



UNIVERSITY OF
CAMBRIDGE

Exactly solving TSP using the Simplex algorithm

Petar Veličković, Thomas Sauerwald

CST Part II
ADVANCED ALGORITHMS

13 May 2016

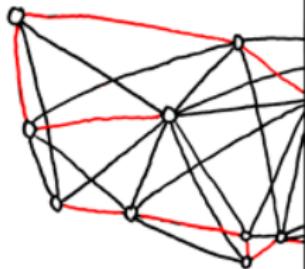
TSP

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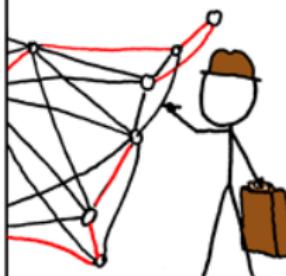
Dynamic programming approach

Travelling Salesman Problem (<http://xkcd.com/399/>)

BRUTE-FORCE
SOLUTION:
 $O(n!)$



DYNAMIC
PROGRAMMING
ALGORITHMS:
 $O(n^2 2^n)$



SELLING ON EBAY:
 $O(1)$

STILL WORKING
ON YOUR ROUTE?

SHUT THE
HELL UP.



Aside: Held-Karp algorithm

- ▶ Dynamic programming approach; *main idea*: solve the slightly simpler problem of the shortest *path* visiting all nodes, then route the end to the beginning.
- ▶ Assume wlog that the path starts from node 1. Maintain the solution $dp(x, S)$ as the shortest path length starting from 1, visiting all nodes in S , and ending in x .
- ▶ Base case: $dp(1, \{1\}) = 0$.
- ▶ Recurrence relation:

$$dp(x, S) = \begin{cases} \min_{y \in S} dp(y, S \setminus \{x\}) + c_{yx} & x \in S \wedge 1 \in S \\ +\infty & \text{otherwise} \end{cases}$$

Aside: Held-Karp algorithm

- ▶ Finally, $dp(x, V)$ will give the shortest path visiting all nodes, starting in 1 and ending in x .
- ▶ Now the optimal TSP length is simply:

$$\min_{x \in V} dp(x, V) + c_{x1}$$

The cycle itself can be extracted by backtracking.

- ▶ The set S can be efficiently maintained as an n -bit number, with the i th bit indicating whether or not the i th node is in S .
- ▶ Complexity: $O(n^2 2^n)$ time, $O(n 2^n)$ space.

LP formulation

- ▶ We will be using *indicator variables* x_{ij} , which should be set to 1 if the edge $i \rightarrow j$ is included in the optimal cycle, and 0 otherwise.
- ▶ An adequate linear program is as follows:

$$\begin{aligned}
 & \text{minimise} && \sum_{i=1}^n \sum_{j=1}^{i-1} c_{ij} x_{ij} \\
 & \text{subject to} \\
 & \forall i. 1 \leq i \leq n && \sum_{j < i} x_{ij} + \sum_{j > i} x_{ji} = 2 \\
 & \forall i, j. 1 \leq j < i \leq n && x_{ij} \leq 1 \\
 & \forall i, j. 1 \leq j < i \leq n && x_{ij} \geq 0
 \end{aligned}$$

- ▶ This is *intentionally* an incompletely specified problem:
 - ▶ We allow for *subcycles* in the returned path.
 - ▶ We allow for “partially used edges” ($0 < x_{ij} < 1$).

LP solution

- ▶ If the Simplex algorithm finds a correct cycle (with no subcycles or partially used edges) on the underspecified LP instance, then we have successfully solved the problem!
- ▶ Otherwise, we need to resort to further specifying the problem by adding additional constraints (manually or automatically).

Further constraints: subcycles

- ▶ If the returned solution contains a subcycle, we may eliminate it by adding an explicit constraint against it, and then attempt solving the LP again.
- ▶ For a subcycle containing nodes from a set $S \subset V$, we may demand at least two edges between S and $V \setminus S$:

$$\sum_{i \in S, j \in V \setminus S} x_{\max(i,j), \min(i,j)} \geq 2$$

- ▶ There are *exponentially many* such constraints in the fully specified problem! However, we often don't need to add all the constraints in order to reach a valid solution.

Further constraints: partially used edges

- ▶ If the returned solution contains a partially used edge, we may attempt a *branch&bound* strategy on it.
- ▶ For a partially used edge $a \rightarrow b$, we initially add a constraint $x_{ab} = 1$, and continue solving the LP.
- ▶ Once a valid solution has been found, we remove all the constraints added since then, add a new constraint $x_{ab} = 0$, and solve the LP again.
- ▶ We may stop searching a branch if we reach a worse objective value than the best valid solution found so far.
- ▶ The optimal solution is the better out of the two obtained solutions! If we choose the edges wisely, we may often obtain a valid solution in a complexity much better than exponential.

Demo: abstract

SOLUTION OF A LARGE-SCALE TRAVELING-SALESMAN PROBLEM*

G. DANTZIG, R. FULKERSON, AND S. JOHNSON

The Rand Corporation, Santa Monica, California

(Received August 9, 1954)

It is shown that a certain tour of 49 cities, one in each of the 48 states and Washington, D. C., has the shortest road distance.

THE TRAVELING-SALESMAN PROBLEM might be described as follows: Find the shortest route (tour) for a salesman starting from a given city, visiting each of a specified group of cities, and then returning to the original point of departure. More generally, given an n by n symmetric matrix $D = (d_{IJ})$, where d_{IJ} represents the 'distance' from I to J , arrange the points in a cyclic order in such a way that the sum of the d_{IJ} between consecutive points is minimal. Since there are only a finite number of possibilities (at most $\frac{1}{2} (n-1)!$) to consider, the problem is to devise a method of picking out the optimal arrangement which is reasonably efficient for fairly large values of n . Although algorithms have been devised for problems of similar nature, e.g., the optimal assignment problem,^{3,7,8} little is known about the traveling-salesman problem. We do not claim that this note alters the situation very much; what we shall do is outline a way of approaching the problem that sometimes, at least, enables one to find an optimal path and prove it so. In particular, it will be shown that a certain arrangement of 49 cities, one in each of the 48 states and Washington, D. C., is best, the d_{IJ} used representing road distances as taken from an atlas.

Demo: nodes

Now we will make advantage of these techniques to solve the TSP problem for 42 cities in the USA—using the *Held-Karp* algorithm would require ~ 4 hours (and unreasonable amounts of memory)!

- | | | |
|--------------------------|--------------------------|------------------------|
| 1. Manchester, N. H. | 18. Carson City, Nev. | 34. Birmingham, Ala. |
| 2. Montpelier, Vt. | 19. Los Angeles, Calif. | 35. Atlanta, Ga. |
| 3. Detroit, Mich. | 20. Phoenix, Ariz. | 36. Jacksonville, Fla. |
| 4. Cleveland, Ohio | 21. Santa Fe, N. M. | 37. Columbia, S. C. |
| 5. Charleston, W. Va. | 22. Denver, Colo. | 38. Raleigh, N. C. |
| 6. Louisville, Ky. | 23. Cheyenne, Wyo. | 39. Richmond, Va. |
| 7. Indianapolis, Ind. | 24. Omaha, Neb. | 40. Washington, D. C. |
| 8. Chicago, Ill. | 25. Des Moines, Iowa | 41. Boston, Mass. |
| 9. Milwaukee, Wis. | 26. Kansas City, Mo. | 42. Portland, Me. |
| 10. Minneapolis, Minn. | 27. Topeka, Kans. | A. Baltimore, Md. |
| 11. Pierre, S. D. | 28. Oklahoma City, Okla. | B. Wilmington, Del. |
| 12. Bismarck, N. D. | 29. Dallas, Tex. | C. Philadelphia, Penn. |
| 13. Helena, Mont. | 30. Little Rock, Ark. | D. Newark, N. J. |
| 14. Seattle, Wash. | 31. Memphis, Tenn. | E. New York, N. Y. |
| 15. Portland, Ore. | 32. Jackson, Miss. | F. Hartford, Conn. |
| 16. Boise, Idaho | 33. New Orleans, La. | G. Providence, R. I. |
| 17. Salt Lake City, Utah | | |

Demo: adjacency matrix

TABLE I

ROAD DISTANCES BETWEEN CITIES IN ADJUSTED UNITS

The figures in the table are mileages between the two specified numbered cities, less 11, divided by 17, and rounded to the nearest integer.

| | | TABLE I | | ROAD DISTANCES BETWEEN CITIES IN ADJUSTED UNITS | |
|-----|-----|---------|-----|---|-----|
| 3 | 4 | 5 | 6 | 7 | 8 |
| 50 | 49 | 21 | 15 | | |
| 6 | 61 | 62 | 21 | 20 | 17 |
| 7 | 58 | 60 | 16 | 17 | 18 |
| 8 | 59 | 60 | 15 | 20 | 26 |
| 9 | 62 | 66 | 20 | 25 | 31 |
| 10 | 81 | 81 | 40 | 44 | 50 |
| | | | 41 | 35 | 24 |
| | | | 20 | | |
| 11 | 103 | 107 | 62 | 67 | 72 |
| | | | 63 | 57 | 46 |
| | | | 41 | 23 | |
| 12 | 108 | 117 | 66 | 71 | 77 |
| | | | 68 | 61 | 51 |
| | | | 46 | 26 | 11 |
| 13 | 145 | 149 | 104 | 108 | 114 |
| | | | 106 | 99 | 88 |
| | | | 84 | 63 | 49 |
| 14 | 181 | 185 | 140 | 144 | 150 |
| | | | 142 | 135 | 124 |
| | | | 120 | 99 | 85 |
| 15 | 187 | 191 | 146 | 150 | 156 |
| | | | 142 | 137 | 130 |
| | | | 125 | 105 | 90 |
| 16 | 161 | 170 | 120 | 124 | 130 |
| | | | 115 | 110 | 104 |
| | | | 105 | 90 | 72 |
| 17 | 142 | 146 | 101 | 104 | 111 |
| | | | 117 | 97 | 91 |
| | | | 85 | 86 | 75 |
| 18 | 174 | 178 | 133 | 138 | 143 |
| | | | 129 | 123 | 117 |
| | | | 118 | 107 | 83 |
| 19 | 183 | 186 | 142 | 143 | 140 |
| | | | 130 | 126 | 124 |
| | | | 128 | 118 | 98 |
| 20 | 164 | 165 | 120 | 123 | 124 |
| | | | 126 | 106 | 105 |
| | | | 110 | 103 | 102 |
| 21 | 137 | 139 | 94 | 96 | 94 |
| | | | 80 | 78 | 77 |
| | | | 84 | 77 | 56 |
| 22 | 64 | 65 | 60 | 60 | 59 |
| | | | 90 | 87 | 87 |
| | | | 88 | 76 | 68 |
| 23 | 58 | 62 | 61 | 59 | 54 |
| | | | 34 | 42 | 49 |
| | | | 49 | 82 | 77 |
| 24 | 60 | 63 | 59 | 57 | 59 |
| | | | 48 | 28 | 36 |
| | | | 43 | 77 | 72 |
| 25 | 45 | 48 | 53 | 41 | 34 |
| | | | 34 | 28 | 29 |
| | | | 23 | 23 | 23 |
| 26 | 35 | 36 | 35 | 36 | 35 |
| | | | 35 | 69 | 105 |
| | | | 102 | 74 | 56 |
| 27 | 77 | 80 | 36 | 40 | 46 |
| | | | 34 | 27 | 19 |
| | | | 21 | 14 | 29 |
| 28 | 47 | 77 | 114 | 111 | 84 |
| | | | 84 | 64 | 107 |
| | | | 87 | 77 | 60 |
| 29 | 36 | 37 | 36 | 37 | 8 |
| 30 | 87 | 89 | 44 | 46 | 46 |
| | | | 30 | 28 | 29 |
| | | | 22 | 32 | 37 |
| 31 | 46 | 47 | 32 | 33 | 46 |
| | | | 36 | 47 | 47 |
| | | | 47 | 78 | 116 |
| 32 | 110 | 115 | 110 | 110 | 112 |
| | | | 83 | 63 | 97 |
| | | | 91 | 72 | 44 |
| 33 | 115 | 116 | 115 | 115 | 115 |
| | | | 88 | 66 | 98 |
| | | | 79 | 59 | 31 |
| 34 | 119 | 119 | 115 | 115 | 115 |
| | | | 88 | 79 | 55 |
| | | | 55 | 36 | 27 |
| 35 | 126 | 126 | 126 | 126 | 126 |
| | | | 98 | 98 | 85 |
| | | | 82 | 38 | 47 |
| 36 | 121 | 121 | 121 | 121 | 121 |
| | | | 73 | 58 | 42 |
| | | | 42 | 38 | 42 |
| 37 | 126 | 126 | 126 | 126 | 126 |
| | | | 98 | 98 | 99 |
| | | | 99 | 81 | 53 |
| 38 | 129 | 130 | 129 | 129 | 129 |
| | | | 109 | 115 | 99 |
| | | | 99 | 81 | 61 |
| 39 | 131 | 131 | 141 | 136 | 109 |
| | | | 109 | 115 | 99 |
| | | | 99 | 81 | 62 |
| 40 | 126 | 126 | 126 | 126 | 126 |
| | | | 126 | 126 | 126 |
| | | | 126 | 126 | 126 |
| 41 | 134 | 134 | 134 | 134 | 134 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 42 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 43 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 44 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 45 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 46 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 47 | 146 | 146 | 134 | 134 | 111 |
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| 48 | 146 | 146 | 134 | 134 | 111 |
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| 49 | 146 | 146 | 134 | 134 | 111 |
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| 50 | 146 | 146 | 134 | 134 | 111 |
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| 51 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 52 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 53 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 54 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 56 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
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| 57 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 58 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 59 | 146 | 146 | 134 | 134 | 111 |
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| | | | 86 | 59 | 52 |
| 60 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 61 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 62 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 63 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 64 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 65 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 66 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 67 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 68 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 69 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 70 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 71 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 72 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 73 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 74 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 75 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 76 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 77 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 78 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 79 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 80 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 81 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 82 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 83 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 84 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 85 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 86 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 87 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 88 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 89 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 90 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 91 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 92 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 93 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 94 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 95 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 96 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 97 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 98 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 99 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 100 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 101 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 102 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 86 | 59 | 52 |
| 103 | 146 | 146 | 134 | 134 | 111 |
| | | | 111 | 85 | 84 |
| | | | 8 | | |

Demo: final solution

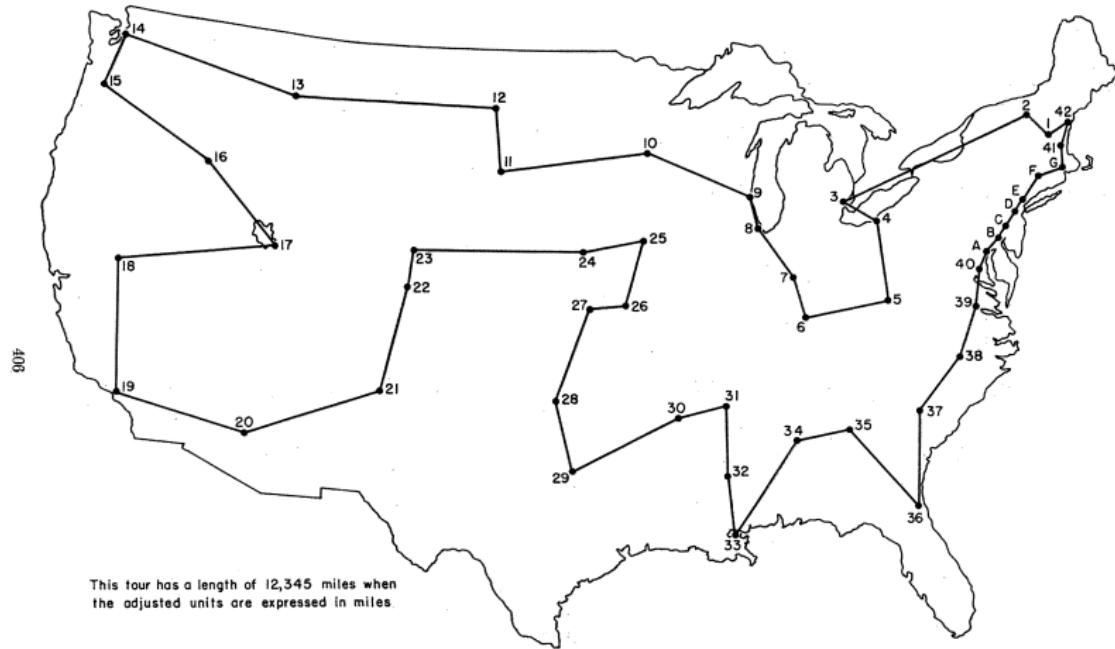


FIG. 16. The optimal tour of 49 cities.

Demo: materials

- ▶ The full implementation of this TSP solver in C++ (along with all the necessary files to perform this demo) may be found at:
<https://github.com/PetarV-/Simplex-TSP-Solver>
- ▶ Methods similar to these have been successfully applied for solving far larger TSP instances...

TSP

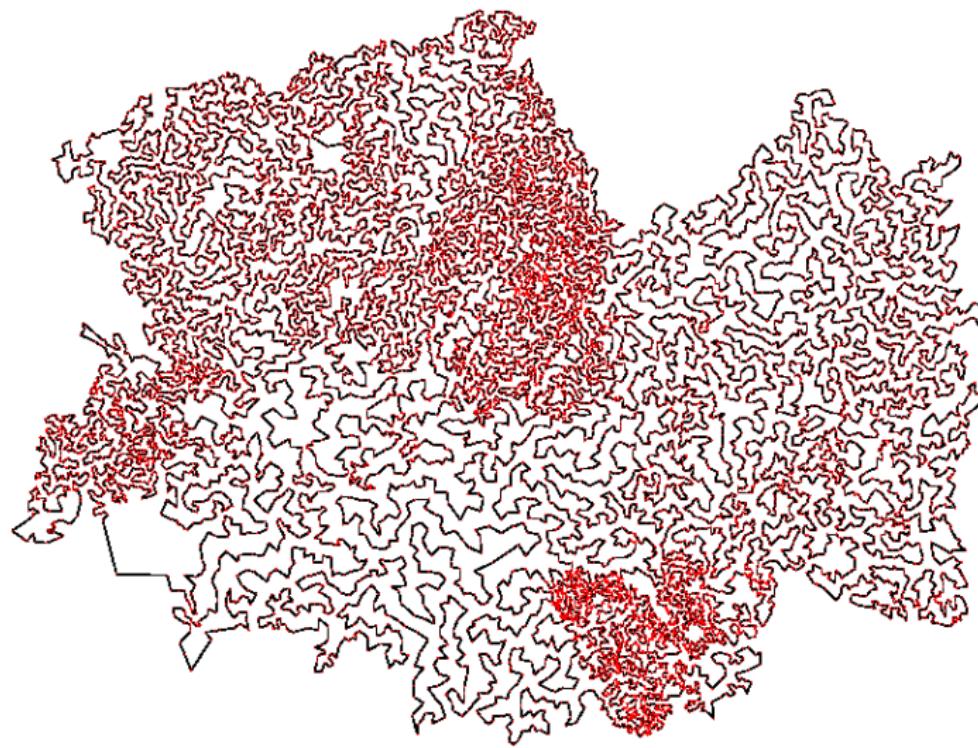
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Demonstration

13,509 largest towns in the US



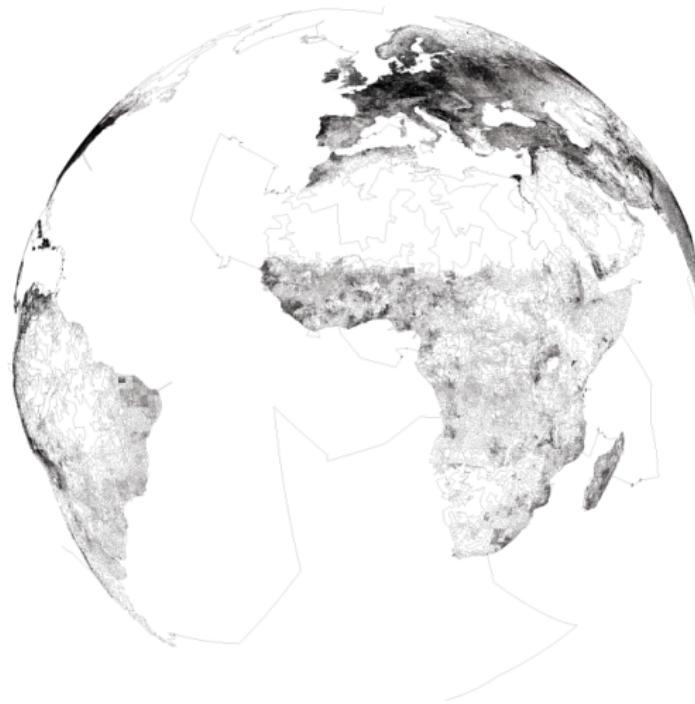
15,112 largest towns in Germany



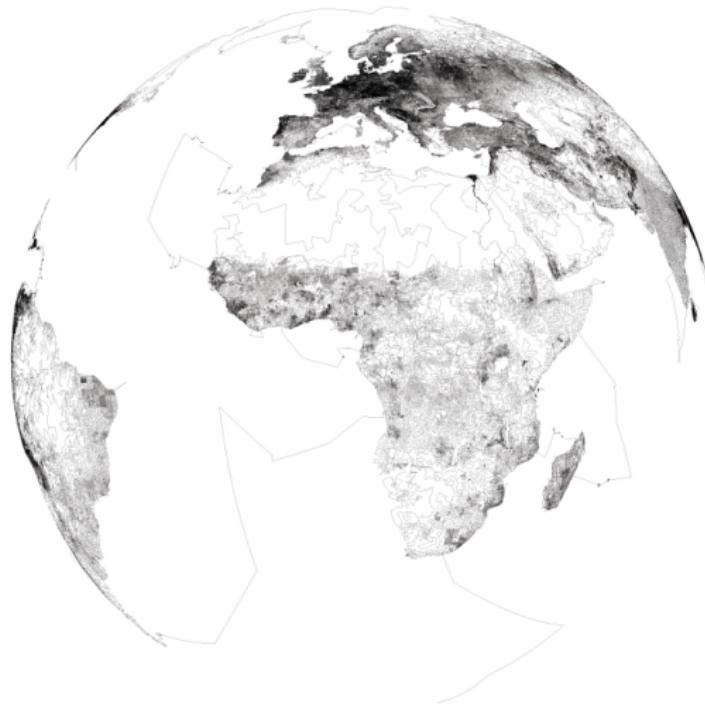
All 24,978 populated places in Sweden



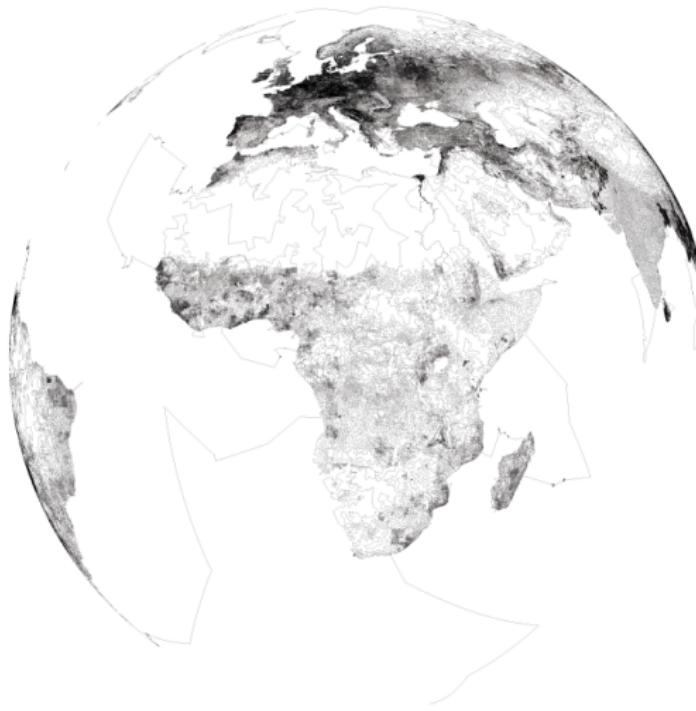
World TSP – 1,904,711 places, error $\leq 0.05\%$



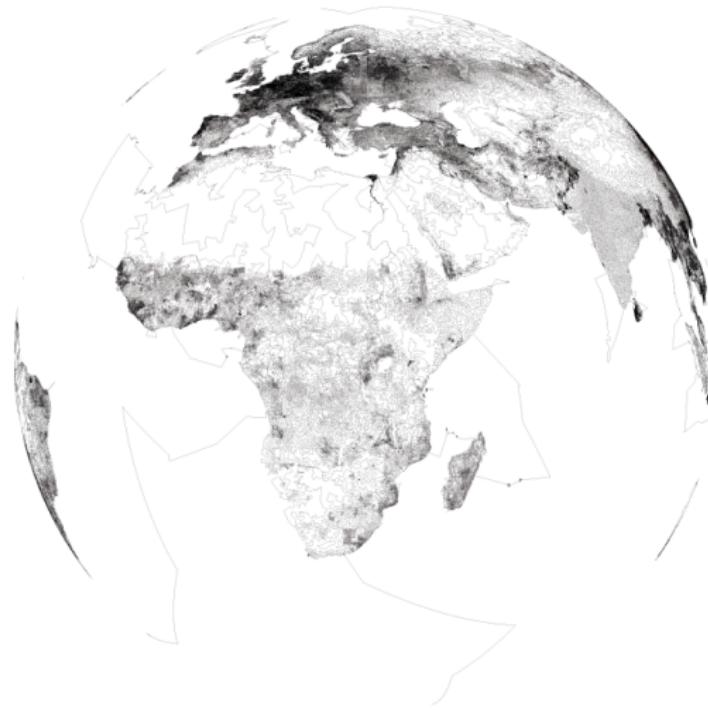
World TSP – 1,904,711 places, error $\leq 0.05\%$



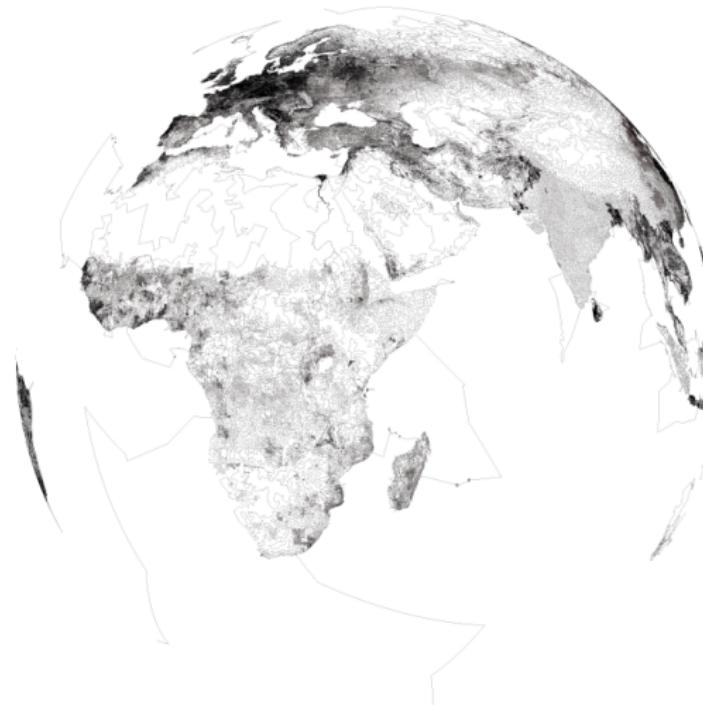
World TSP – 1,904,711 places, error $\leq 0.05\%$



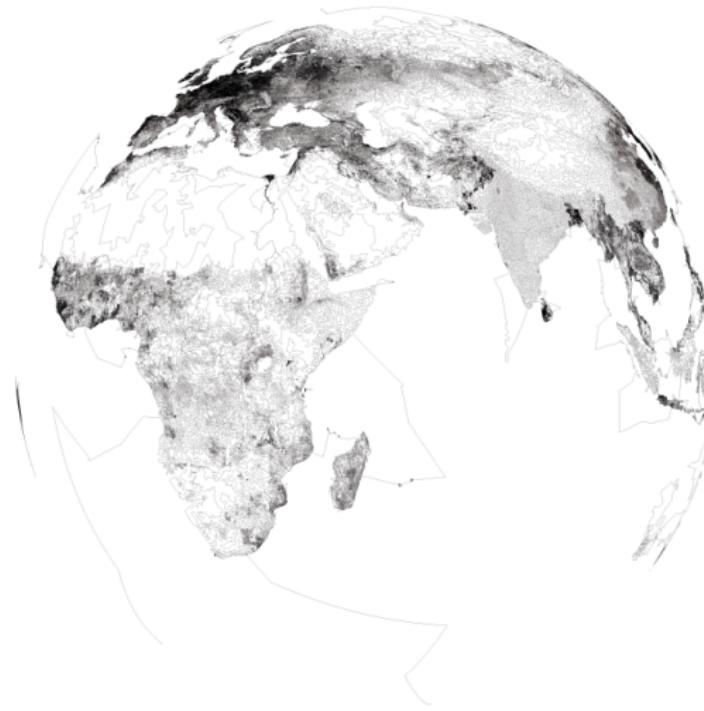
World TSP – 1,904,711 places, error $\leq 0.05\%$



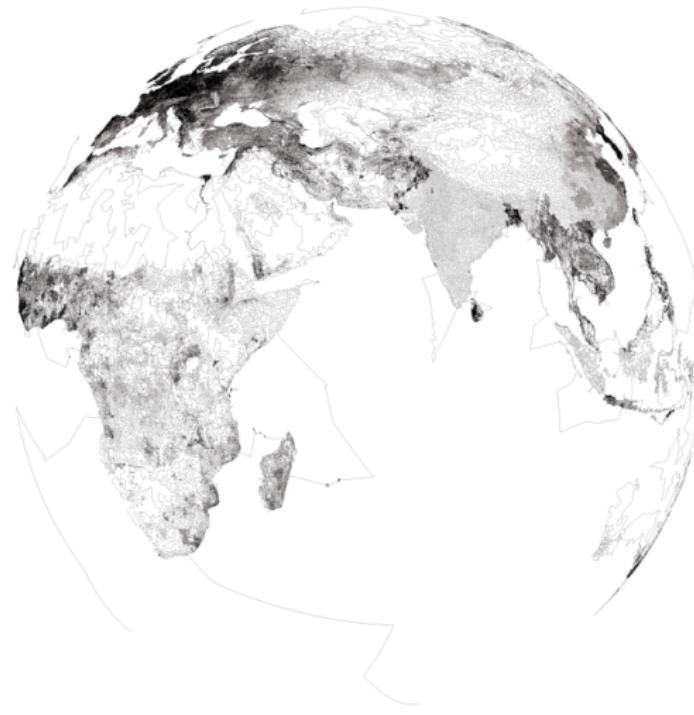
World TSP – 1,904,711 places, error $\leq 0.05\%$



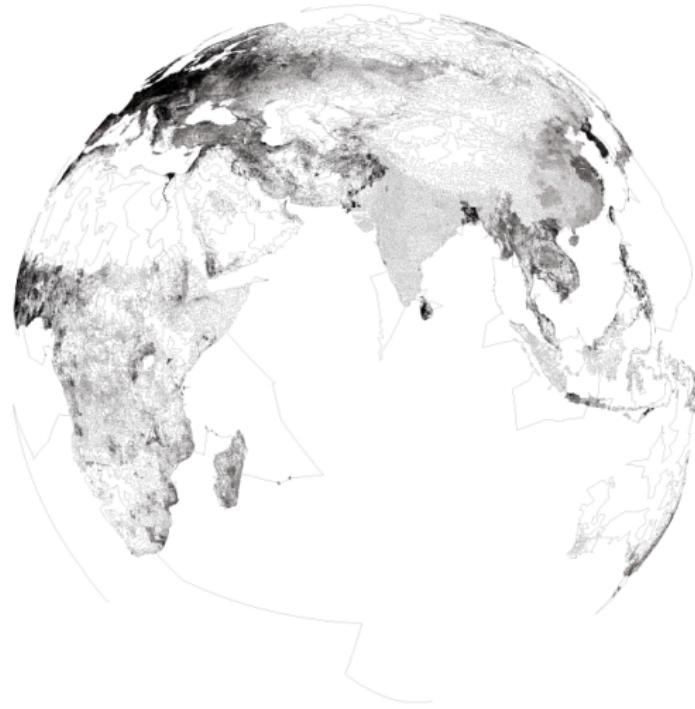
World TSP – 1,904,711 places, error $\leq 0.05\%$



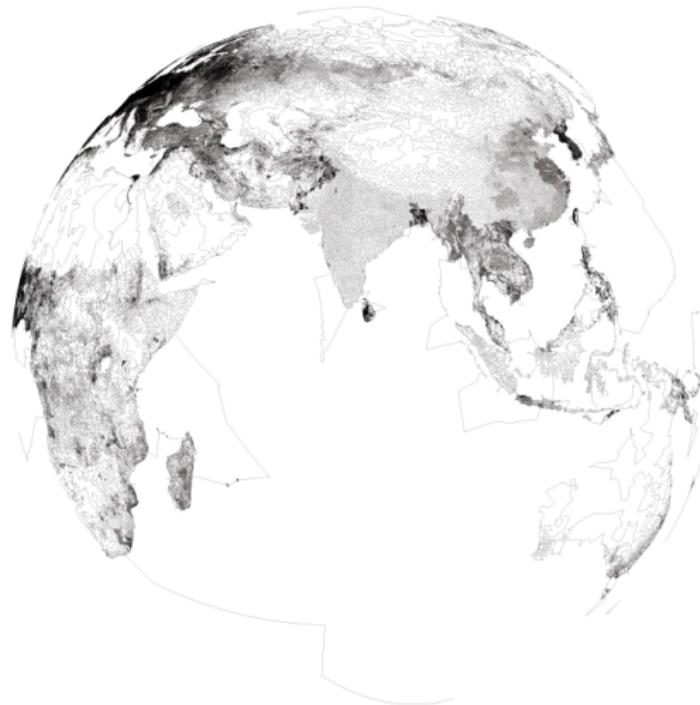
World TSP – 1,904,711 places, error $\leq 0.05\%$



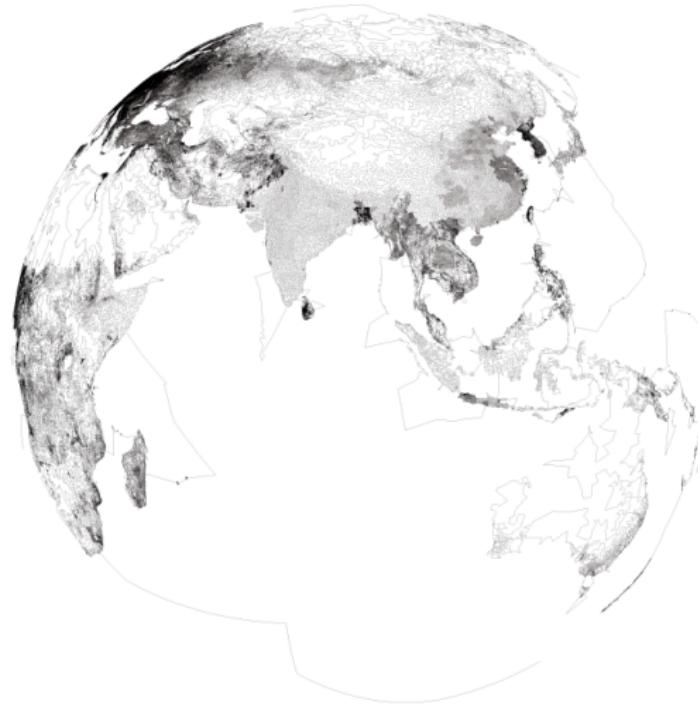
World TSP – 1,904,711 places, error $\leq 0.05\%$



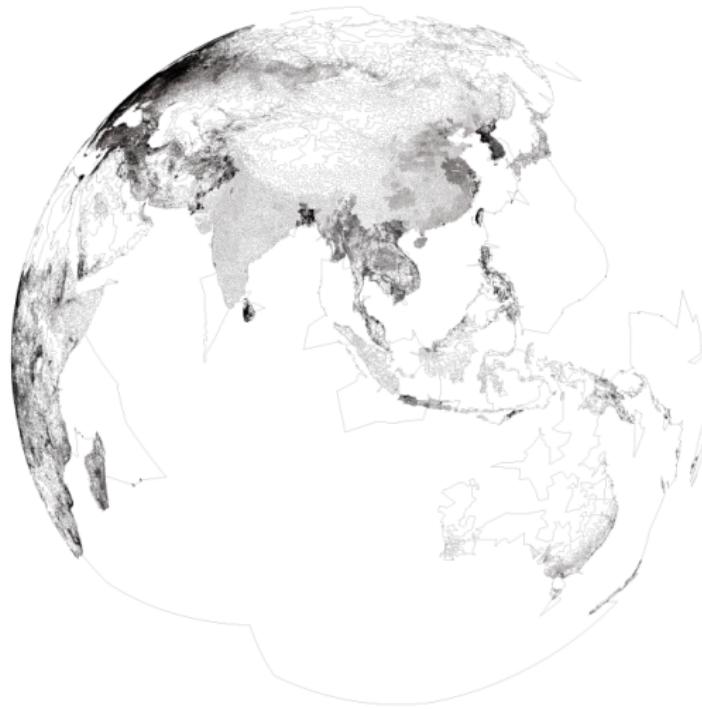
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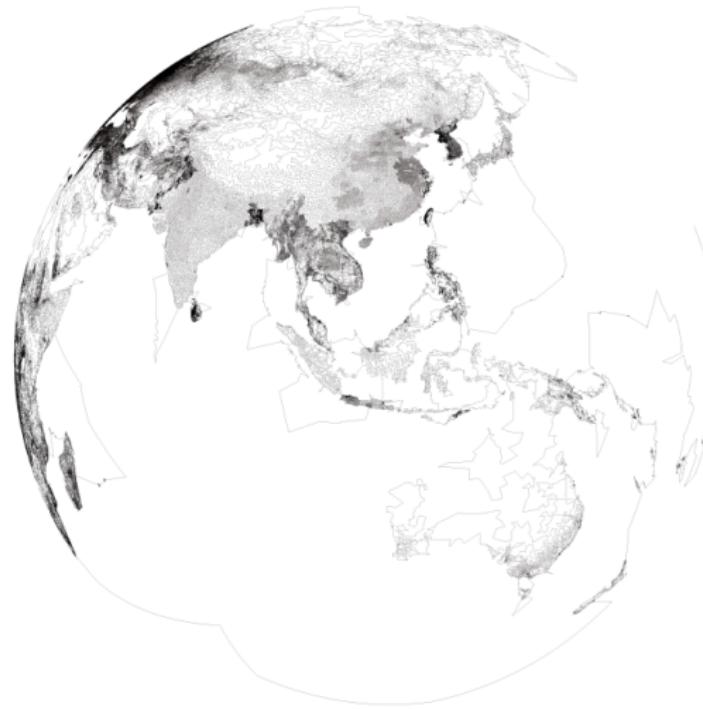
World TSP – 1,904,711 places, error $\leq 0.05\%$



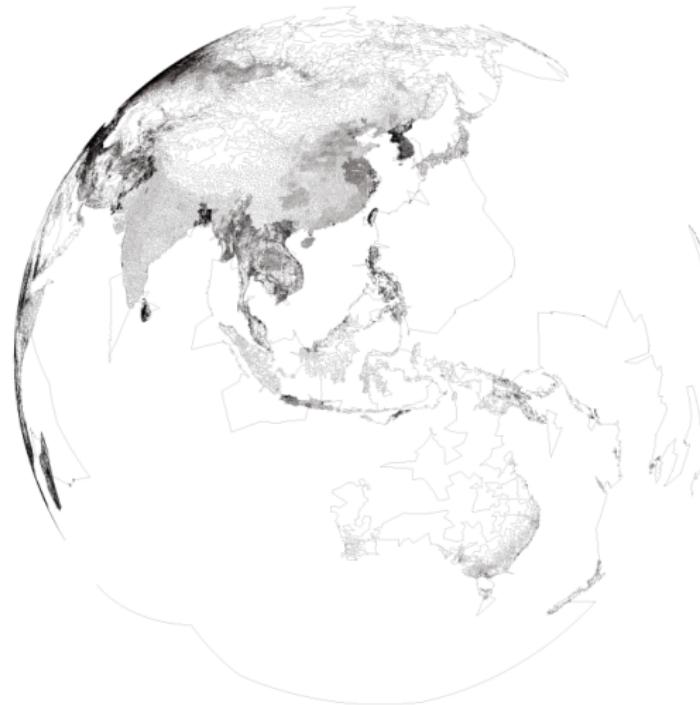
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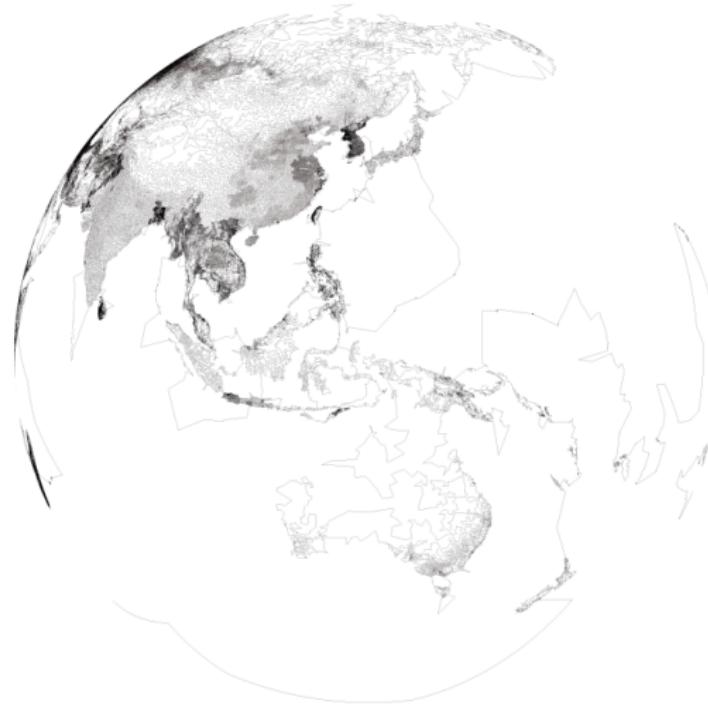
World TSP – 1,904,711 places, error $\leq 0.05\%$



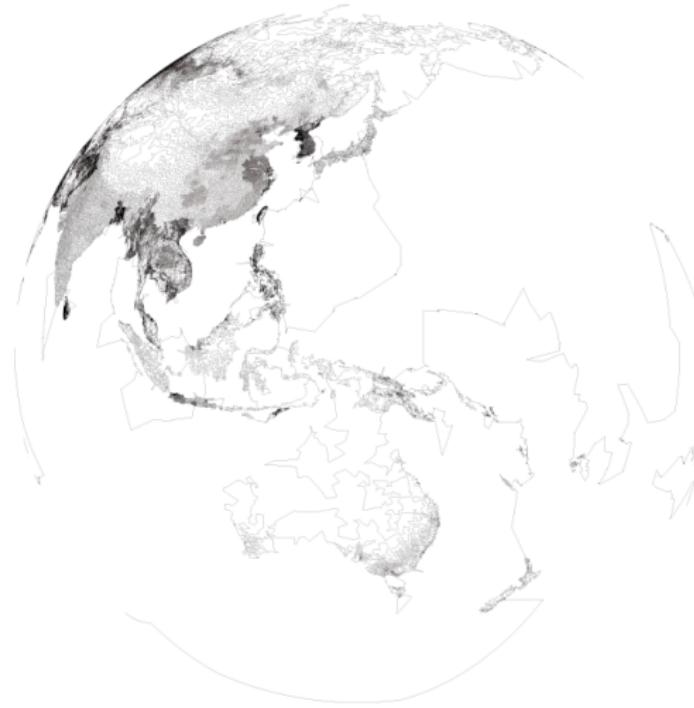
World TSP – 1,904,711 places, error $\leq 0.05\%$



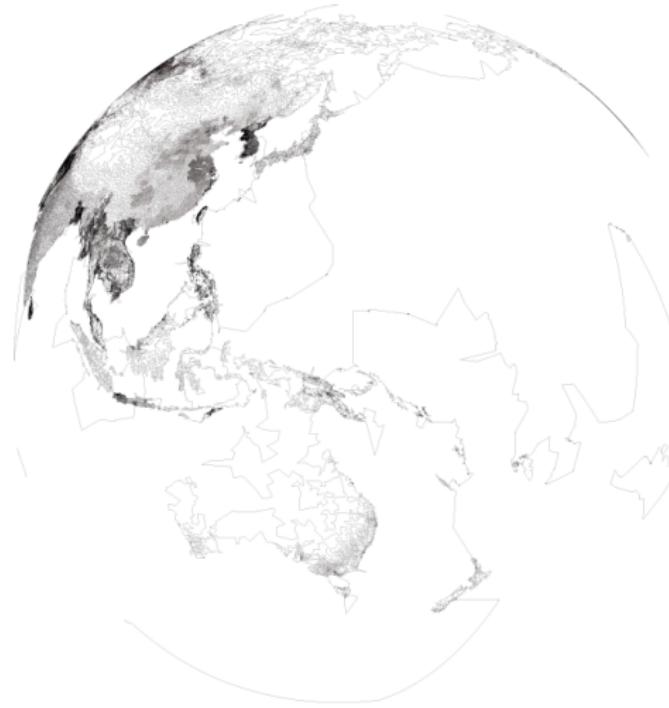
World TSP – 1,904,711 places, error $\leq 0.05\%$



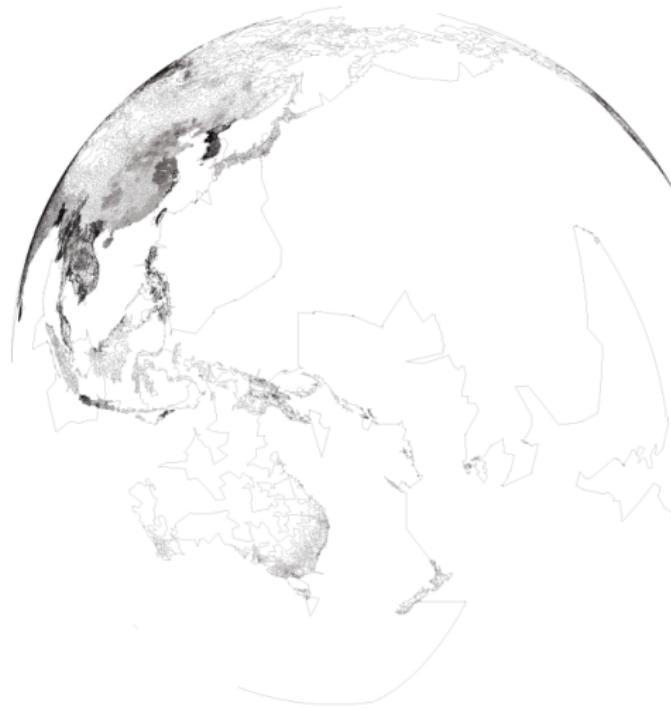
World TSP – 1,904,711 places, error $\leq 0.05\%$



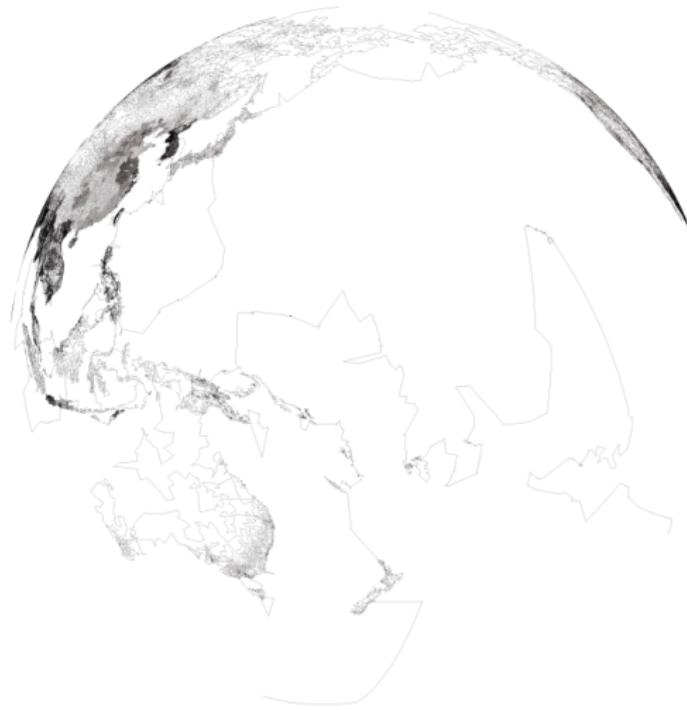
World TSP – 1,904,711 places, error $\leq 0.05\%$



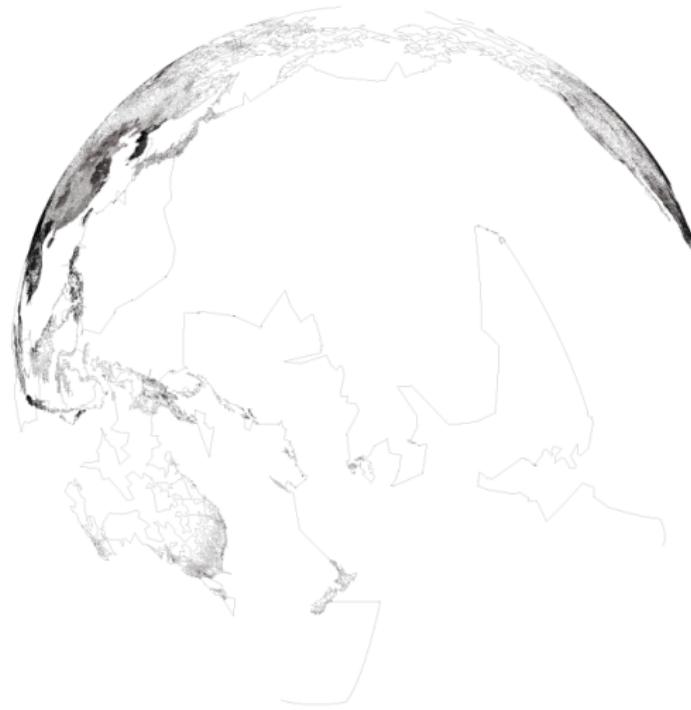
World TSP – 1,904,711 places, error $\leq 0.05\%$



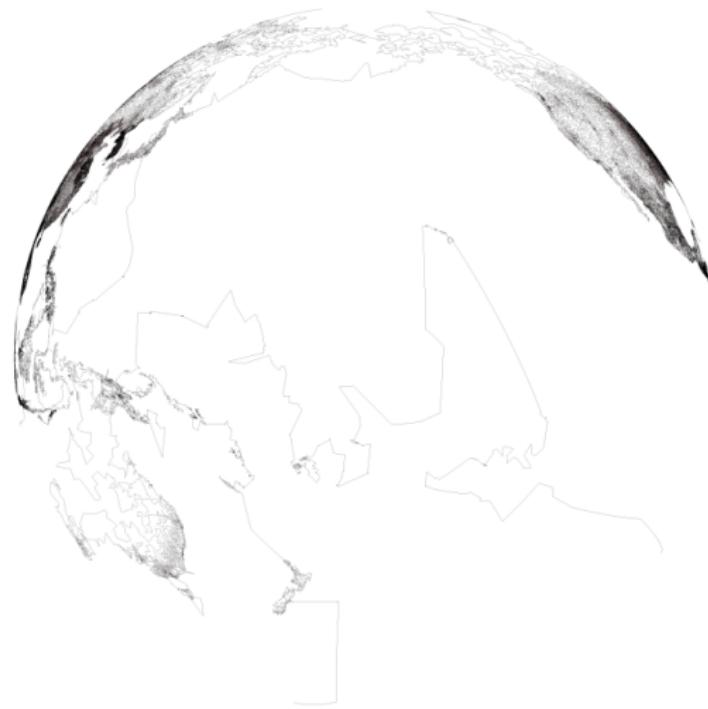
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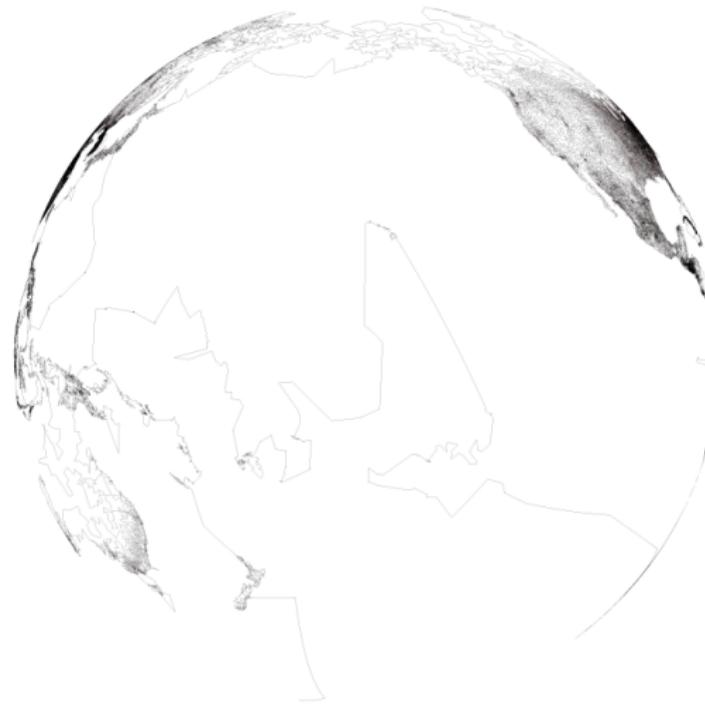
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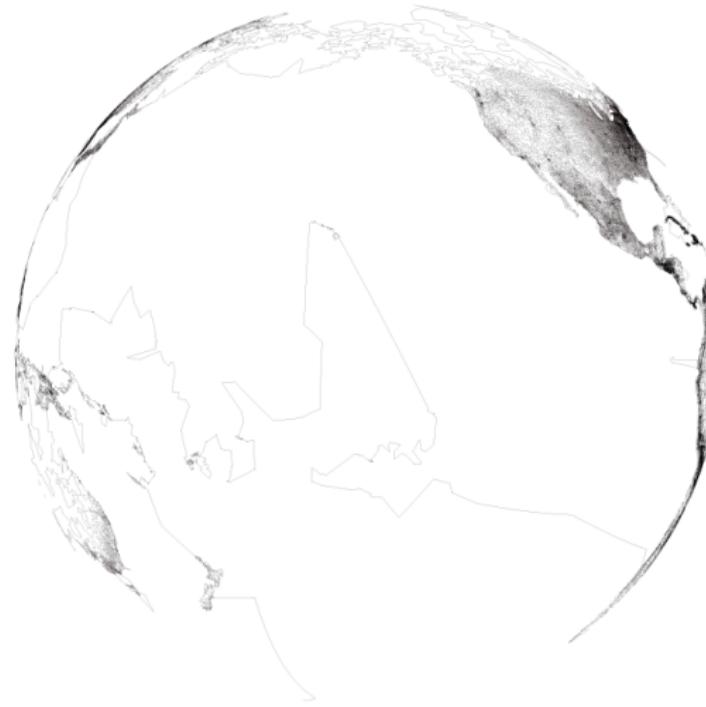
World TSP – 1,904,711 places, error $\leq 0.05\%$



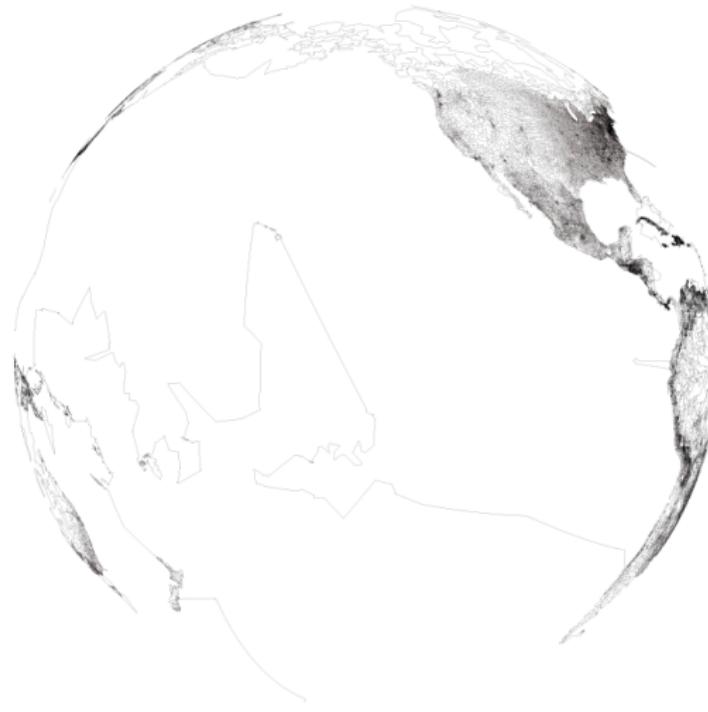
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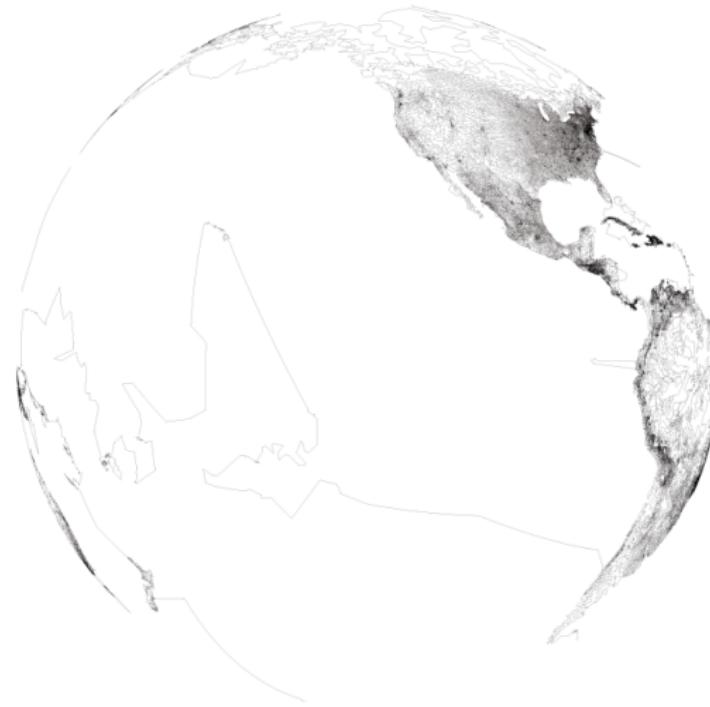
World TSP – 1,904,711 places, error $\leq 0.05\%$



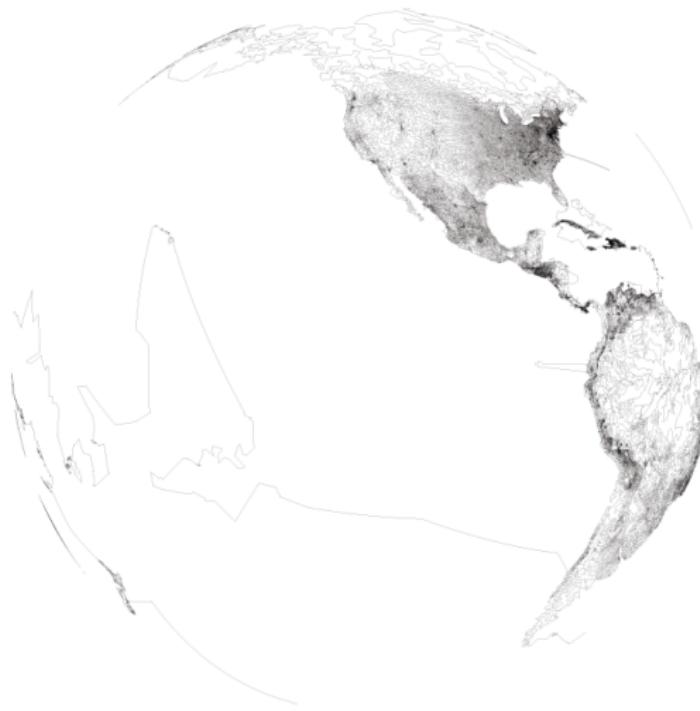
World TSP – 1,904,711 places, error $\leq 0.05\%$



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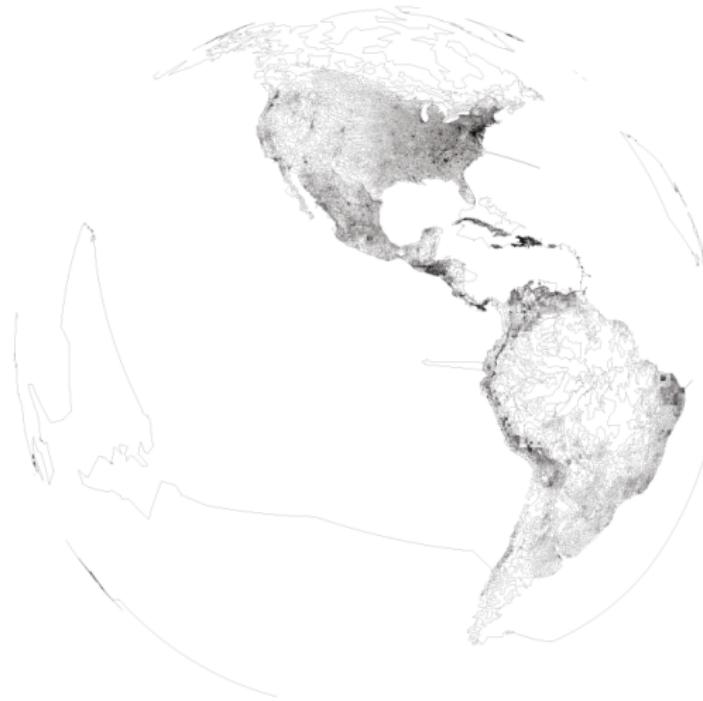
World TSP – 1,904,711 places, error $\leq 0.05\%$



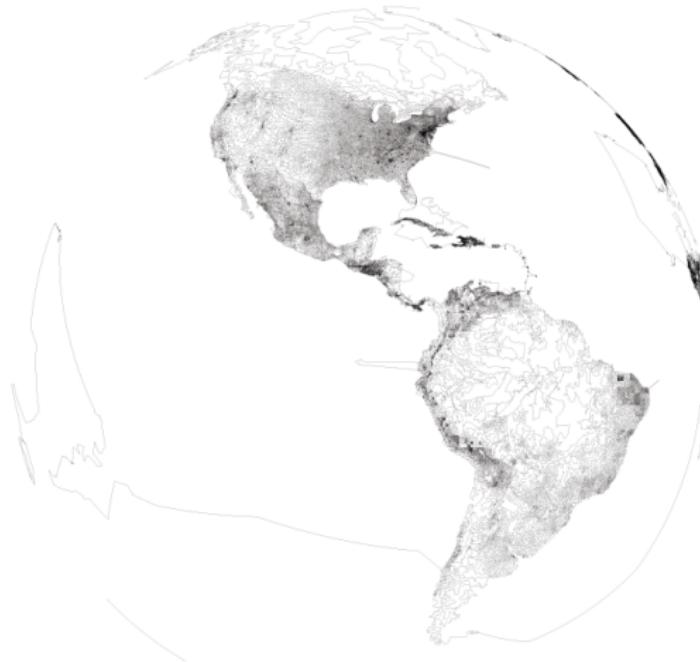
World TSP – 1,904,711 places, error $\leq 0.05\%$



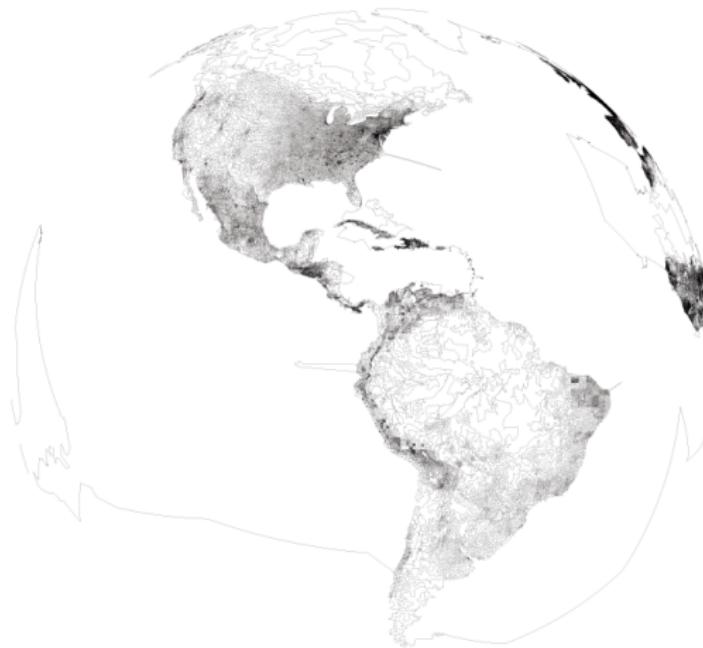
World TSP – 1,904,711 places, error $\leq 0.05\%$



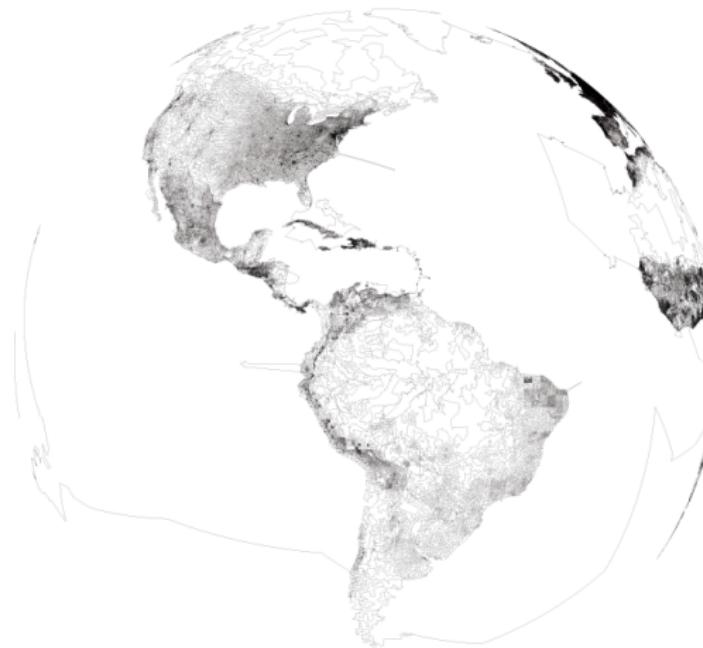
World TSP – 1,904,711 places, error $\leq 0.05\%$



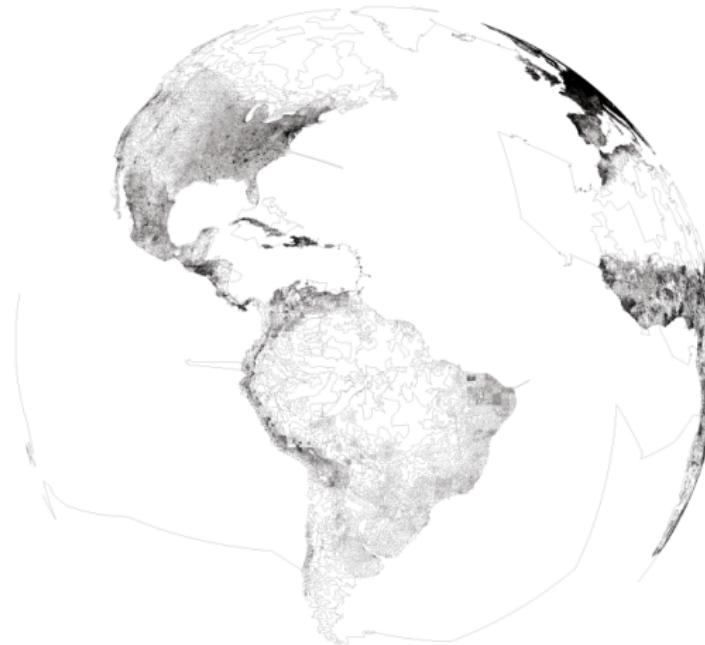
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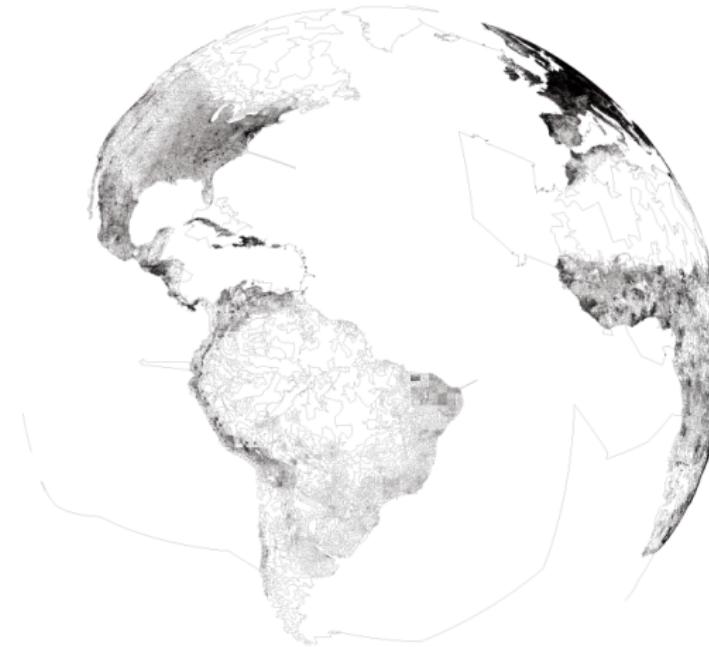
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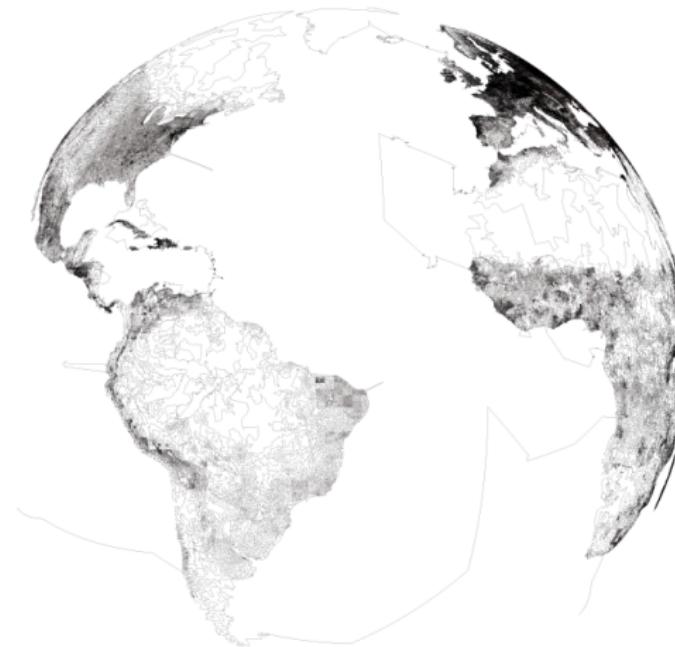
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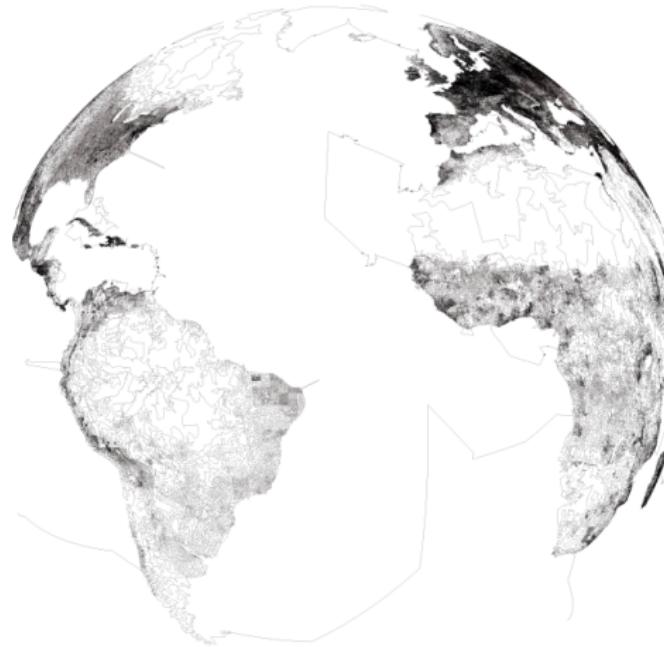
World TSP – 1,904,711 places, error $\leq 0.05\%$



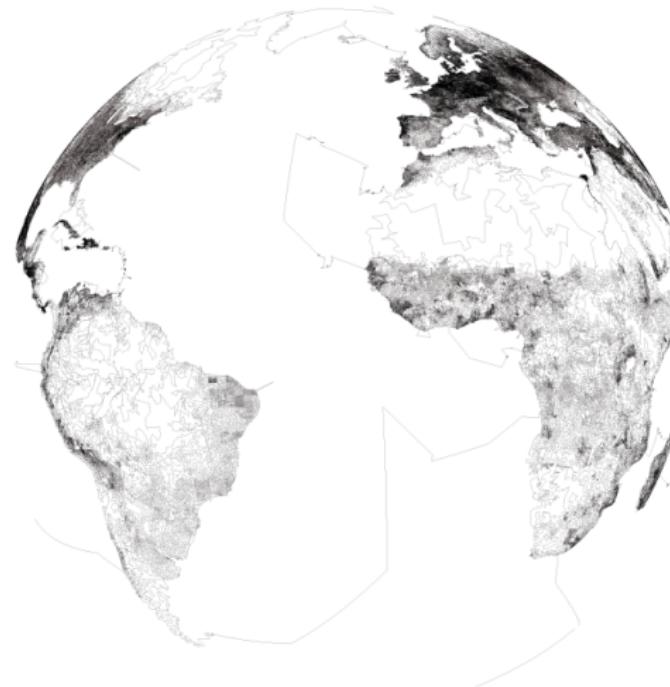
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