# Approximation Algorithms

Many of the NP-Complete problems are most naturally expressed as optimization problems: TSP, Graph Coloring, Vertex Cover etc.

It is widely believed That $\mathbf{P} \neq \mathbf{NP}$ so that it is impossible to solve the problems in poly-momial time.

An *approximation algorithm* for solving an optimization problem corresponding to a decision problem in NP is an algorithm which in polynomial time finds an approximative solution which is guaranteed to be close to the optimal solution.

## Approximation of Vertex Cover

ApproxVertexCover($G = (V, E)$)

(1) $C \leftarrow \emptyset$

(2) **while** $E \neq \emptyset$

(3) Chose an arbitrary edge $(u, v) \in E$

(4) $C \leftarrow C \cup \{u\} \cup \{v\}$

(5) Remove all edges in $E$ which contains $u$ or $v$

(6) **return** $C$

The algorithm always returns a vertex cover. When an edge is removed both of its vertices are added to $C$.

Now consider the edge $(u, v)$. At least one of the vertices $u$ and $v$ must be in an optimal vertex cover.
$\Rightarrow$ The vertex cover returned by the algorithm cannot be more than twice the size of an optimal vertex cover.

Time-complexity: $O(|E|)$

## To measure approximability

*The Approximation Quotient* for an algorithm is

$$\max \frac{approx}{opt} \quad \text{for minimization problems}$$

$$\max \frac{opt}{approx} \quad \text{for maximization problems}$$

This means that the quotient is always $\geq 1$ with equality if the algorithm always returns the optimal solution.

In all other cases the quotient is a measure of how far from the optimal solution we can get in the worst case.

The algorithm for finding minimal vertex covers has approximation quotient 2 since it returns a vertex cover at most twice as large as the minimal one.

## Degrees of approximability

There is a difference between the NP-Complete problems regarding how hard they are to approximate:

- For some problems you can, for every $\epsilon > 0$, find a polynomial algorithm with approximation quotient $1 + \epsilon$.
  Ex.: The Knapsack Problem

- Other problems can be approximated within a constant $> 1$ but not arbitrarily close to 1 $\mathbf{P} \neq \mathbf{NP}$.
  Ex.: Vertex Cover

- Then the are problems that cannot be approximated within any constant if $\mathbf{P} \neq \mathbf{NP}$.
  Ex.: Maximal Clique

# Approximation of TSP

We show that TSP$\notin$ APX , i.e. TSP cannot be approximated. Assume, to reach a contradiction, that TSP can be approximated within a factor B.

Reduction from Hamiltonian Cycle:

Hamiltoncykel($G$)

$n \leftarrow |V|$<br>
**foreach** $(v_i, v_j) \in E$<br>
    $w(p_i, p_j) \leftarrow 1$<br>
**foreach** $(v_i, v_j) \notin E$<br>
    $w(p_i, p_j) \leftarrow |V|B$<br>
**if** TSAPPROX($p_i$,t) $\leq |V|B$<br>
    **return** TRUE<br>
**return** FALSE

If TSAPPROX can approximate TSP within factor B, then the algorithm decides in polynomial time if there is a Hamiltonian Cycle in $G$ or not. That is impossible!

## Approximation of TSP with the triangle inequality

This is a special case of TSP which can be approximated.

**The triangle inequality:** $w(i,j) \leq w(i,k) + w(k,j)$ for all nodes $i,j,k$.

The triangle inequality shows that if $i, j, k_1, k_2, ..., k_s$ form a cycle in the graph, we have $w(i,j) \leq w(i,k_s) + w(k_s, k_{s-1}) + ...w(k_1, j)$.

TSP with the triangle inequality is called $\Delta$ TSP.

**Theorem:** $\Delta$ TSP is NP- Complete.

Assume that we have a minimal spanning tree $T$ in the graph. If we go back and forth along the edges in $T$ we get a *walk* of length $2w(T)$ where $w(T)$ is the weight sum of the edges in $T$. This walk of course is no solution to the TSP-problem since it is not a cycle. Now, let $C$ be an optimal cycle.

$w(C) = OPT$. Since $C$ is a spanning tree $+$ an edge, we get $w(T) \leq w(C)$.

$$2 \cdot w(T) \leq 2 \cdot w(C) \leq 2 \cdot OPT$$

We can rearrange the walk along the tree $T$ to a cycle $C_1$ by visiting the nodes in the order that is given by the *inorder* ordering of the nodes in the tree.

**Claim:** $w(C_1) \leq 2 \cdot w(T)$

This can be shown by repeated use of the triangle inequality.

We now get:

$$w(C) \leq w(C_1) \leq 2 \cdot w(T) \leq 2 \cdot w(C)$$

we set $APP = w(C_1)$. We the get:

$$OPT \leq APP \leq 2 \cdot OPT$$

We can compute $APP$ in polynomial time. The approximation quotient is $B = 2$.

There are more advanced algorithms for approximation of $\Delta$ TSP One is *Christofides algoritm*. It uses the same ideas as our algorithm but has an approximation quotient $\frac{3}{2}$.