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OAR Lib:
An Open Source Arc Routing Library

COLLEGE OF COMPUTER, MATHEMATICAL, & NATURAL SCIENCES

Oliver Lum
Research Advisor: Bruce Golden
Course Advisors: Radu Balan, Kayo Ide

What is OAR Lib?

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- An open-source java library aimed at new operations researchers in the field of arc routing.
- An architecture for future software development in routing and scheduling.
- Design Philosophy: Usability First, Performance Second
- Well-Documented

Why Java?

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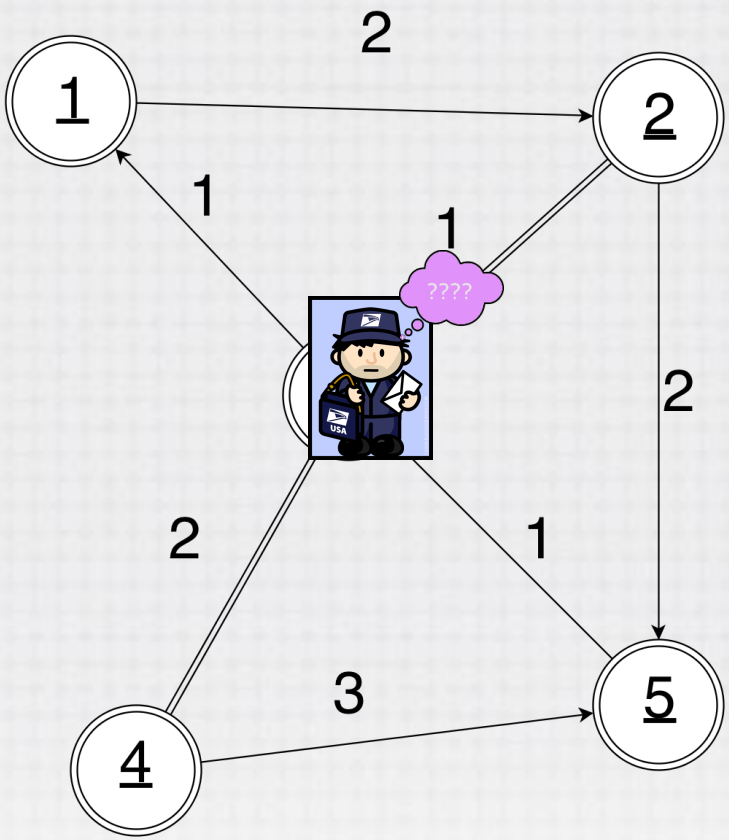
1. Industry-standard
2. Balances developer-friendliness with speed
3. Java Native Interface (JNI) allows for C/C++ interfacing
4. Portable
5. Massive-Scale Parallelism Possible
6. Ease of Coding

What's the Problem?

- Similar to the well-studied Vehicle Routing Problems (VRPs)
- Seeks a minimum cost traversal of a graph's arcs:
  - Chinese Postman Problem
    - Undirected
    - Directed
    - Mixed
    - Windy
    - Rural Variants



Applications

- Ubiquitous:
  - Package Delivery
  - Snow Plowing
  - Military Patrols
- Various interesting wrinkles:
  - Time-Windows
  - Close-Enough
  - Turn Penalties
  - Asymmetric Costs

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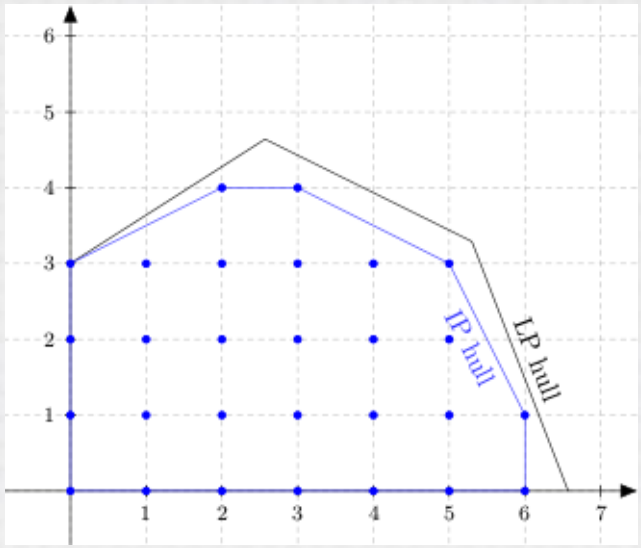
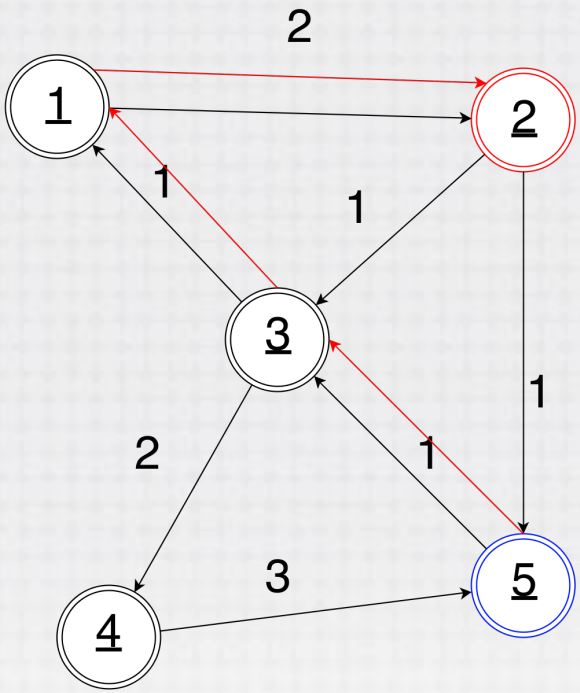
IP Solvers



Constructive Heuristics



IP Formulation [10]

$$\text{minimize} \sum_{i \text{ or } j \in \{D^+ \cup D^-\}} c_{ij} x_{ij}$$

subject to:

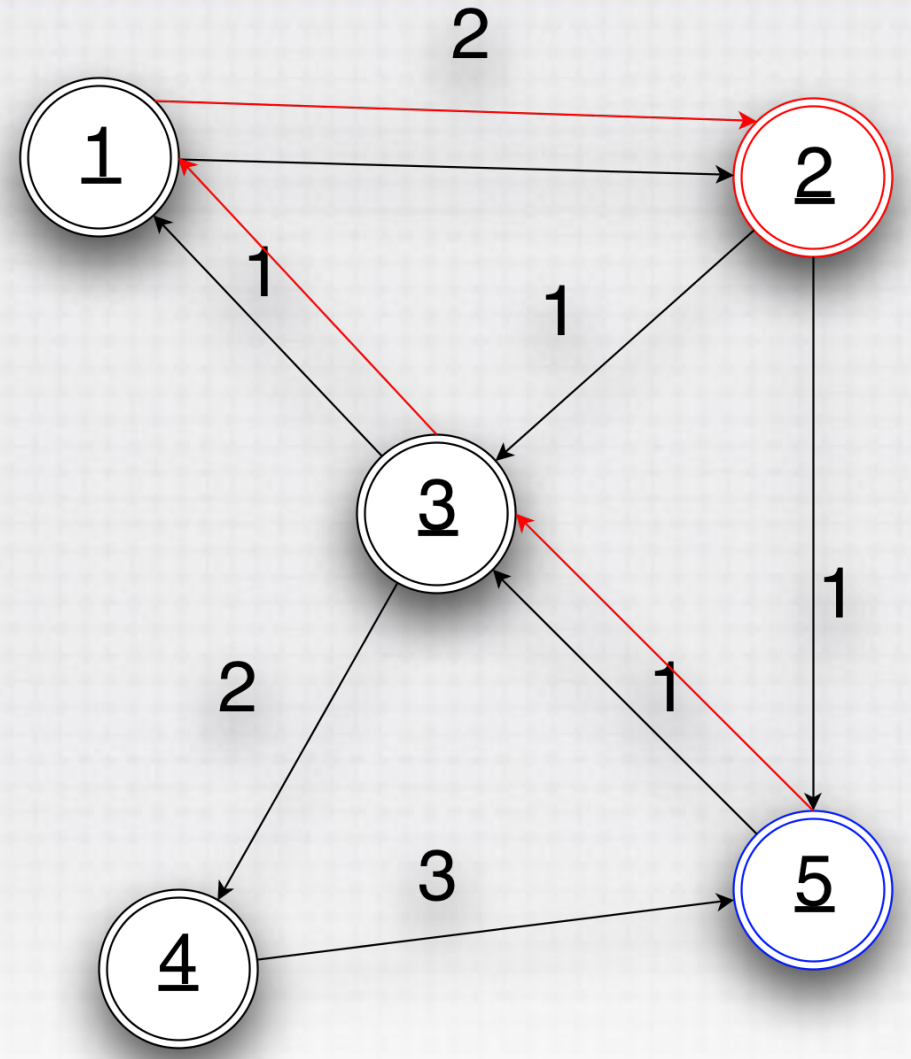
$$\sum_{j \in D^+} x_{ij} = -\delta(i), \ \forall i \in D^-$$

$$\sum_{i \in D^-} x_{ij} = \delta(j), \quad \forall j \in D^+$$

$$x_{ij} \in \mathbb{Z}_+^0$$

- Cost function: C
- f_{ij} : represents number of additional times we traverse the shortest path from i to j.
- $\delta(v)$: outdegree – indegree of vertex v.
- $D\uparrow+$: set of vertices with excess outgoing arcs.
- $D\uparrow-$: set of vertices with excess incoming arcs.

Directed Solver [10]



OAR Lib

1. Background
2. What is OAR Lib?
3. Why Java?
4. What's the Problem?
5. Applications
6. **What's In the Library?**
7. Example
8. Further Work
9. Special Thanks
10. References

IP Formulation [5]

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$$\text{minimize} \quad \sum_{(i,j)\in E} c_{ij}x_{ij}$$

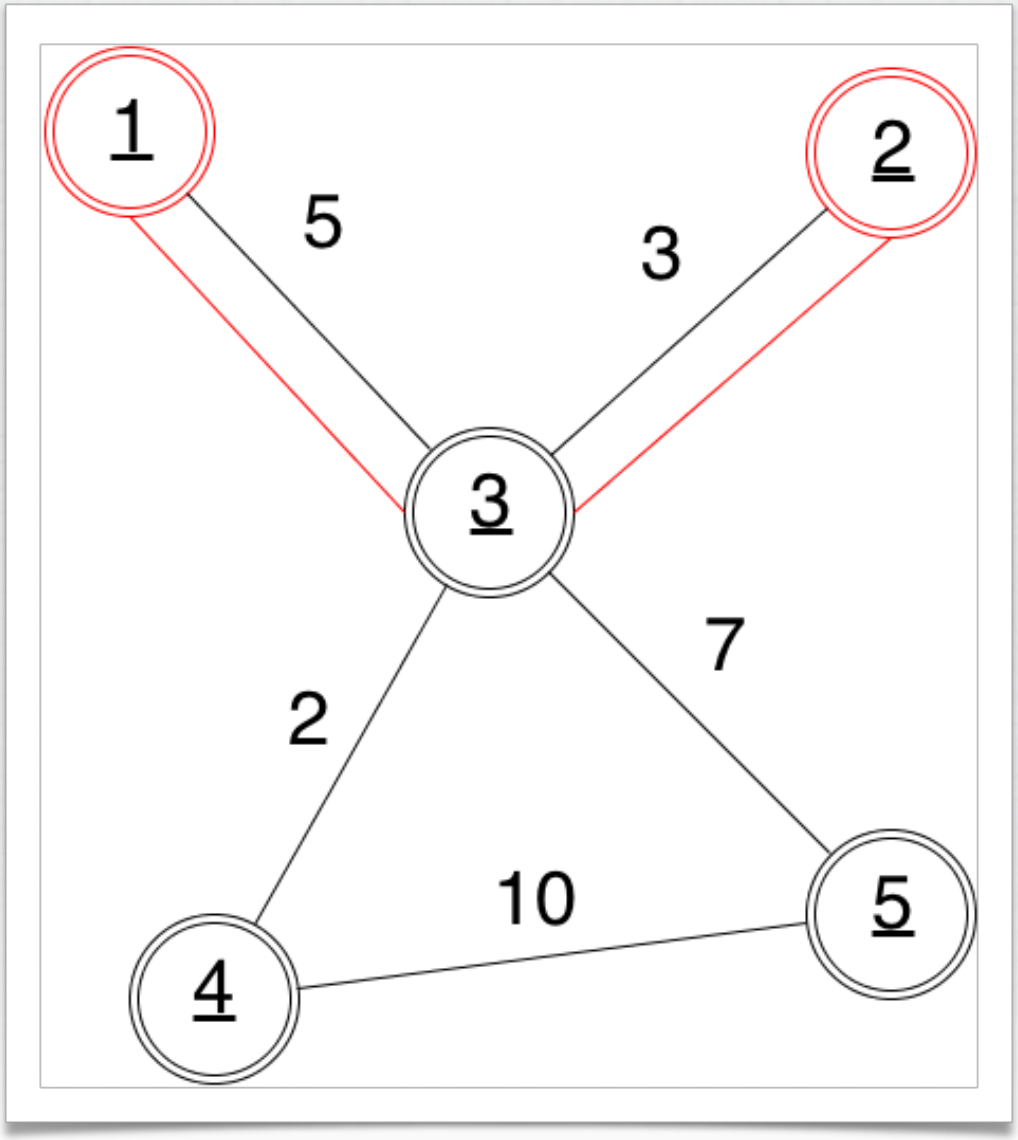
$$\text{subject to:}$$

$$\sum_{(i,j)\in E_v} (x_{ij}+1) \equiv 0 \ mod\ 2, \forall v \in V$$

$$x_{ij} \in \mathbb{Z}_{+}^{0}$$

- Cost function: C
- Edge set: E
- Vertex set: V
- t_e : represents number of additional times we traverse edge e.
- $\delta(v)$: set of edges incident on v.

Undirected Solver [5]



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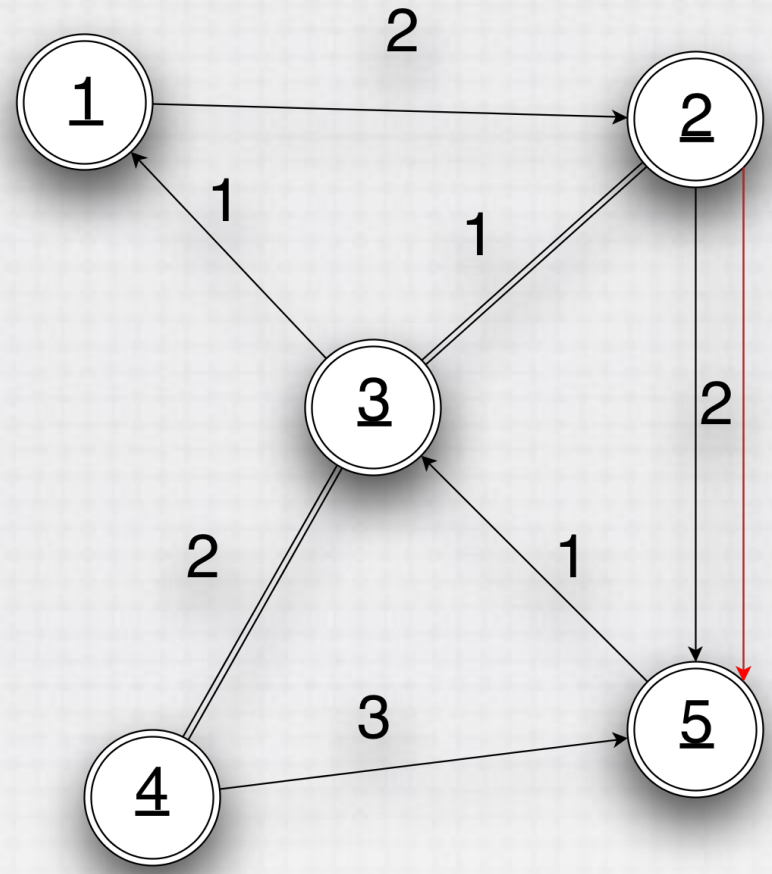
IP Formulation

$$\text{minimize} \quad \sum_{s \in \{A \cup \hat{E} \cup \check{E}\}} c_s x_s$$

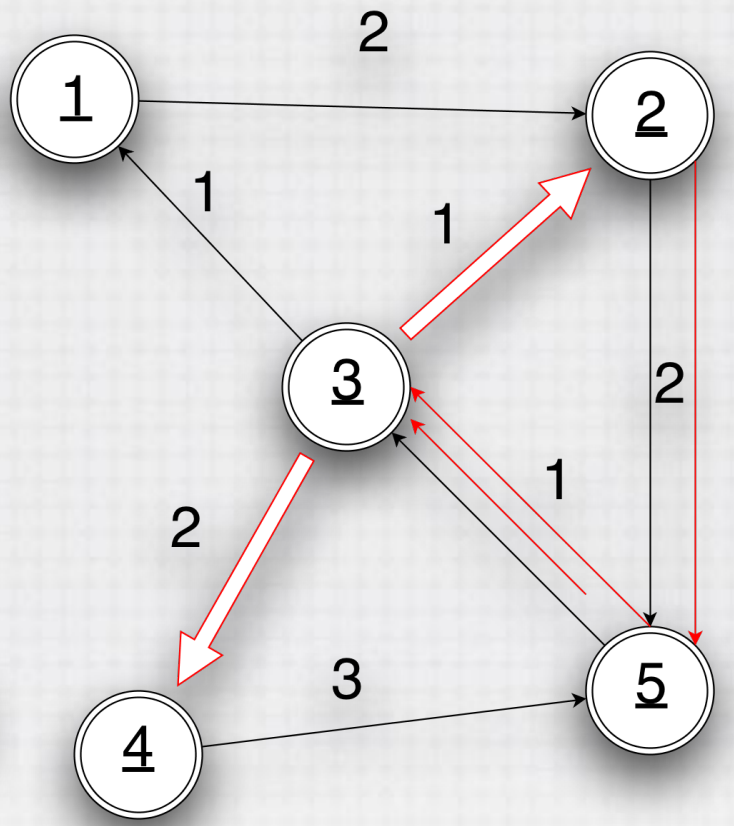
subject to:

$$\begin{aligned}
y'_e + y'_{\bar{e}} &\geq 1, && \forall e \in E \\
x_s &= y'_s + y_s, && \forall s \in A \cup \hat{E} \cup \check{E} \\
\sum_{s \in S_v^+} x_s - \sum_{s \in S_v^-} x_s &= 0, && \forall v \in V \\
y'_a &= 1, && \forall a \in A \\
y'_e &\in \{0,1\}, && \forall e \in \hat{E} \cup \check{E} \\
y_s &\in \mathbb{Z}_+^0
\end{aligned}$$

- Cost function: C
- x_s : represents number of times we traverse link s.
- $\delta\uparrow+(v)$: arcs / directed edges going out of v.
- $y\downarrow e\uparrow'$: 1 if we orient edge e from i to j, o oth.
- $y\downarrow s$: the number of additional times we traverse link s.



Even Degree



In-Out Degree

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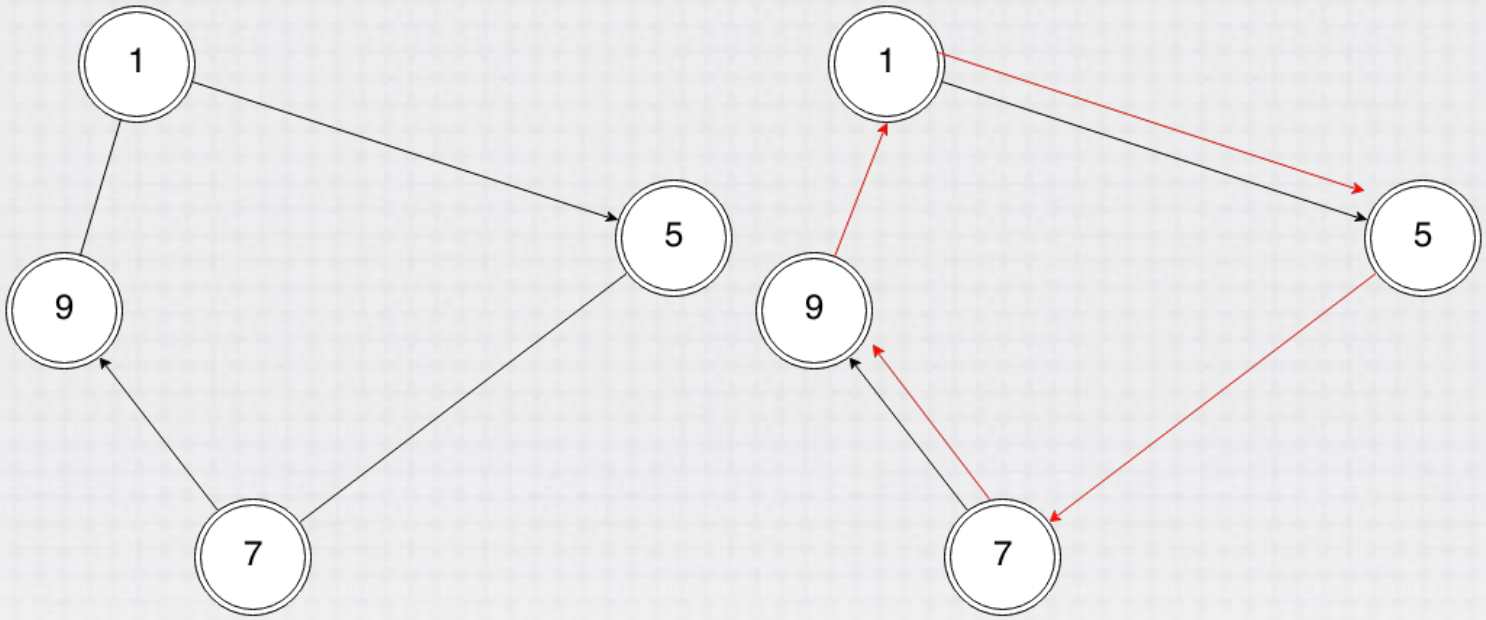
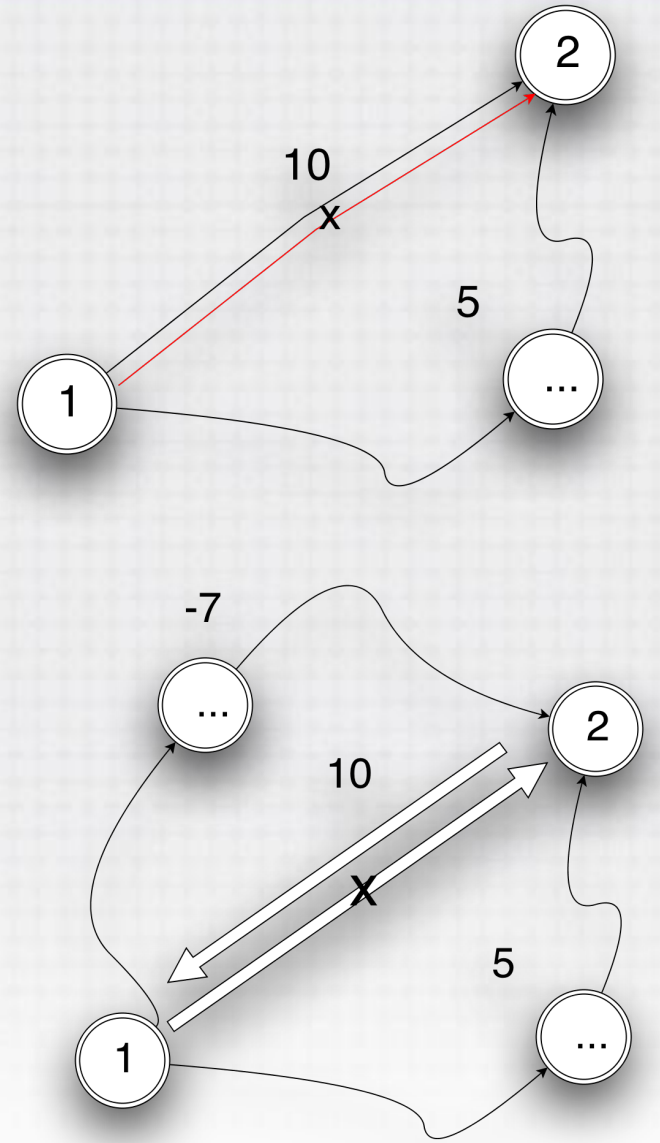
Mixed 1 [8]



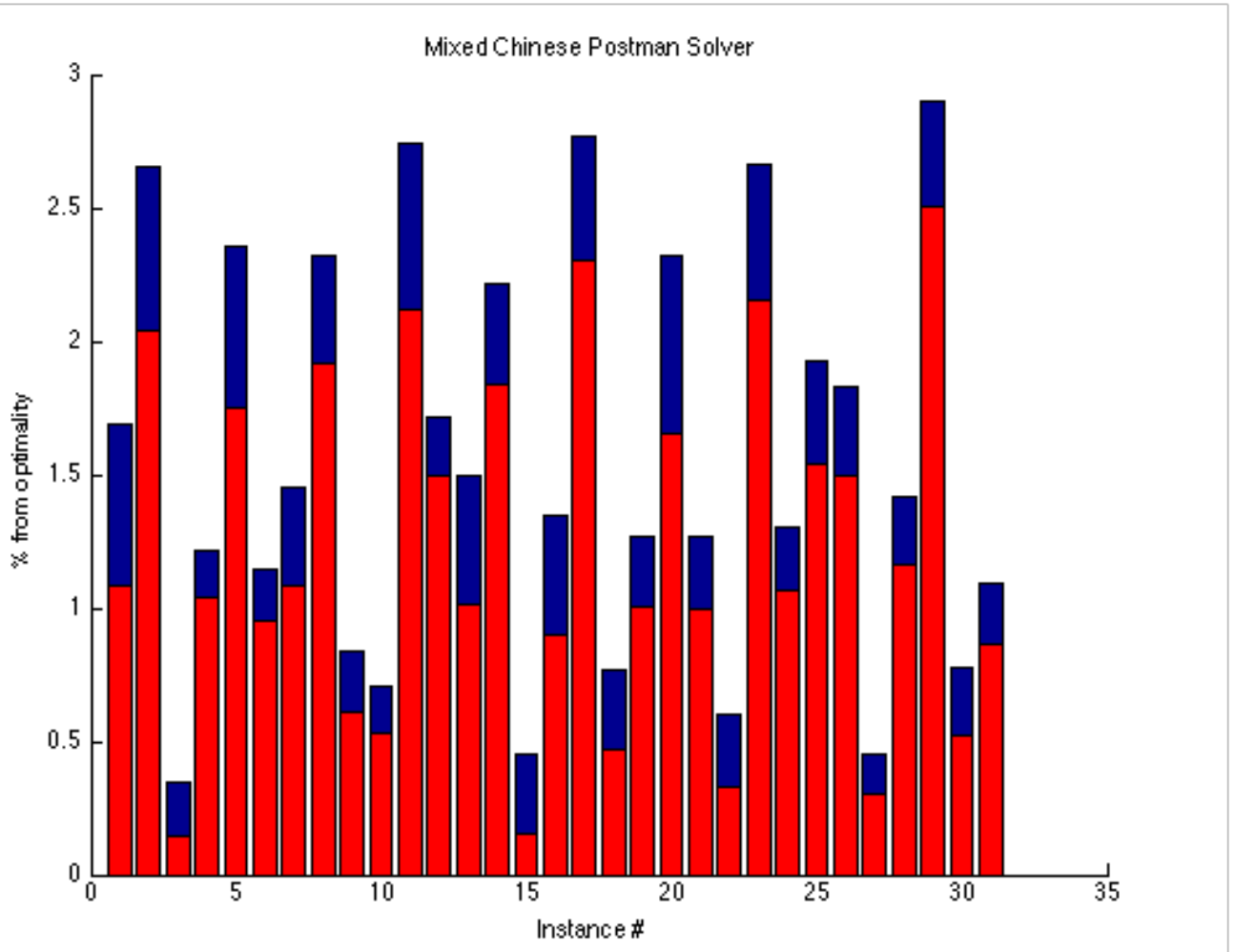
Even Parity

Mixed 2

- There are two ideas encapsulated by the algorithm:
  - Wherever possible, replace an added arc with a ‘shortest path’ if it reduces cost.
  - Wherever possible, reverse the direction of a directed edge and add two ‘shortest paths’ from i to j if it reduces cost.



Computational Results



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IP Formulation [9]

$$\text{minimize} \quad \sum_{e^+ \in E^+} c_{e^+} x_{e^+} + \sum_{e^- \in E^-} c_{e^-} x_{e^-}$$

subject to:

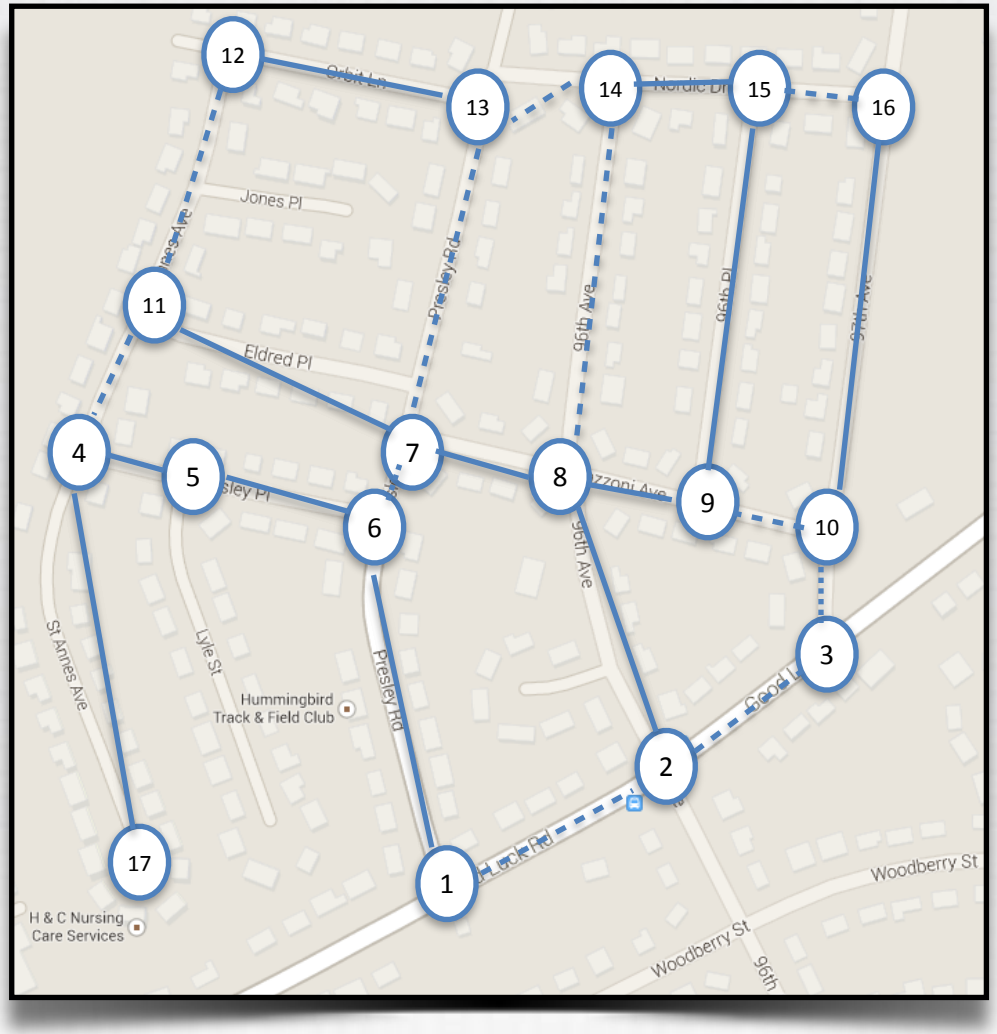
$$\sum_{e^+ \in E^+} x_{e^+} - \sum_{e^- \in E^-} x_{e^-} = 0, \quad \forall v \in V$$

$$x_{e^+} + x_{e^-} \geq 1, \quad \forall e \in E$$

$$x_{e^+}, x_{e^-} \in \mathbb{Z}_+^0, \quad \forall e \in E$$

- Cost function: C
- x_{e^+} : represents number of times we traverse edge e from i to j.
- $\delta(v)$: arcs / directed edges going into v.

Example [1]



- Rural Postman Problem
  - Set of required / non-required edges

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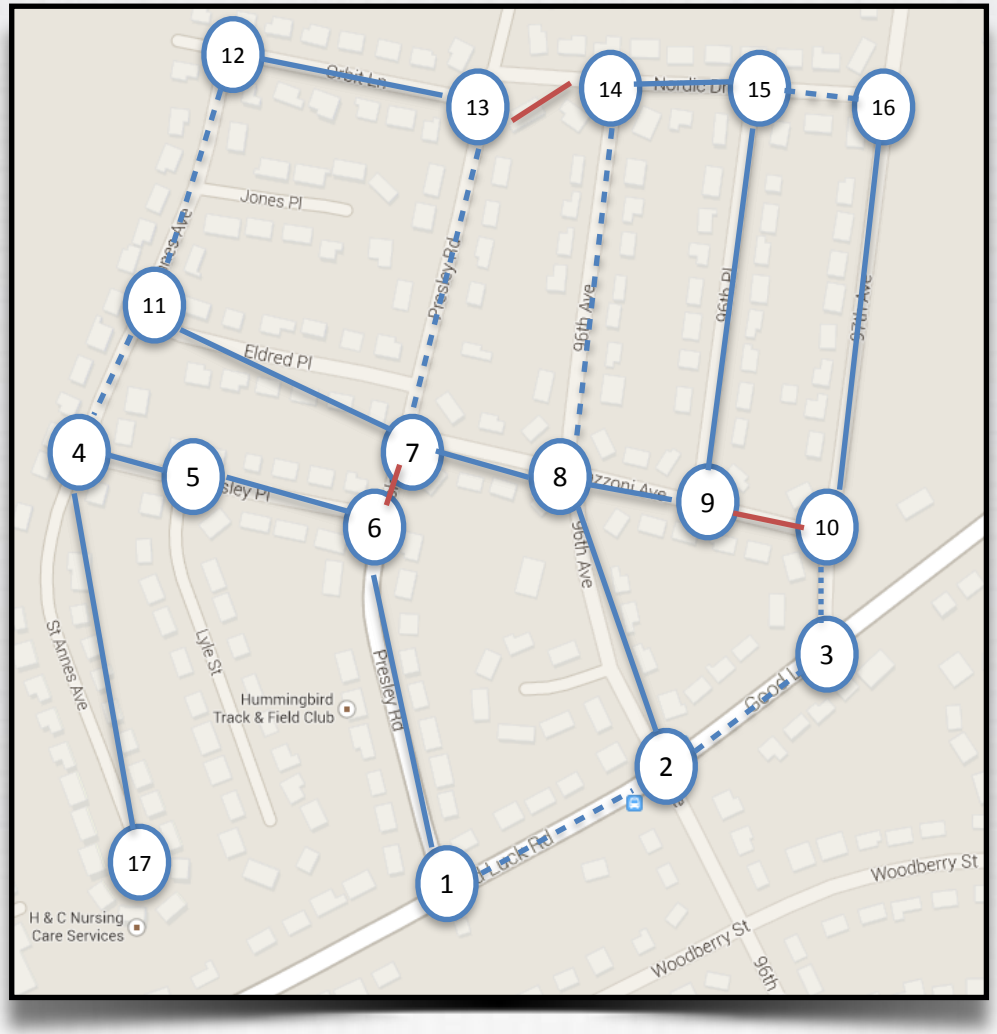

- Rural Postman Problem
  - Set of required / non-required edges
  - Solve an MST over the required components

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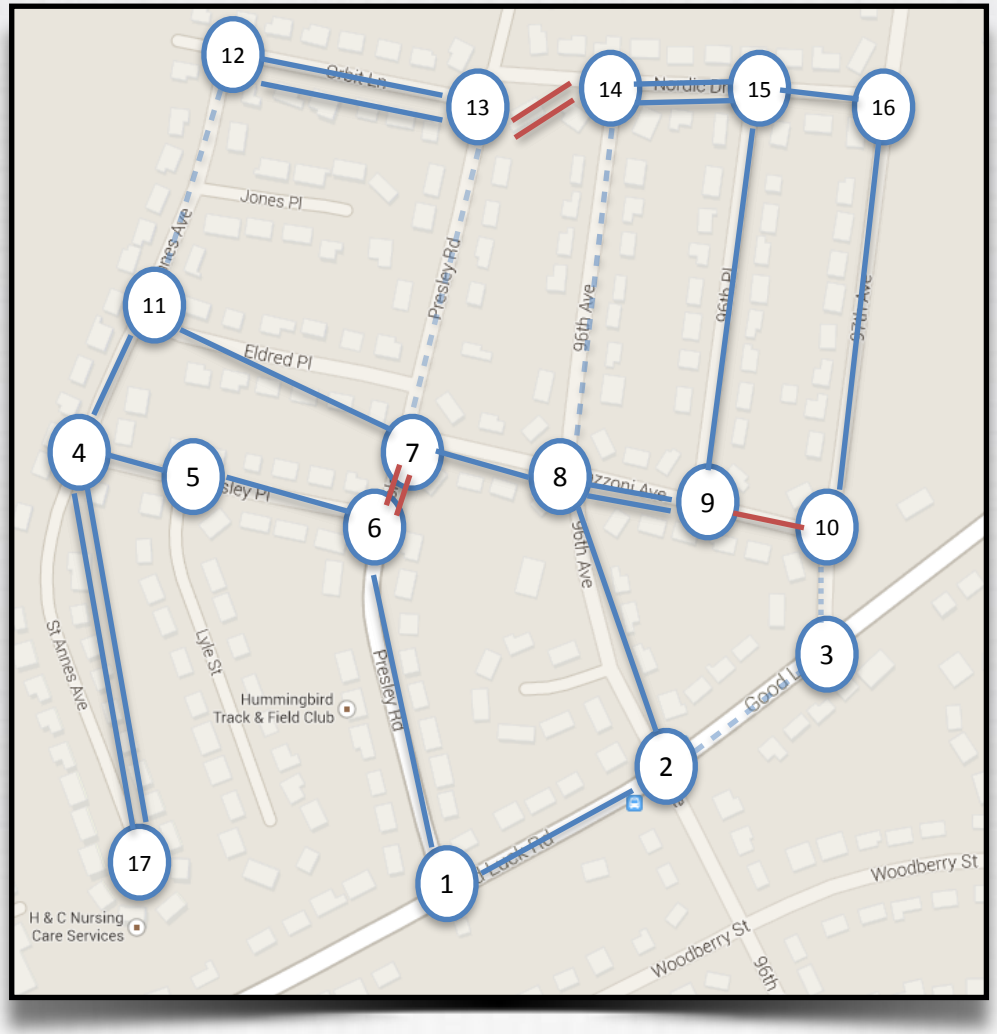
Example [1]



- Rural Postman Problem
  - Set of required / non-required edges
  - Solve an MST over the required components
  - Solve a min-cost matching over the remaining odd vertices

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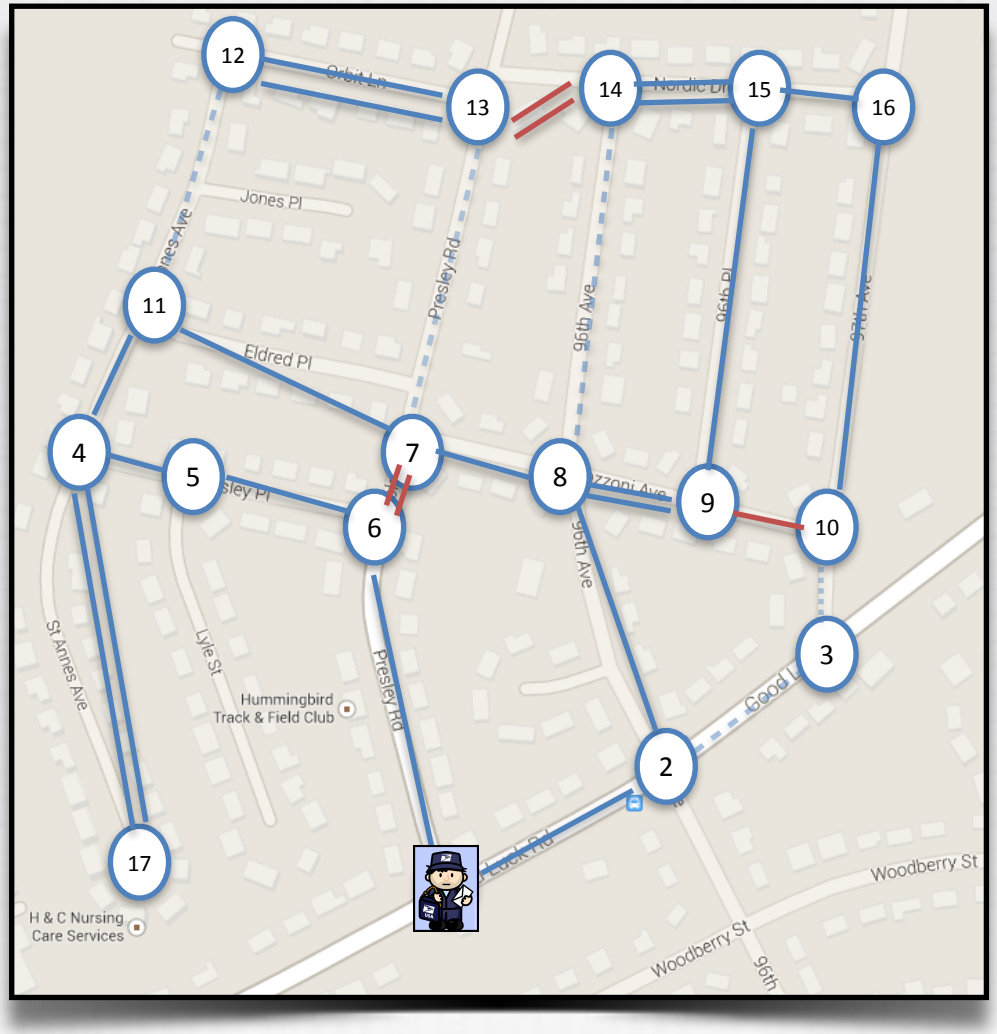

- Rural Postman Problem
  - Set of required / non-required edges
  - Solve an MST over the required components
  - Solve a min-cost matching over the remaining odd vertices
  - Solve a min-cost flow to determine the optimal tour

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Example

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- Code Snippet:

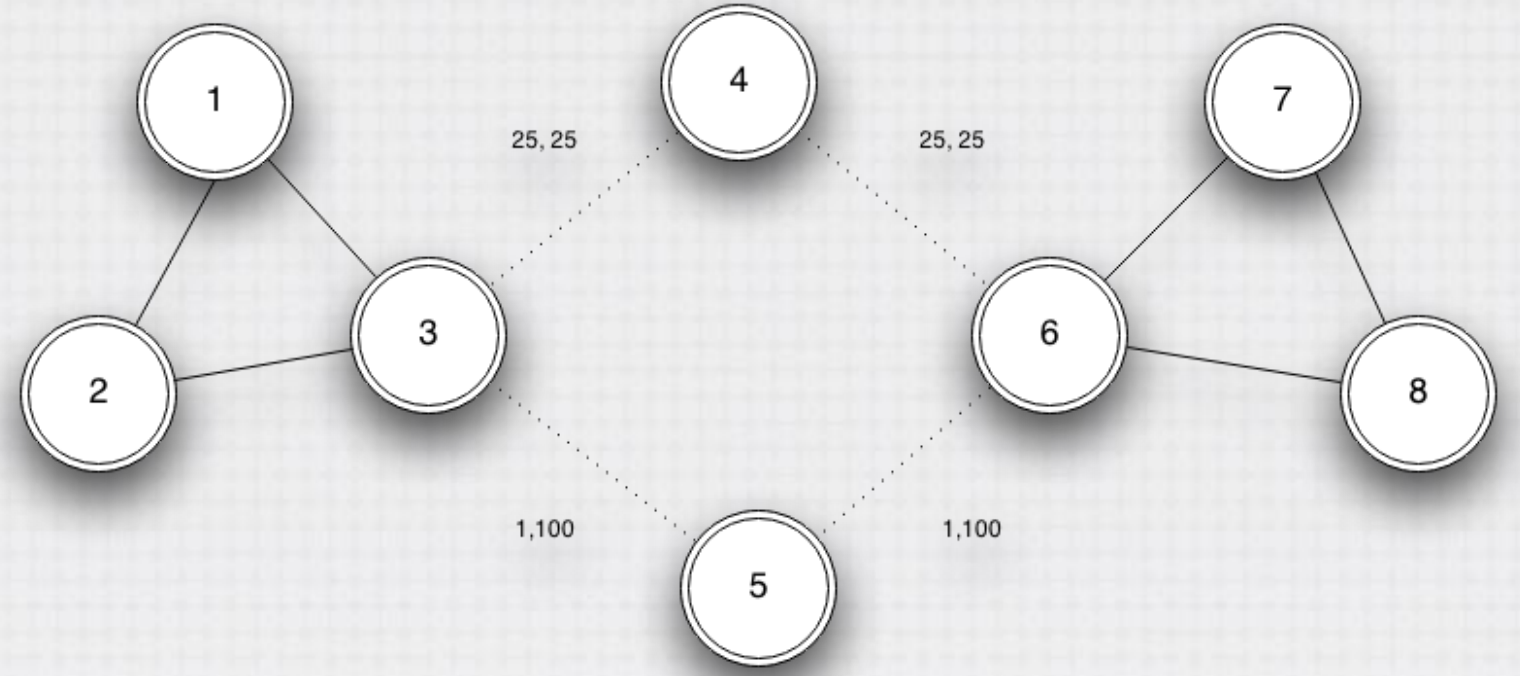
```
WindyGraph neighborhood = new WindyGraph(17);
neighborhood.addEdge(1, 2, 5, 5, false);
neighborhood.addEdge(2, 3, 4, 4, false);
neighborhood.addEdge(4, 17, 7, 7, true);
neighborhood.addEdge(1, 6, 6, 6, true);
neighborhood.addEdge(2, 8, 5, 5, true);
neighborhood.addEdge(3, 10, 3, 3, false);
neighborhood.addEdge(4, 5, 2, 2, true);
neighborhood.addEdge(5, 6, 3, 3, true);
neighborhood.addEdge(6, 7, 1, 1, false);
neighborhood.addEdge(7, 8, 3, 3, true);
neighborhood.addEdge(8, 9, 2, 2, true);
neighborhood.addEdge(9, 10, 2, 2, false);
neighborhood.addEdge(4, 11, 3, 3, false);
neighborhood.addEdge(7, 11, 5, 5, true);
neighborhood.addEdge(11, 12, 5, 5, false);
neighborhood.addEdge(7, 13, 7, 7, false);
neighborhood.addEdge(8, 14, 8, 8, false);
neighborhood.addEdge(9, 15, 7, 7, true);
neighborhood.addEdge(10, 16, 8, 8, true);
neighborhood.addEdge(12, 13, 4, 4, true);
neighborhood.addEdge(13, 14, 3, 3, false);
neighborhood.addEdge(14, 15, 3, 3, true);
neighborhood.addEdge(15, 16, 2, 2, false);

WindyRPP testProblem = new WindyRPP(neighborhood);
WRPPSolver_Win testSolver = new WRPPSolver_Win(testProblem);
Route ans = testSolver.trySolve();
System.out.println(ans.toString());
```

```
Cost is: 91
6-7-11-4-17-4-5-6-1-2-8-9-15-14-13-12-13-14-15-16-10-9-8-7-6
```

Graph Initialization:

- Can be done by hand (left)
- Can be parsed from a text file using GraphReader object
- Modular Graph / Problem / Solver architecture provides

Windy Rural 2 [1]



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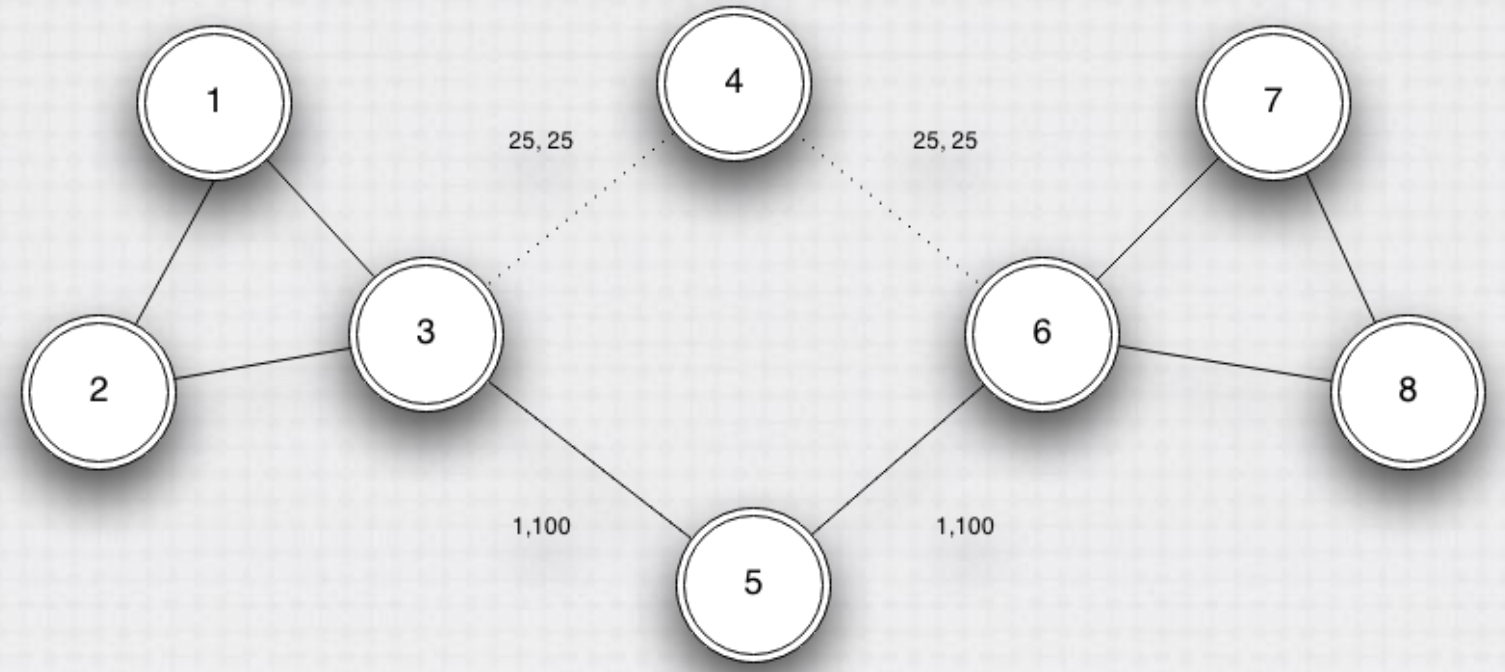
Windy Rural 2 [1]



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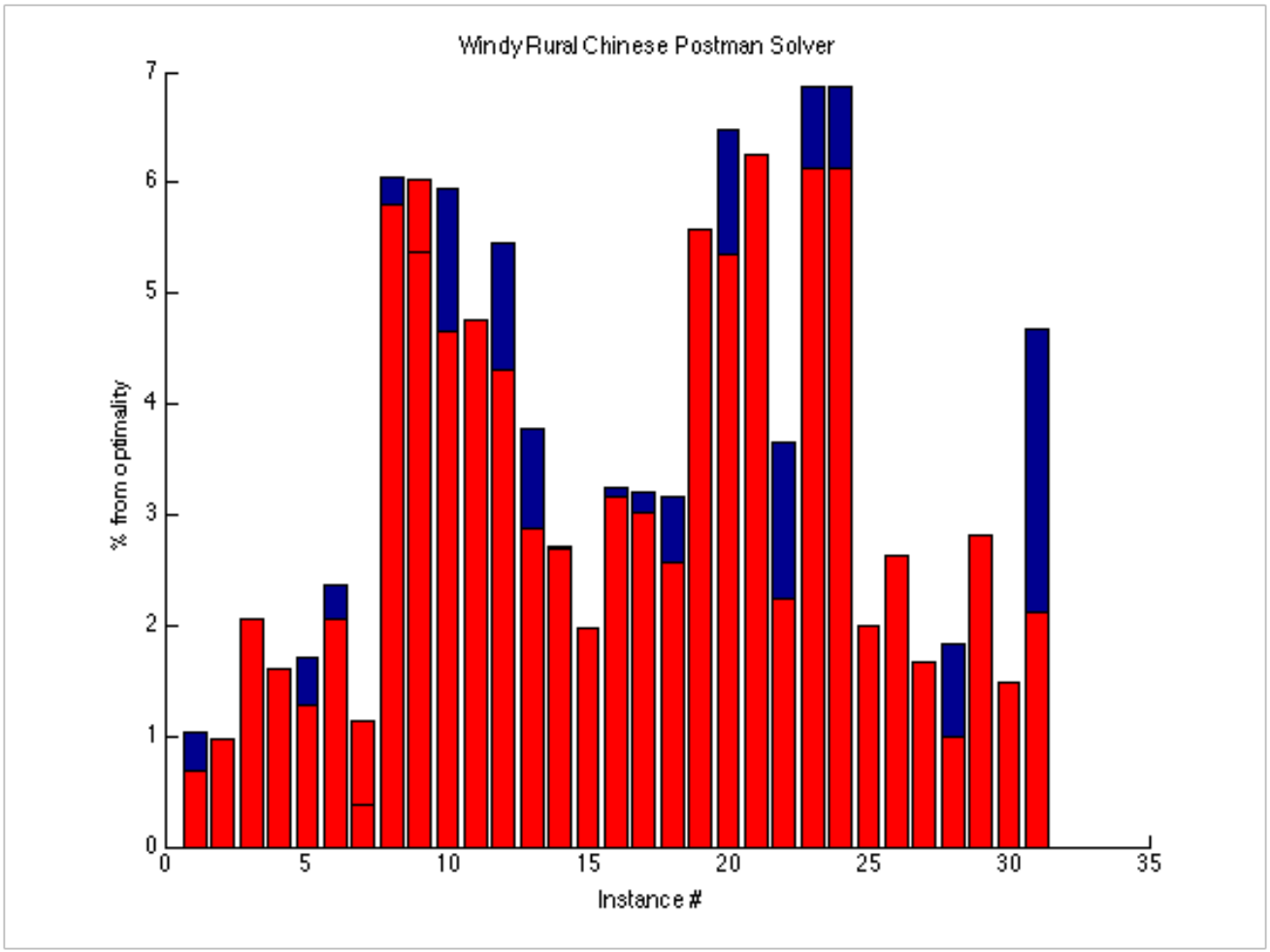
Computational Results



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What's In the Library?

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Problem	Classical	Modern
Undirected Chinese Postman Problem	1. Edmonds 2. Exact IP	N/A
Directed Chinese Postman Problem	1. Edmonds 2. Exact IP	N/A
Mixed Chinese Postman Problem	1. Frederickson 2. Exact IP	Yaoyuenyeung
Windy Chinese Postman Problem	1. Win 2. Exact IP	Benavent
Directed Rural Postman Problem	1. Christofides	N/A

What's In the Library?

Common Algorithms:

- Several Shortest Paths implementations
- Min-Cost Flow Implementation
- Hierholzer's Algorithm
- Min-Cost Spanning Tree
- Connected Components Algorithms
- Min-Cost Spanning Arborescence (JNI)
- Min-Cost Matching (JNI)

What's In the Library?

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- Example Code Snippets
- Documentation
- Test Data
  - WPP / WRPP Albaida-Madrigueras Instances
  - DRPP Instances from Campos
  - MCPP Instances from Yaoyuenyong
  - Random test instances for UCPP, DCPP

Validation

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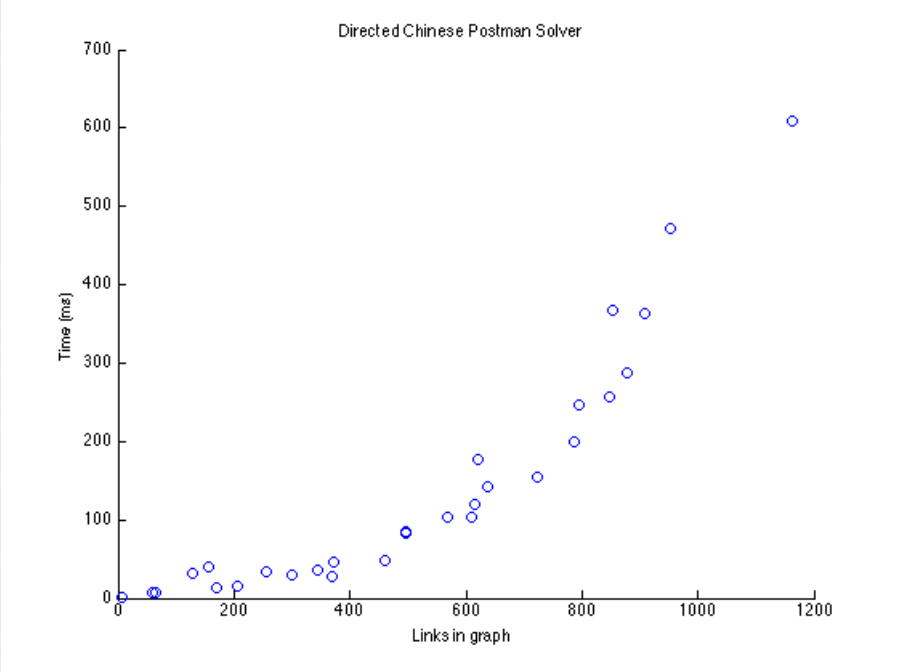
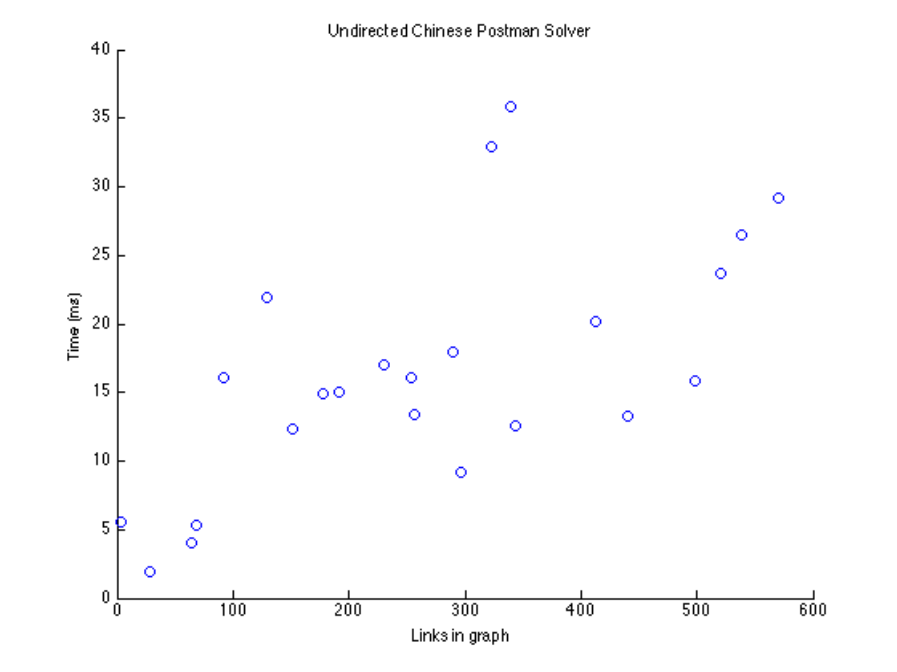
- DCPP: Compare Results to Gurobi Solver
- UCPP: Compare Results to Gurobi Solver
- MCPP1: Validate using the Yaoyuenyong instances, and reproducing the table given in the paper.
- MCPP2: Validate using the Yaoyuenyong instances, and reproducing the table given in the paper.
- MCPP Exact: Validate using the mixed Albaida-Madrigueras instances.
- WPP Exact: Validate using the windy Albaida-Madrigueras instances.
- WRPP 1: Validate using the windy rural Albaida-Madrigueras instances to duplicate average % deviation for the algorithm with / without improvement procedures.
- WRPP 2: Validate using the windy rural Albaida-Madrigueras instances to duplicate average % deviation for the algorithm with / without improvement procedures.
- DRPP: Validate using the Campos DRPP instances.

Computational Results





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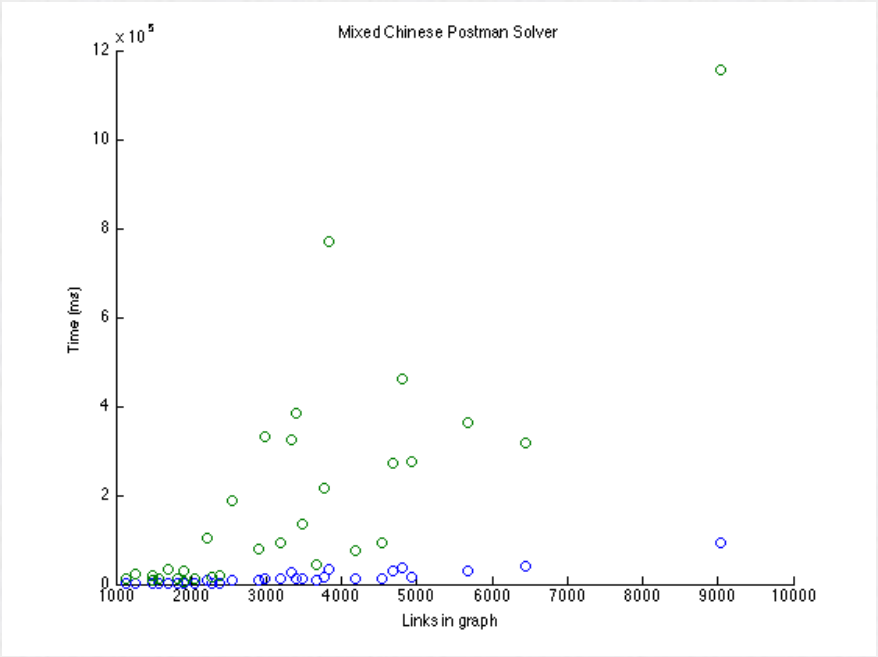

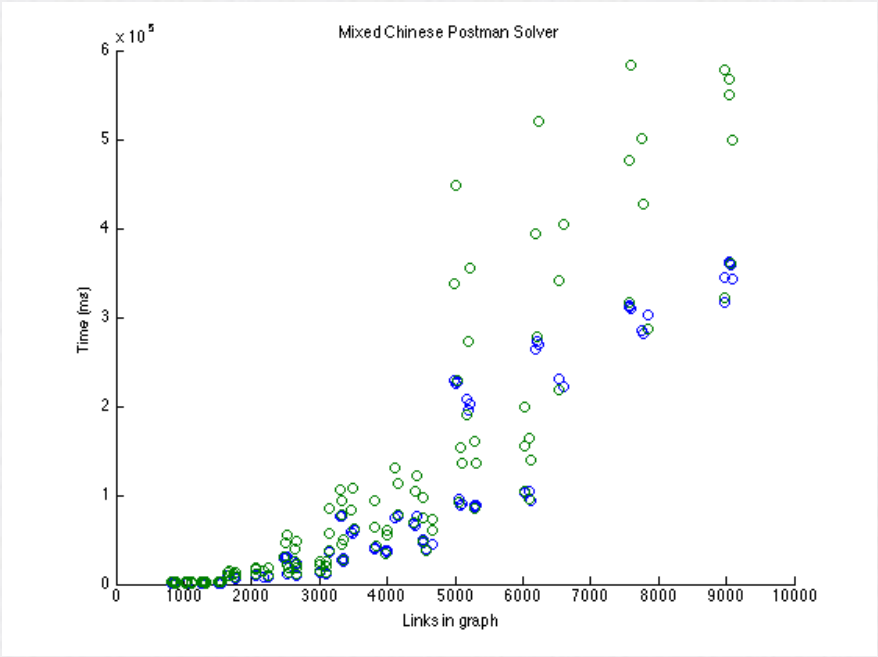

Further Work

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- Visualization
- Multi-Vehicle Solvers
- OSM graph ingestion
- More Parsers / Format Conversion
- Decoupled Improvement Procedure Framework
- New Research
- Integrate Faster Open Source Replacements for Common Algorithms
- Suggestions(?)

Schedule

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Required:

- DCPP Solver ✓
- UCPP Solver ✓
- Test Framework ✓
- MCPP Heuristics
  - Frederickson's ✓
  - Shortest Additional Paths ✓
- ~~WPP Heuristics~~ WRPP Heuristics
  - Win's ✓
  - Benavent's ✓
- DRPP Heuristics
  - Christofides' ✓
  - Benavent's - (Alternative Model) ✓
- Final Report (May)

Optional:

- Visualization
- Gurobi Integration
  - DCPP Exact Solver ✓
  - UCPP Exact Solver ✓
  - MCPP Exact Solver ✓
  - WPP Exact Solver ✓
  - WPP Cutting Plane Heuristic ✓
- Performance Optimization (Ongoing)

Deliverables

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- Code hosted at my personal github at https://github/com/olibear.
  - Test Instances
  - All Code
    - Solvers
    - Graph Architecture
    - Extensible interfaces and abstract classes
    - Common Algorithms
    - Custom Errors
    - Documentation
  - Final Report

Code

Graph Architecture:

- Graph.java
  - DirectedGraph.java
  - UndirectedGraph.java
- Link.java
  - Arc.java
  - Edge.java
  - MultiEdge.java
  - MixedEdge.java
  - WindyEdge.java
- Vertex.java
  - DirectedVertex.java
  - UndirectedVertex.java
  - MixedVertex.java
  - WindyVertex.java

Problems:

- Problem.java
  - UndirectedCPP.java
  - DirectedCPP.java
  - MixedCPP.java
  - WindyCPP.java
  - DirectedRPP.java
  - WindyRPP.java

Solvers:

- SingleVehicleSolver.java
  - DCPPSolver_Edmonds.java
  - DCPPSolver_Gurobi.java
  - UCPPSolver_Edmonds.java
  - UCPPSolver_Gurobi.java
  - MCPPSolver_Gurobi.java
  - MCPPSolver_Frederickson.java
  - MCPPSolver_Yaoyuenyong.java

Code

- WPPSolver_Gurobi.java
- WPPSolver_Gurobi_CuttingPlane.java
- WRPPSolver_Win.java
- WRPPSolver_Benavent_H1.java
- DRPPSolver_Christofides.java

Utilities:

- CommonAlgorithms.java
- Pair.java
- BlossomV.java

Graph I/O:

- GraphGenerator.java
  - DirectedGraphGenerator.java
  - UndirectedGraphGenerator.java
  - MixedGraphGenerator.java
  - WindyGraphGenerator.java
- GraphReader.java

Testing:

- GeneralTestbed.java

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Special Thanks to:

Dr. Bruce Golden

Dr. Angel Corberan

Dr. Zaw Win

Dr. Vincente Campos

Dr. Kriangchai Yaoyuenyong

OAR Lib is available at

https://github.com/Olibear/ArcRoutingLibrary

References

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9. Grötschel, Martin, and Zaw Win. "A cutting plane algorithm for the windy postman problem." Mathematical Programming 55.1-3 (1992): 339-358.
10. Thimbleby, Harold. "The directed chinese postman problem." *Software: Practice and Experience* 33.11 (2003): 1081-1096.
11. Win, Zaw. "On the windy postman problem on Eulerian graphs." *Mathematical Programming* 44.1-3 (1989): 97-112.
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Backup Slides

Background

- Successful software systems are platforms, not projects.
- Extensibility / Flexibility of code should be a pre-requisite, not a feature.
- Standards benefit all developers, especially in the research community.

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Computational Results

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Graph	HashMap<Integer, Vertex> internalVertexMap	HashMap<Integer,Vertex> globalVertexMap
	HashMap<Integer, Edge> internalEdgeMap	HashMap<Integer, Edge> globalEdgeMap
Vertex	int mID	int matchID
	int globalID	int mDemand
	boolean demandSet	
Link	int mID	int matchId
	int globalID	int mCapacity
	int mCost	boolean isDirected
	boolean capacitySet	Pair<Vertex> endpoints