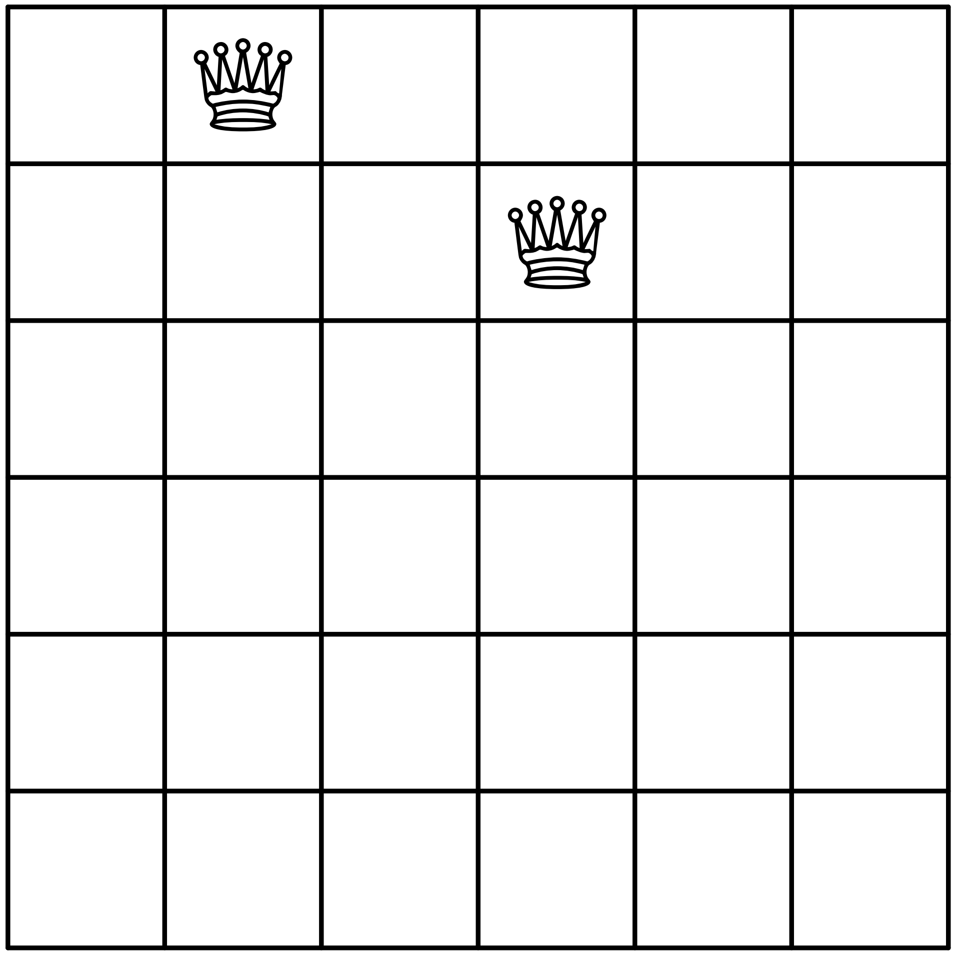

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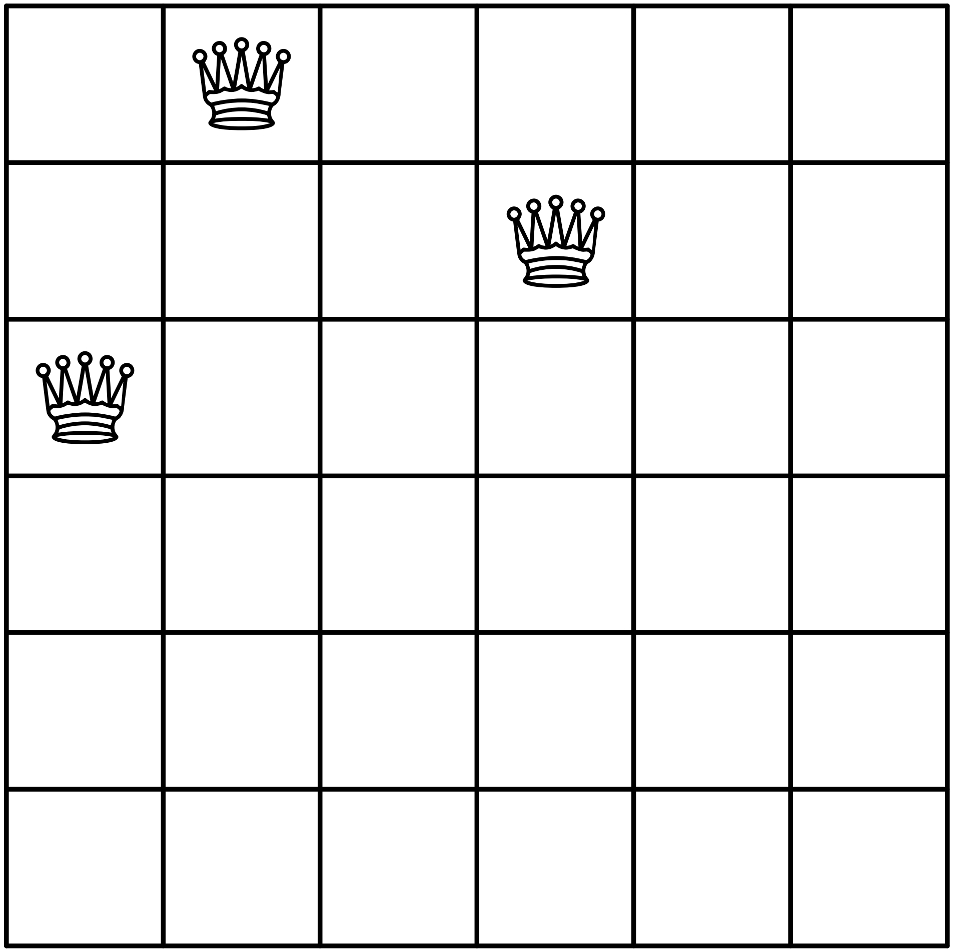

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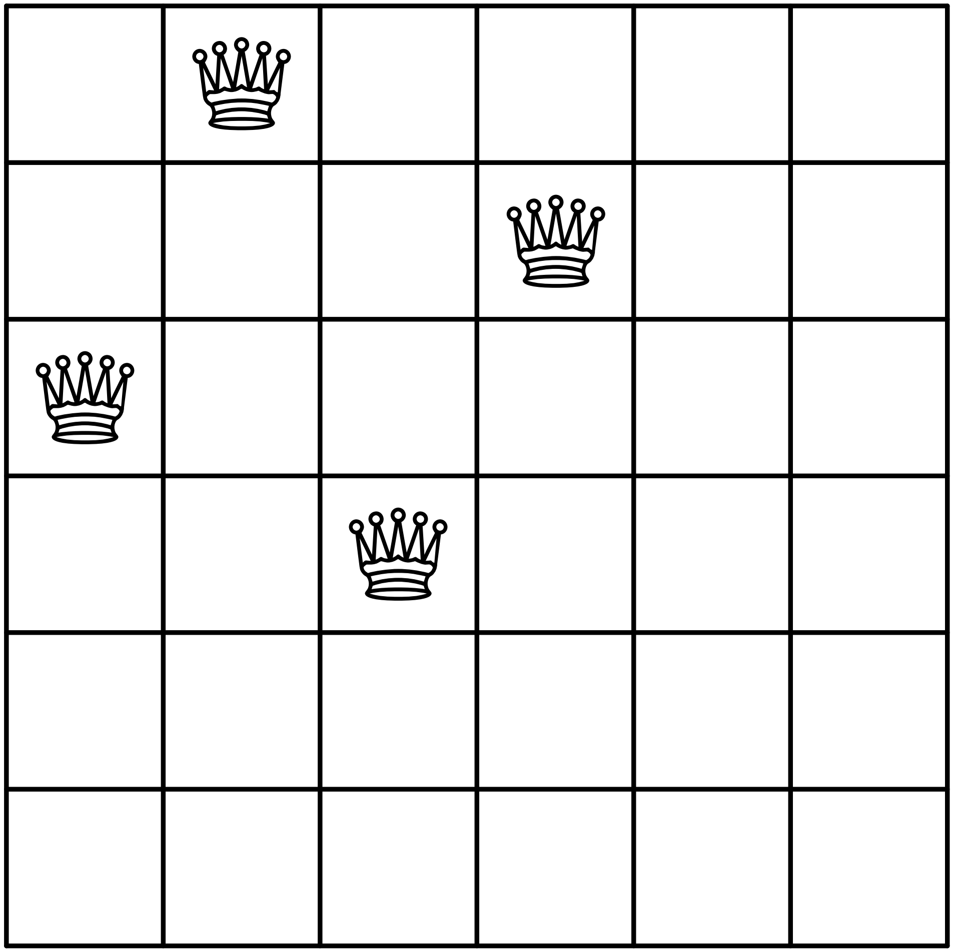

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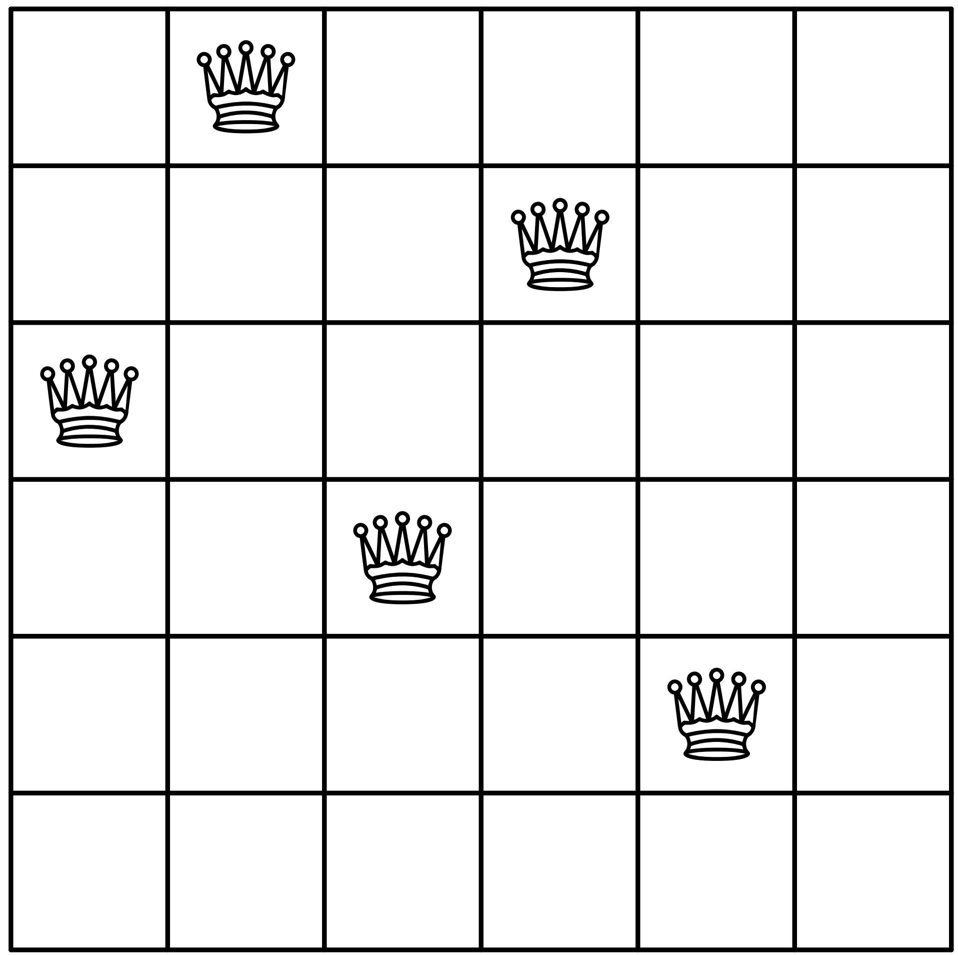

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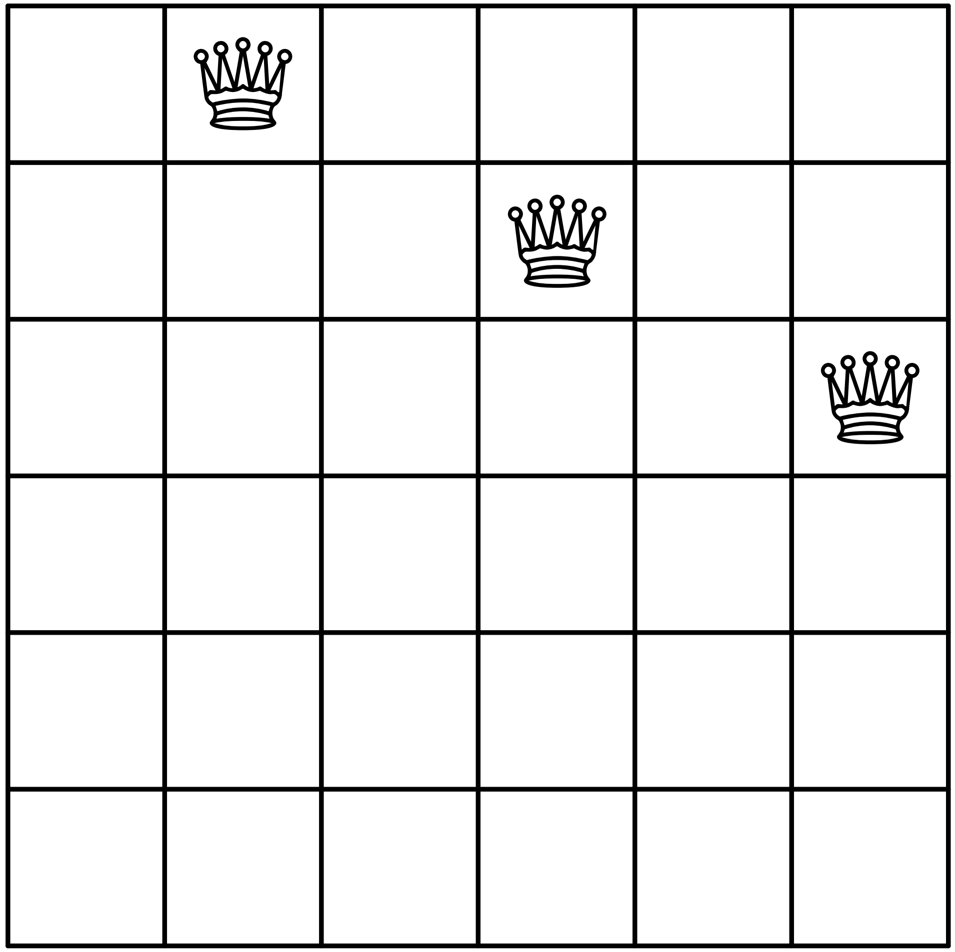

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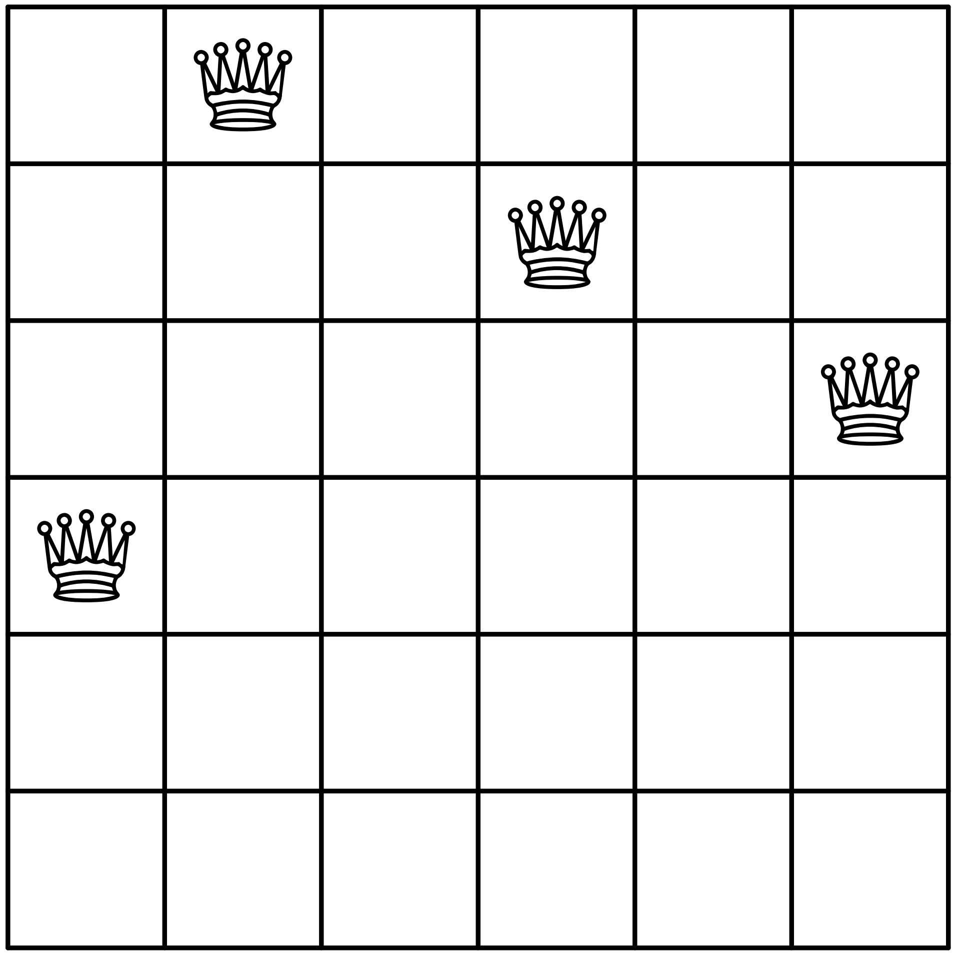

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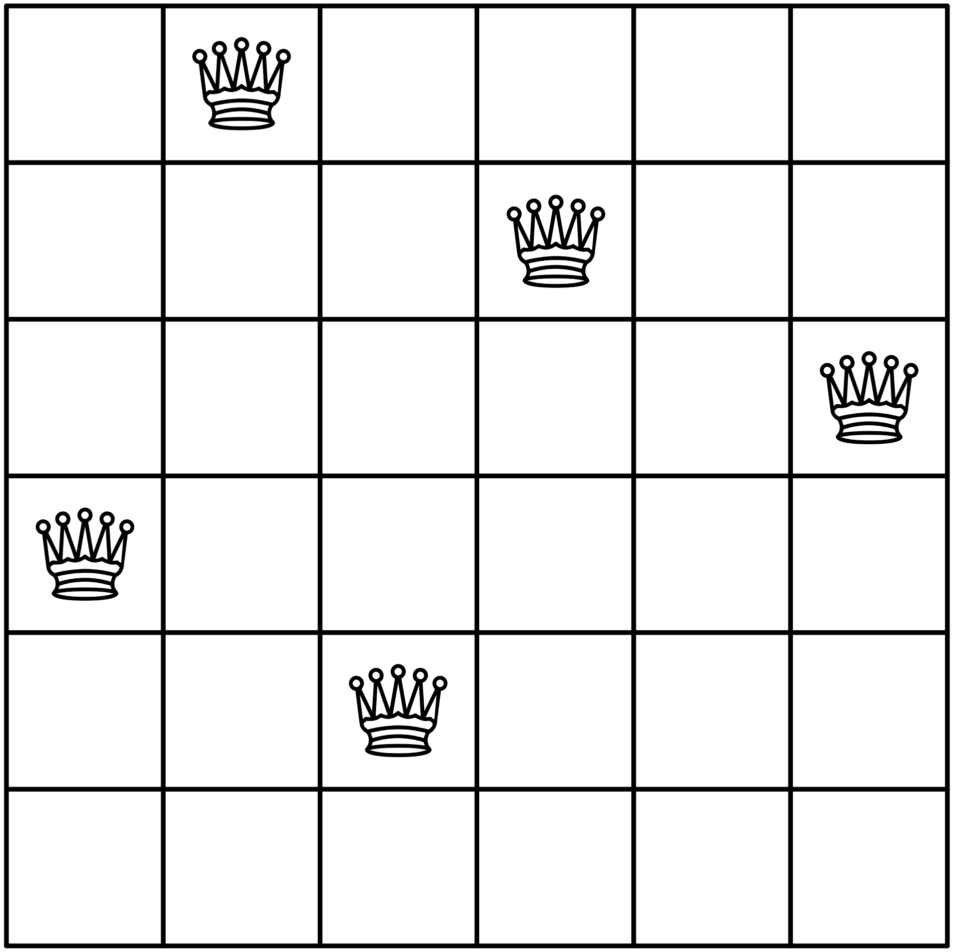

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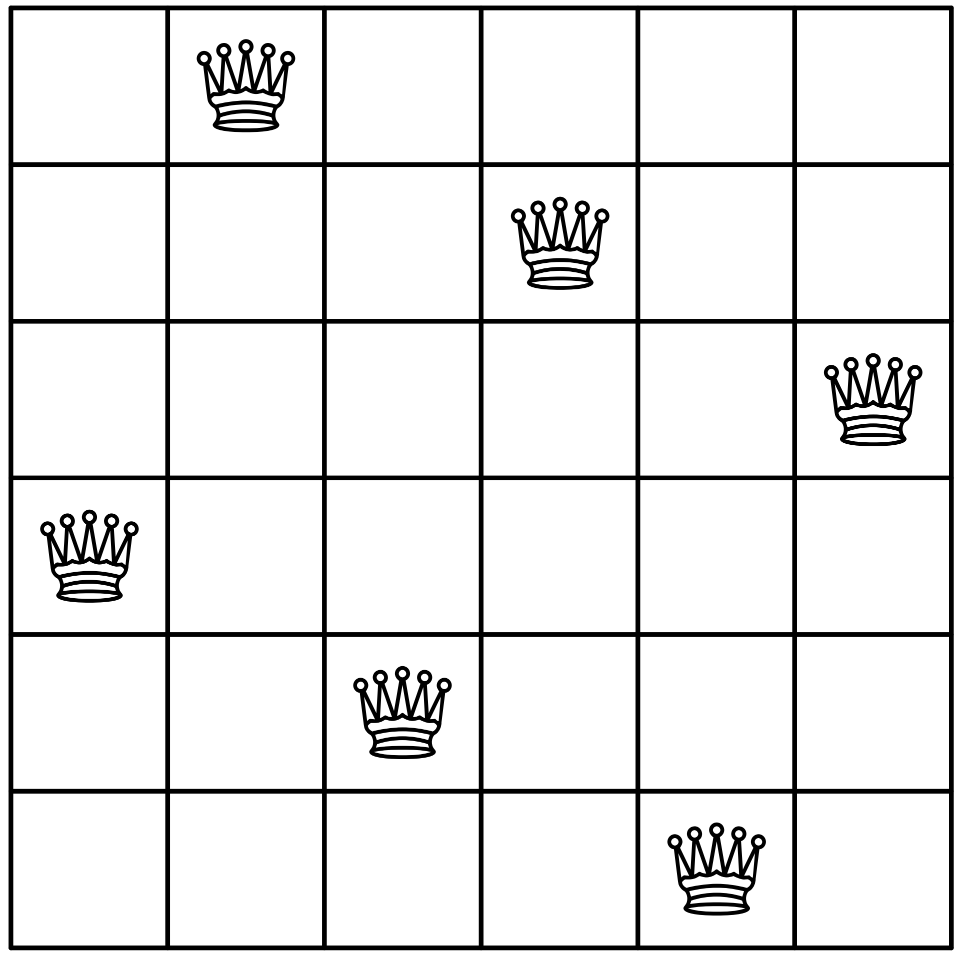

Implementing n-Queens

- Implementing backtracking is easily done using recursion
- Recall depth-first search is easily implemented using recursion
- We just need a recursive function `next(n, row, sol)` which for a n-Queens problem searches new solutions in `row` given queens in previous rows given in `sol`
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Code

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List nextRow(int noRows, int row, List queenPositions) {
  if (row==noRows) {return queenPositions;}
  for (int col=0; col<noRows; ++col) {
    if (legalQueen(col, row, queenPositions)) {
      queenPositions.add(col);
      List solution = nextRow(noRows, row+1, queenPositions);
      if (solution!=null)
        return solution;
    }
  }
  return null;
}

bool LegalQueen(int col, int row, List sol) {
  for(int r=0; r<row: ++r) {
    rf (sol[r] == col || sol[r]-row+r == col || sol[r]+row-r==col) {
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  for(int r=0; r<row: ++r) {
    rf (sol[r] == col || sol[r]-row+r == col || sol[r]+row-r==col) {
      return false;
    }
  }
  return true;
}
```

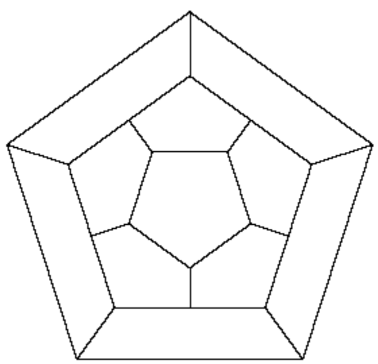
Code

```
List nextRow(int noRows, int row, List queenPositions) {
  if (row==noRows) {return queenPositions;}
  for (int col=0; col<noRows; ++col) {
    if (legalQueen(col, row, queenPositions)) {
      queenPositions.add(col);
      List solution = nextRow(noRows, row+1, queenPositions);
      if (solution!=null)
        return solution;
    }
  }
  return null;
}

bool LegalQueen(int col, int row, List sol) {
  for(int r=0; r<row: ++r) {
    rf (sol[r] == col || sol[r]-row+r == col || sol[r]+row-r==col) {
      return false;
    }
  }
  return true;
}
```

Hamiltonian Circuit

- A Hamiltonian cycle is a tour through a graph which visits every vertex once only and returns to the start
- It is a hard problem in that there are no known algorithms that are guaranteed to find a Hamiltonian cycle in polynomial time
- For many graphs it is not too hard



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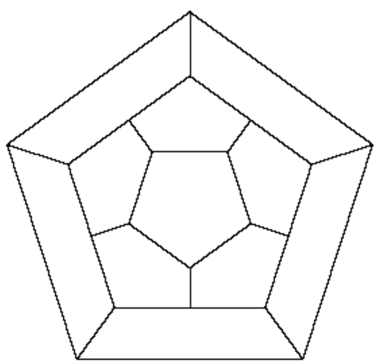

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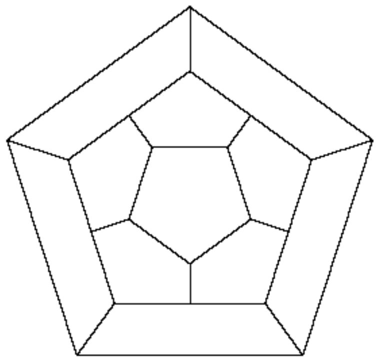
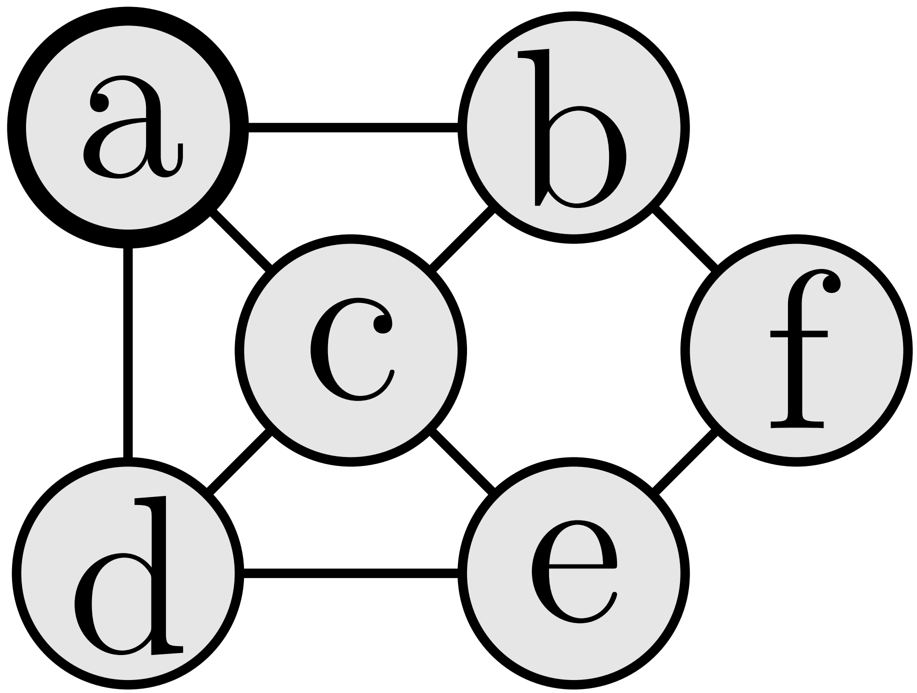
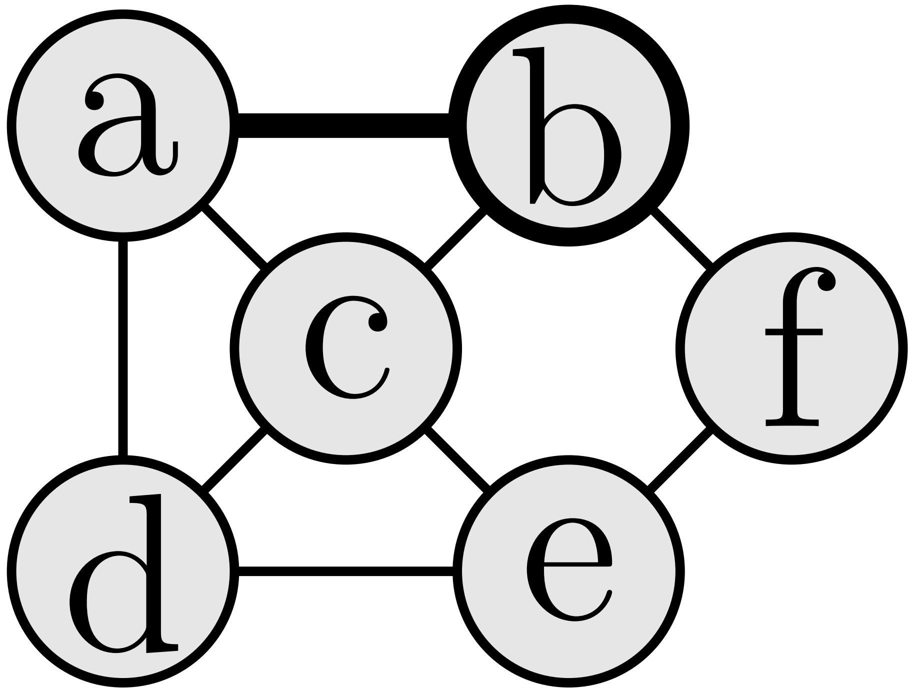


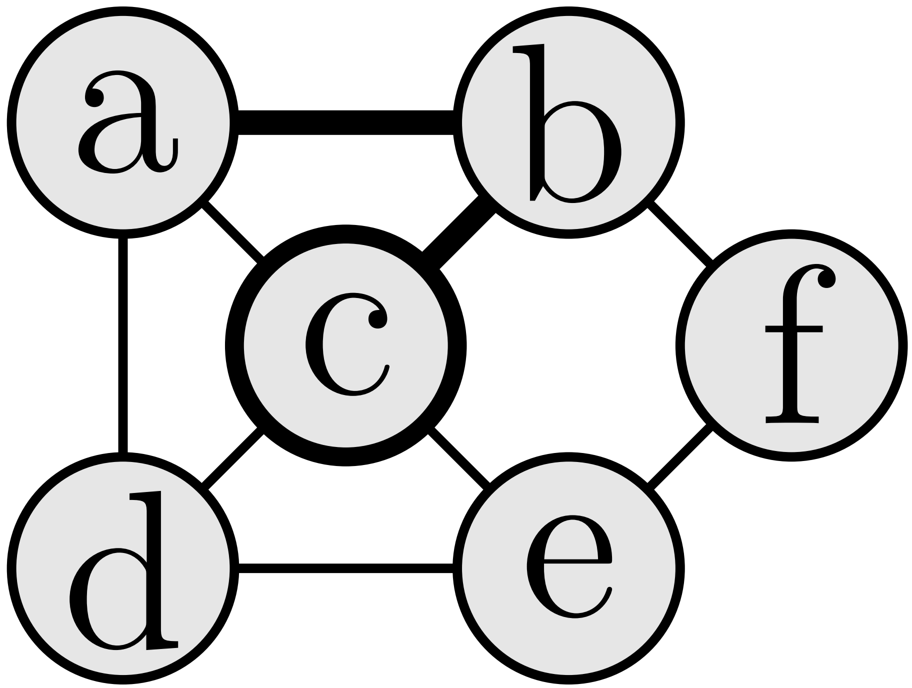
Hamiltonian Circuit Example



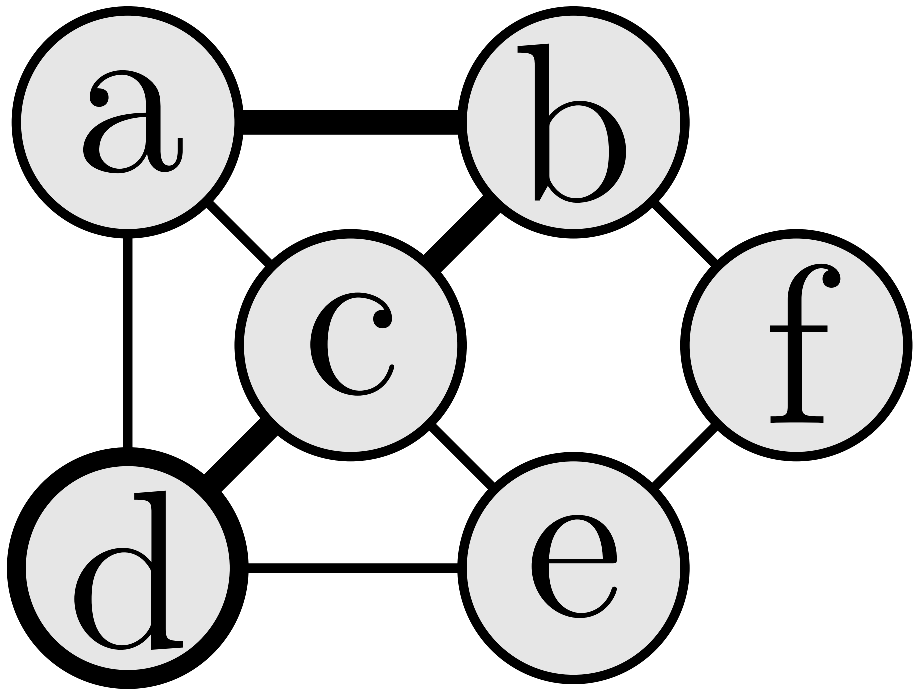
Hamiltonian Circuit Example



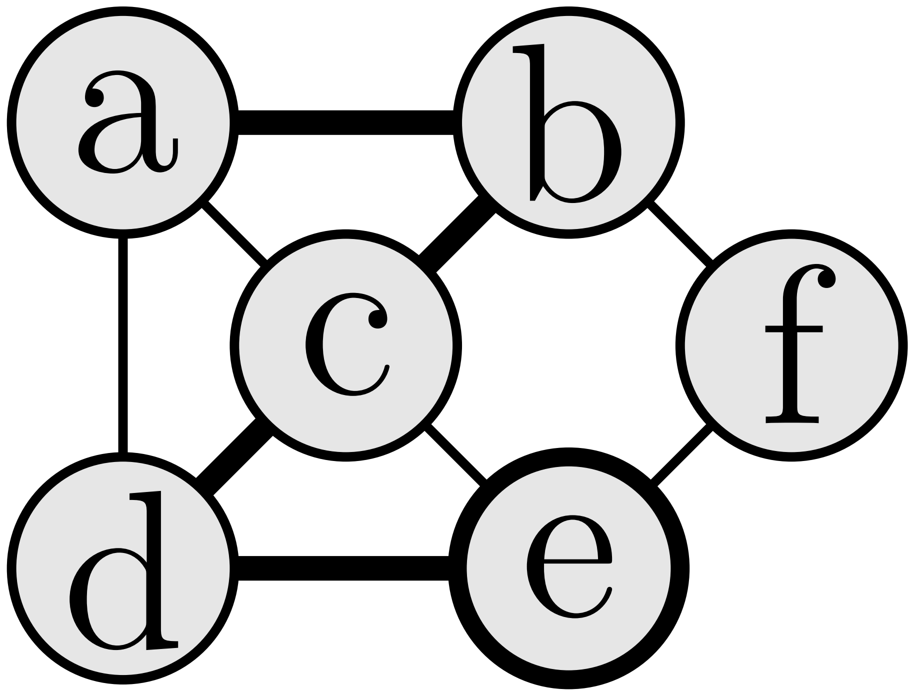
Hamiltonian Circuit Example



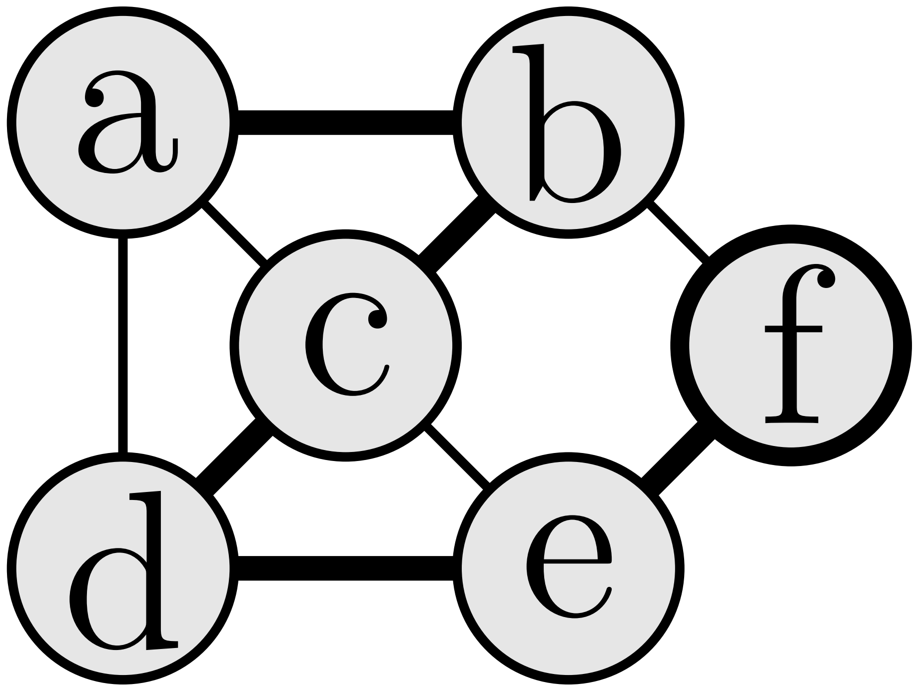
Hamiltonian Circuit Example



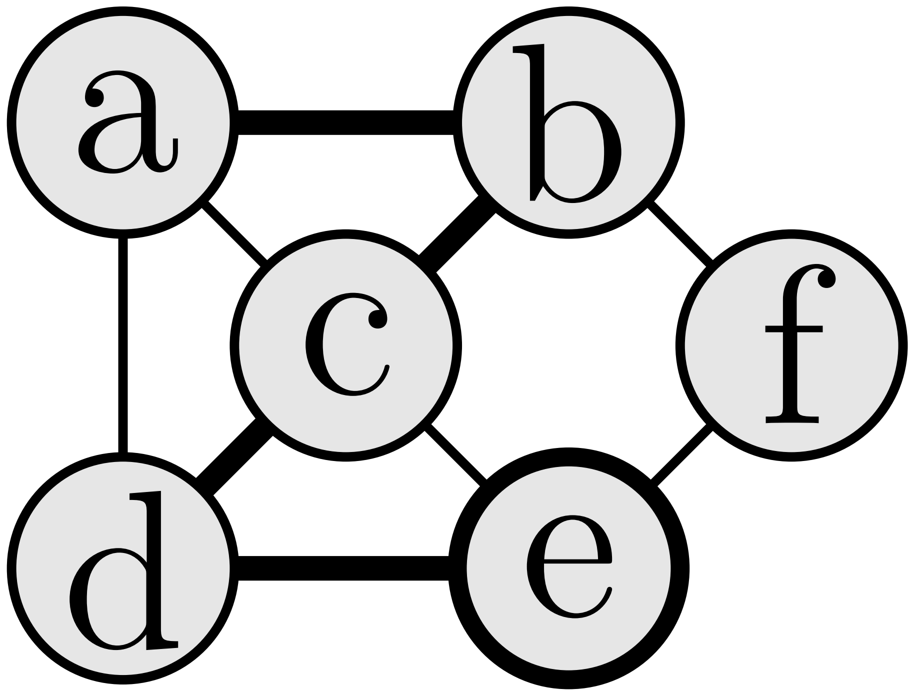
Hamiltonian Circuit Example



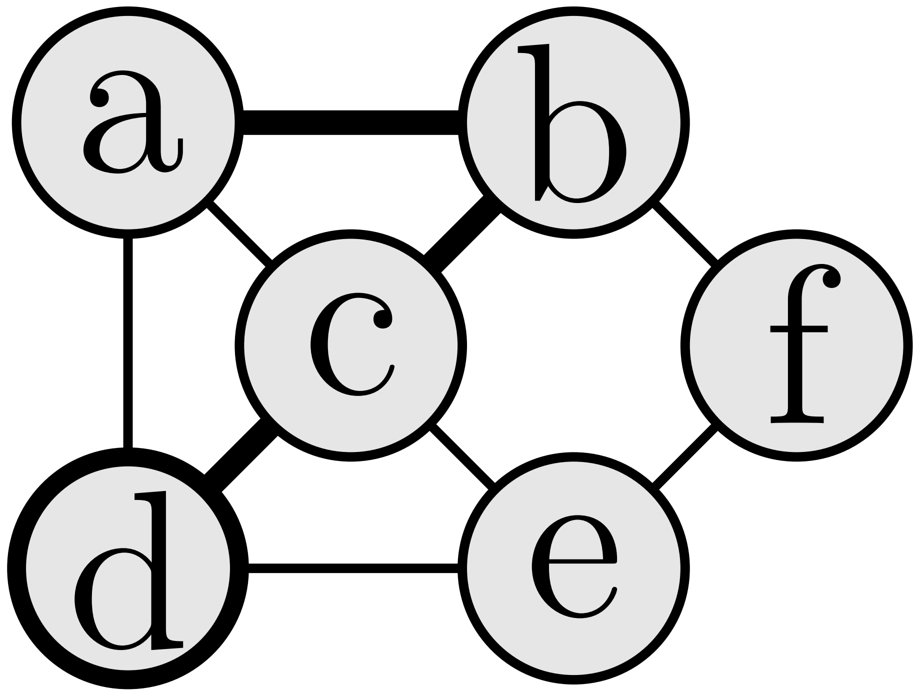
Hamiltonian Circuit Example



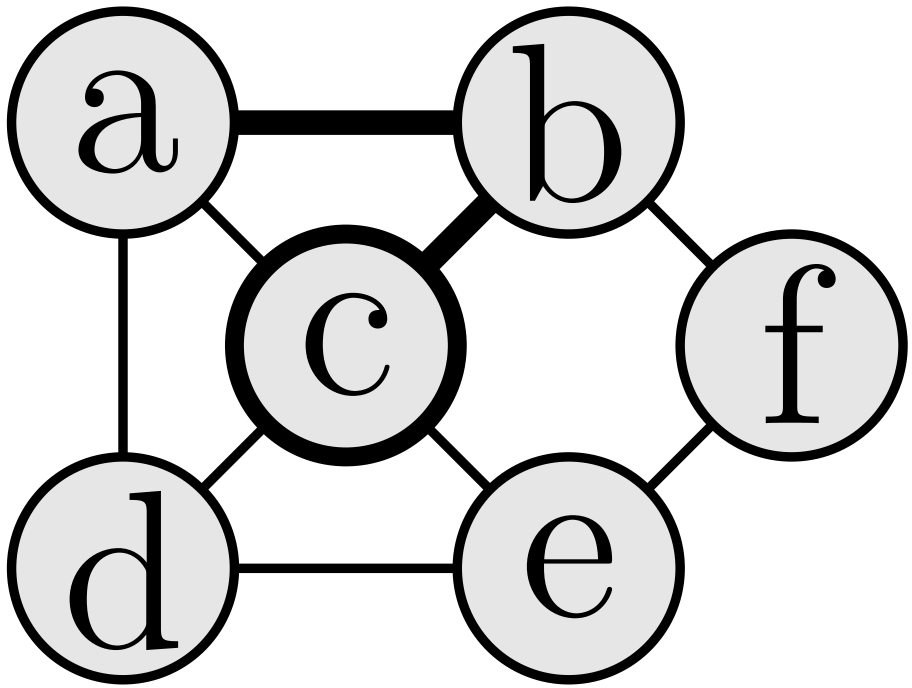
Hamiltonian Circuit Example



Hamiltonian Circuit Example



Hamiltonian Circuit Example



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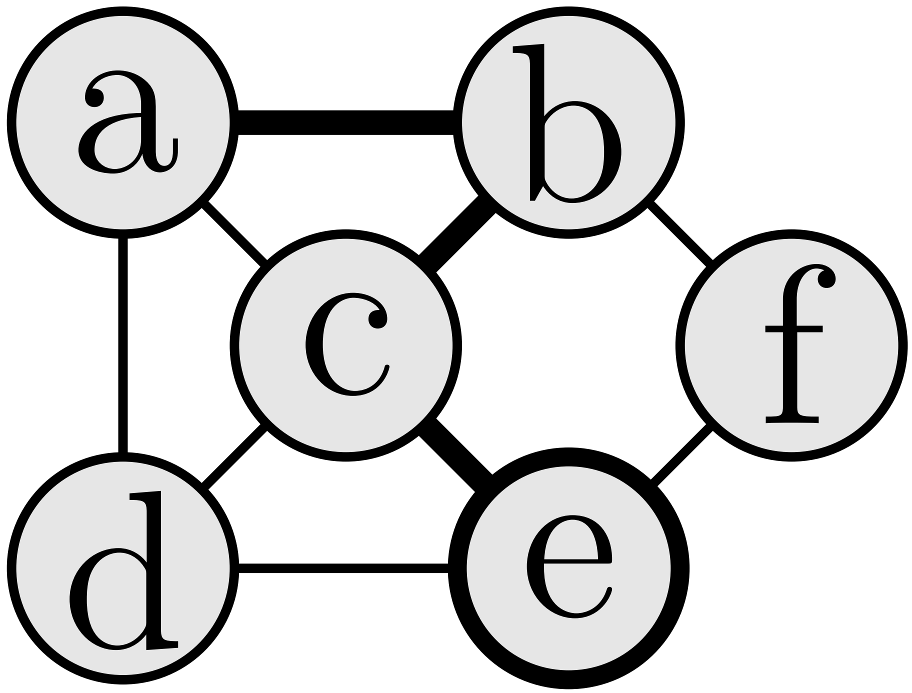
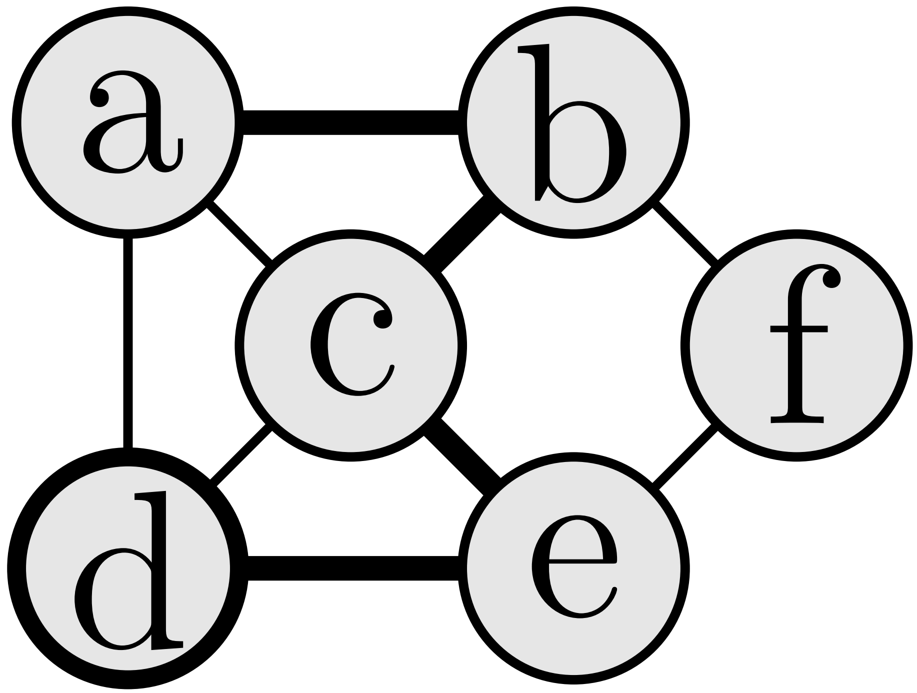
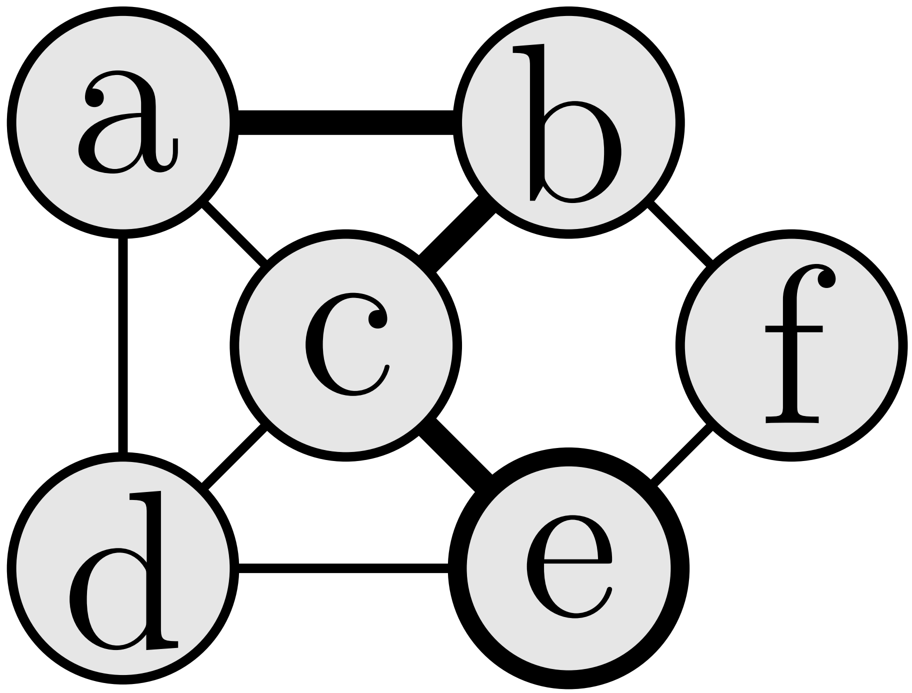


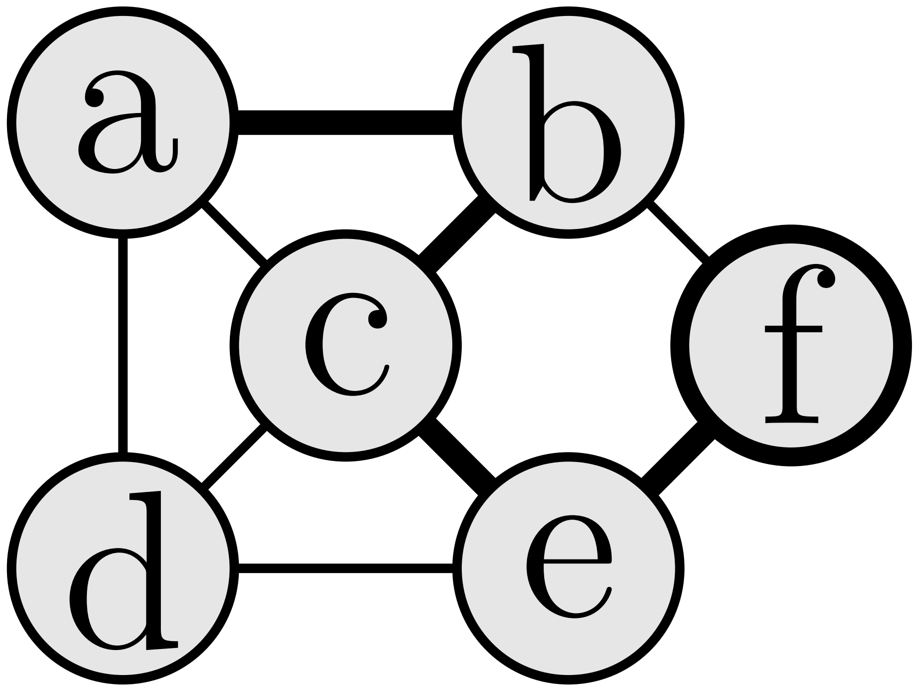
Hamiltonian Circuit Example



Hamiltonian Circuit Example



Hamiltonian Circuit Example



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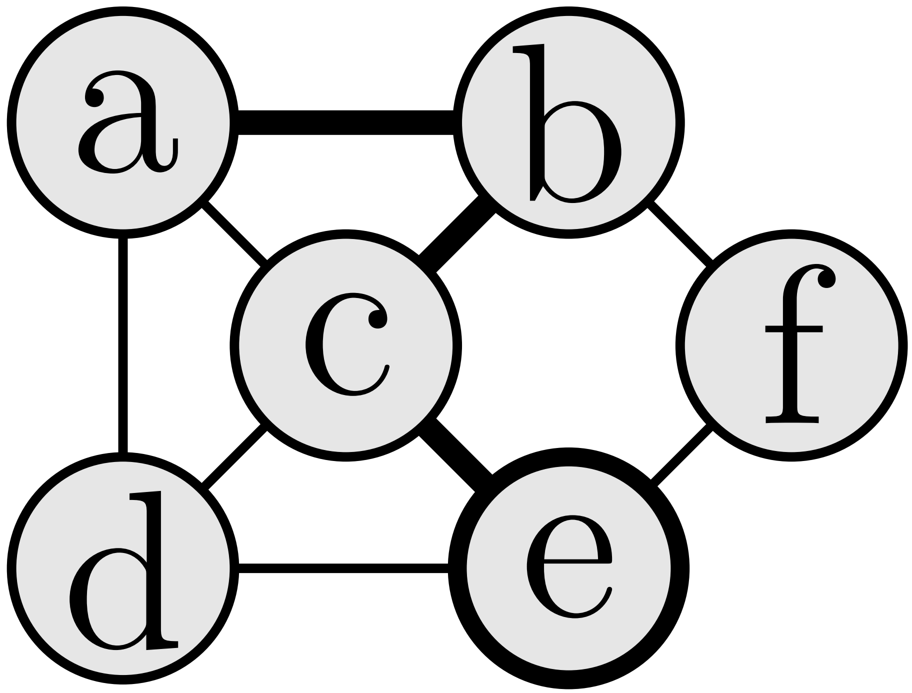

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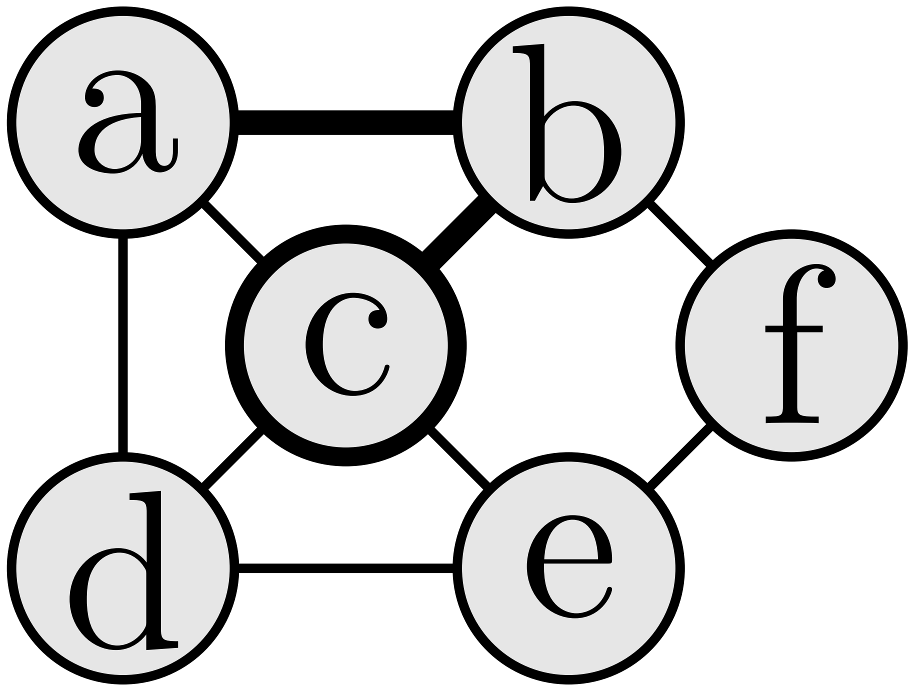

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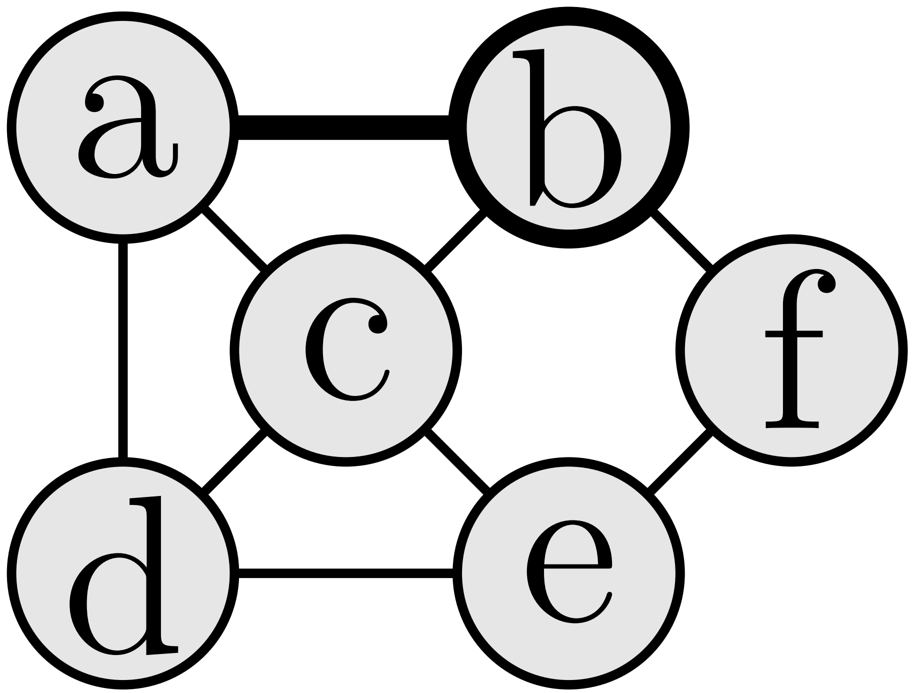
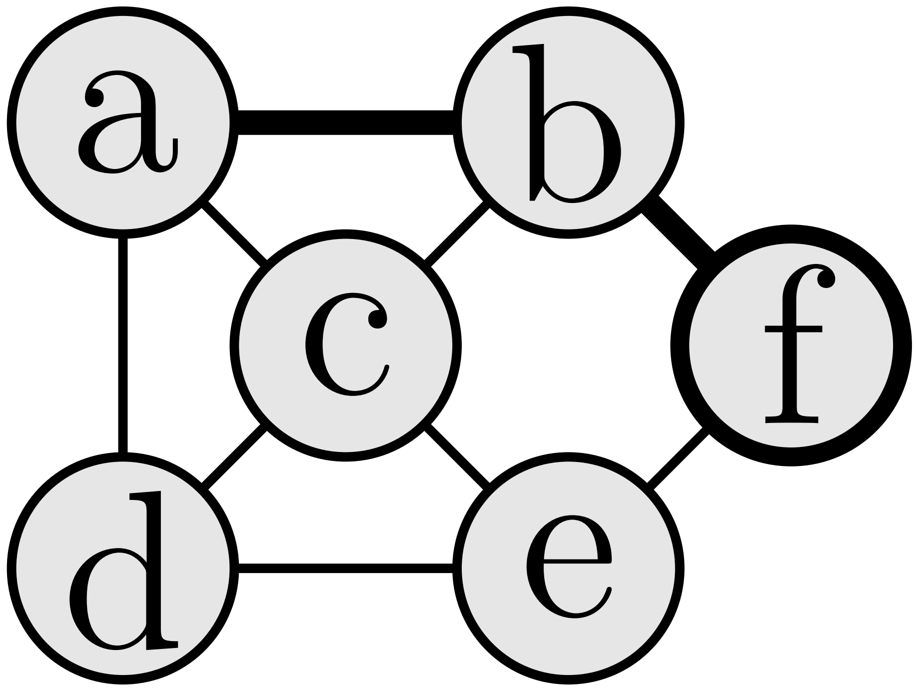
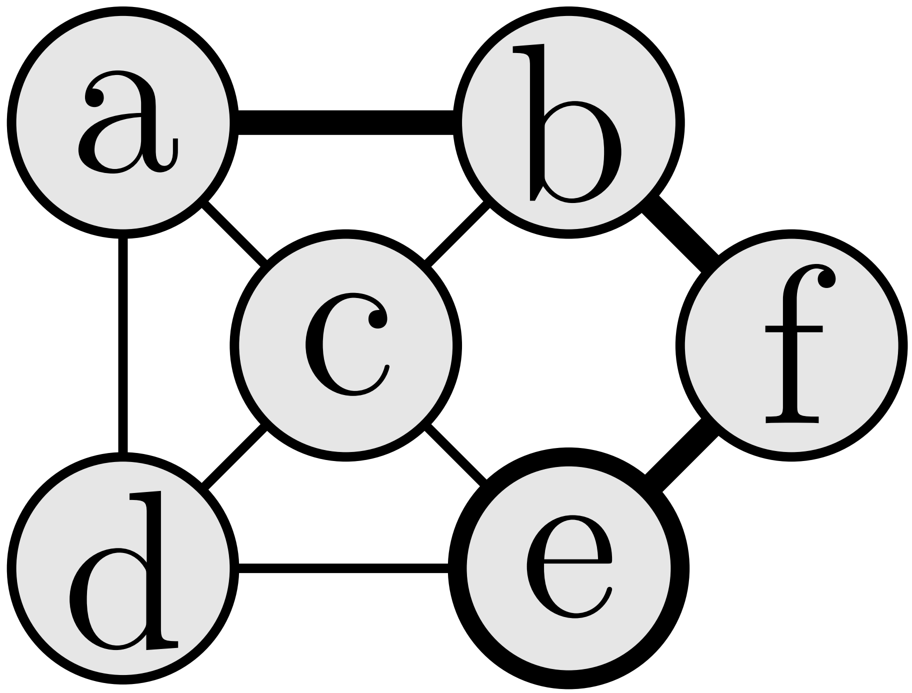


Hamiltonian Circuit Example



Hamiltonian Circuit Example



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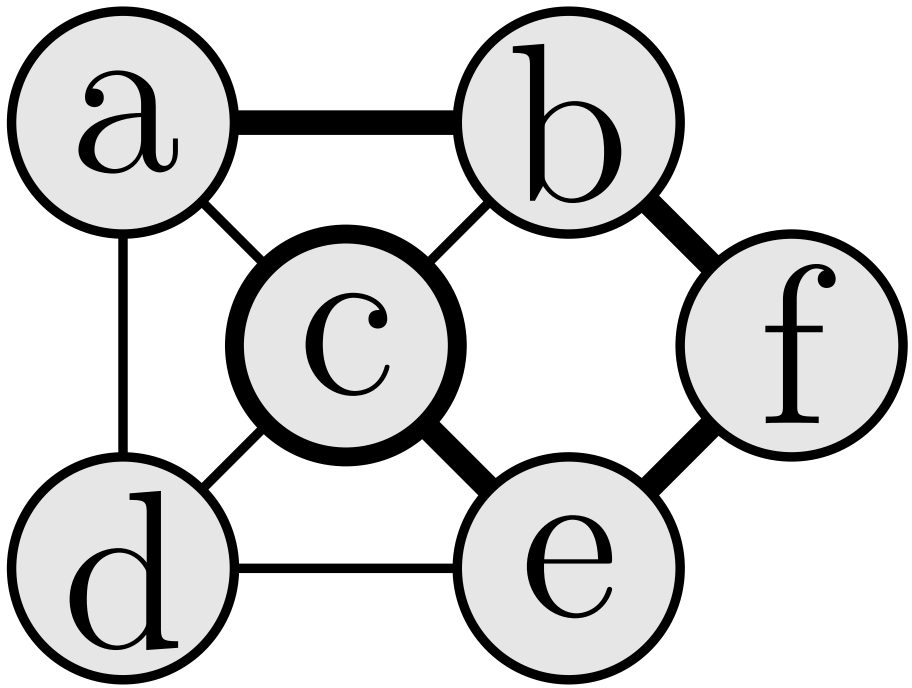

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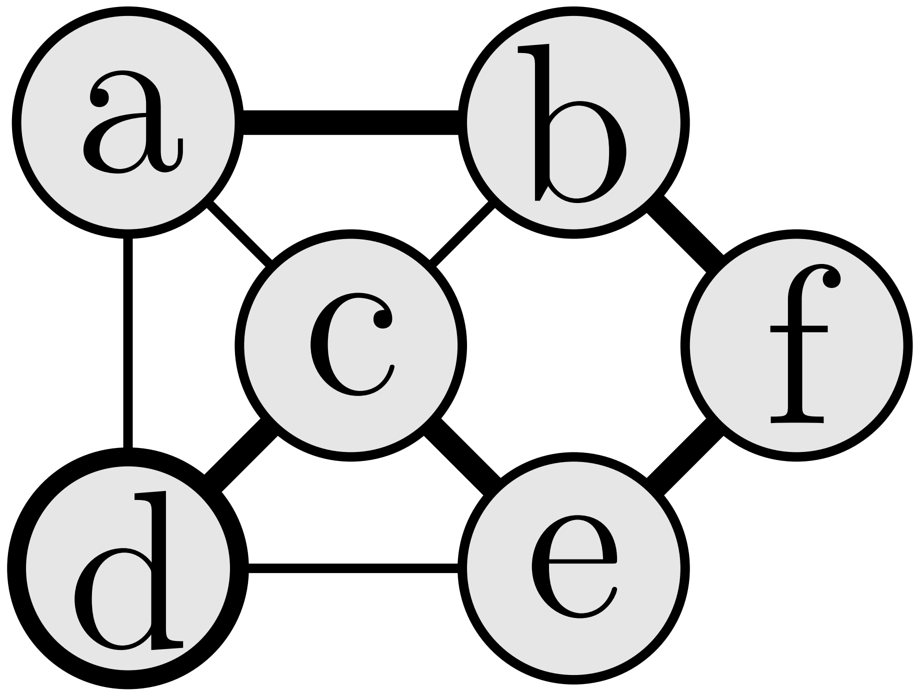

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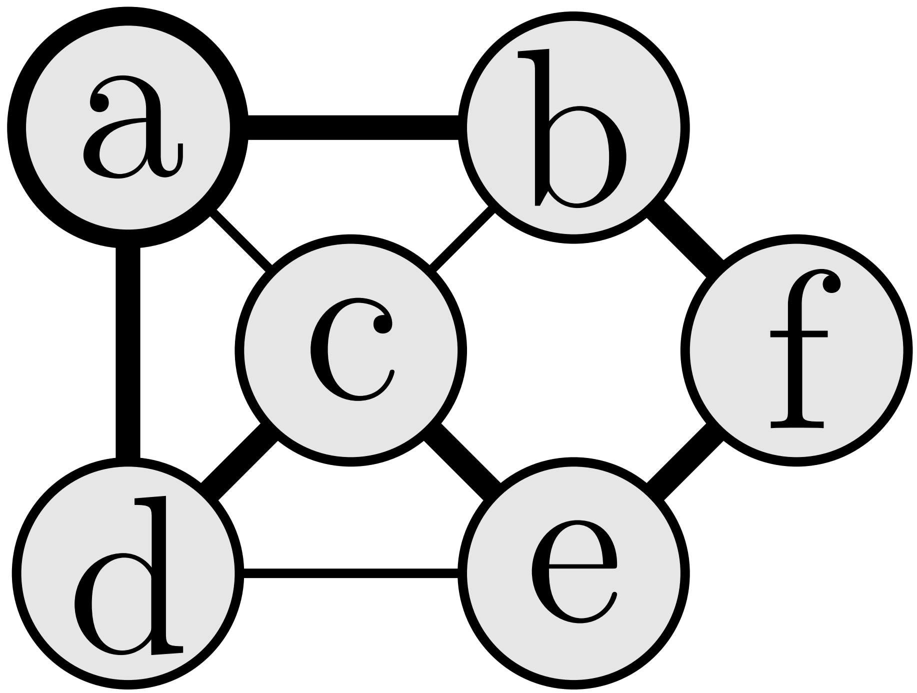

Backtracking

- Backtracking is a standard algorithm for solving constraint problems with large search spaces
- It can take exponential amount of time, however with many constraints it will often find solutions relatively quickly
- A backtracking algorithm does not solve, for example, sudoku in the same way as a human
- We can often speed up backtracking by adding more constraints (although, this can make writing the program longer)

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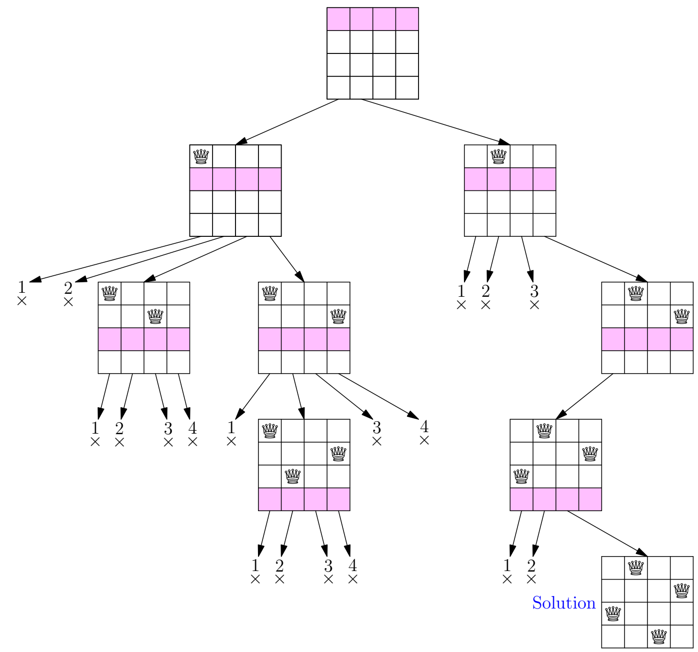
Outline

1. Search Trees
2. Backtracking
3. **Branch and Bound**
4. Search in AI



Optimisation Problems

- In many optimisation problems (TSP, Graph-colouring, etc.) we again have a huge search space ($n!$, k^n)
- However, we don't have hard constraints
- If we are interested in finding the optimal then we can use the cost as a constraint

  any partial solution has to have a lower cost than the best solution we have found so far

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Branch and Bound

- Branch and bound is used on optimisation problems where efficient strategies just don't work
- It beats exhaustive enumeration by eliminate many possible solutions without having to enumerate them all
- Branch and bound can be slow as the constraints aren't necessarily very strong
- By working harder we can sometimes strengthen the constraints thus eliminating much of the search space
- This strategy works quite well on smallish problems, but usually fails on large problems

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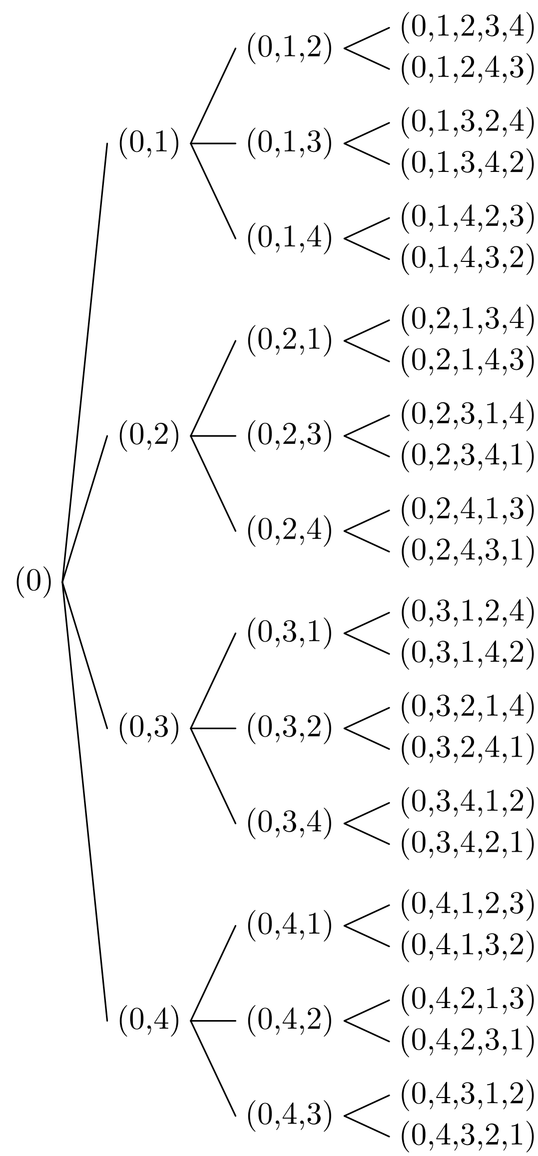
Cutting the Search Tree

- We can think of exact enumeration as exploring a giant search tree
- If we know a partial solution is worse than our bound we cut the search tree
- The earlier we cut the tree the more we can save



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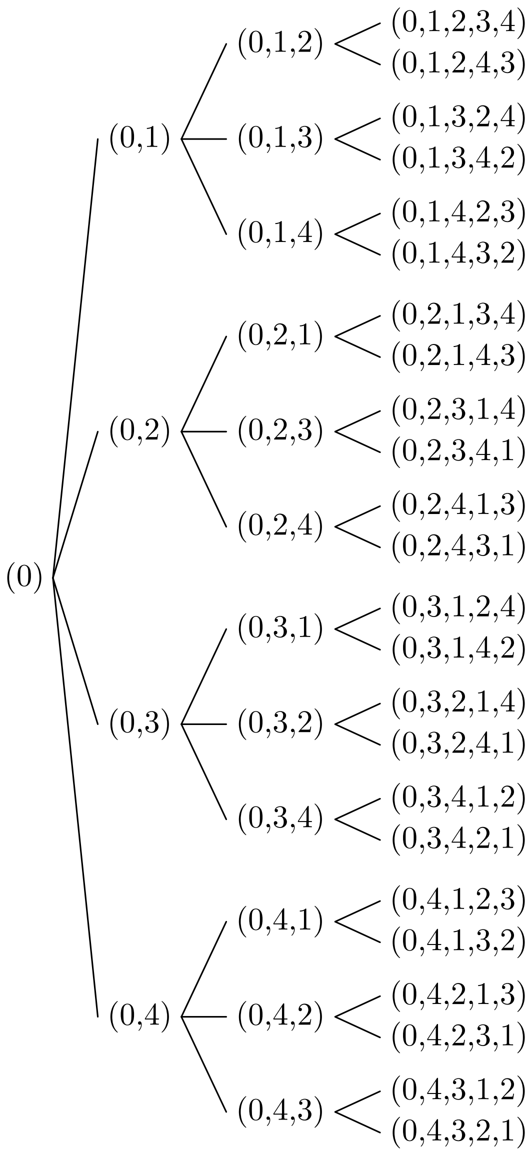

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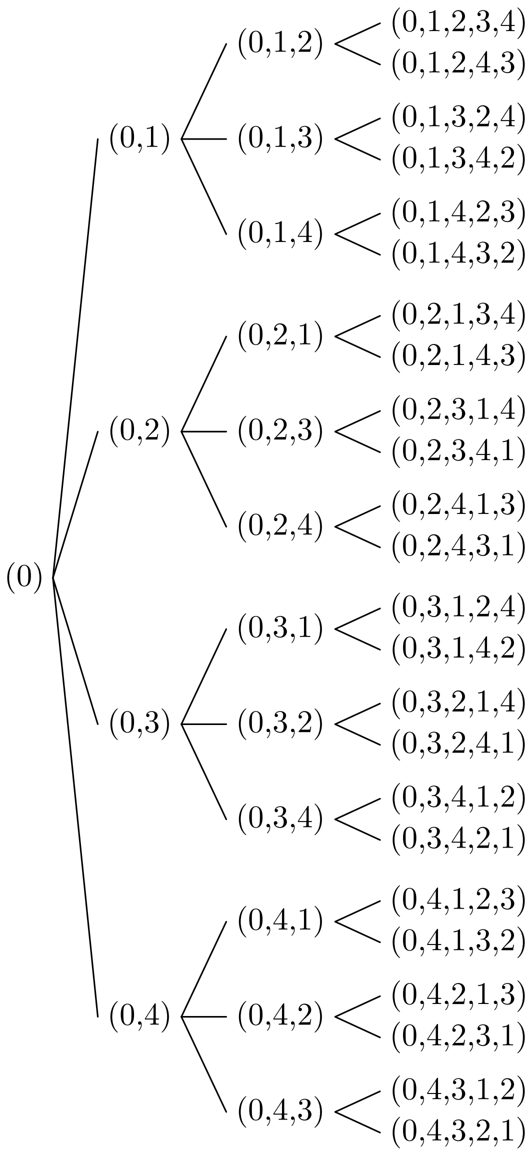
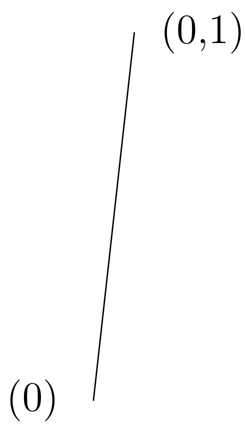
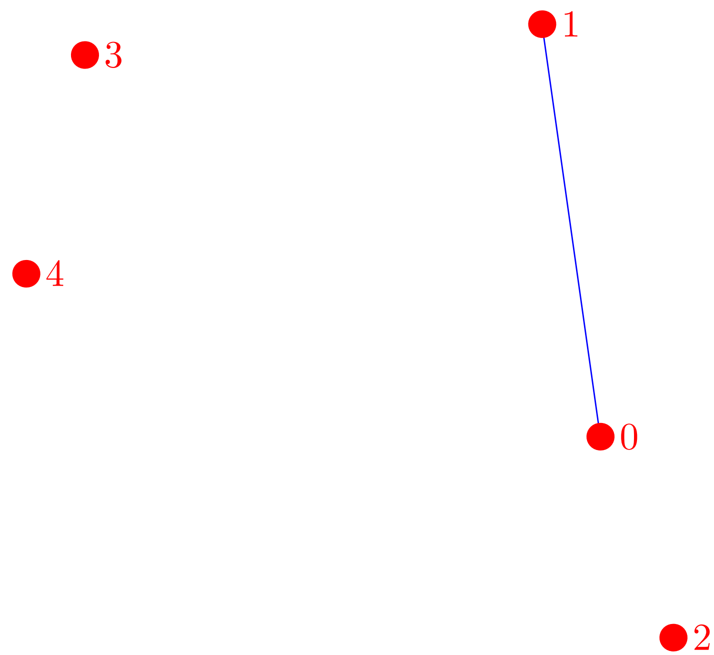


Branch and Bound in Action

bound = 10000

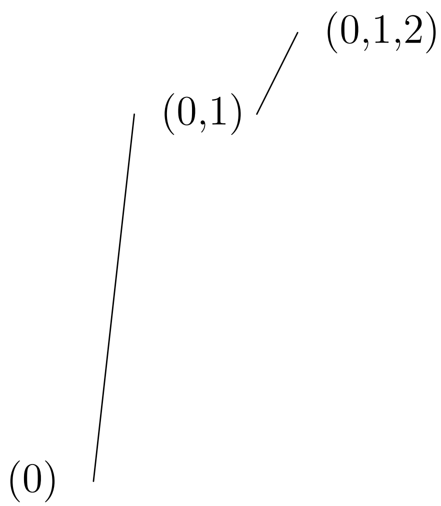
length = 61.211





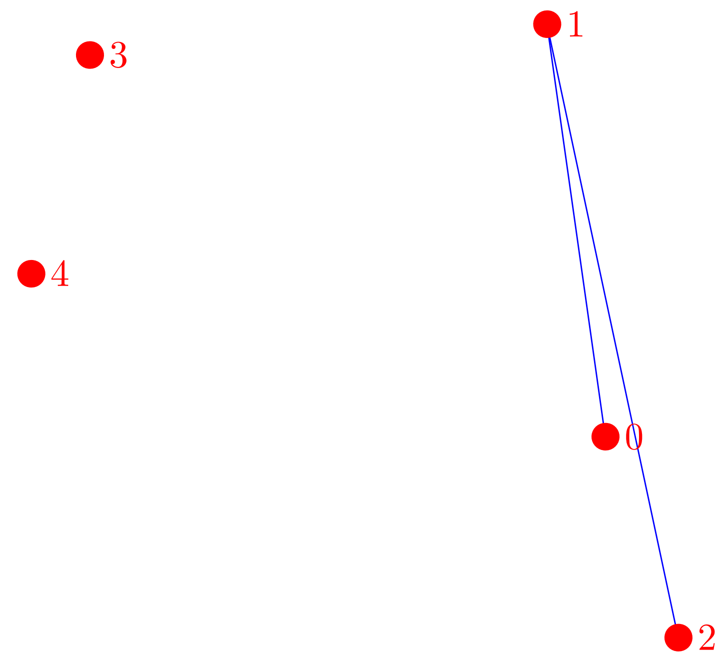
(0,1)

Branch and Bound in Action



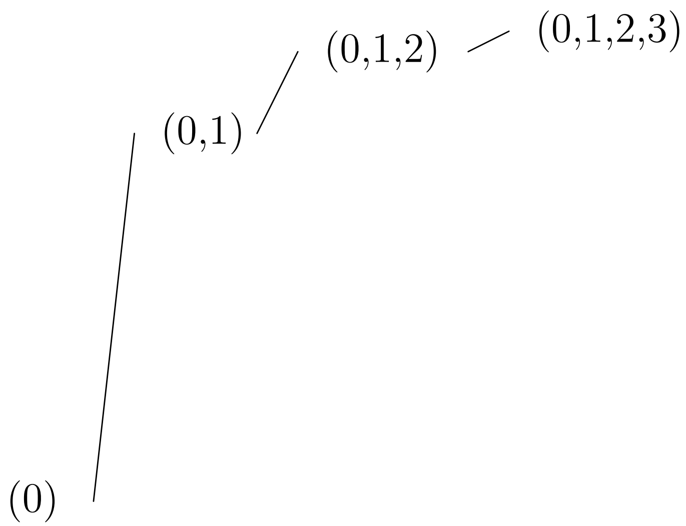
bound = 10000

length = 153.38



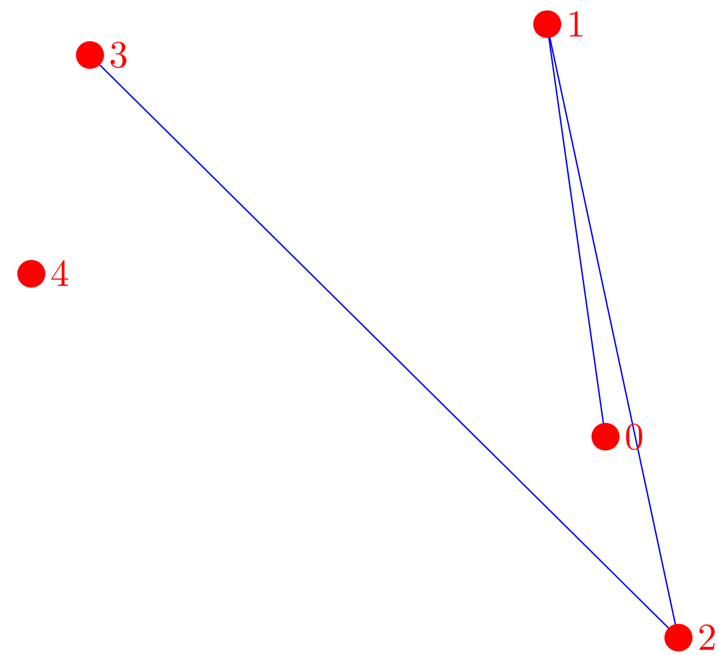
(0,1,2)

Branch and Bound in Action



bound = 10000

length = 275.05



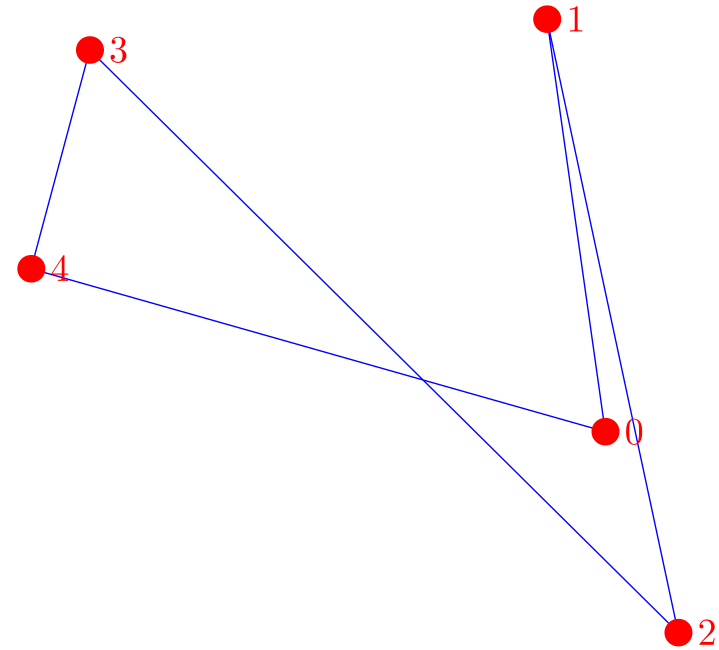
(0,1,2,3)

Branch and Bound in Action

(0) — (0,1) — (0,1,2) — (0,1,2,3) — (0,1,2,3,4)*

bound = 396.02

length = 396.02



(0,1,2,3,4)

Branch and Bound in Action

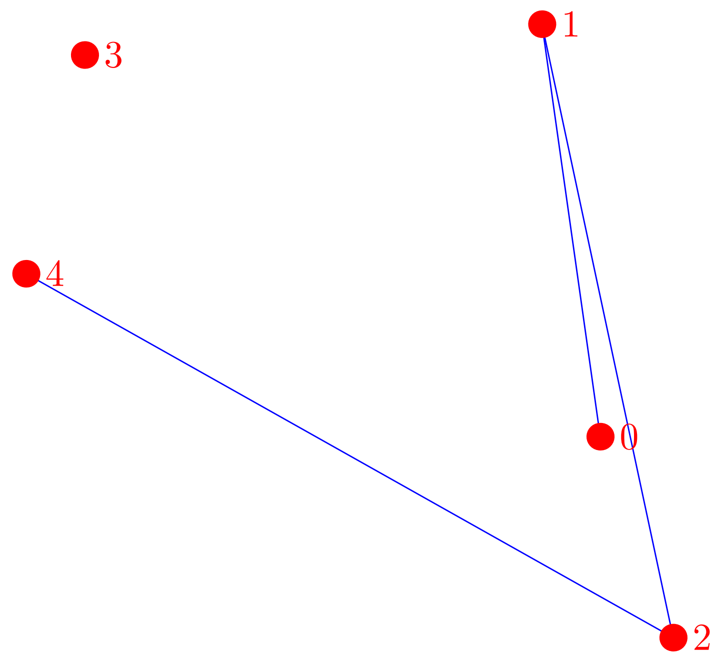
(0,1,2) < (0,1,2,3) — (0,1,2,3,4)*
(0,1,2,4)

(0,1)

(0)

bound = 396.02

length = 262.46



(0,1,2,4)

Branch and Bound in Action

(0,1,2,3) — (0,1,2,3,4)*

(0,1,2) <

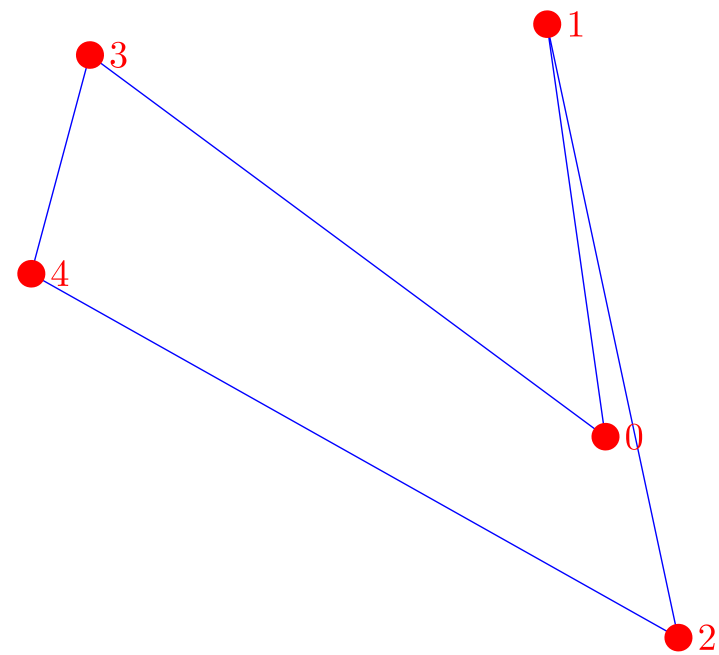
(0,1,2,4) — (0,1,2,4,3)*

(0,1)

(0)

bound = 389.98

length = 389.98



(0,1,2,4,3)

Branch and Bound in Action

(0) — (0,1)

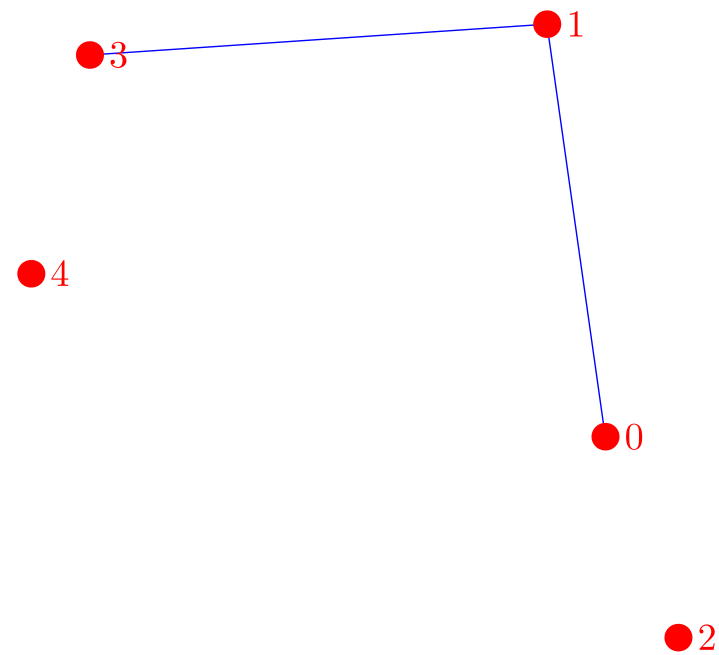
(0,1) — (0,1,2), (0,1,3)

(0,1,2) — (0,1,2,3) — (0,1,2,3,4)*

(0,1,2) — (0,1,2,4) — (0,1,2,4,3)*

bound = 389.98

length = 128.54



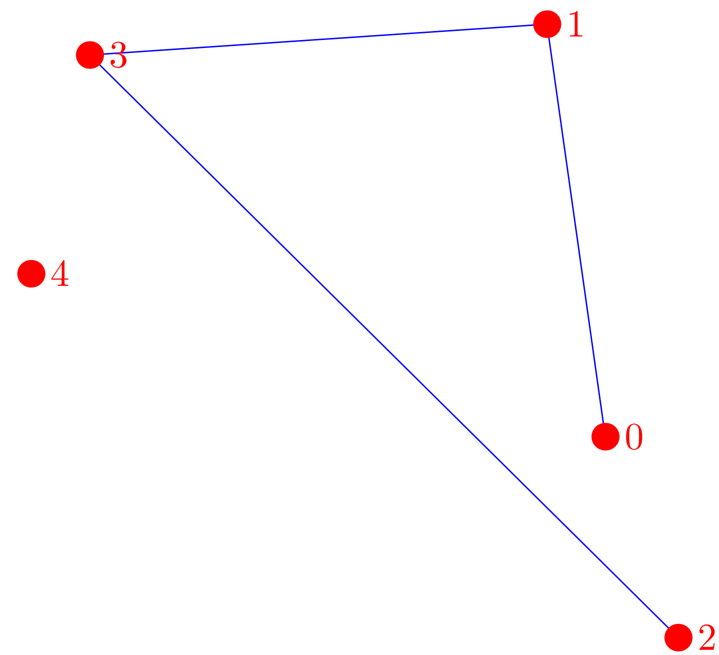
(0,1,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2)

bound = 389.98

length = 250.21



(0,1,3,2)

Branch and Bound in Action

(0)

(0,1)

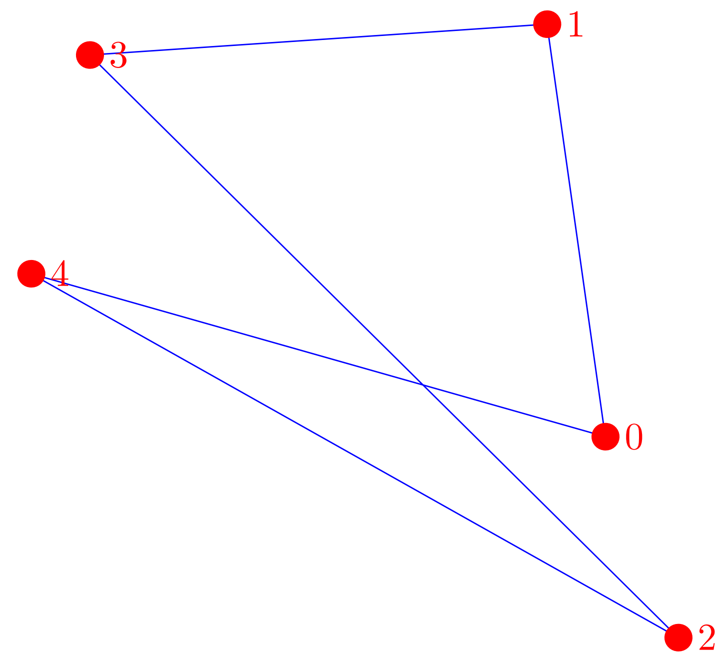
(0,1,2) — (0,1,2,3) — (0,1,2,3,4)*

(0,1,2) — (0,1,2,4) — (0,1,2,4,3)*

(0,1,3) — (0,1,3,2) — (0,1,3,2,4)

bound = 389.98

length = 446.99



(0,1,3,2,4)

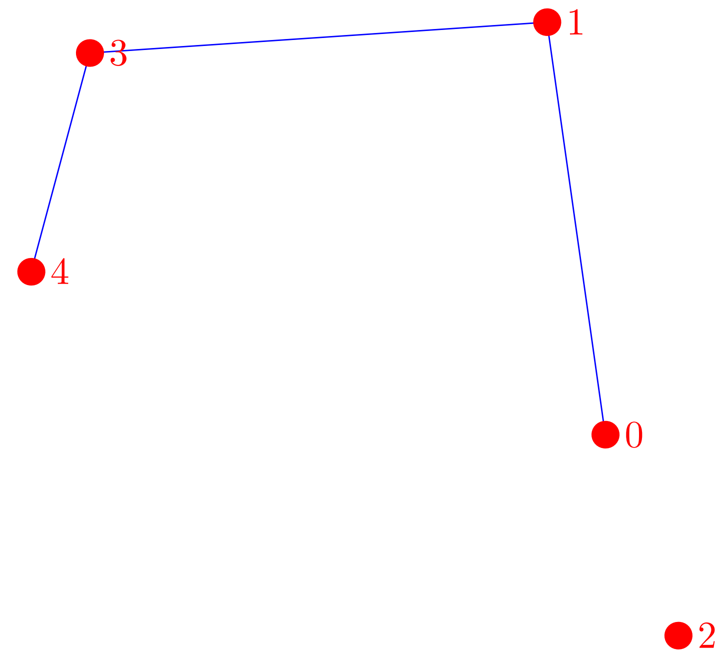
Branch and Bound in Action

(0,1,2) < (0,1,2,3) — (0,1,2,3,4)*
(0,1,2,4) — (0,1,2,4,3)*

(0) — (0,1) — (0,1,3) < (0,1,3,2) — (0,1,3,2,4)
(0,1,3,4)

bound = 389.98

length = 161.82



(0,1,3,4)

Branch and Bound in Action

bound = 302.31

length = 302.31

(0) — (0,1)

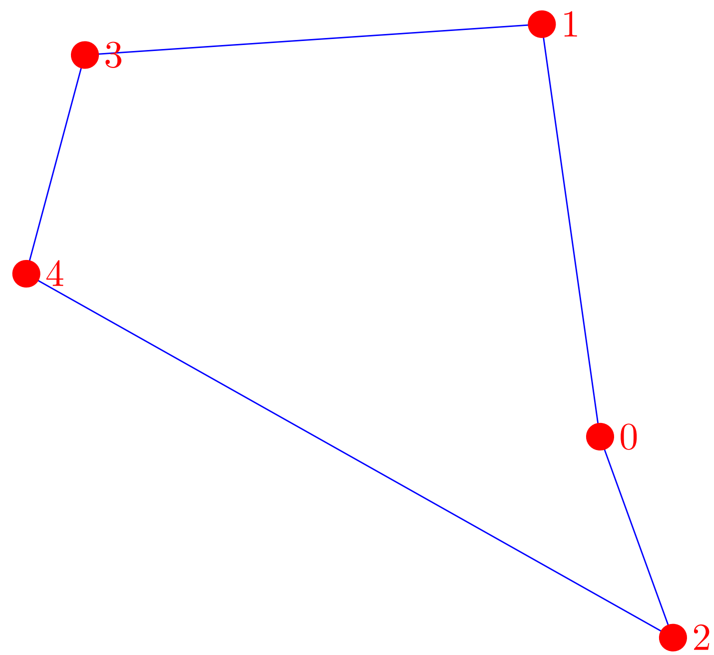
(0,1) < (0,1,2), (0,1,3)

(0,1,2) < (0,1,2,3) — (0,1,2,3,4)*

(0,1,2) < (0,1,2,4) — (0,1,2,4,3)*

(0,1,3) < (0,1,3,2) — (0,1,3,2,4)

(0,1,3) < (0,1,3,4) — (0,1,3,4,2)*



(0,1,3,4,2)

Branch and Bound in Action

(0)

(0,1)

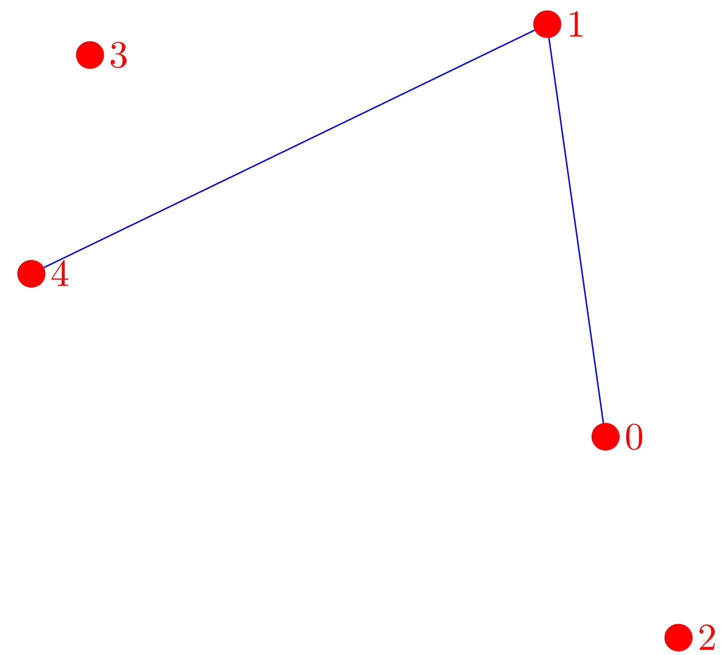
(0,1,2)
- (0,1,2,3) — (0,1,2,3,4)*
- (0,1,2,4) — (0,1,2,4,3)*

(0,1,3)
- (0,1,3,2) — (0,1,3,2,4)
- (0,1,3,4) — (0,1,3,4,2)*

(0,1,4)

bound = 302.31

length = 145.41



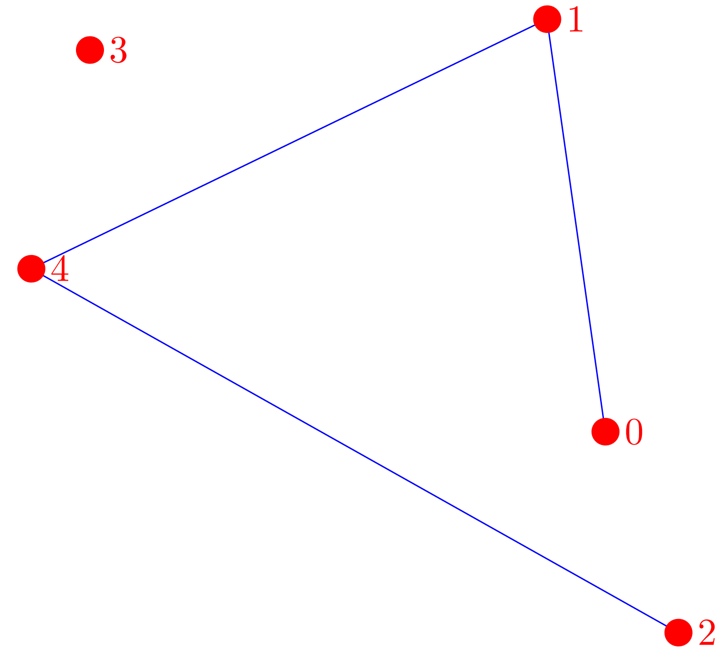
(0,1,4)

Branch and Bound in Action

(0)
- (0,1)
  - (0,1,2)
    - (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
    - (0,1,4,2)

bound = 302.31

length = 254.49



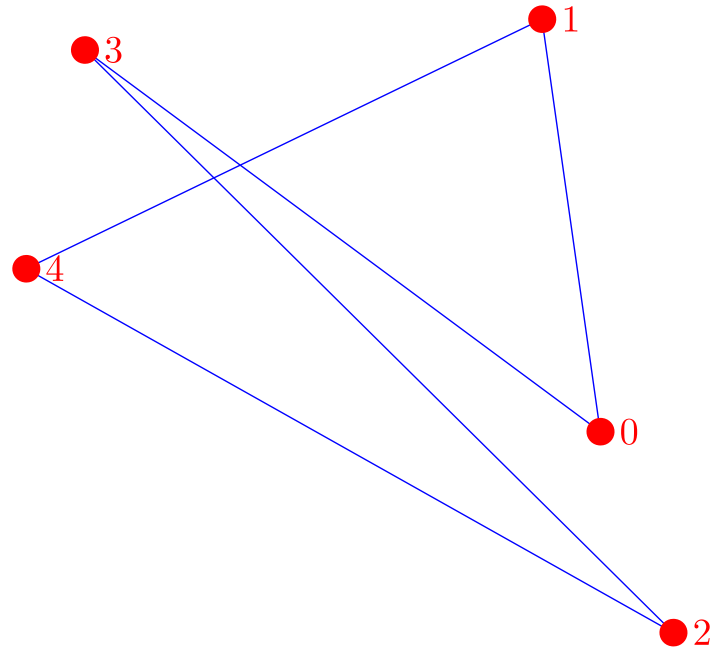
(0,1,4,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)

bound = 302.31

length = 470.41



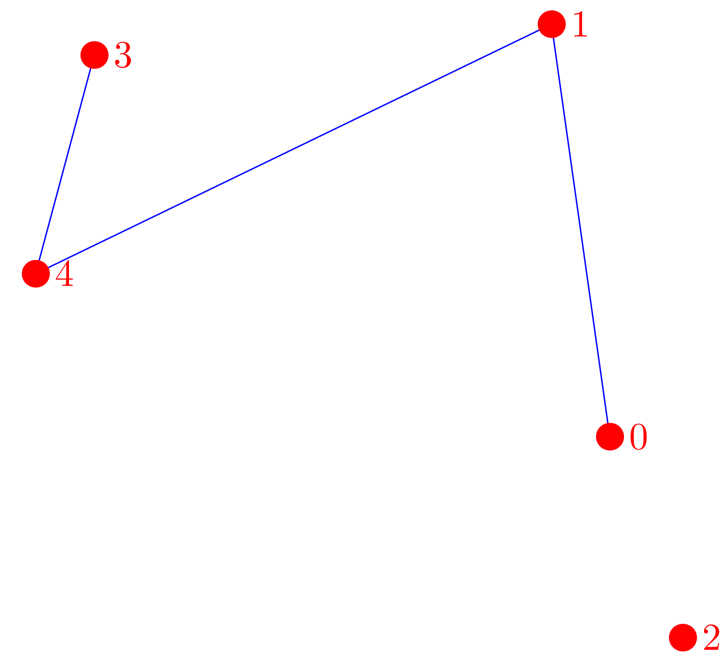
(0,1,4,2,3)

Branch and Bound in Action

(0)
- (0,1)
  - (0,1,2)
    - (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
    - (0,1,4,2) — (0,1,4,2,3)
    - (0,1,4,3)

bound = 302.31

length = 178.69



(0,1,4,3)

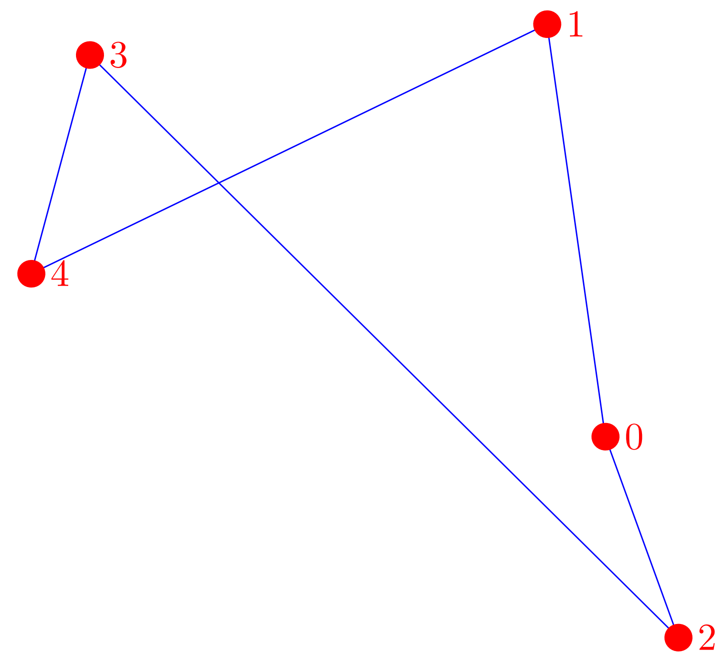
Branch and Bound in Action

(0) — (0,1)

- (0,1,2)
  - (0,1,2,3) — (0,1,2,3,4)*
  - (0,1,2,4) — (0,1,2,4,3)*
- (0,1,3)
  - (0,1,3,2) — (0,1,3,2,4)
  - (0,1,3,4) — (0,1,3,4,2)*
- (0,1,4)
  - (0,1,4,2) — (0,1,4,2,3)
  - (0,1,4,3) — (0,1,4,3,2)

bound = 302.31

length = 331.77



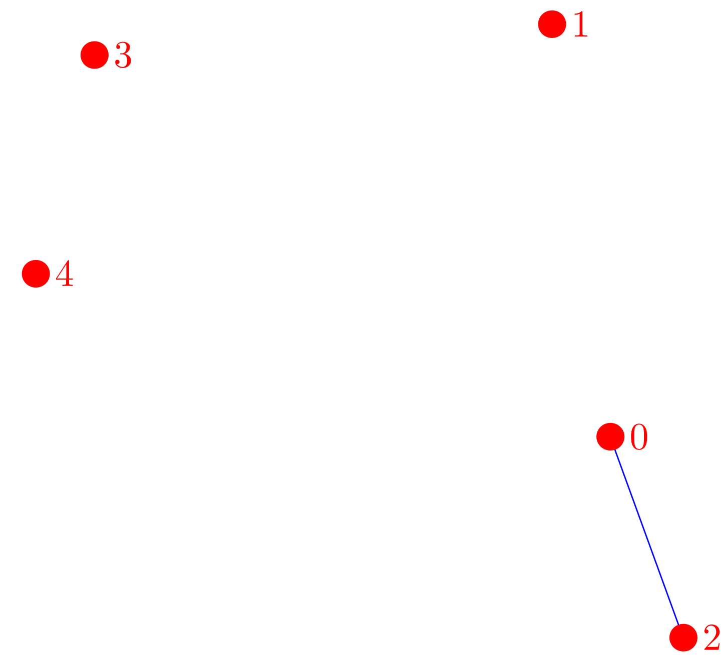
(0,1,4,3,2)

Branch and Bound in Action

bound = 302.31

length = 31.41

(0)
- (0,1)
  - (0,1,2)
    - (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
    - (0,1,4,2) — (0,1,4,2,3)
    - (0,1,4,3) — (0,1,4,3,2)
- (0,2)



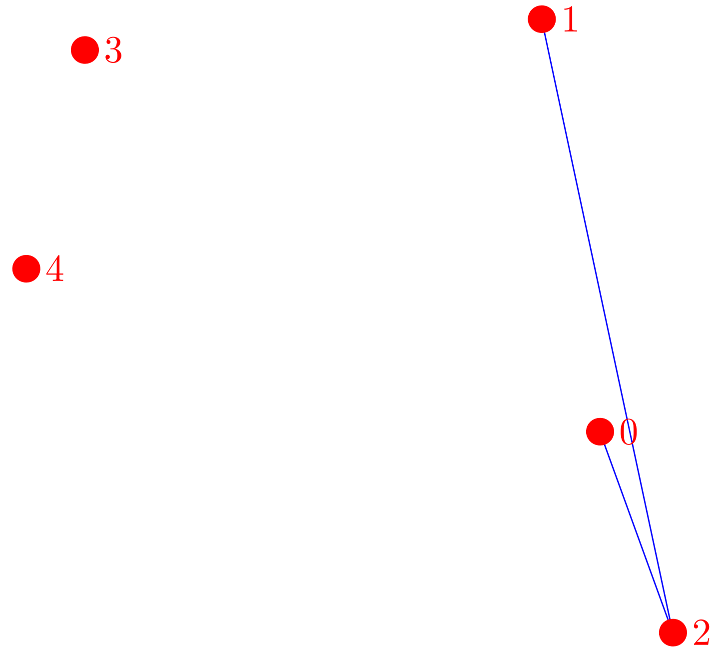
(0,2)

Branch and Bound in Action

bound = 302.31

length = 123.58

(0)
- (0,1)
  - (0,1,2)
    - (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
    - (0,1,4,2) — (0,1,4,2,3)
    - (0,1,4,3) — (0,1,4,3,2)
- (0,2)
  - (0,2,1)



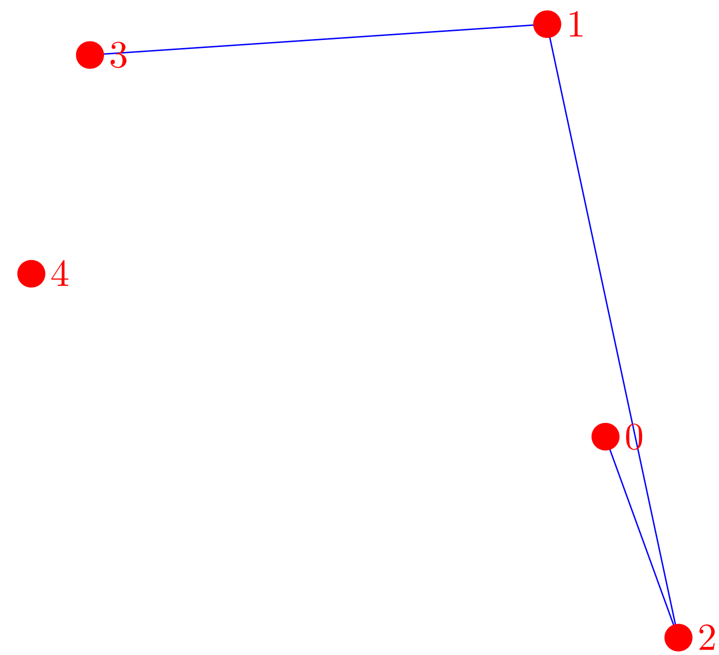
(0,2,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3)

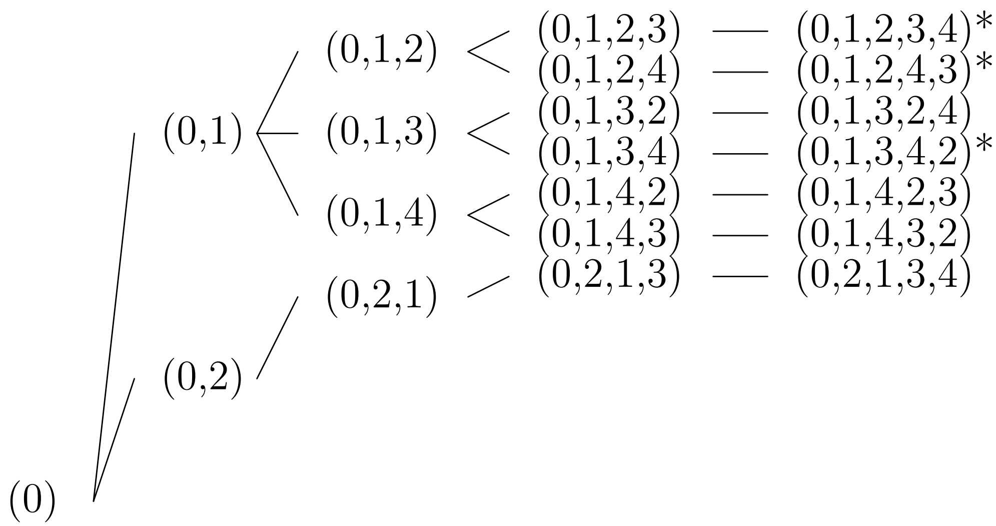
bound = 302.31

length = 190.92



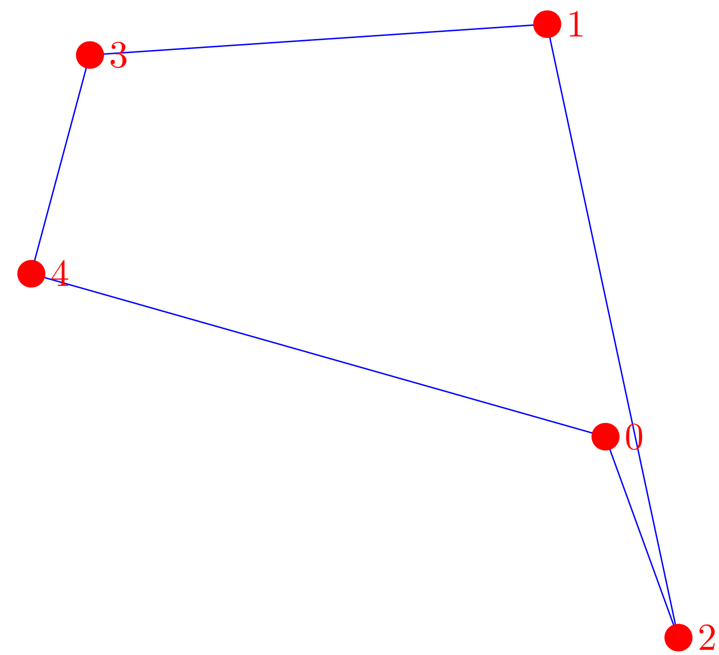
(0,2,1,3)

Branch and Bound in Action



bound = 302.31

length = 311.88



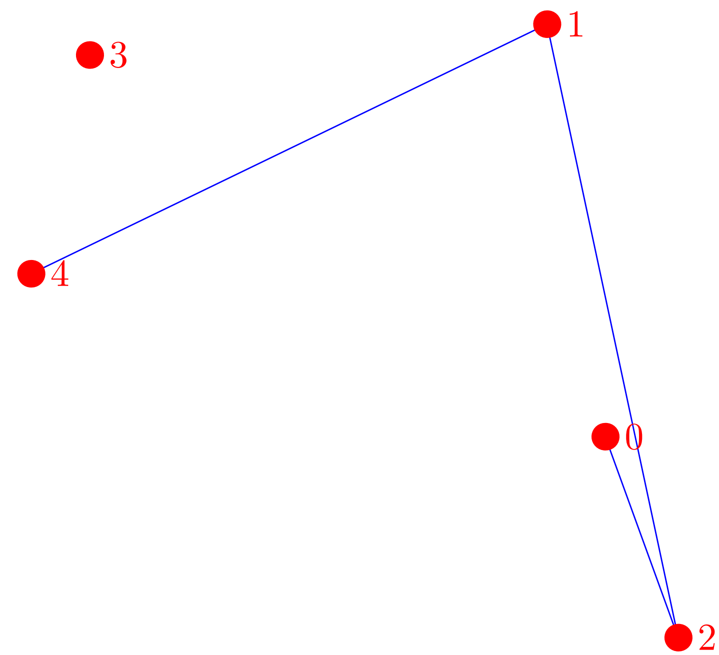
(0,2,1,3,4)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4)

bound = 302.31

length = 207.79



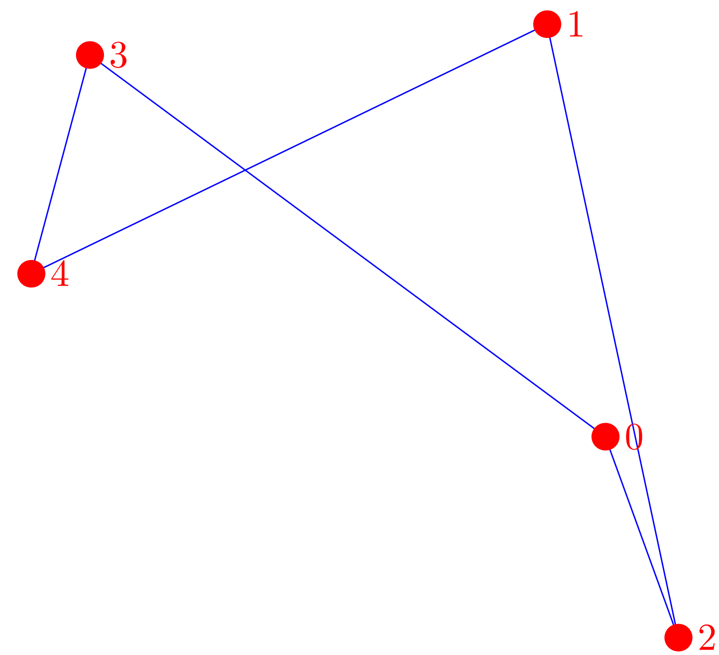
(0,2,1,4)

Branch and Bound in Action

(0)
- (0,1)
  - (0,1,2) < (0,1,2,3) — (0,1,2,3,4)*
  - (0,1,2) < (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3) < (0,1,3,2) — (0,1,3,2,4)
  - (0,1,3) < (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4) < (0,1,4,2) — (0,1,4,2,3)
  - (0,1,4) < (0,1,4,3) — (0,1,4,3,2)
- (0,2)
  - (0,2,1) < (0,2,1,3) — (0,2,1,3,4)
  - (0,2,1) < (0,2,1,4) — (0,2,1,4,3)

bound = 302.31

length = 335.3



(0,2,1,4,3)

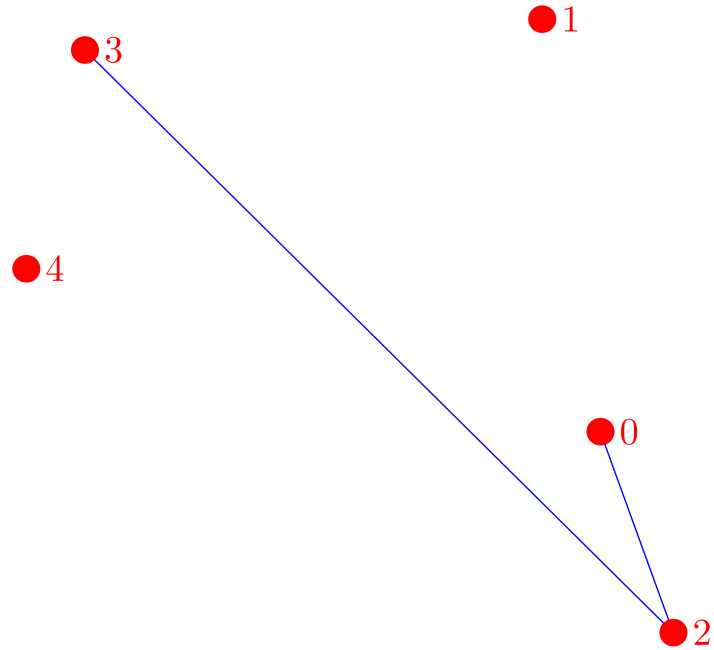
Branch and Bound in Action

(0)

- (0,1)
  - (0,1,2)
    - (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
    - (0,1,4,2) — (0,1,4,2,3)
    - (0,1,4,3) — (0,1,4,3,2)
- (0,2)
  - (0,2,1)
    - (0,2,1,3) — (0,2,1,3,4)
    - (0,2,1,4) — (0,2,1,4,3)
  - (0,2,3)

bound = 302.31

length = 153.08



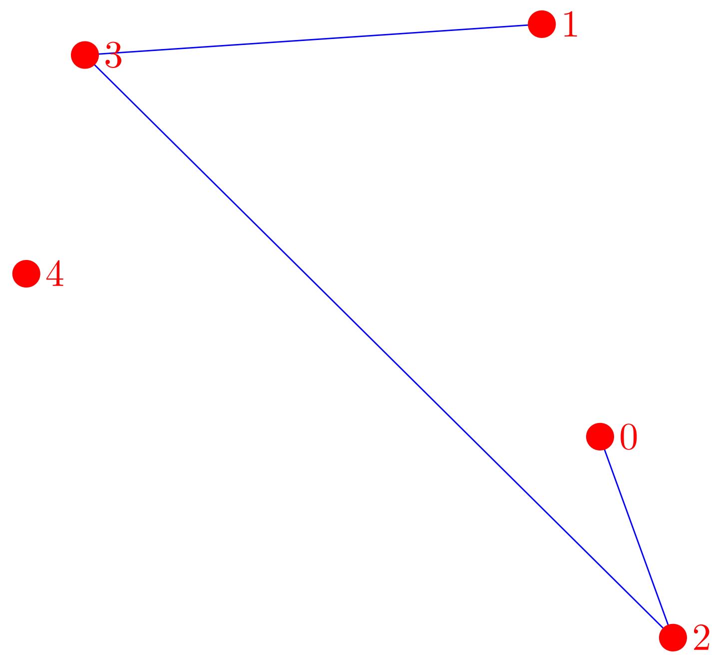
(0,2,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1)

bound = 302.31

length = 220.41



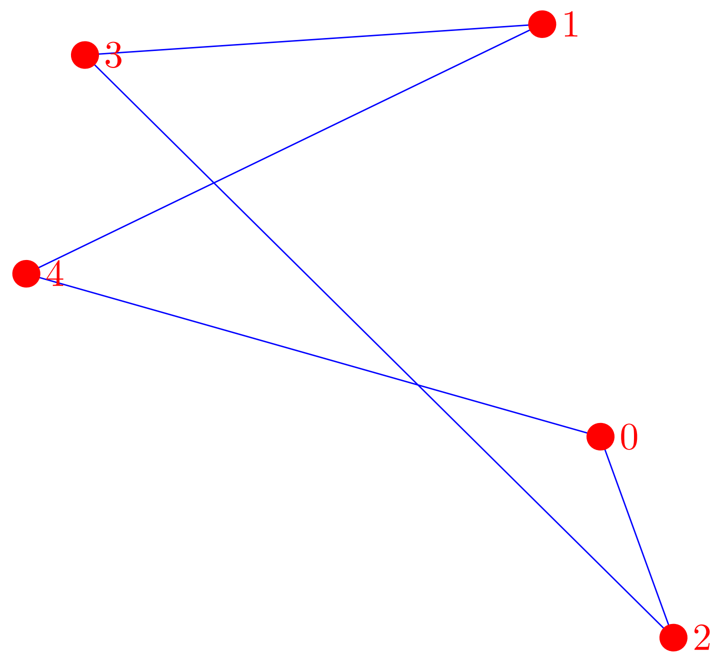
(0,2,3,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)

bound = 302.31

length = 392.31



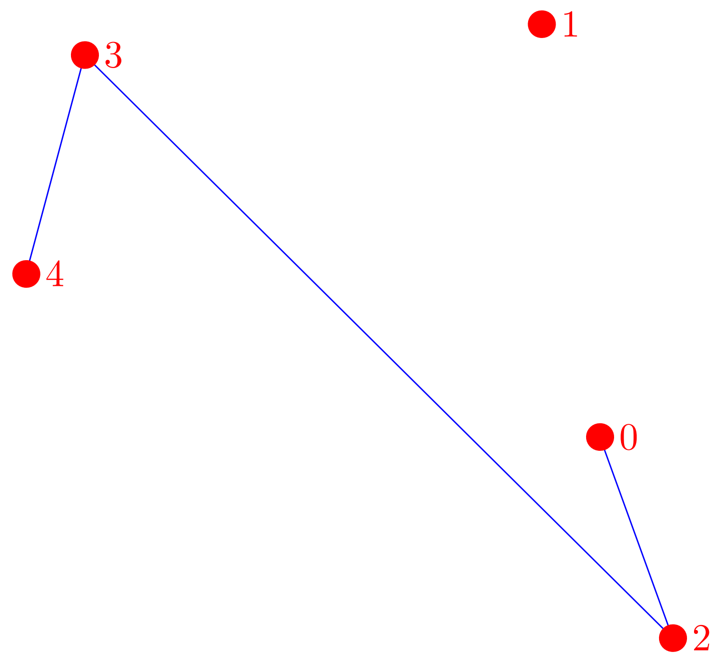
(0,2,3,1,4)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4)

bound = 302.31

length = 186.35



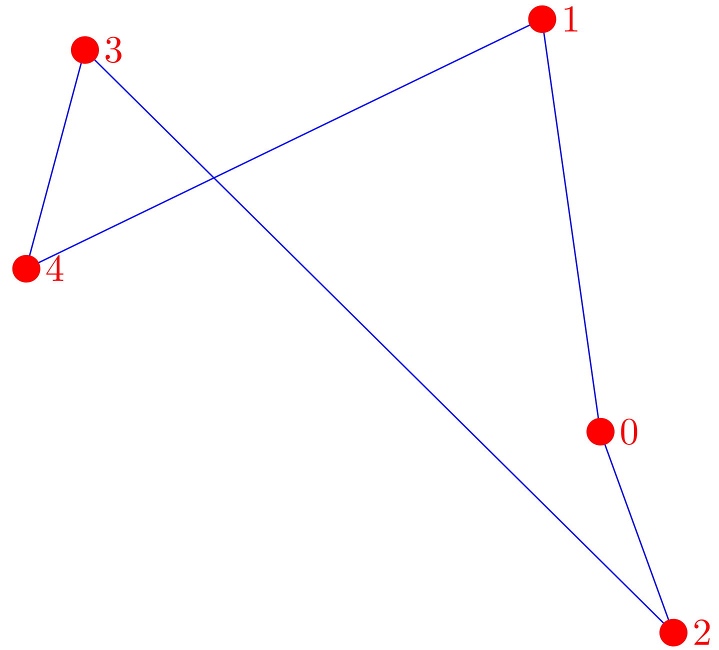
(0,2,3,4)

Branch and Bound in Action

(0)
- (0,1)
  - (0,1,2) < (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3) < (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4) < (0,1,4,2) — (0,1,4,2,3)
    - (0,1,4,3) — (0,1,4,3,2)
- (0,2)
  - (0,2,1) < (0,2,1,3) — (0,2,1,3,4)
    - (0,2,1,4) — (0,2,1,4,3)
  - (0,2,3) < (0,2,3,1) — (0,2,3,1,4)
    - (0,2,3,4) — (0,2,3,4,1)

bound = 302.31

length = 331.77



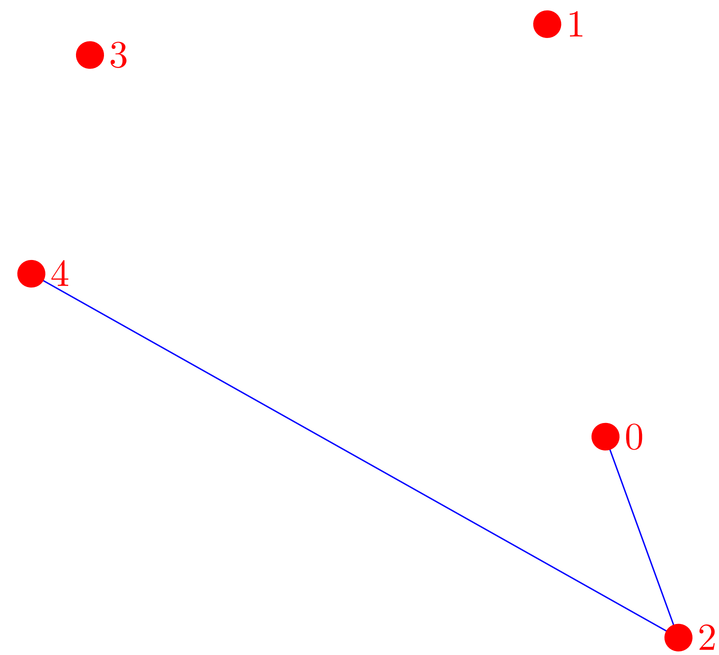
(0,2,3,4,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)

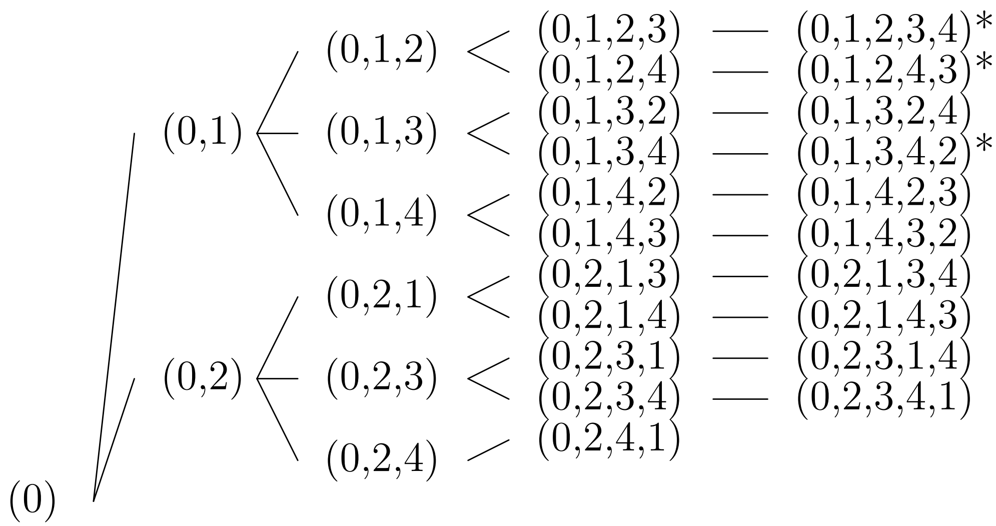
bound = 302.31

length = 140.49



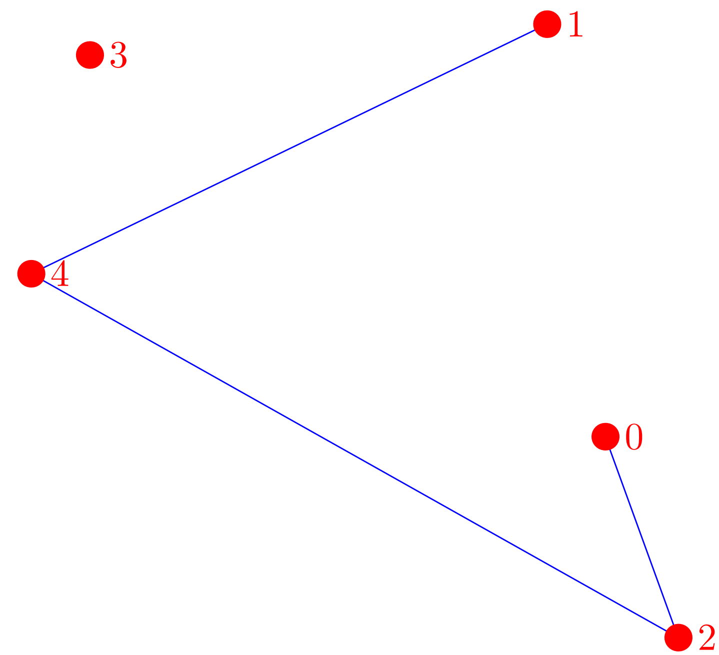
(0,2,4)

Branch and Bound in Action



bound = 302.31

length = 224.69



(0,2,4,1)

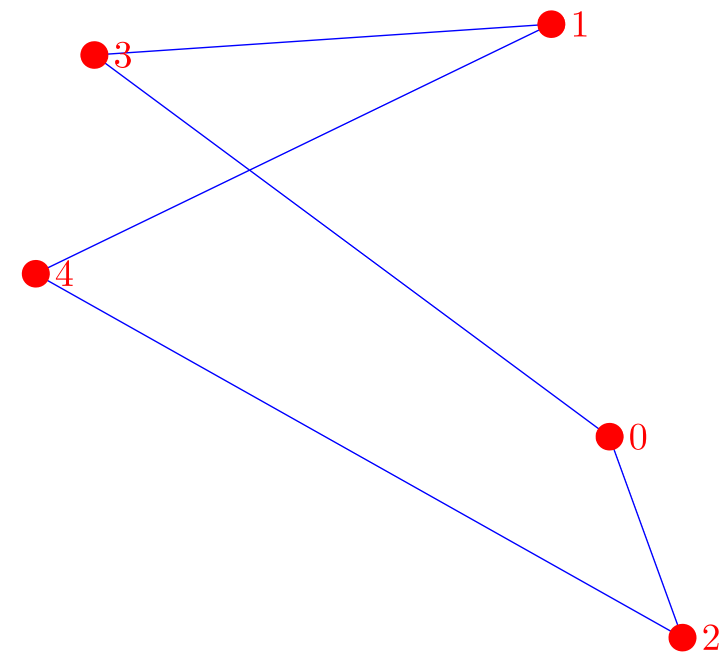
Branch and Bound in Action

(0)

- (0,1)
  - (0,1,2)
    - (0,1,2,3) — (0,1,2,3,4)*
    - (0,1,2,4) — (0,1,2,4,3)*
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
    - (0,1,4,2) — (0,1,4,2,3)
    - (0,1,4,3) — (0,1,4,3,2)
- (0,2)
  - (0,2,1)
    - (0,2,1,3) — (0,2,1,3,4)
    - (0,2,1,4) — (0,2,1,4,3)
  - (0,2,3)
    - (0,2,3,1) — (0,2,3,1,4)
    - (0,2,3,4) — (0,2,3,4,1)
  - (0,2,4)
    - (0,2,4,1) — (0,2,4,1,3)

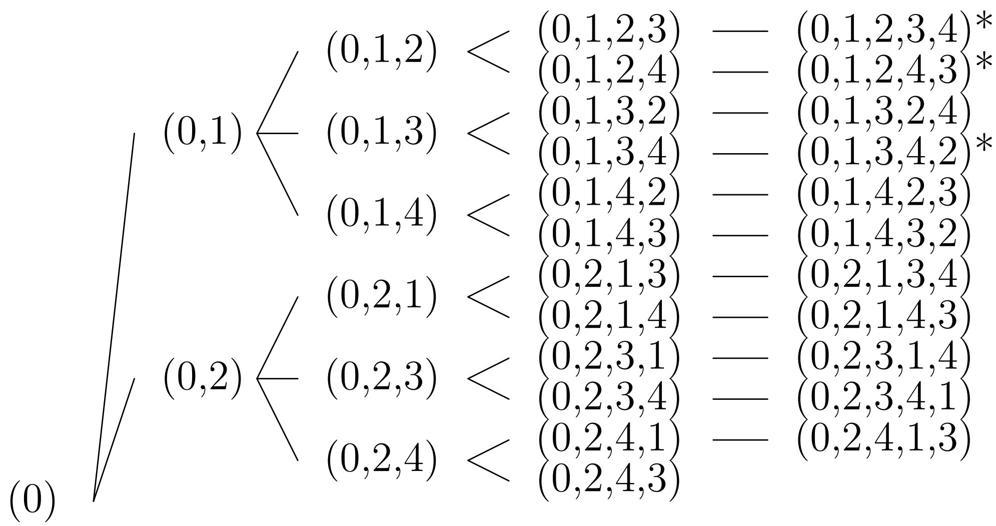
bound = 302.31

length = 386.27



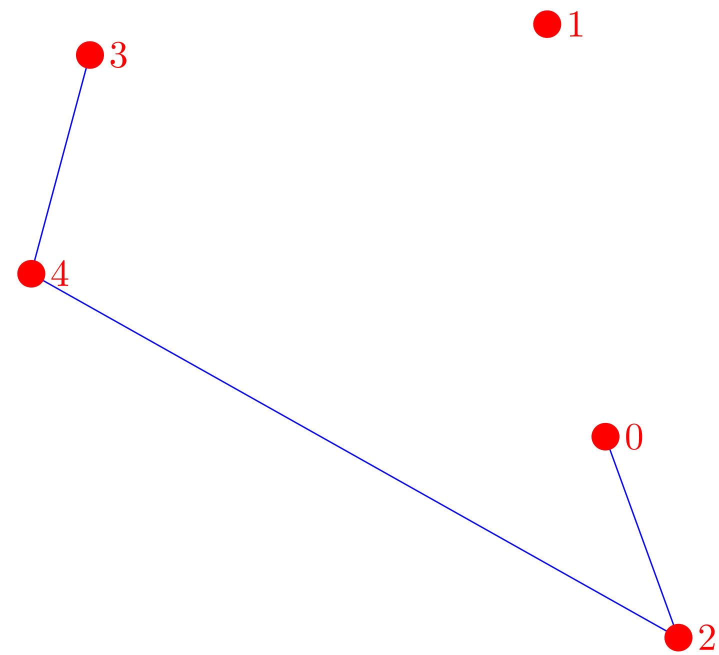
(0,2,4,1,3)

Branch and Bound in Action



bound = 302.31

length = 173.77



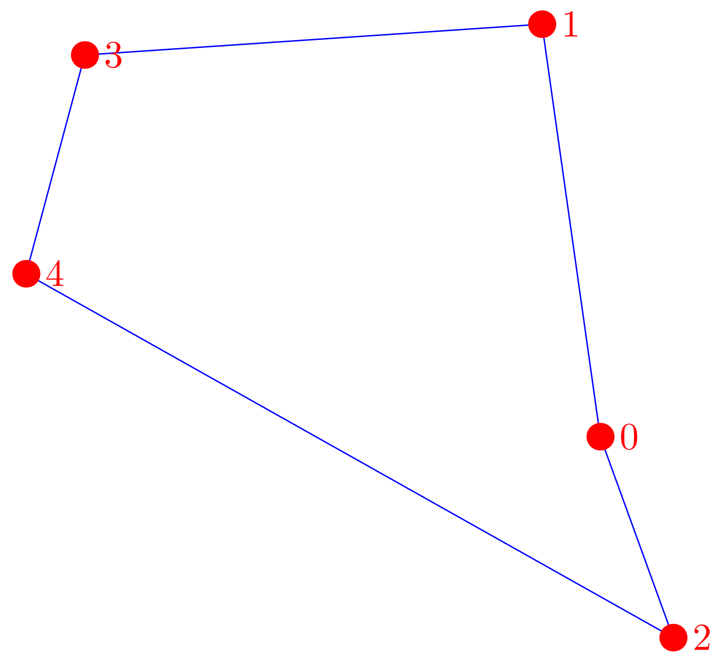
(0,2,4,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*

bound = 302.31

length = 302.31



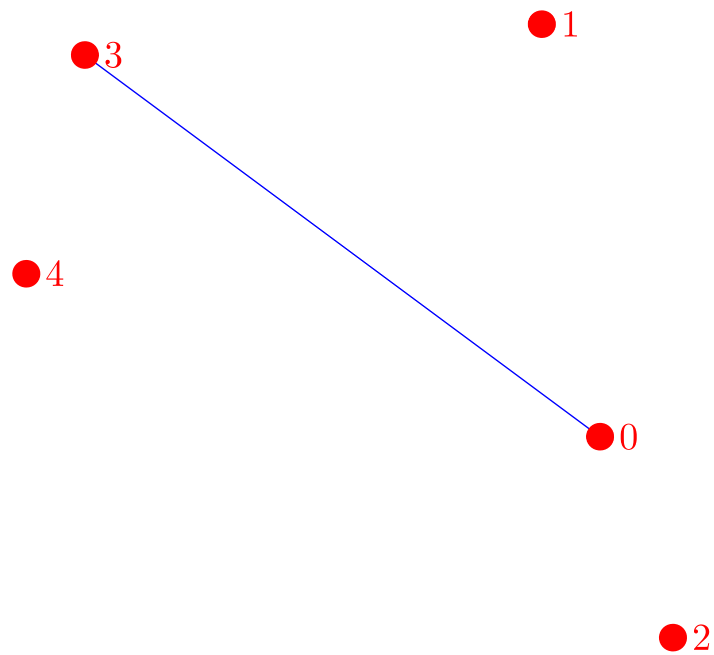
(0,2,4,3,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)

bound = 302.31

length = 94.244



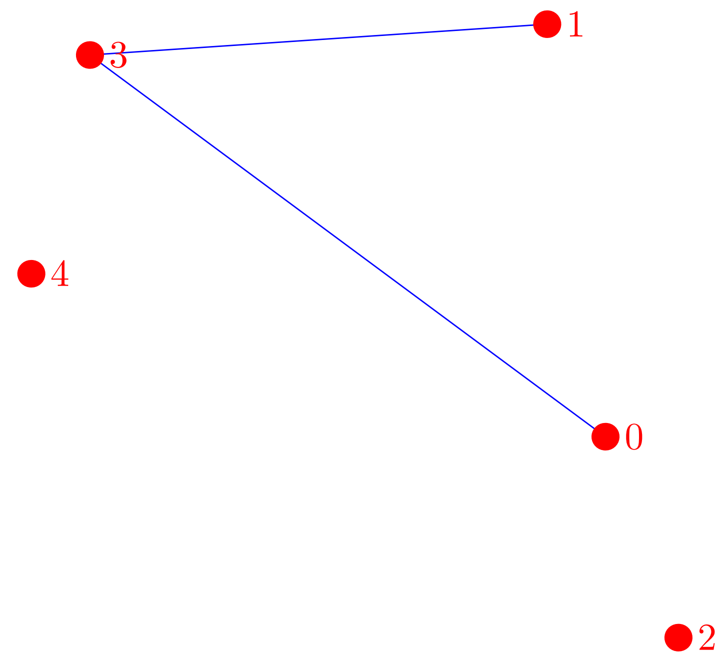
(0,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)

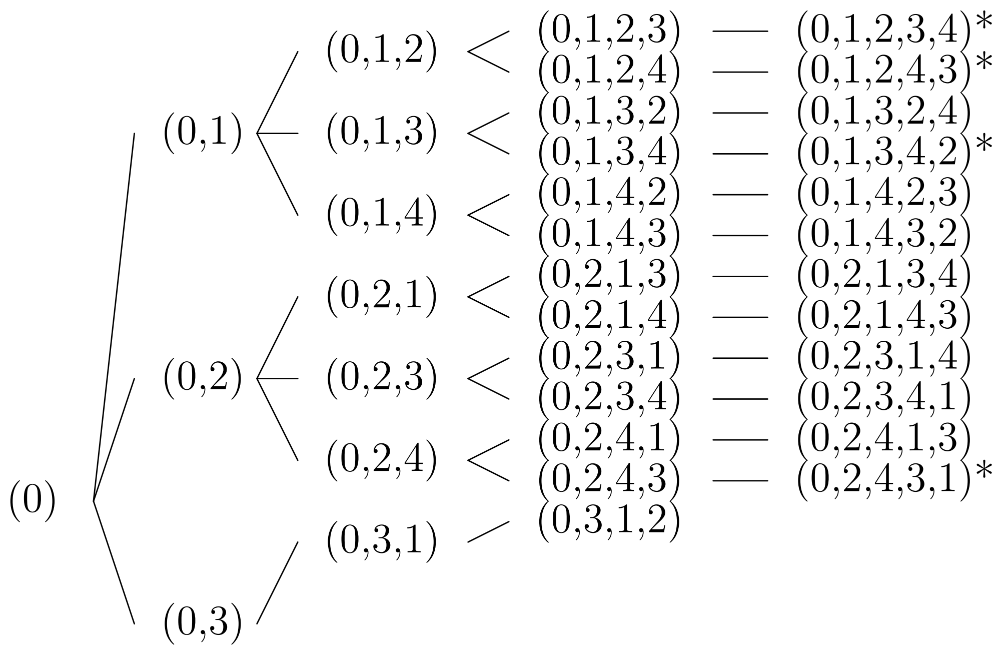
bound = 302.31

length = 161.58



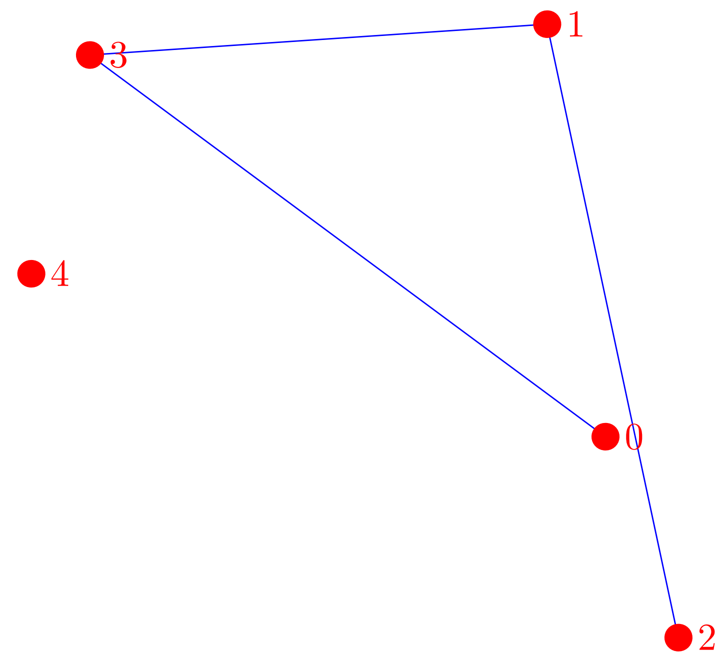
(0,3,1)

Branch and Bound in Action



bound = 302.31

length = 253.75



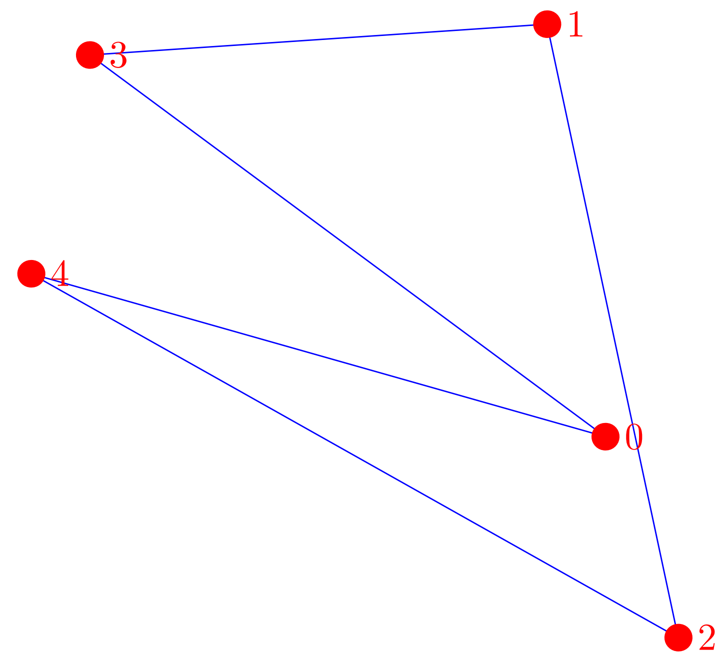
(0,3,1,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)

bound = 302.31

length = 450.52



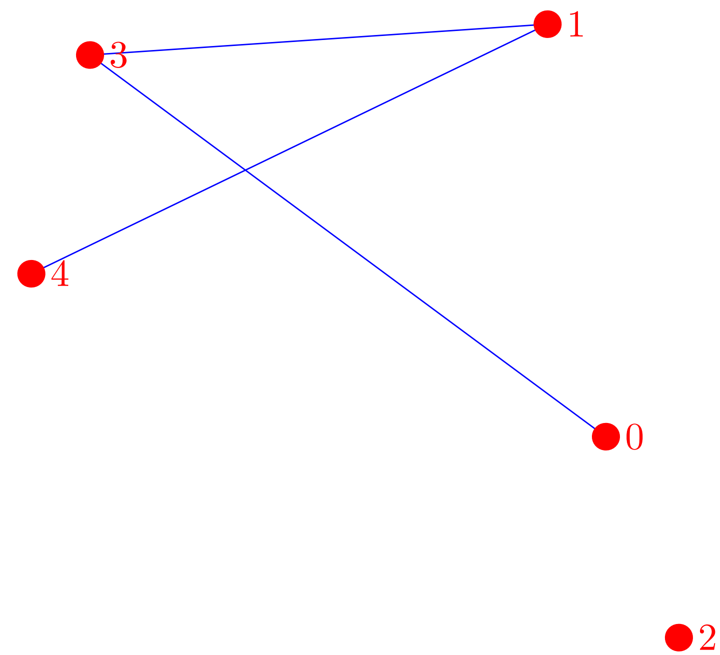
(0,3,1,2,4)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4)

bound = 302.31

length = 245.78



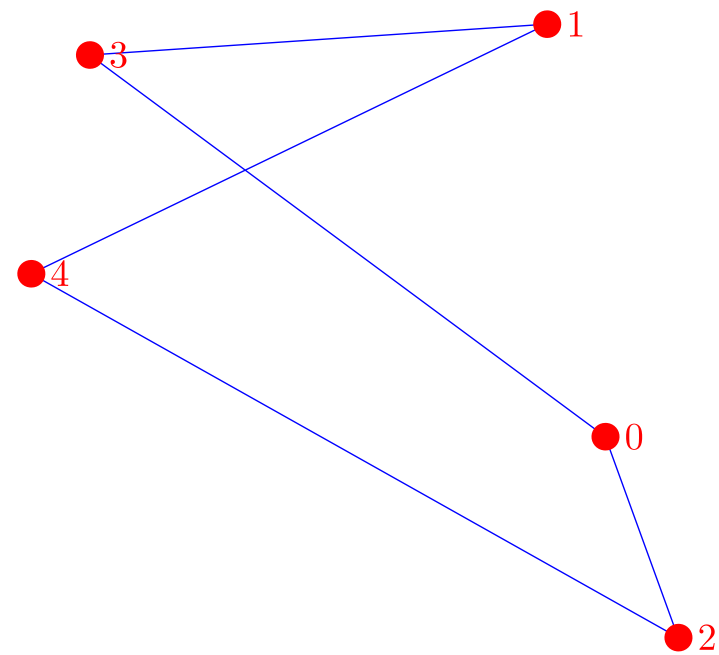
(0,3,1,4)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)

bound = 302.31

length = 386.27



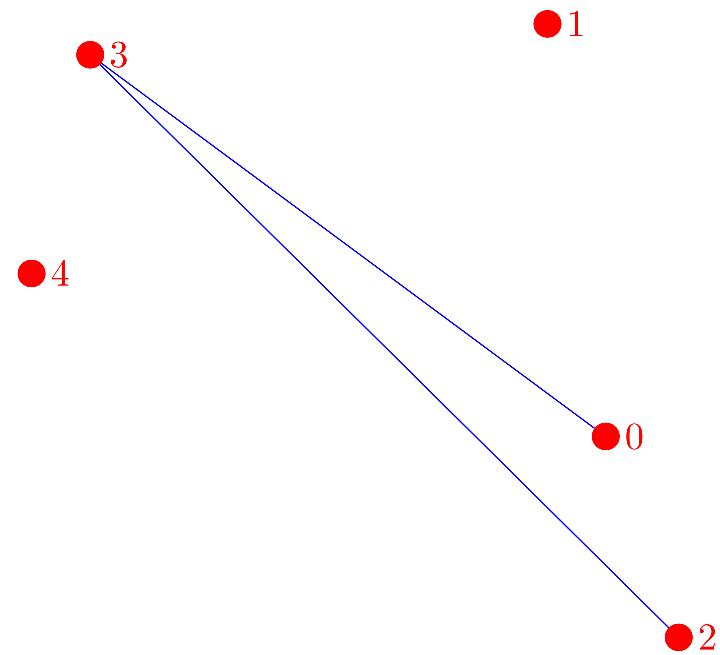
(0,3,1,4,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)

bound = 302.31

length = 215.91



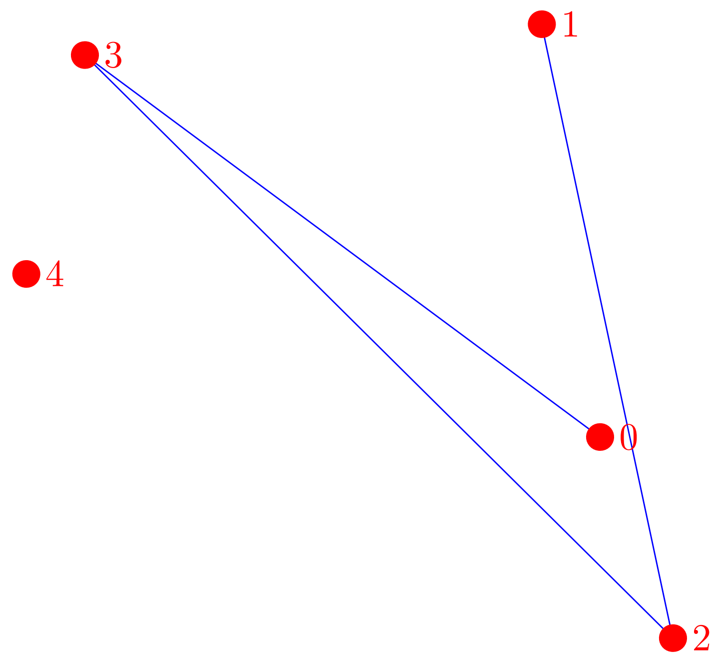
(0,3,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)

bound = 302.31

length = 308.09



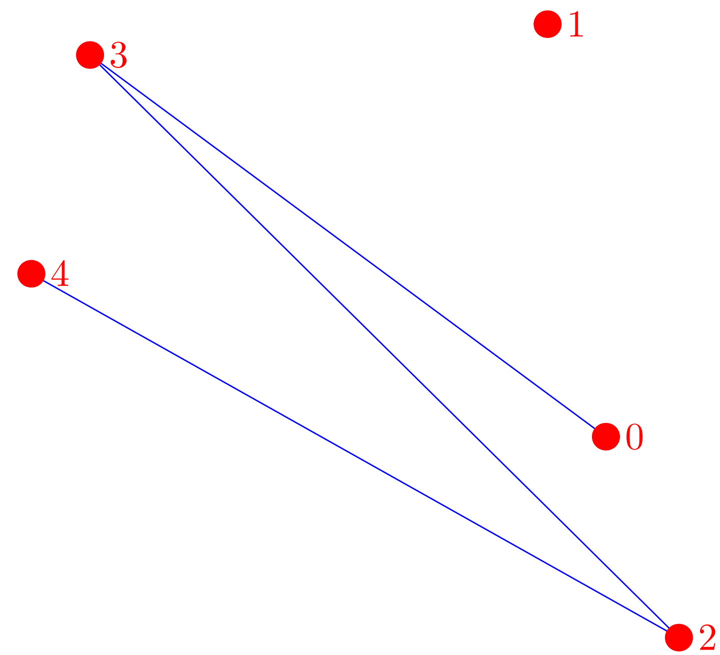
(0,3,2,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)

bound = 302.31

length = 324.99



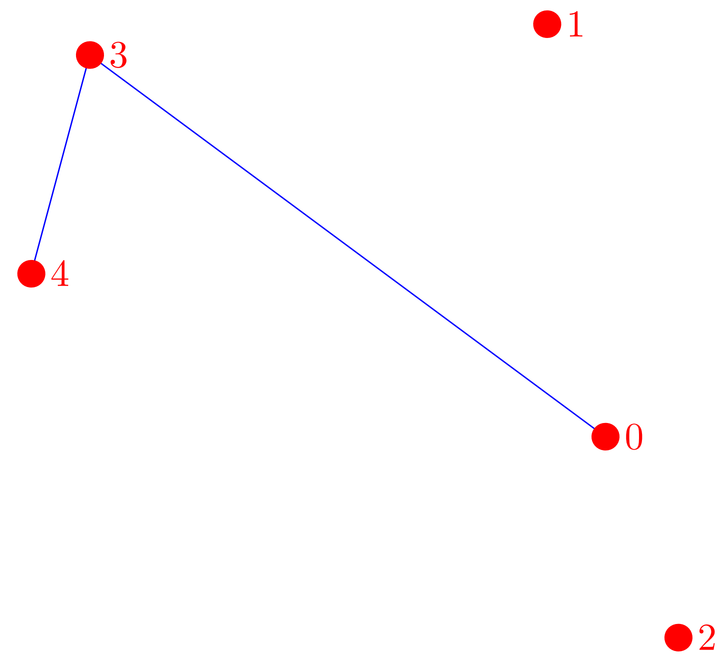
(0,3,2,4)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)

bound = 302.31

length = 127.52



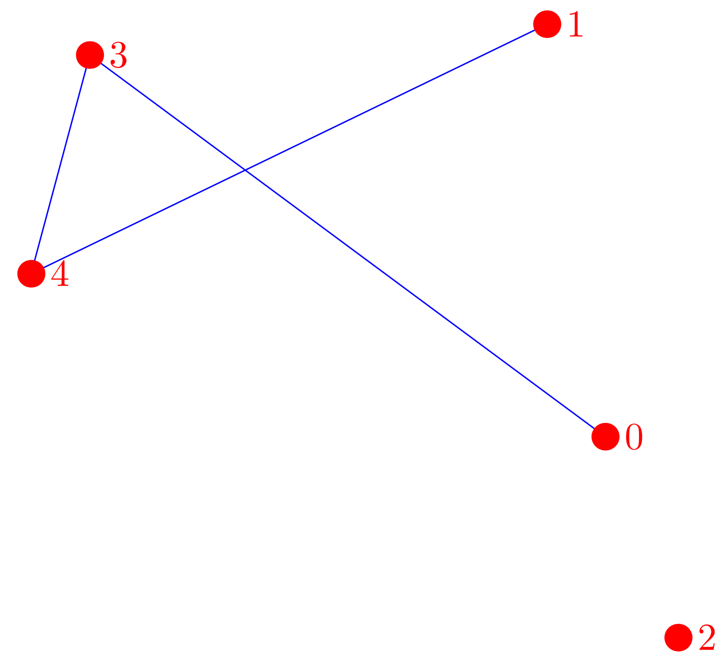
(0,3,4)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1)

bound = 302.31

length = 211.72



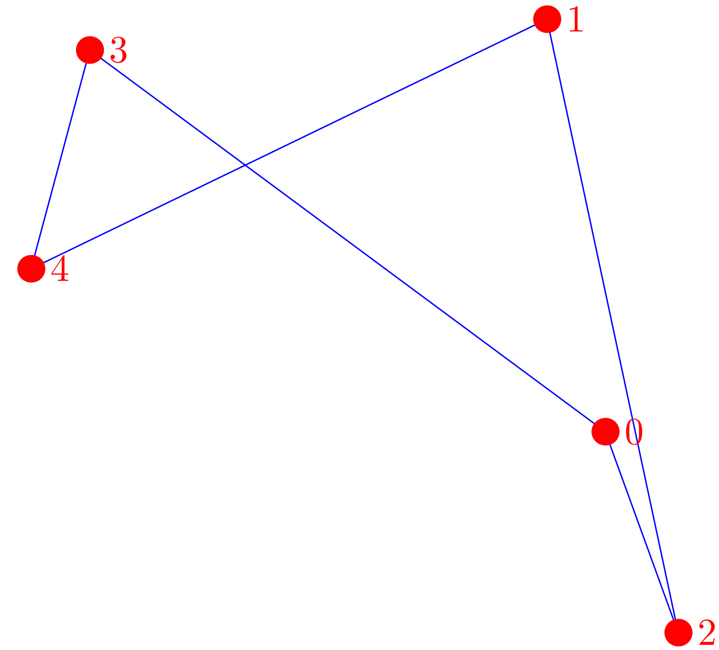
(0,3,4,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)

bound = 302.31

length = 335.3



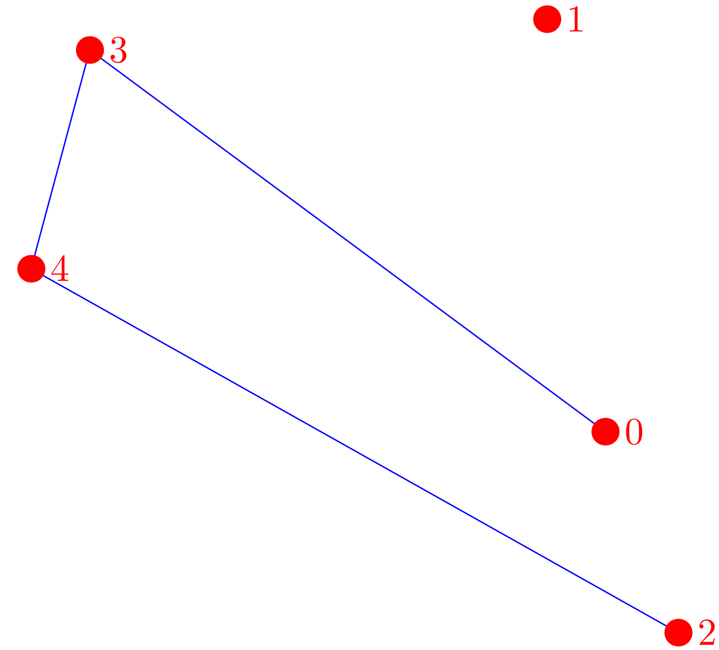
(0,3,4,1,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2)

bound = 302.31

length = 236.6



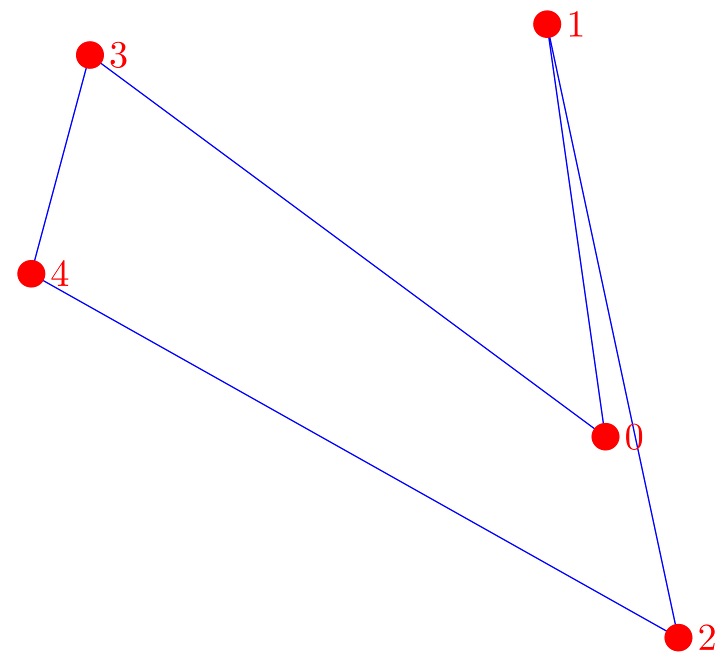
(0,3,4,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)

bound = 302.31

length = 389.98



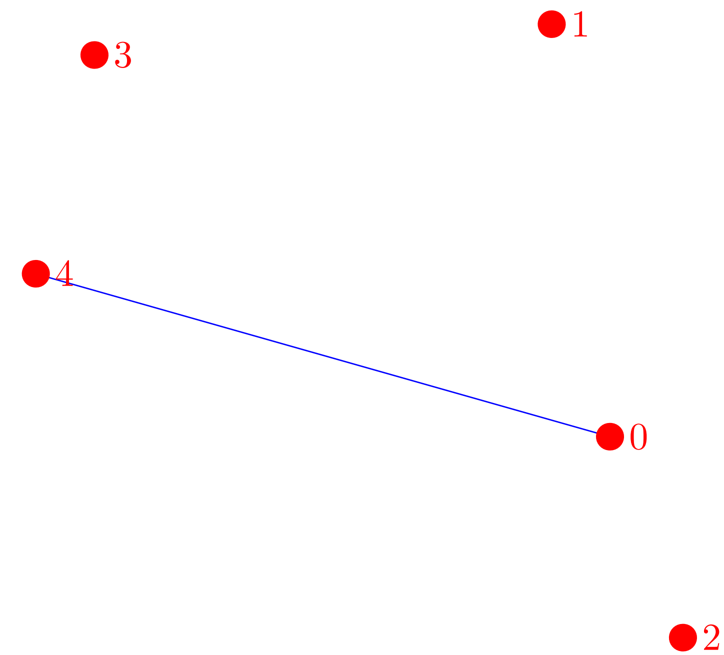
(0,3,4,2,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)

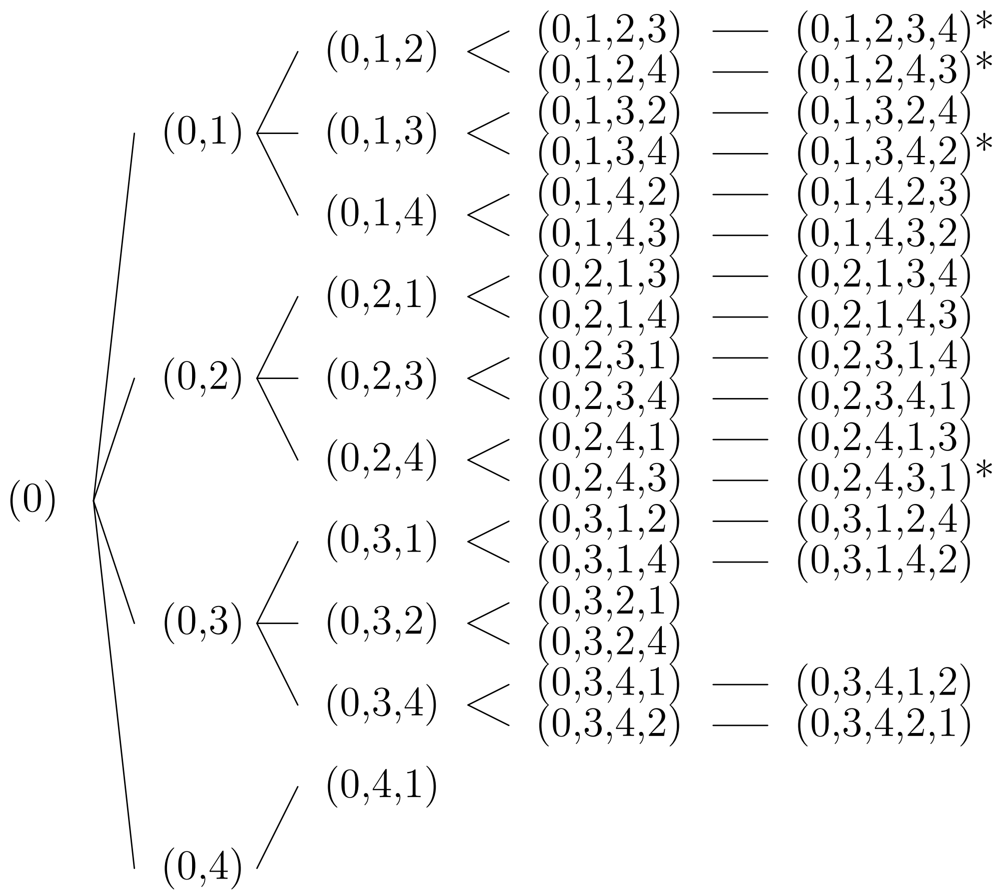
bound = 302.31

length = 87.692



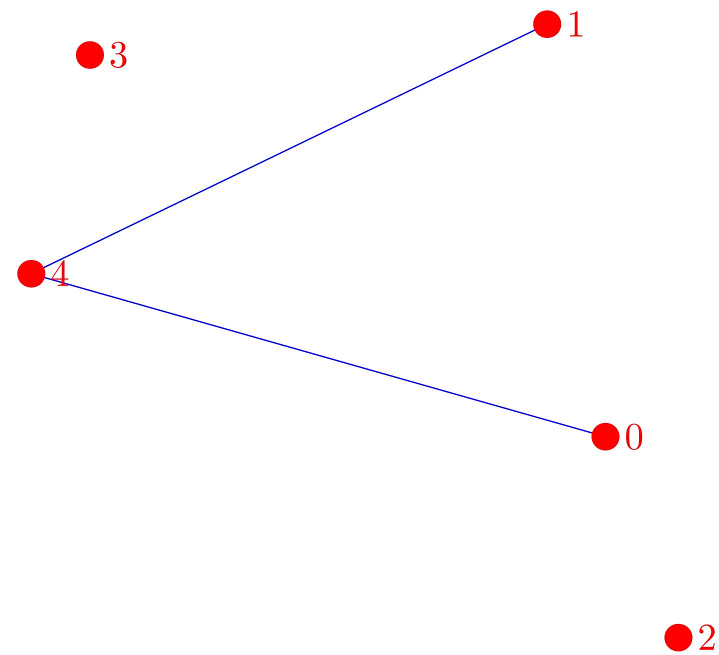
(0,4)

Branch and Bound in Action



bound = 302.31

length = 171.9



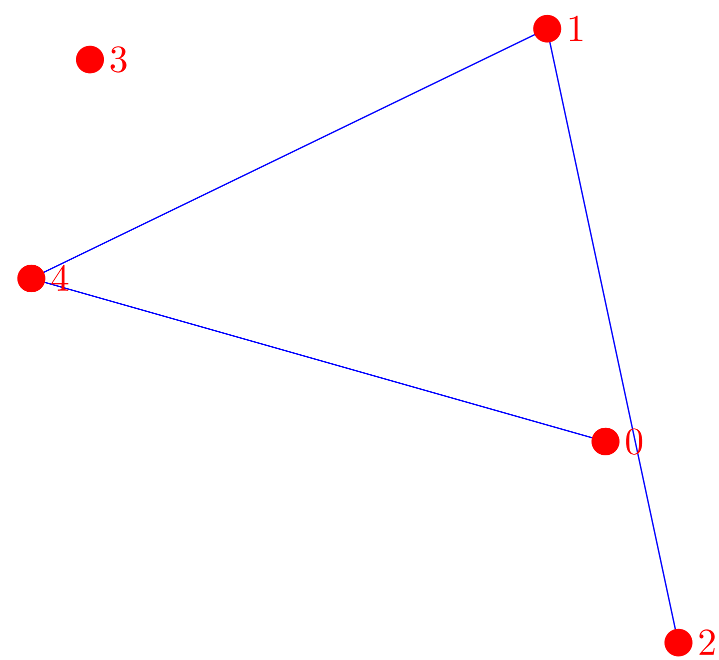
(0,4,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2)

bound = 302.31

length = 264.07



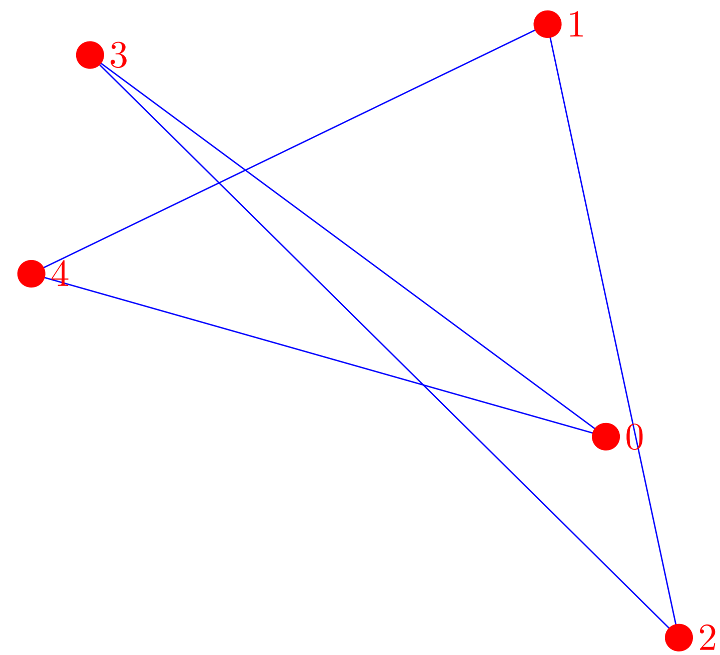
(0,4,1,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)

bound = 302.31

length = 479.98



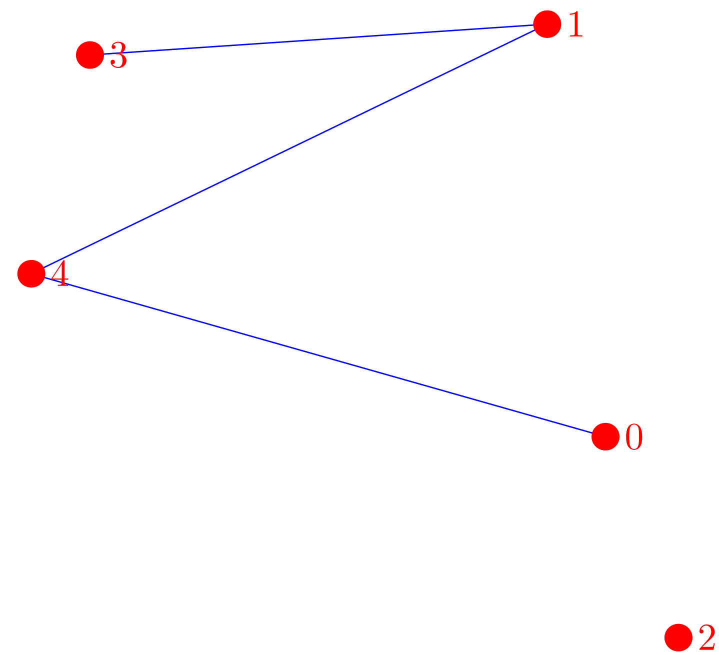
(0,4,1,2,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3)

bound = 302.31

length = 239.23



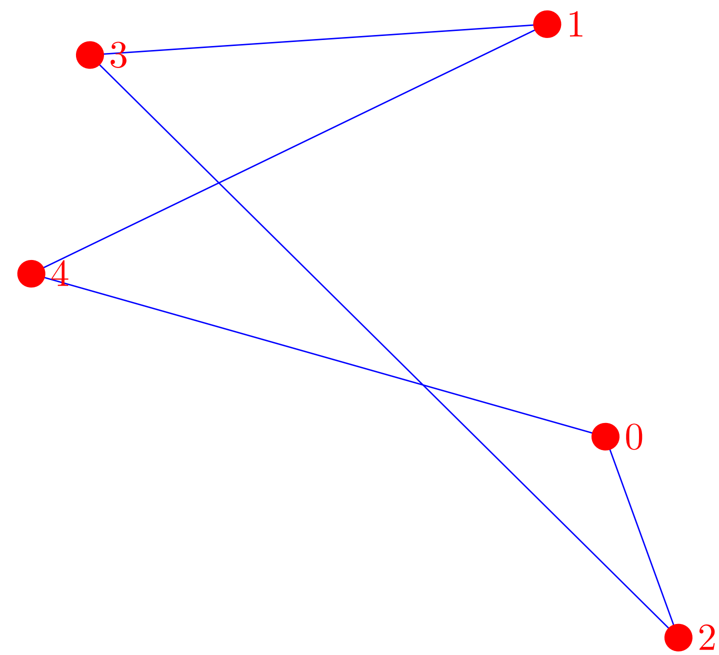
(0,4,1,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)

bound = 302.31

length = 392.31



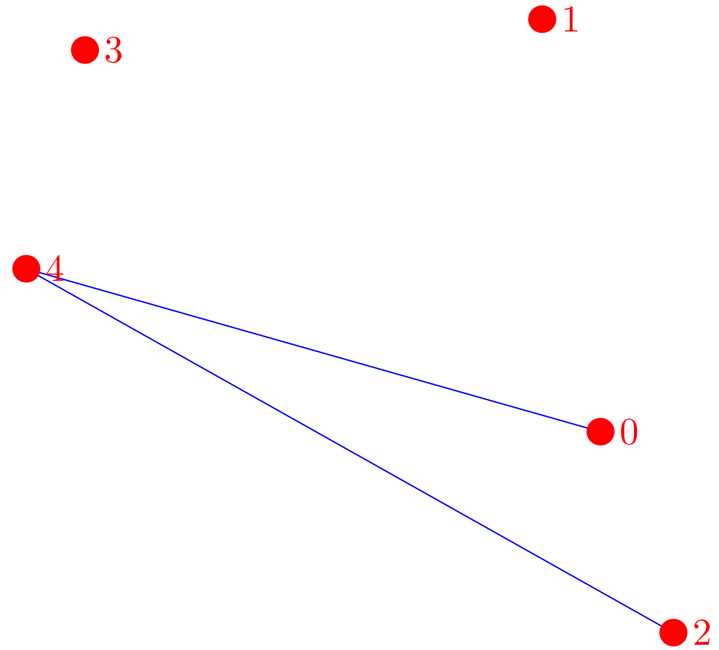
(0,4,1,3,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)

bound = 302.31

length = 196.77



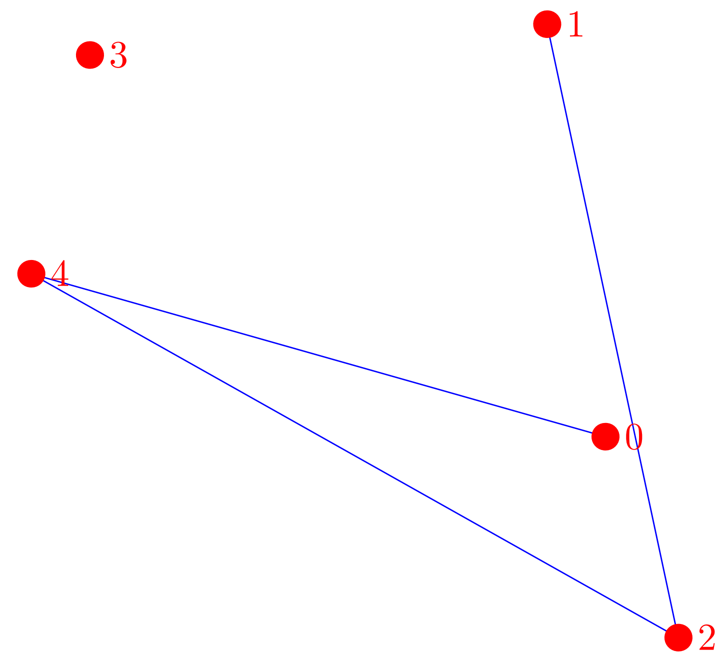
(0,4,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1)

bound = 302.31

length = 288.95



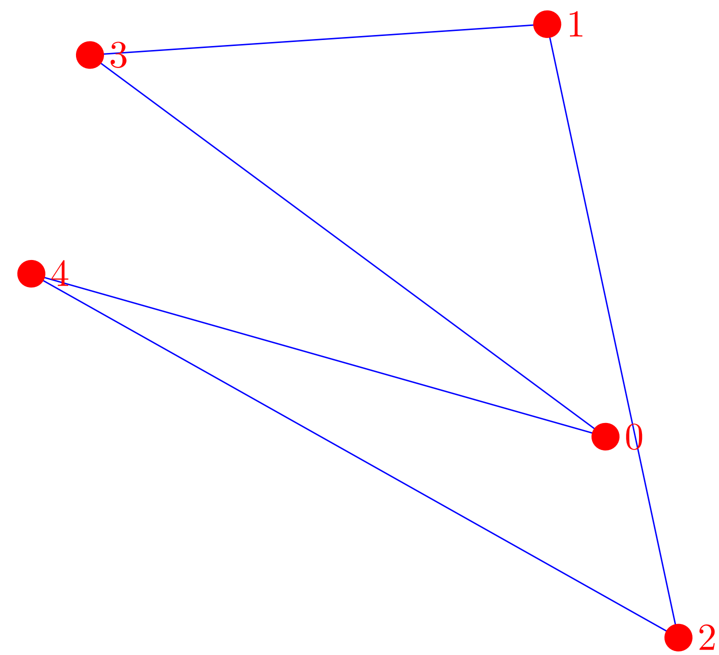
(0,4,2,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)

bound = 302.31

length = 450.52



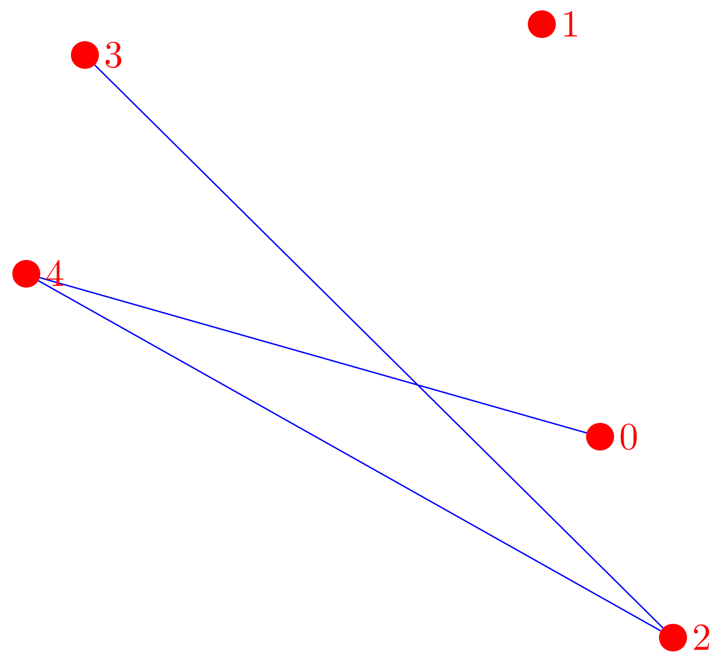
(0,4,2,1,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)
      - (0,4,2,3)

bound = 302.31

length = 318.44



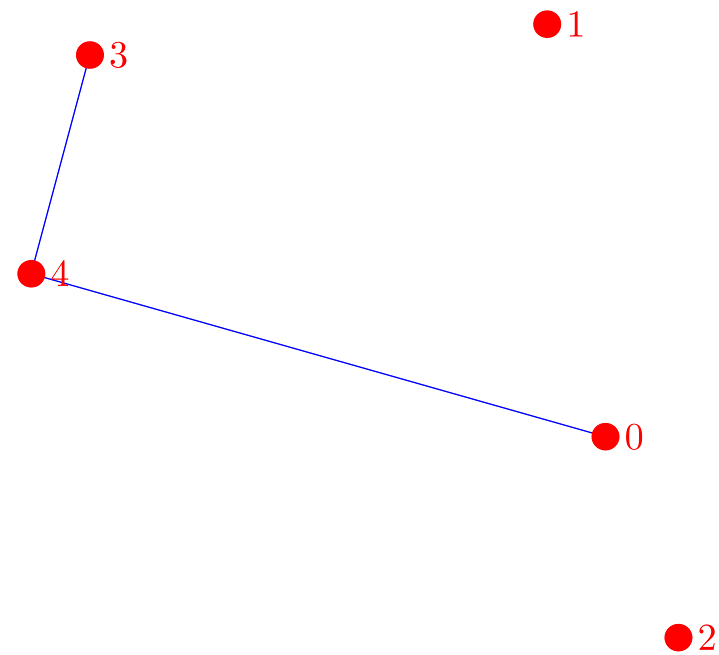
(0,4,2,3)

Branch and Bound in Action

bound = 302.31

length = 120.97

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)
      - (0,4,2,3)
    - (0,4,3)



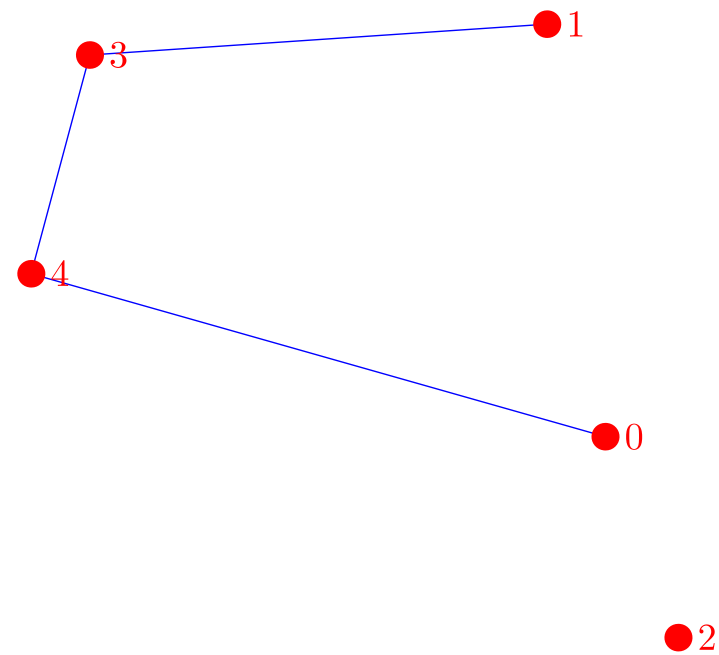
(0,4,3)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)
      - (0,4,2,3)
    - (0,4,3)
      - (0,4,3,1)

bound = 302.31

length = 188.3



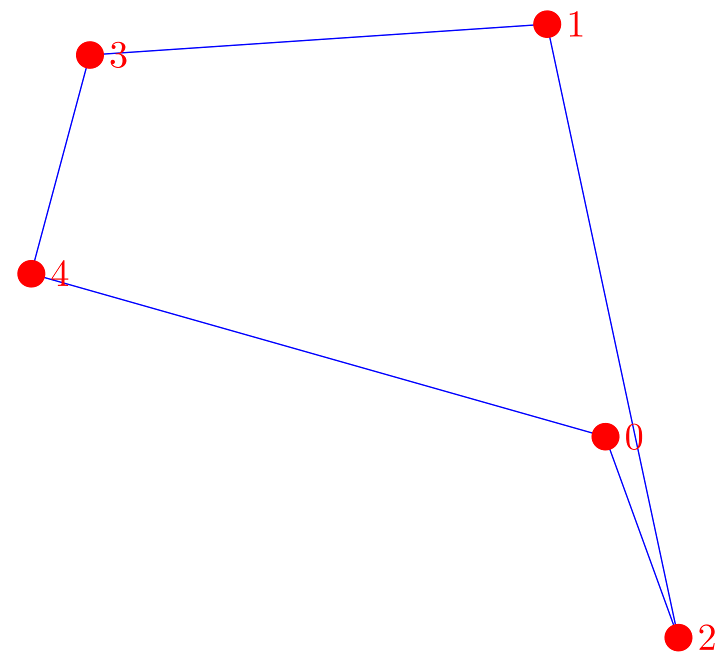
(0,4,3,1)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)
      - (0,4,2,3)
    - (0,4,3)
      - (0,4,3,1) — (0,4,3,1,2)

bound = 302.31

length = 311.88



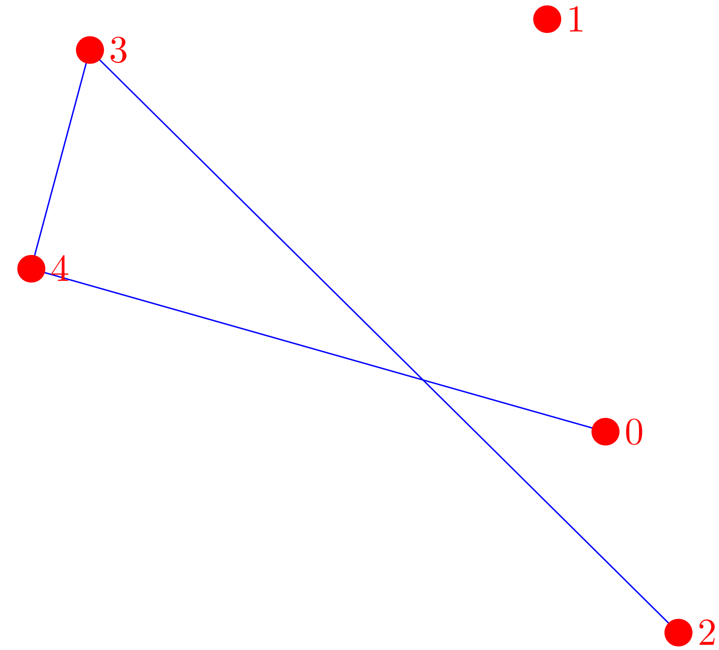
(0,4,3,1,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)
      - (0,4,2,3)
    - (0,4,3)
      - (0,4,3,1) — (0,4,3,1,2)
      - (0,4,3,2)

bound = 302.31

length = 242.64



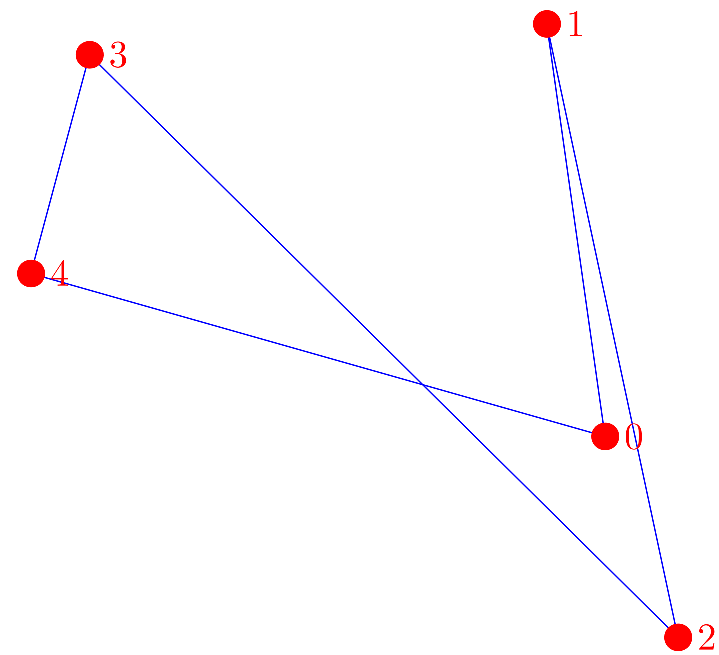
(0,4,3,2)

Branch and Bound in Action

- (0)
  - (0,1)
    - (0,1,2)
      - (0,1,2,3) — (0,1,2,3,4)*
      - (0,1,2,4) — (0,1,2,4,3)*
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
      - (0,1,4,2) — (0,1,4,2,3)
      - (0,1,4,3) — (0,1,4,3,2)
  - (0,2)
    - (0,2,1)
      - (0,2,1,3) — (0,2,1,3,4)
      - (0,2,1,4) — (0,2,1,4,3)
    - (0,2,3)
      - (0,2,3,1) — (0,2,3,1,4)
      - (0,2,3,4) — (0,2,3,4,1)
    - (0,2,4)
      - (0,2,4,1) — (0,2,4,1,3)
      - (0,2,4,3) — (0,2,4,3,1)*
  - (0,3)
    - (0,3,1)
      - (0,3,1,2) — (0,3,1,2,4)
      - (0,3,1,4) — (0,3,1,4,2)
    - (0,3,2)
      - (0,3,2,1)
      - (0,3,2,4)
    - (0,3,4)
      - (0,3,4,1) — (0,3,4,1,2)
      - (0,3,4,2) — (0,3,4,2,1)
  - (0,4)
    - (0,4,1)
      - (0,4,1,2) — (0,4,1,2,3)
      - (0,4,1,3) — (0,4,1,3,2)
    - (0,4,2)
      - (0,4,2,1) — (0,4,2,1,3)
      - (0,4,2,3)
    - (0,4,3)
      - (0,4,3,1) — (0,4,3,1,2)
      - (0,4,3,2) — (0,4,3,2,1)

bound = 302.31

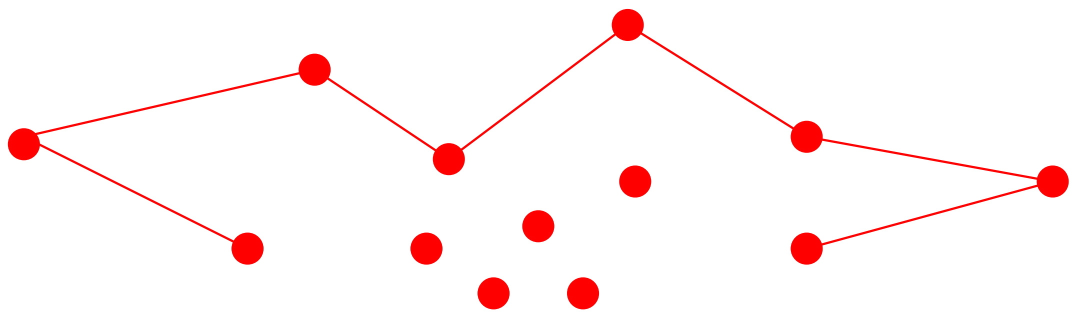
length = 396.02



(0,4,3,2,1)

Bound on Partial Solution

- We know that the partial solution has to include all the remaining cities



- We can use this to obtain a lower bound on the partial solution
- We know the remaining tour will go through each of the unvisited cities and the two edge cities
- In fact the remaining part of the tour is a spanning tree of these vertices (it connects all the vertices once and has no cycles)
- But we know a lower bound for this

Bound on Partial Solution

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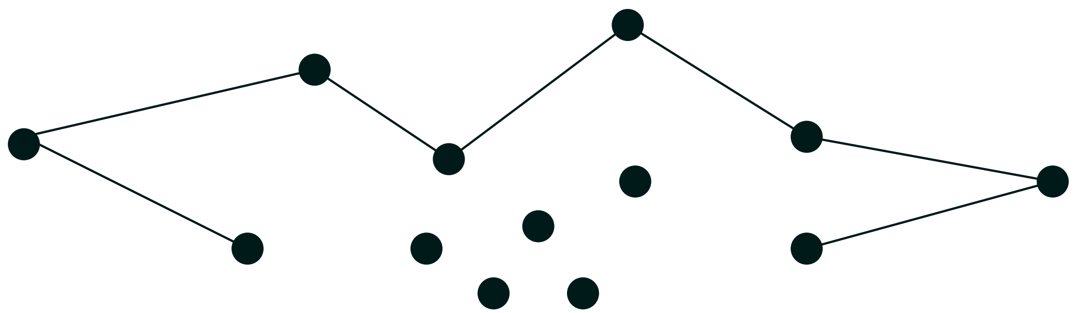

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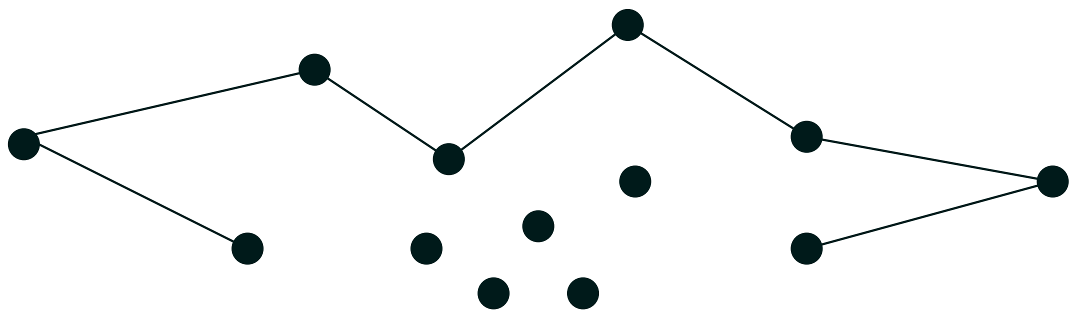

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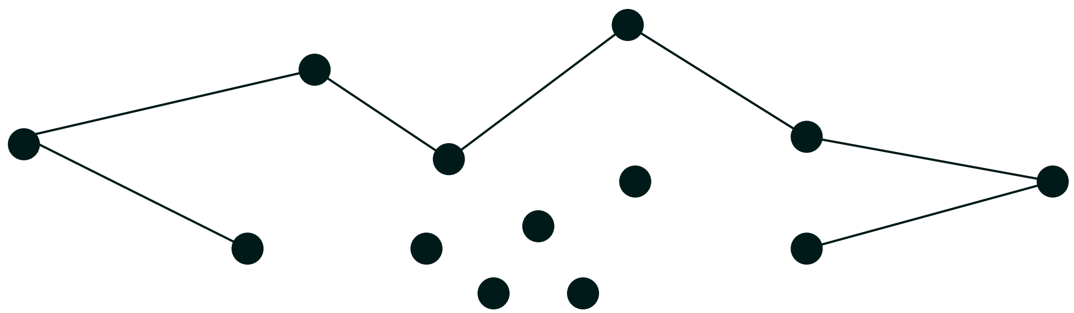

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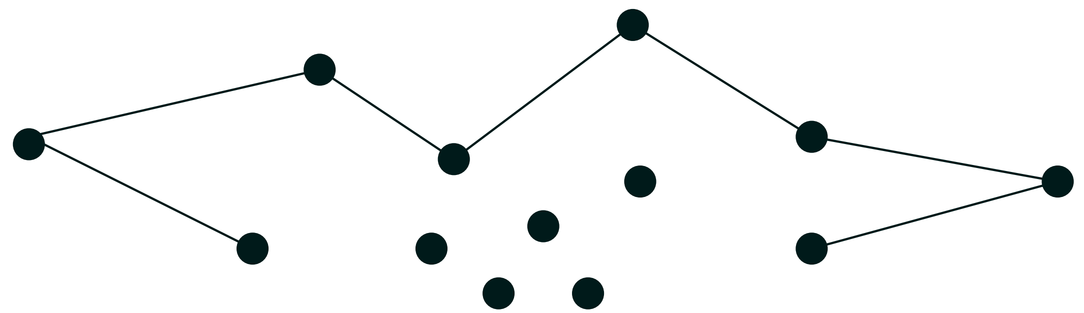

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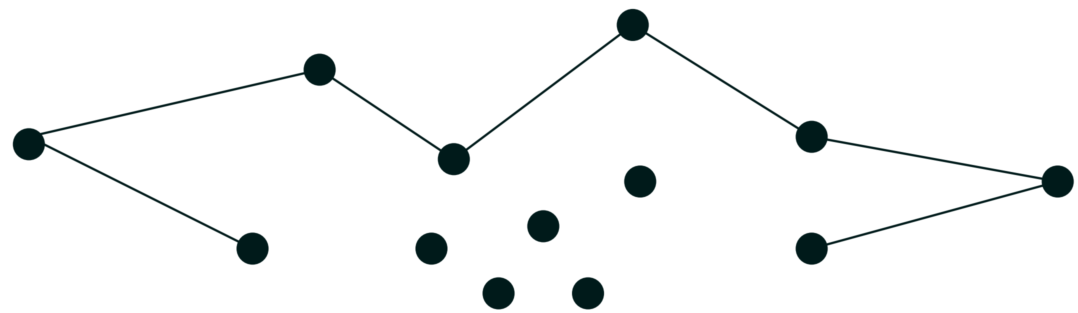

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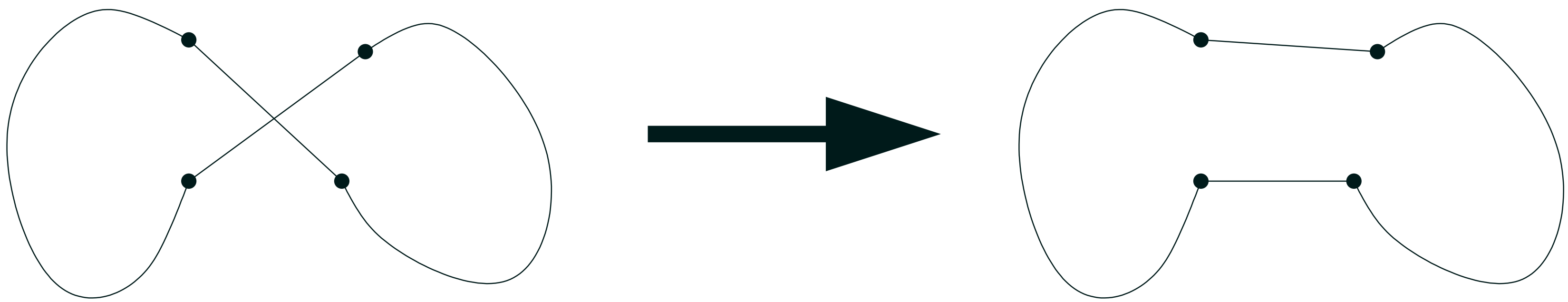
- We know the remaining tour will go through each of the unvisited cities and the two edge cities
- In fact the remaining part of the tour is a spanning tree of these vertices (it connects all the vertices once and has no cycles)
- But we know a lower bound for this—**the minimum spanning tree**

Other Cuts

- For 2-D Euclidean TSPs edges should never cross



- In fact we can check that we cannot perform a 2-opt move

- We can also halve the search by considering only one direction—for example, by insisting we visit city 1 before city 2

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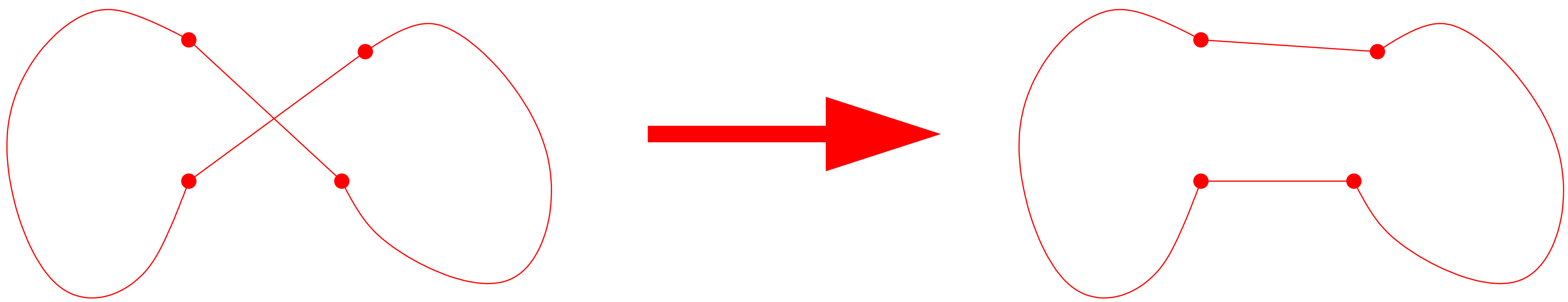

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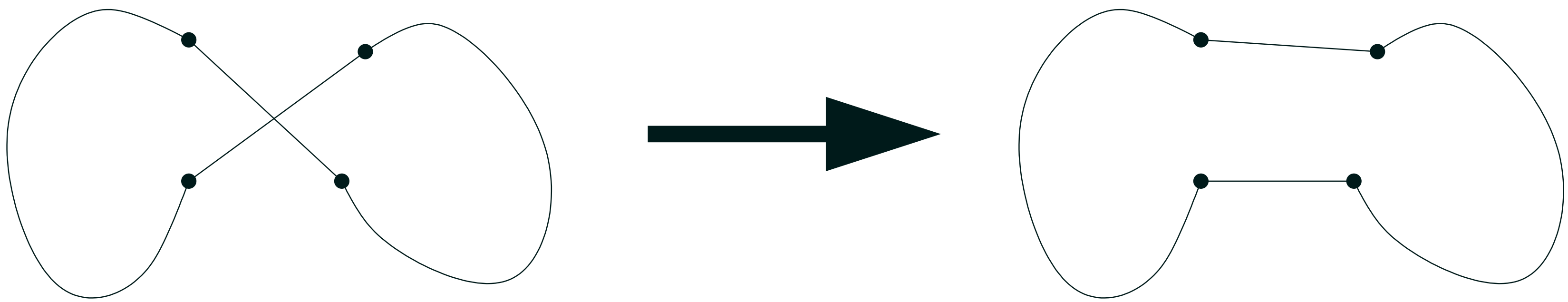

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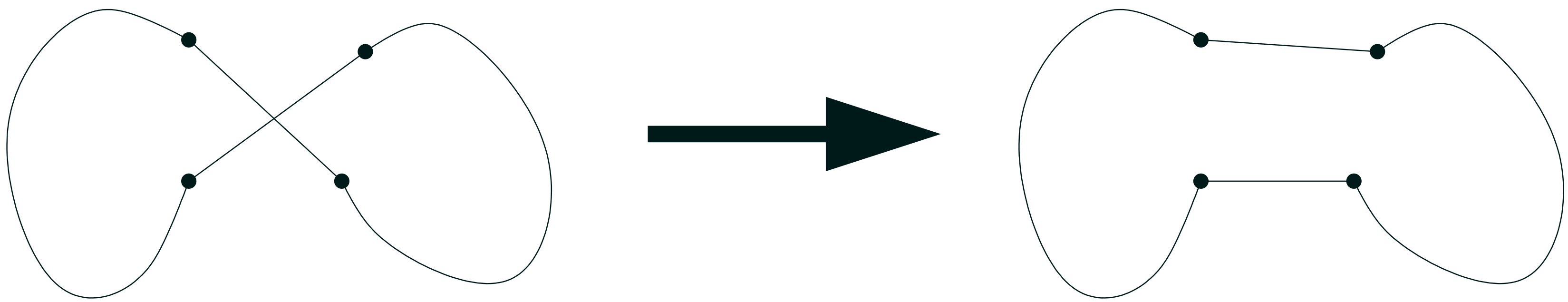

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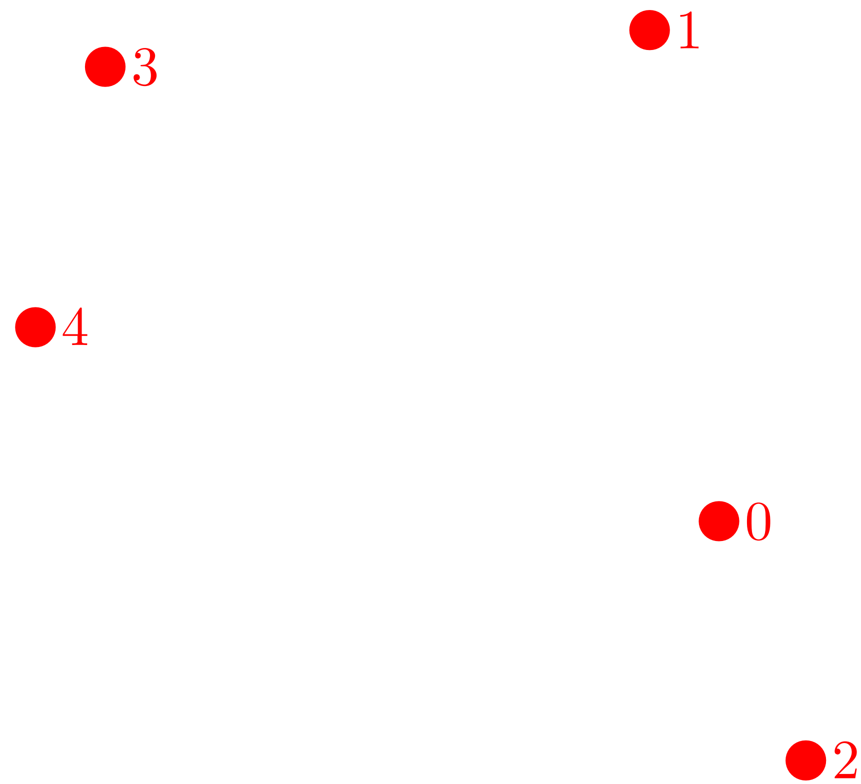
Good Starting Bound

- It helps to start with a good bound
- We can use an *incomplete heuristic algorithm* to find a good solution which will act as a starting bound
- One very simple heuristic is a greedy algorithm



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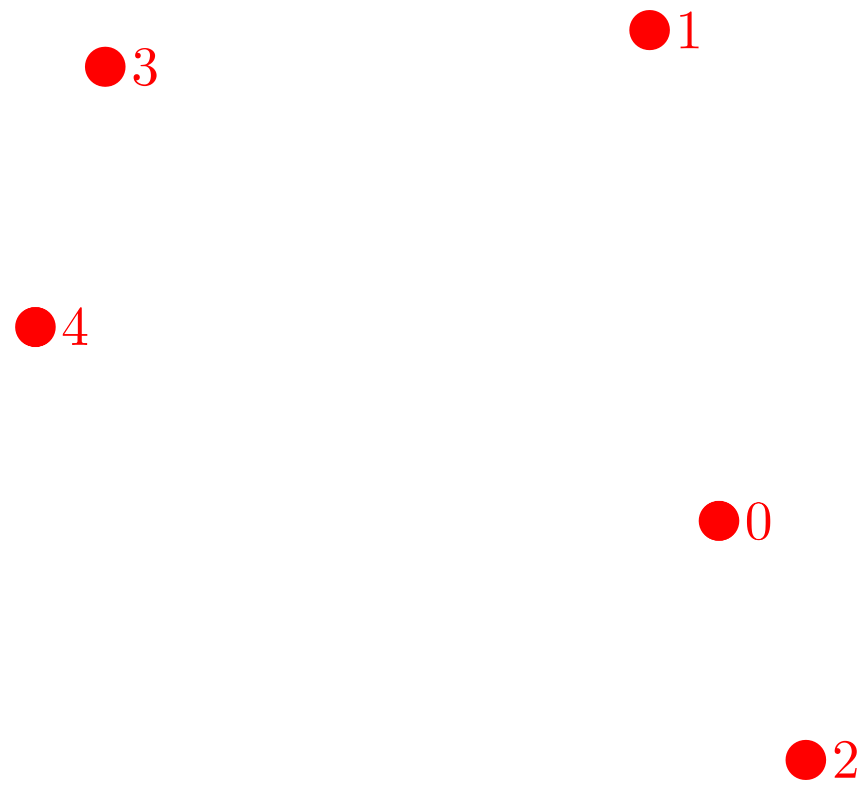

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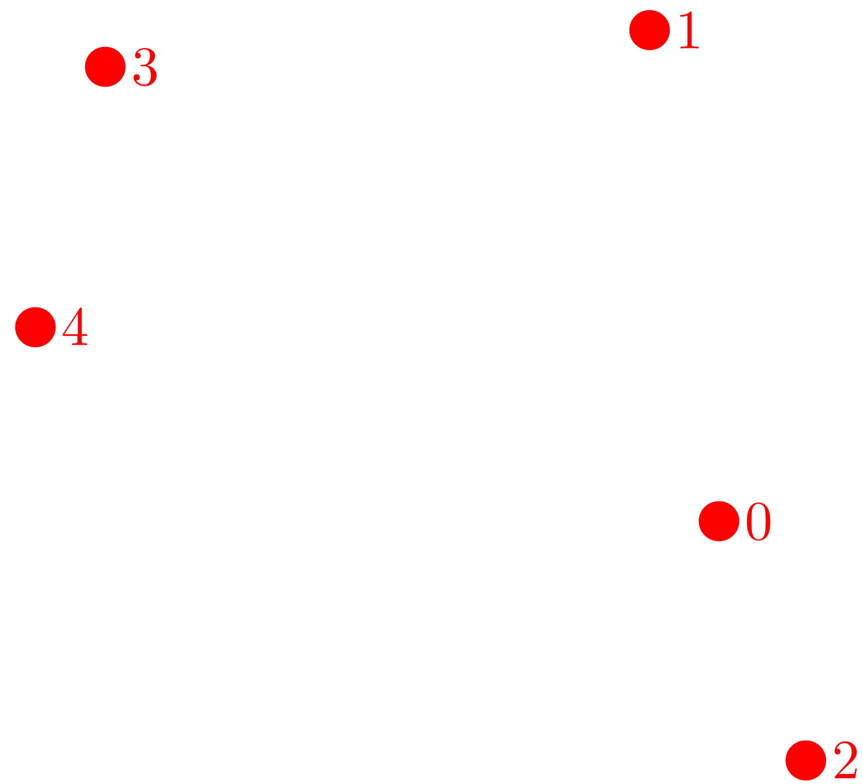

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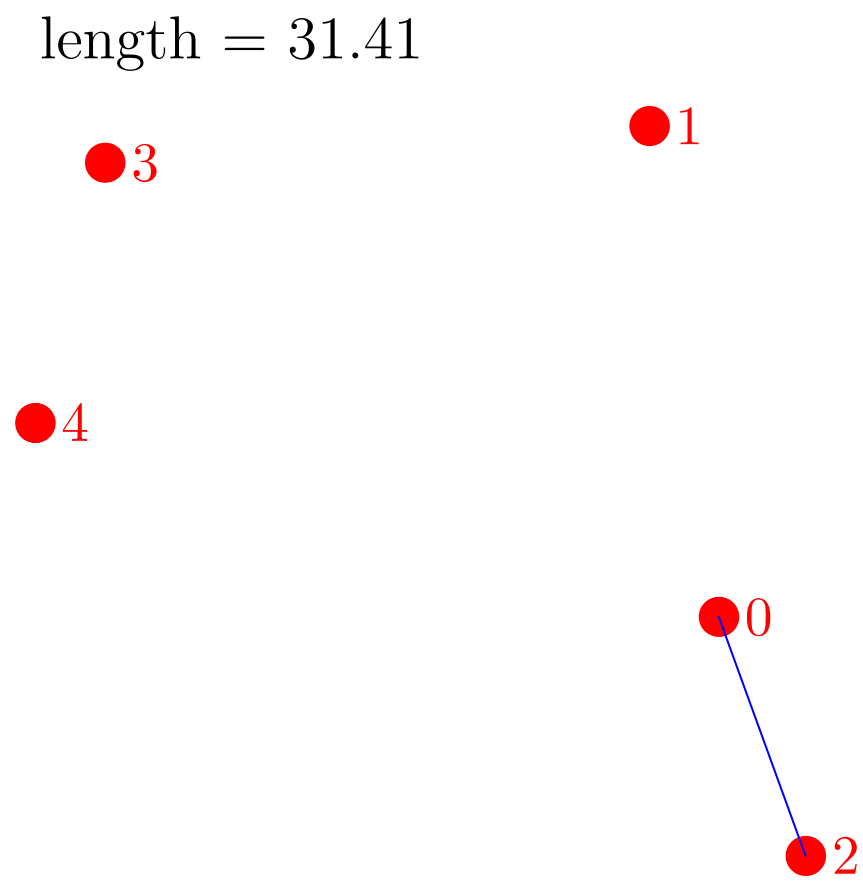

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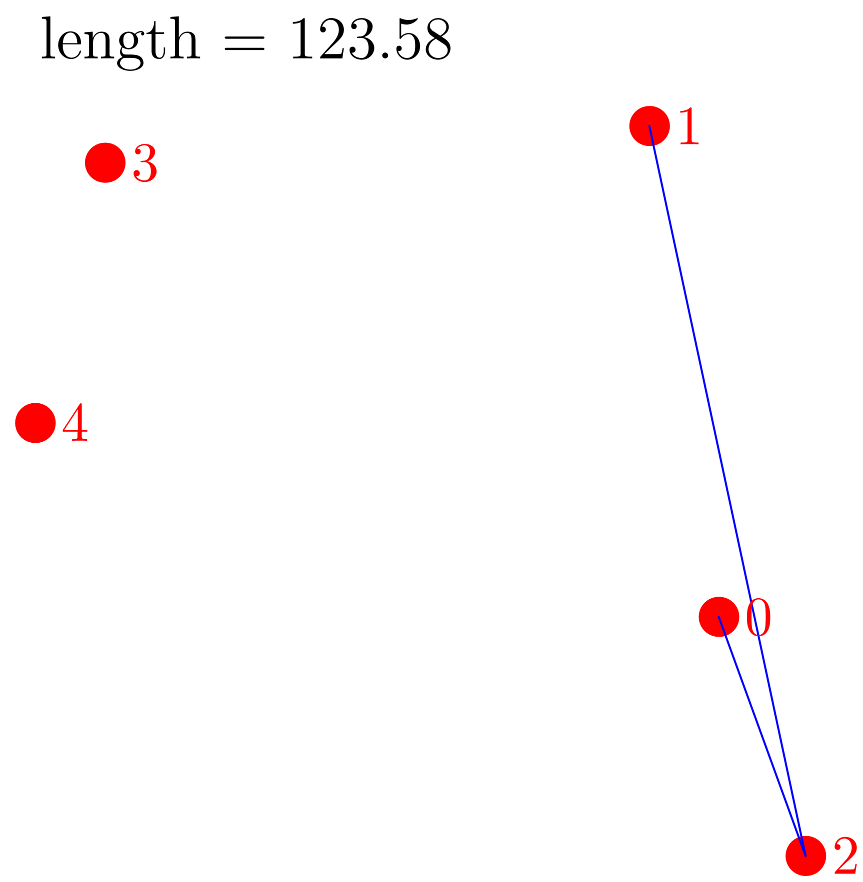

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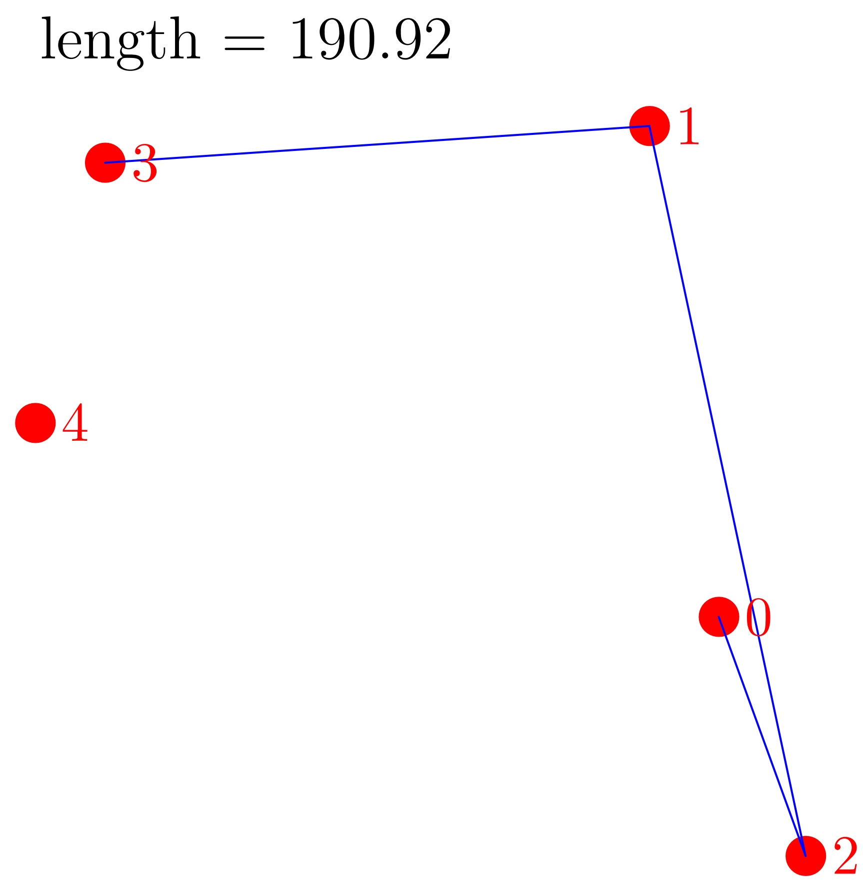

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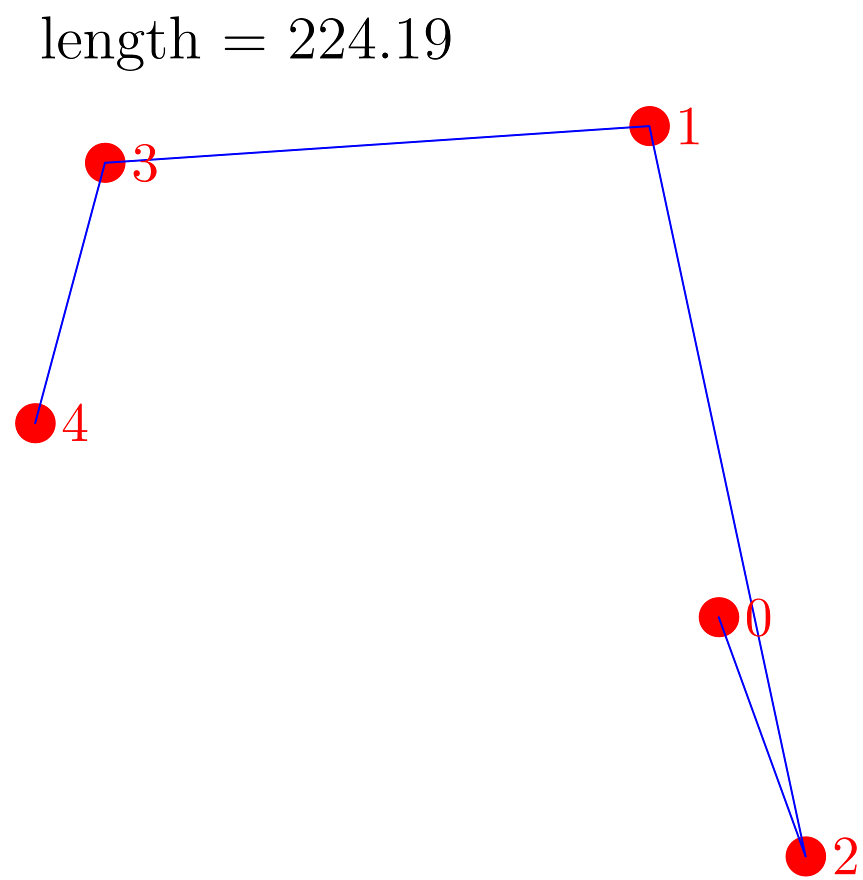

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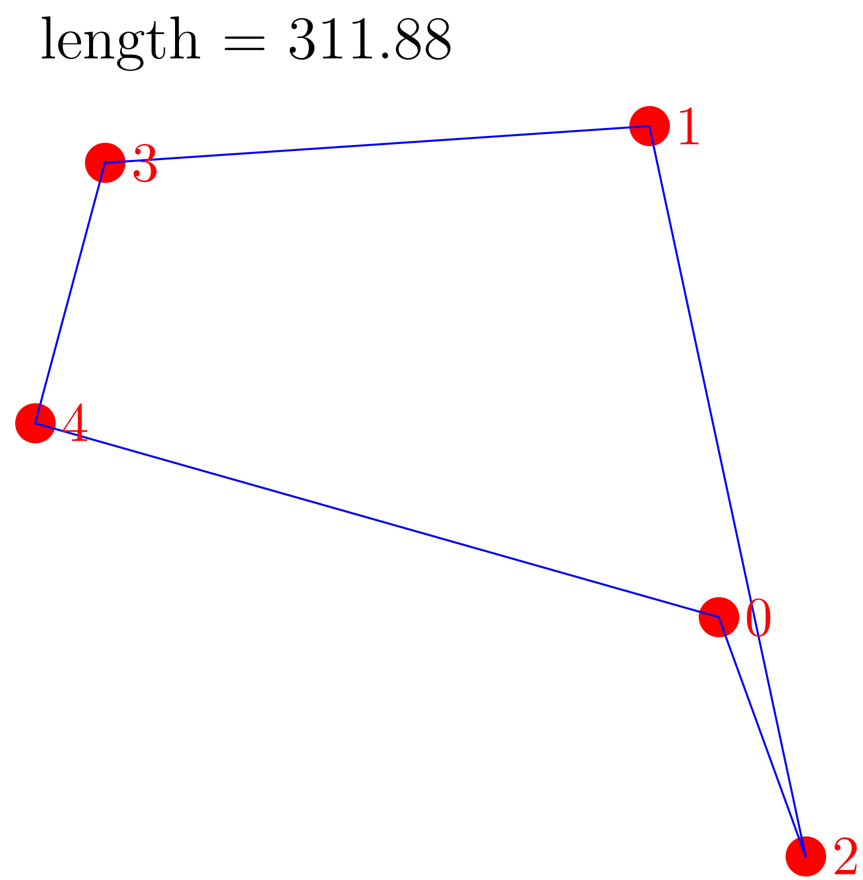
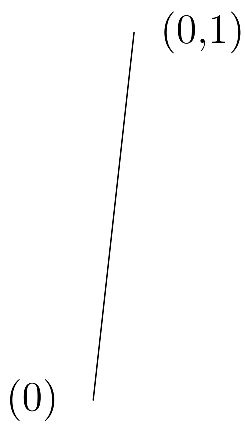
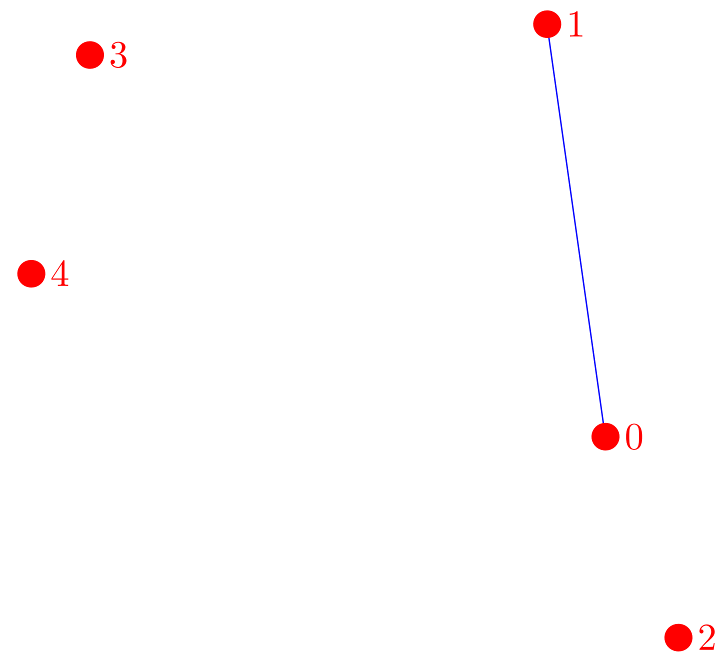


Branch and Bound after Pruning



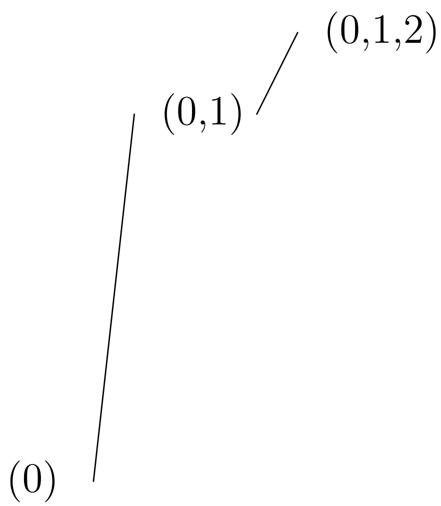
bound = 311.88

length = 61.211 + 193.23 = 254.44



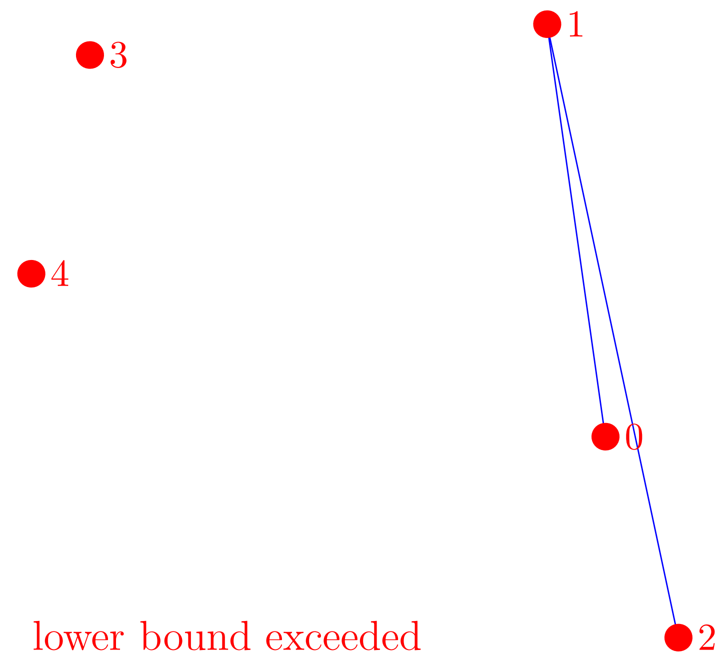
(0,1)

Branch and Bound after Pruning



bound = 311.88

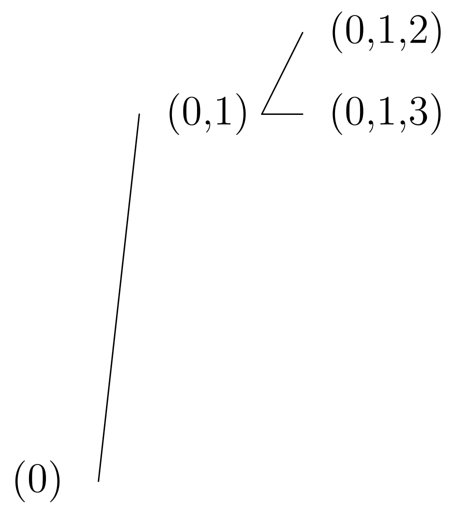
length = 153.38 + 159.95 = 313.34



lower bound exceeded

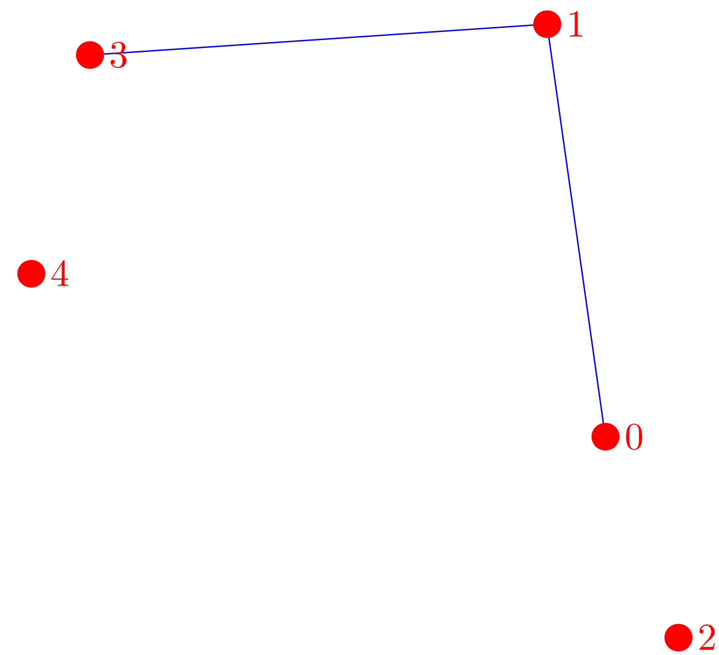
(0,1,2)

Branch and Bound after Pruning



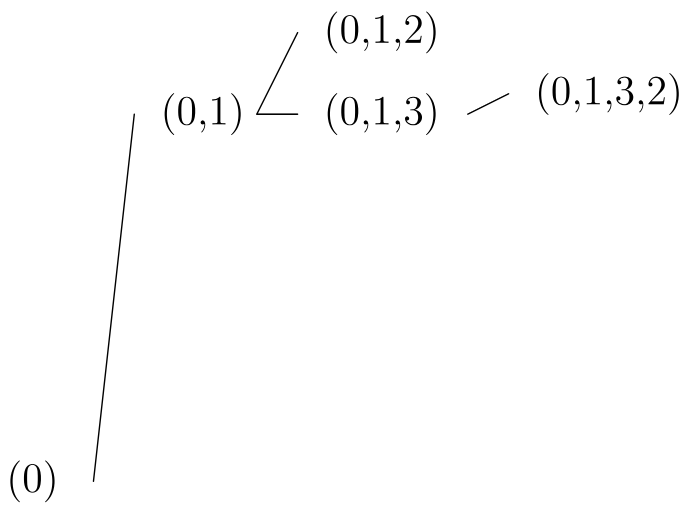
bound = 311.88

length = 128.54 + 159.95 = 288.5



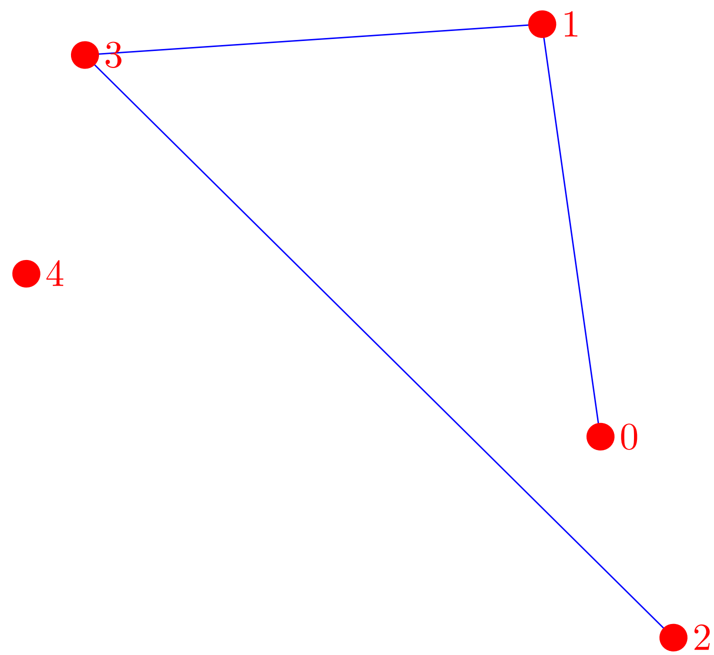
(0,1,3)

Branch and Bound after Pruning



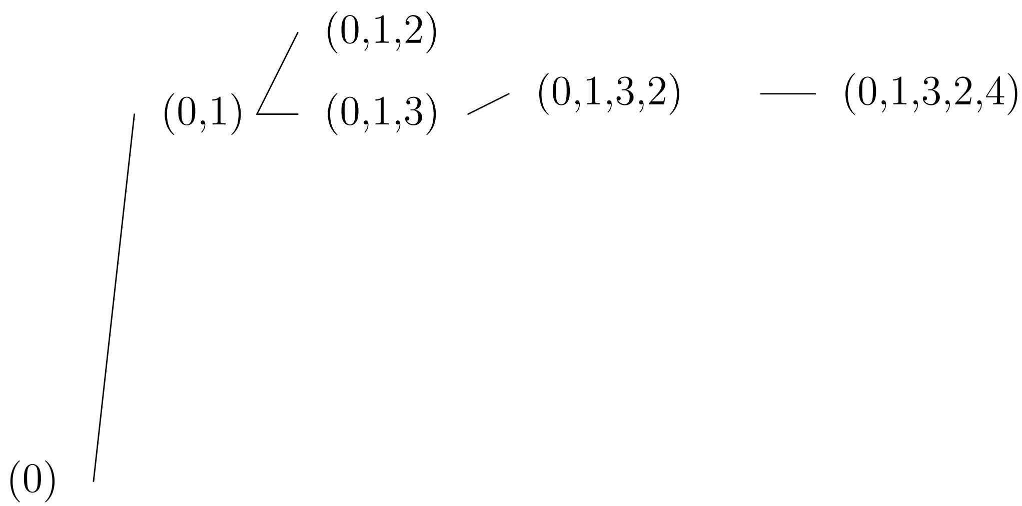
bound = 311.88

length = 250.21 + 31.41 = 281.63



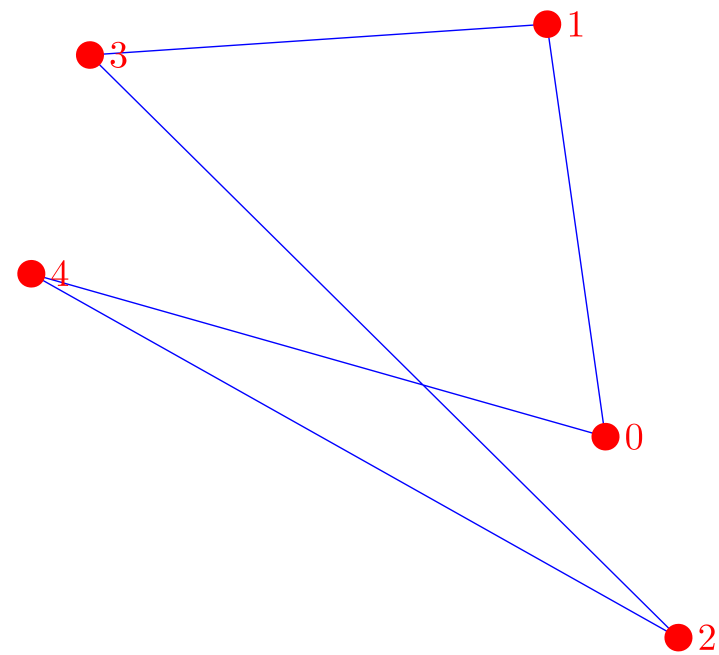
(0,1,3,2)

Branch and Bound after Pruning



bound = 311.88

length = 446.99 + 0 = 446.99



(0,1,3,2,4)

Branch and Bound after Pruning

(0,1,2)

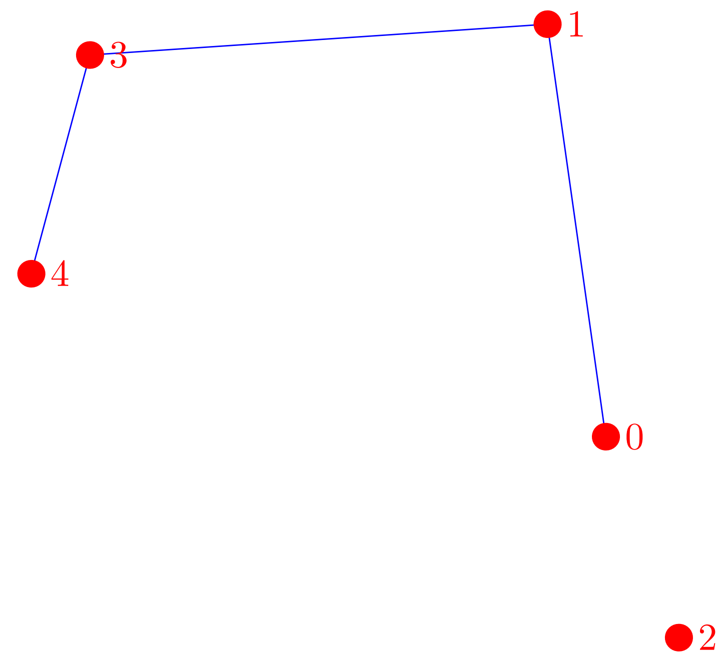
(0,1) — (0,1,3) < (0,1,3,2) — (0,1,3,2,4)

(0,1,3,4)

(0)

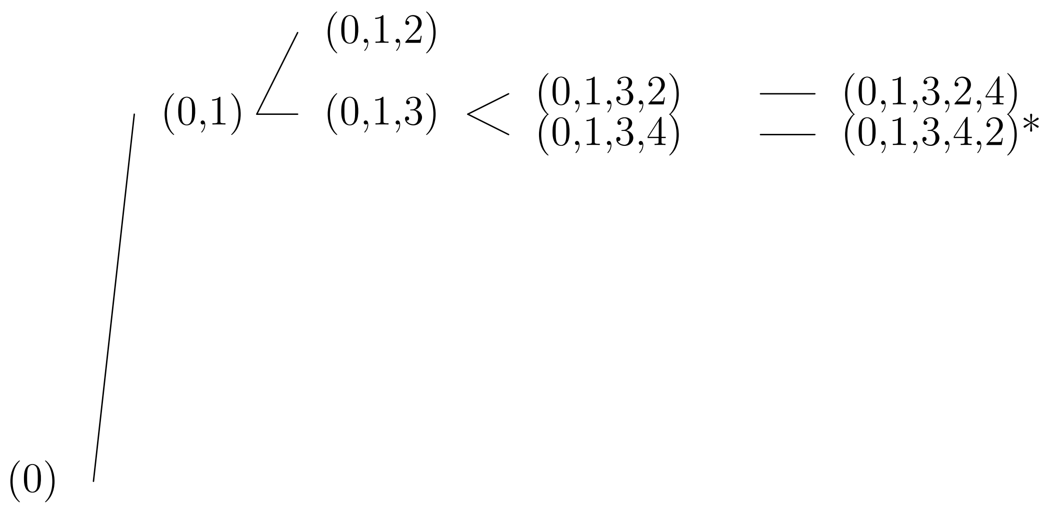
bound = 311.88

length = 161.82 + 31.41 = 193.23



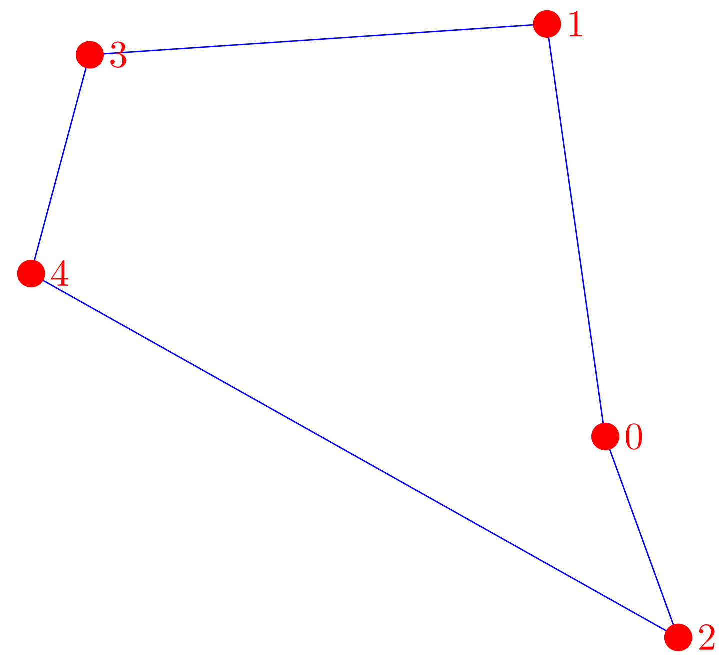
(0,1,3,4)

Branch and Bound after Pruning



bound = 302.31

length = 302.31 + 0 = 302.31



(0,1,3,4,2)

Branch and Bound after Pruning

(0) — (0,1) — (0,1,2)

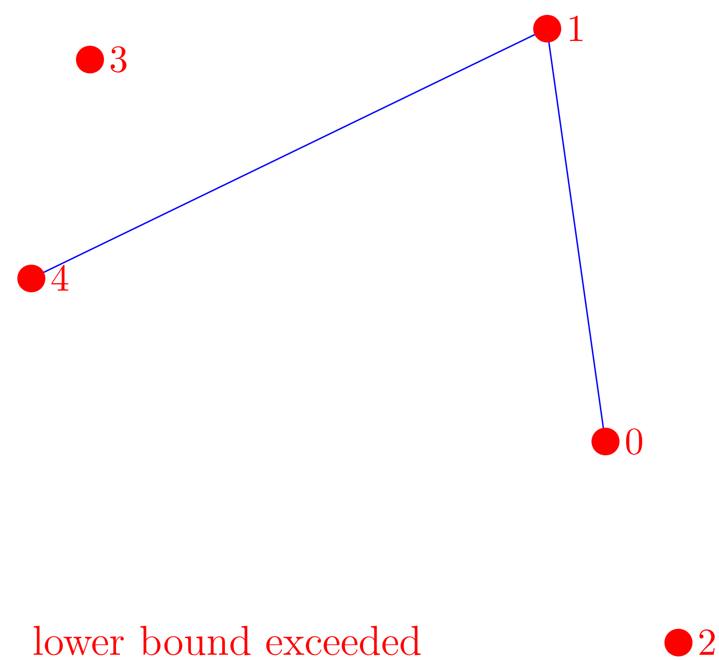
(0,1) — (0,1,3) — (0,1,3,2) — (0,1,3,2,4)

(0,1,3) — (0,1,3,4) — (0,1,3,4,2)*

(0,1) — (0,1,4)

bound = 302.31

length = 145.41 + 159.95 = 305.37



lower bound exceeded

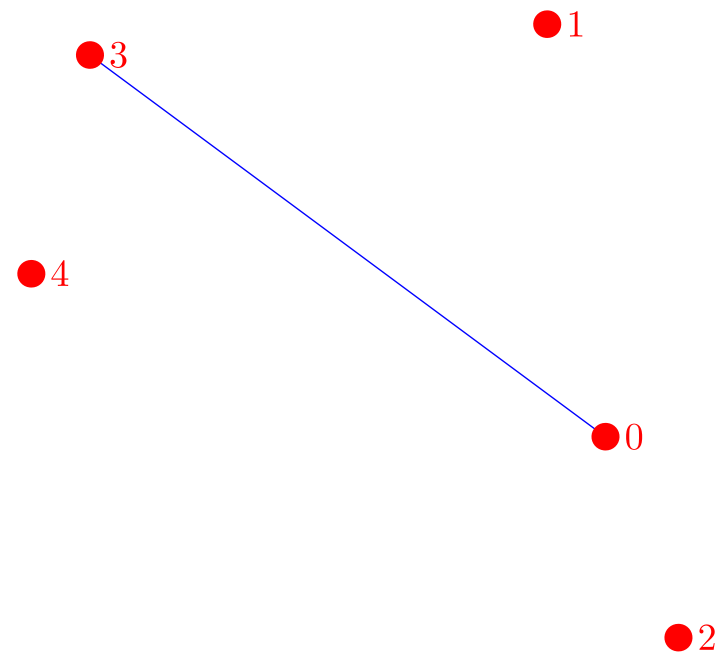
(0,1,4)

Branch and Bound after Pruning

(0)
- (0,1)
  - (0,1,2)
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
- (0,3)

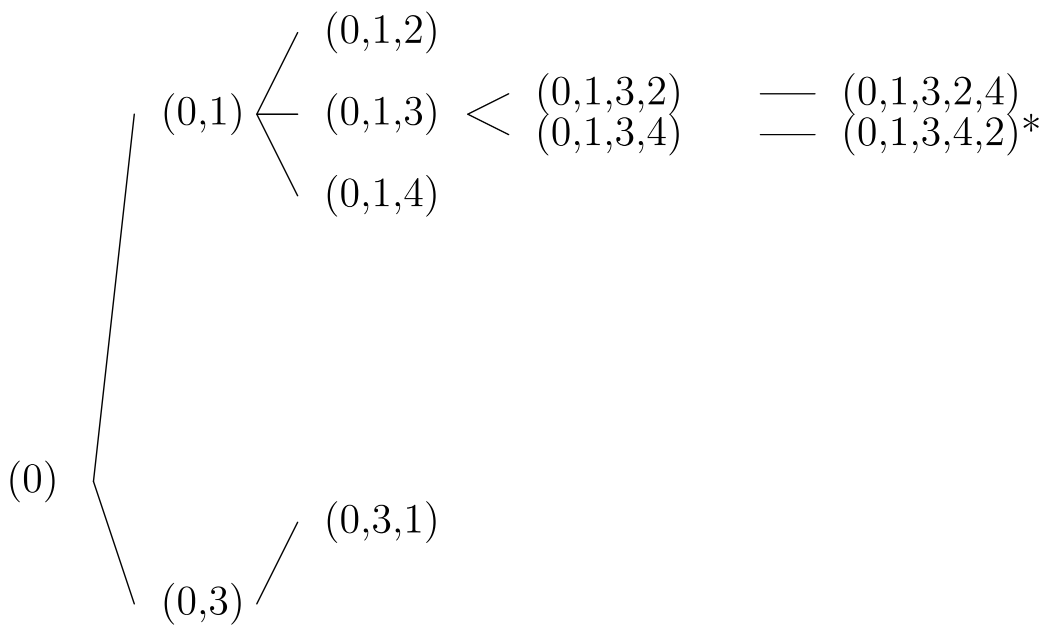
bound = 302.31

length = 94.244 + 193.23 = 287.47



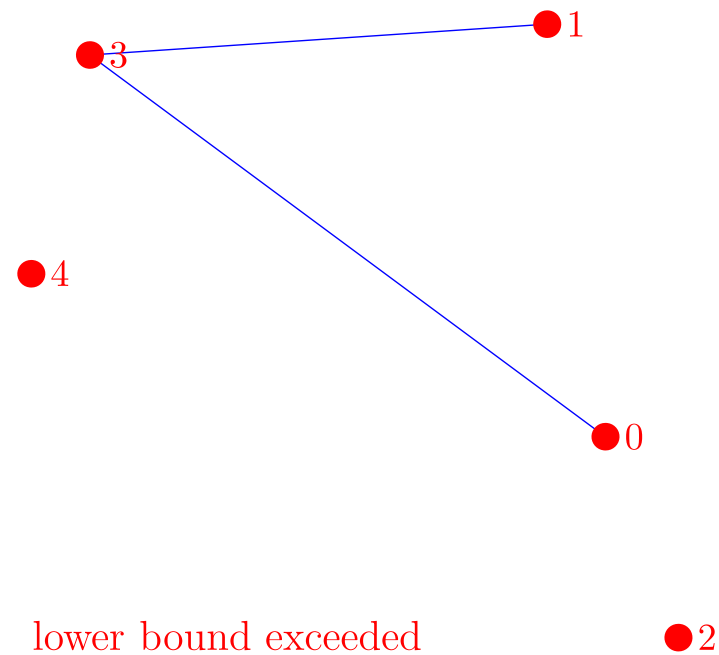
(0,3)

Branch and Bound after Pruning



bound = 302.31

length = 161.58 + 159.95 = 321.53



lower bound exceeded

(0,3,1)

Branch and Bound after Pruning

(0)

(0,1)

(0,1,2)

(0,1,3) — (0,1,3,2) — (0,1,3,2,4)

(0,1,3) — (0,1,3,4) — (0,1,3,4,2)*

(0,1,4)

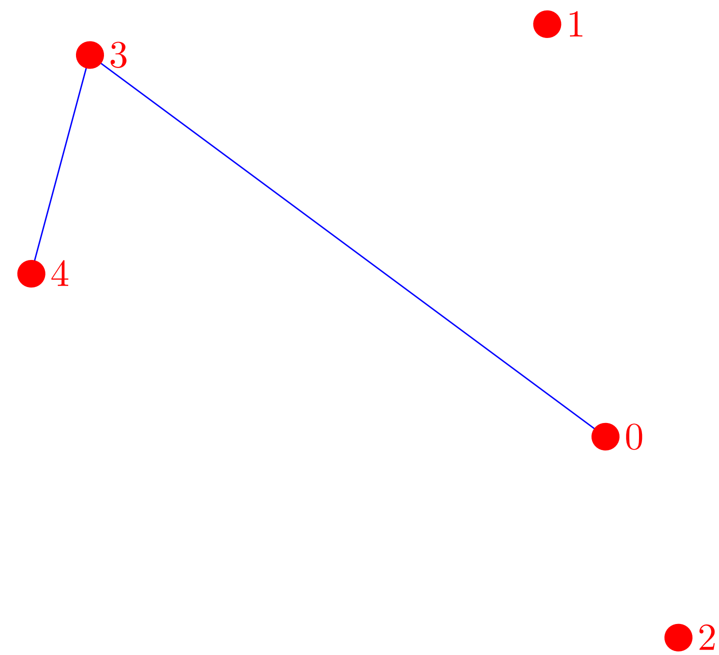
(0,3)

(0,3,1)

(0,3,4)

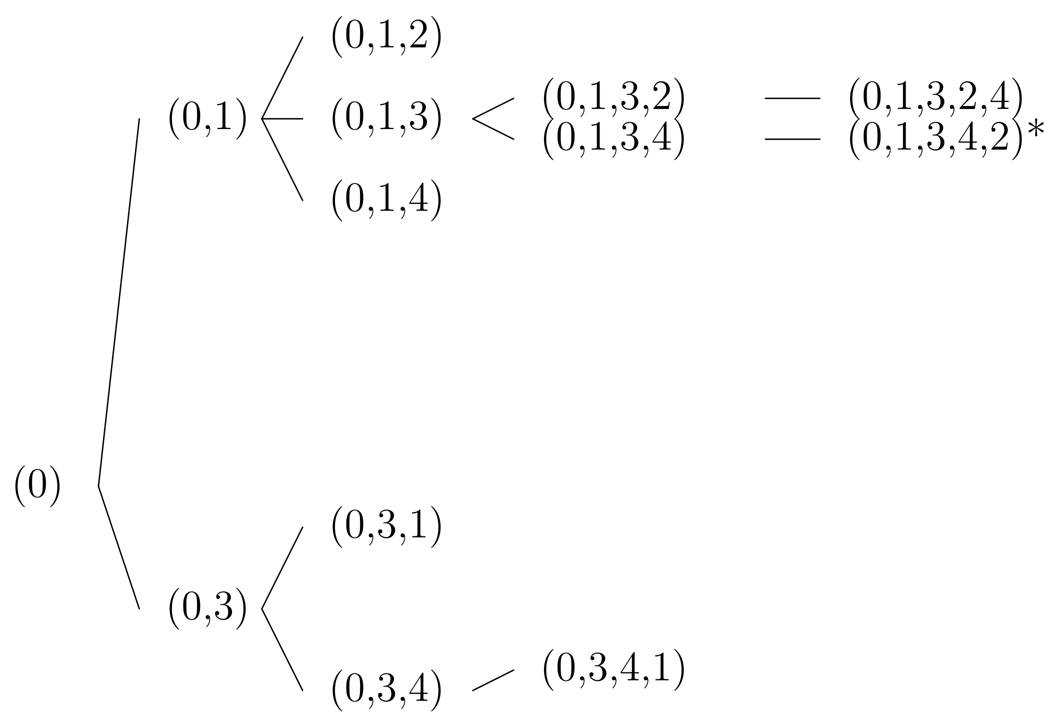
bound = 302.31

length = 127.52 + 159.95 = 287.47



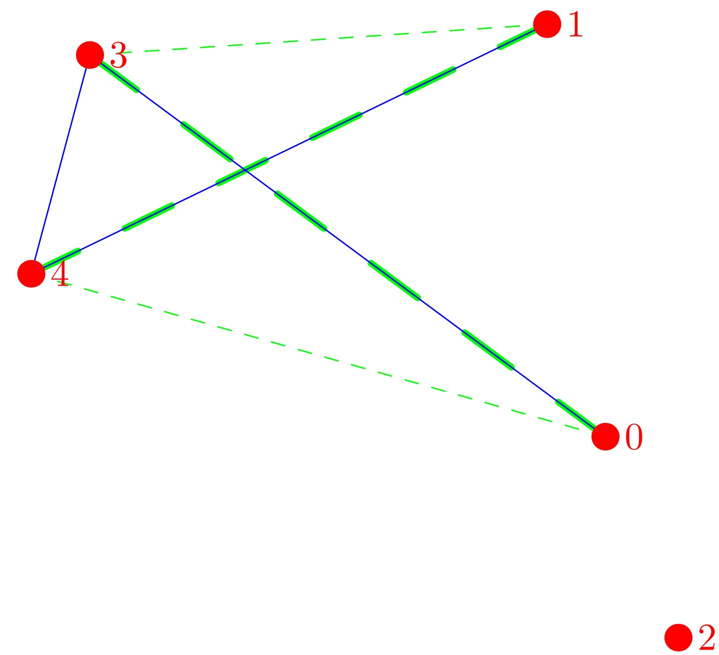
(0,3,4)

Branch and Bound after Pruning



bound = 302.31

length = 211.72 + 61.211 = 272.93



Not 2-opt

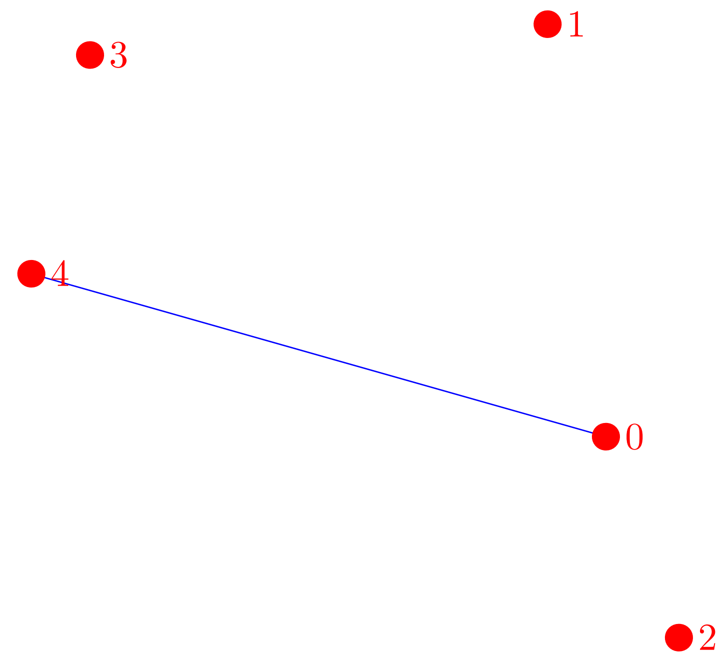
(0,3,4,1)

Branch and Bound after Pruning

- (0)
  - (0,1)
    - (0,1,2)
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
  - (0,3)
    - (0,3,1)
    - (0,3,4)
      - (0,3,4,1)
  - (0,4)

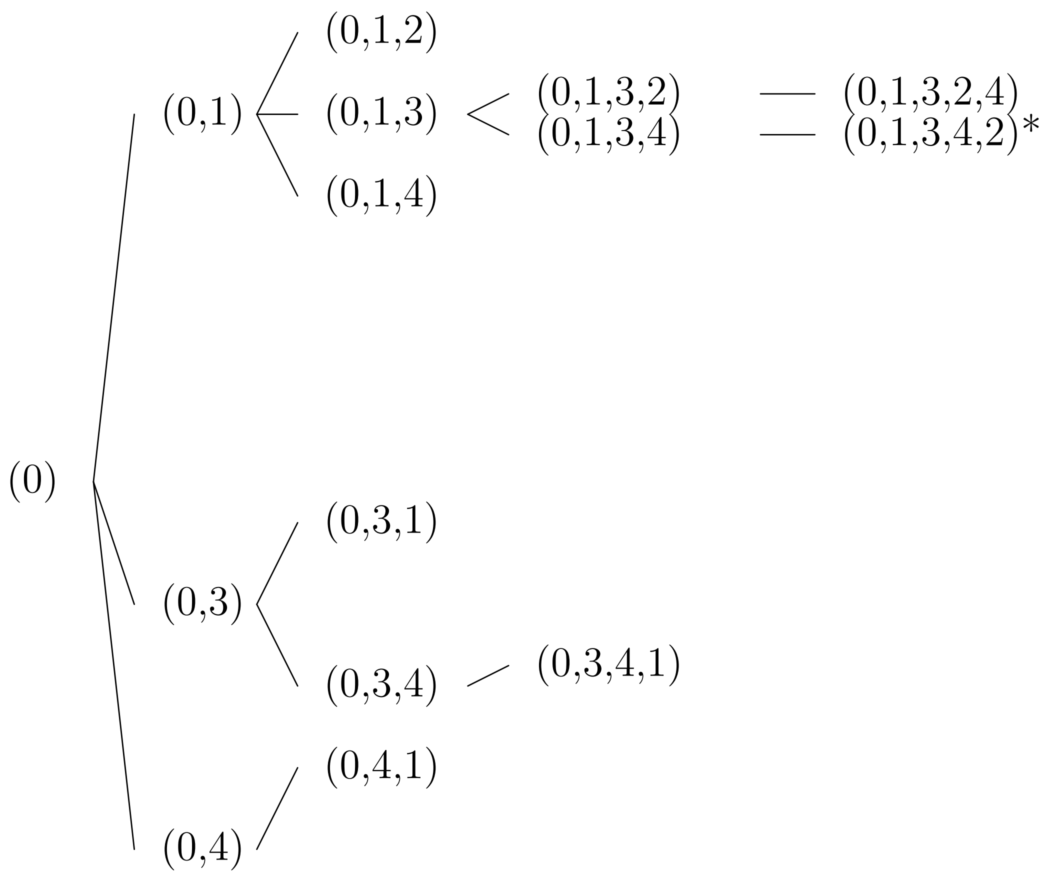
bound = 302.31

length = 87.692 + 193.23 = 280.92



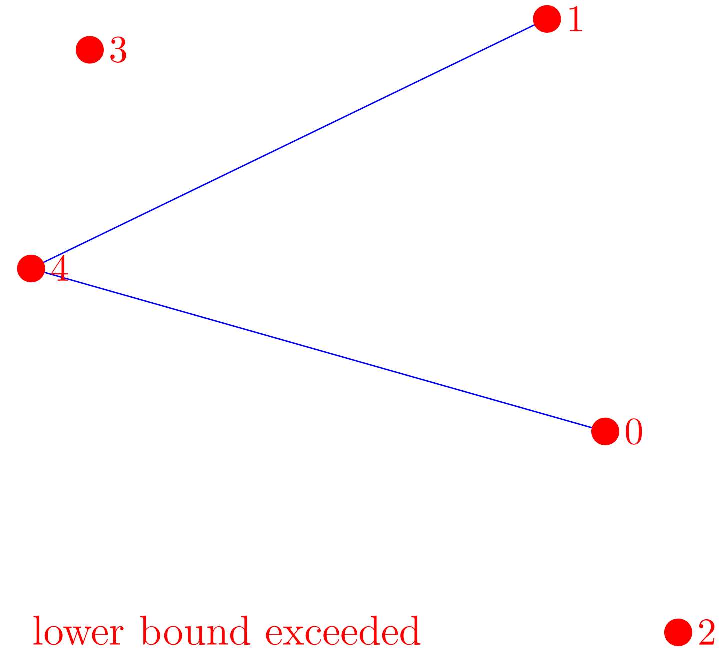
(0,4)

Branch and Bound after Pruning



bound = 302.31

length = 171.9 + 159.95 = 331.85



lower bound exceeded

(0,4,1)

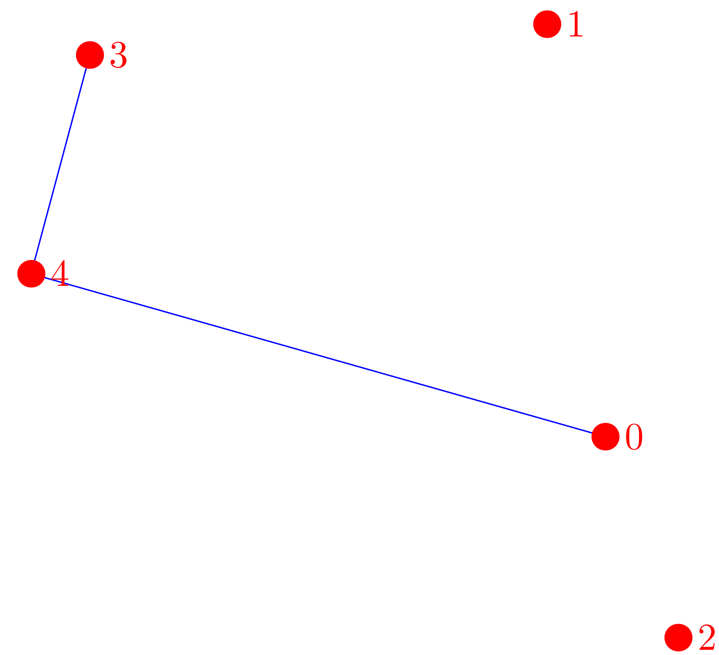
Branch and Bound after Pruning

(0)

- (0,1)
  - (0,1,2)
  - (0,1,3)
    - (0,1,3,2) — (0,1,3,2,4)
    - (0,1,3,4) — (0,1,3,4,2)*
  - (0,1,4)
- (0,3)
  - (0,3,1)
  - (0,3,4) — (0,3,4,1)
- (0,4)
  - (0,4,1)
  - (0,4,3)

bound = 302.31

length = 120.97 + 159.95 = 280.92



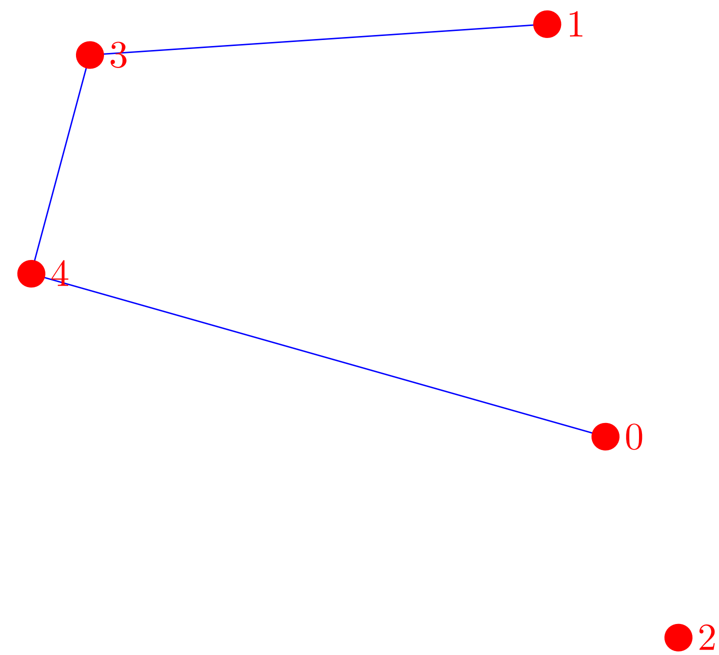
(0,4,3)

Branch and Bound after Pruning

- (0)
  - (0,1)
    - (0,1,2)
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
  - (0,3)
    - (0,3,1)
    - (0,3,4)
      - (0,3,4,1)
  - (0,4)
    - (0,4,1)
    - (0,4,3)
      - (0,4,3,1)

bound = 302.31

length = 188.3 + 61.211 = 249.51



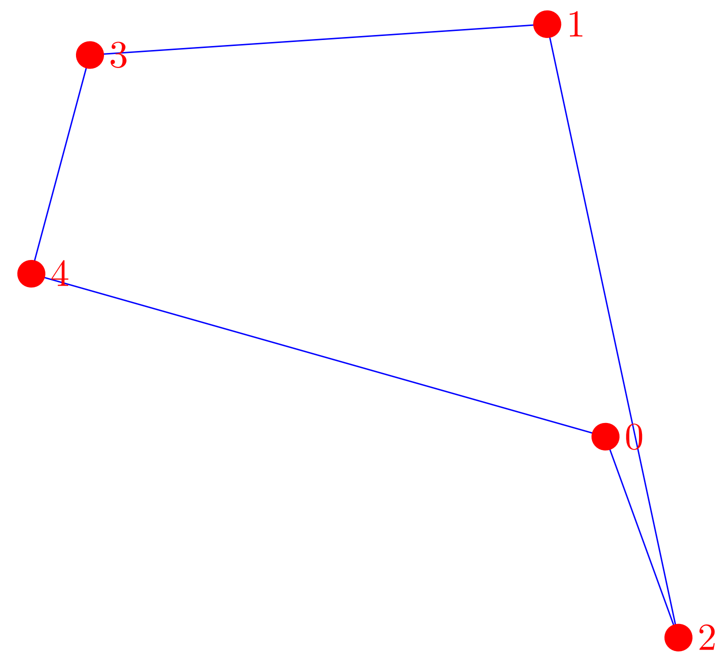
(0,4,3,1)

Branch and Bound after Pruning

- (0)
  - (0,1)
    - (0,1,2)
    - (0,1,3)
      - (0,1,3,2) — (0,1,3,2,4)
      - (0,1,3,4) — (0,1,3,4,2)*
    - (0,1,4)
  - (0,3)
    - (0,3,1)
    - (0,3,4)
      - (0,3,4,1)
  - (0,4)
    - (0,4,1)
    - (0,4,3)
      - (0,4,3,1) — (0,4,3,1,2)

bound = 302.31

length = 311.88 + 0 = 311.88



(0,4,3,1,2)

Applications of Branch and Bound

- Branch and bound works for many optimisation problems
- It's drawback is that you often end up still searching an exponentially large search space even though it might be massively faster than exhaustive enumeration
- To make it work well requires considerable work
- This is not an instantaneous algorithm, you may be waiting hours before you find a solution
- For really large problems branch and bound might be too slow

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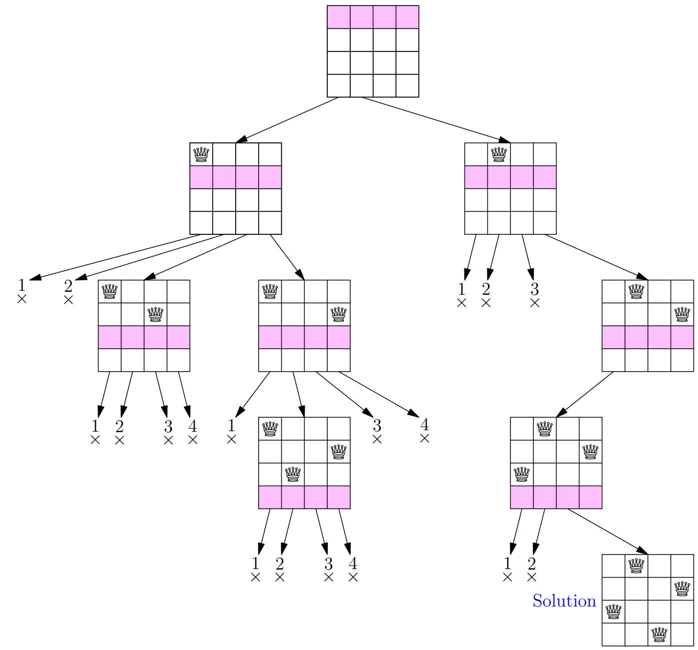
Outline

1. Search Trees
2. Backtracking
3. Branch and Bound
4. **Search in AI**



Other Search Strategies

- Search is a big topic in AI
- The algorithms used depends on the information available
- A classic search scenario is when there is "heuristic" information which provides a hint as to where an optimal solution lies
- Algorithms such as A^* exist which will finds the best route given an (admissible) heuristic as efficiently as possible
- You should learn about this next year in AI

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Planning and Game Paying

- Search is also used to find the best action to take in planning problems and game playing (e.g. computer chess)
- Again it is useful to think in terms of a search tree
- Searching all paths on the search tree is usually infeasible
- Look for ways of pruning the search tree to focus on good moves
- Strategies include *minimax* and *alpha-beta pruning*

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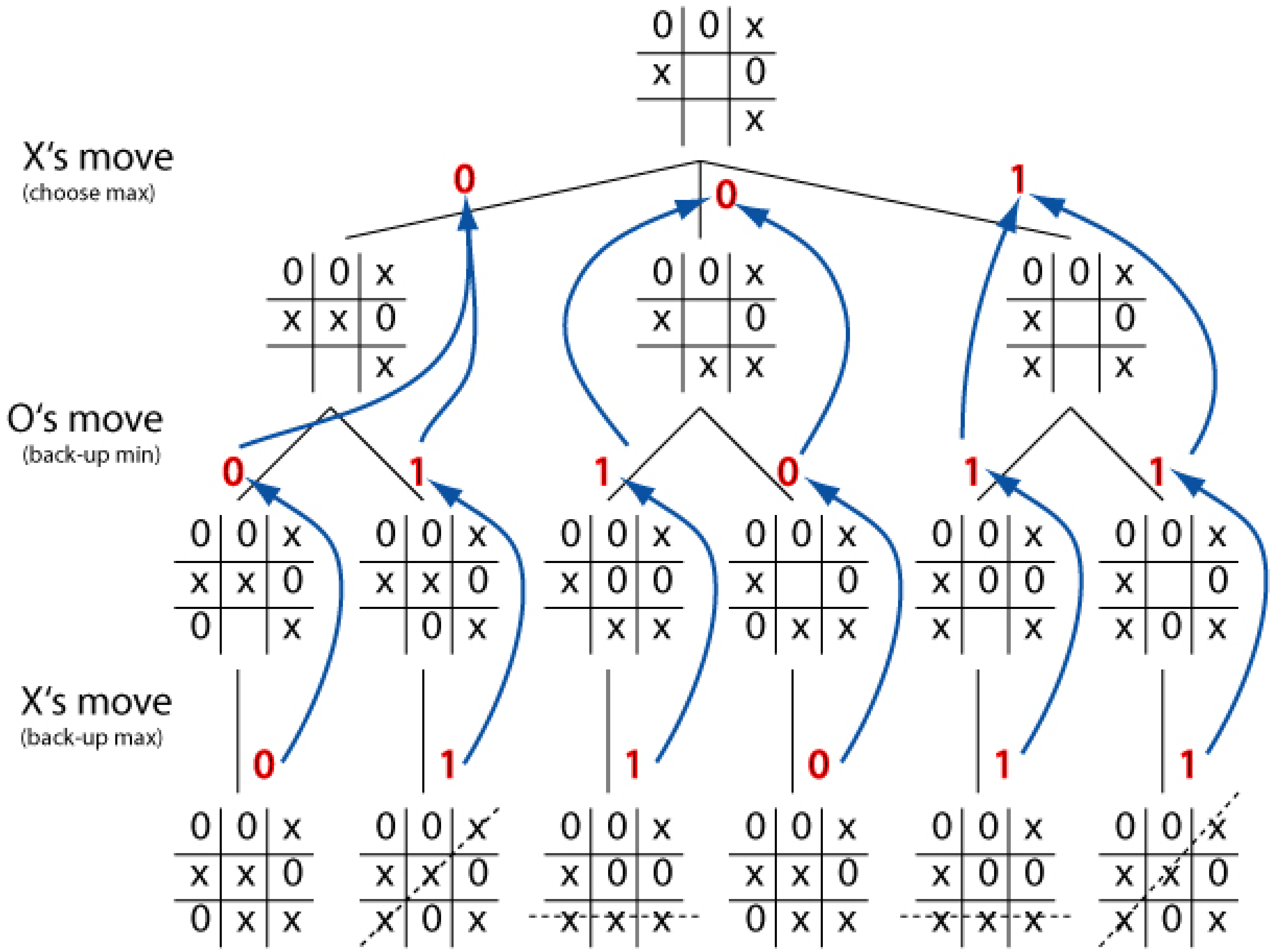
Minimax with Alpha-Beta Prunning



Lessons

- Search has many applications
- It is helpful to consider the search space as a tree whose branch corresponds to possible actions
- Backtracking is useful in search trees with constraints
- For optimisation problems branch and bound uses backtracking and costs of partial solutions as constraints
- Widely applicable, but can take too long

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