

# The Travelling Salesman Problem

The Ultimate Route Planning Challenge - When Efficiency Meets Real World!

CS 101 - Fall 2025

## What is the Travelling Salesman Problem?

### The Ultimate Route Challenge

**The Problem:** A salesperson needs to visit every city exactly once and return home, using the **shortest possible route**.

**Real-World Analogy:** \* Like a **delivery driver** planning the most efficient route \* **GPS apps** finding the fastest path through multiple stops \* **Amazon trucks** optimizing deliveries to save time and fuel \* **Tour guides** planning the best sightseeing route

## Why It Matters

- **Delivery Services:** UPS saves millions by optimizing routes
- **Circuit Board Manufacturing:** Drilling holes efficiently
- **DNA Sequencing:** Finding optimal gene arrangements
- **School Bus Routes:** Getting kids to school faster

## The Challenge

- Seems simple with 3-4 cities
- Gets **impossibly hard** very quickly
- With just 10 cities: **3,628,800** possible routes!
- With 20 cities: More routes than atoms in the universe!

**Key Question:** *“How do we find the best route without checking every possibility?”*

## Interactive TSP Demo: Plan Your Route!

### The Mathematics Behind The Factorial Explosion!

**i** For  $n$  cities, there are  $(n-1)!/2$  unique routes to check Why? We fix the starting city and divide by 2 since routes can go clockwise or counterclockwise.

#### Route Count Growth

```
def calculate_routes(n_cities):
    """Calculate number of TSP routes"""
    if n_cities <= 1:
        return 0

    # (n-1)! / 2 unique routes
    factorial = 1
    for i in range(1, n_cities):
        factorial *= i

    return factorial // 2

# Let's see the explosion!
for cities in range(2, 11):
    routes = calculate_routes(cities)
    print(f"{cities} cities: {routes:,} routes")
```

#### Real Numbers:

- 3 cities  $\rightarrow$  1 route, 4 cities  $\rightarrow$  3 routes
- 5 cities  $\rightarrow$  12 routes, 10 cities  $\rightarrow$  181,440 routes
- 15 cities  $\rightarrow$  43,589,145,600 routes!

#### The Pattern:

- Each new city **multiplies** the complexity
- Not addition - **factorial growth!**
- This is why TSP is so challenging
- Real-world problems have 100+ cities!

## Time Complexity: When Mathematics Meets Reality

The Scary Truth About Computation Time

Even with the world's fastest computers, brute force TSP becomes impossible very quickly!

### Time Complexity Analysis

```
import time
import math

def time_estimate(n_cities):
    """Estimate computation time for brute force TSP"""
    routes = math.factorial(n_cities - 1) // 2

    # Assume 1 million routes per second
    seconds = routes / 1_000_000

    if seconds < 60:
        return f"{seconds:.2f} seconds"
    elif seconds < 3600:
        return f"{seconds/60:.2f} minutes"
    elif seconds < 86400:
        return f"{seconds/3600:.2f} hours"
    elif seconds < 31536000:
        return f"{seconds/86400:.2f} days"
    else:
        return f"{seconds/31536000:.2f} years"

# The scary truth
print("Time to solve TSP by brute force:")
for n in [10, 15, 20, 25]:
    print(f"{n} cities: {time_estimate(n)}")
```

### Reality Check

- 10 cities: 0.18 seconds
- 15 cities: 21.8 days
- 20 cities: 77 billion years
- 25 cities: Longer than universe exists!

### Why This Matters

- **UPS trucks** visit 100+ stops daily
- **Amazon deliveries** optimize thousands of routes
- **GPS systems** need real-time solutions
- Need **better algorithms** than brute force!

## Python Implementation: Brute Force Approach

 Warning: This Gets Slow Fast!

Our brute force solution checks every possible route. It works great for small examples, but becomes impossible for real-world problems.

### The Core Algorithm

```
def tsp_brute_force(cities, current_city=0,
                   visited=None, path=None):
    """
    Solve TSP by checking ALL possible routes
    Time Complexity: O(n!) - FACTORIAL!
    """
    # Initialize first call
    if visited is None:
        visited = {current_city}
        path = [current_city]

    # Base case: visited all cities, return home
    if len(visited) == len(cities):
        complete_path = path + [0] # Return to start
        total_distance = calculate_distance(complete_path)
        return complete_path, total_distance

    # Try every unvisited city next
    best_path = None
    best_distance = float('inf')

    for next_city in range(len(cities)):
        if next_city not in visited:
            # Recursive magic: solve for remaining cities
            new_path, distance = tsp_brute_force(
                cities, next_city,
                visited | {next_city},
```

```

        path + [next_city]
    )

    # Keep the best route found so far
    if distance < best_distance:
        best_distance = distance
        best_path = new_path

    return best_path, best_distance

```

## Distance Calculation

```

def calculate_distance(path):
    """Calculate total route distance"""
    # Example distance matrix for 4 cities
    distances = {
        (0, 1): 10, (1, 0): 10, # City 0 City 1
        (0, 2): 15, (2, 0): 15, # City 0 City 2
        (0, 3): 20, (3, 0): 20, # City 0 City 3
        (1, 2): 25, (2, 1): 25, # City 1 City 2
        (1, 3): 30, (3, 1): 30, # City 1 City 3
        (2, 3): 35, (3, 2): 35, # City 2 City 3
        # Distance to self is 0
        (0, 0): 0, (1, 1): 0, (2, 2): 0, (3, 3): 0
    }

    total = 0
    for i in range(len(path) - 1):
        current = path[i]
        next_city = path[i + 1]
        total += distances.get((current, next_city), 999)

    return total

# Real-world: use Euclidean distance
def euclidean_distance(city1, city2):
    """Calculate straight-line distance between cities"""
    x1, y1 = city1
    x2, y2 = city2
    return ((x2 - x1)**2 + (y2 - y1)**2)**0.5

```

## Build a Project From This Code?!

Left to the reader...

Copy these blocks into two files (`main.py`, `examples.py` and `tsp.py`) to run this larger demo from the command line.

**`tsp.py`**

```

def tsp_brute_force(cities, current_city=0,
                    visited=None, path=None):
    """
    Solve TSP by checking ALL possible routes
    Time Complexity: O(n!) - FACTORIAL!
    """
    # Initialize first call
    if visited is None:
        visited = {current_city}
        path = [current_city]

    # Base case: visited all cities, return home
    if len(visited) == len(cities):
        complete_path = path + [0] # Return to start
        total_distance = calculate_distance(complete_path)
        return complete_path, total_distance

    # Try every unvisited city next
    best_path = None
    best_distance = float('inf')

    for next_city in range(len(cities)):
        if next_city not in visited:
            # Recursive magic: solve for remaining cities
            new_path, distance = tsp_brute_force(
                cities, next_city,
                visited | {next_city},
                path + [next_city]
            )

            # Keep the best route found so far
            if distance < best_distance:
                best_distance = distance
                best_path = new_path

    return best_path, best_distance

def calculate_distance(path):
    """Calculate total route distance"""
    # Example distance matrix for 4 cities
    distances = {
        (0, 1): 10, (1, 0): 10, # City 0 City 1
        (0, 2): 15, (2, 0): 15, # City 0 City 2
        (0, 3): 20, (3, 0): 20, # City 0 City 3
        (1, 2): 25, (2, 1): 25, # City 1 City 2
        (1, 3): 30, (3, 1): 30, # City 1 City 3
        (2, 3): 35, (3, 2): 35, # City 2 City 3
        # Distance to self is 0
        (0, 0): 0, (1, 1): 0, (2, 2): 0, (3, 3): 0
    }

    total = 0
    for i in range(len(path) - 1):

```

examples.py





*main.py*



## Output

### Note

#### TSP Solver - Usage Example

=====

1 Using built-in distance matrix:

Input: [0, 1, 2, 3]

Best path: [0, 1, 2, 3, 0]

Distance: 90

Time: 0.0001s

2 Using custom city coordinates:

Coordinates: [(0, 0), (1, 3), (4, 1), (2, 4)]

Best path: [0, 1, 3, 2, 0]

Distance: 12.31

Time: 0.0001s

3 Performance for different city counts:

3 cities: 2 routes, 0.0000s

4 cities: 6 routes, 0.0000s

5 cities: 24 routes, 0.0001s

6 cities: 120 routes, 0.0007s

7 cities: 720 routes, 0.0041s

Solving a specific problem:

Visiting 5 offices in a city

Offices: ['HQ', 'Branch A', 'Branch B', 'Branch C', 'Branch D']

Best route: HQ → Branch B → Branch D → Branch A → Branch C → HQ

Total distance: 16.03 km

Solve time: 0.0001 seconds

Want more examples? Run 'python3 main.py' for interactive mode!

## TSP is Everywhere!

```

# Delivery route optimization
delivery_stops = [
    "Warehouse",      # Start/end point
    "123 Main St",    # Customer 1
    "456 Oak Ave",    # Customer 2
    "789 Pine Rd",    # Customer 3
    "321 Elm St"      # Customer 4
]

# TSP finds shortest route visiting all stops
optimal_route = tsp_solver(delivery_stops)
print(f"Optimal delivery route: {optimal_route}")

# Real impact:
# - UPS saves $50M+ annually with route optimization
# - FedEx reduces fuel consumption by 10%
# - Amazon uses TSP for same-day delivery

```

```

# Circuit board drilling optimization
drill_points = [
    (10, 20), # Hole 1 coordinates
    (30, 15), # Hole 2 coordinates
    (25, 35), # Hole 3 coordinates
    (40, 25)  # Hole 4 coordinates
]

# TSP minimizes drill head movement
optimal_drilling = tsp_solver(drill_points)
# Result: Faster manufacturing, less wear on equipment

```

## TSP Environmental Impacts: The Green Side of TSP

- 1. Positive Environmental Effects** - TSP optimization reduces fuel consumption and lowers emissions - Decreases overall traffic congestion - Minimizes unnecessary vehicle miles traveled
- 2. The Consumption Paradox** - Does efficient delivery encourage more online shopping? - Could TSP optimization actually *increase* total environmental impact? - Are we solving the right problem or enabling overconsumption?
- 3. Future Transportation Challenges** - How should TSP algorithms adapt for electric delivery vehicles? - What about charging station stops and battery range limits? - How do we optimize for renewable energy usage timing?

**i** Think: What is an Eco-Friendly TSP Design

**If you could design a TSP system, what factors besides distance would you optimize for?**

Consider these green factors: - Carbon footprint per route segment - Real-time traffic patterns to reduce idling - Air quality levels in different neighborhoods - Time-of-day energy grid efficiency

**Research Task:** Find one company using TSP for environmental benefits. What measurable impact have they achieved?

## Summary: TSP - The Beautiful Impossible Problem

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### And, Also Good to Know Too!

#### ! Important

##### Remember:

- Not all problems have efficient exact solutions
- Creativity beats raw computational power
- Real-world constraints matter more than textbook perfection
- Technology should serve people and planet

#### i Note

##### Questions to Explore:

- How do we know when a “good enough” solution is actually good enough?
- What happens when we combine multiple optimization techniques?
- How is AI changing the way we solve impossible problems?