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# Hamiltonicity and Longest Path Problem on Special Classes of Graphs

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# Fault Tolerance and Hamiltonicity of the Optical Transpose Interconnection System of Non-Hamiltonian Base Graphs

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# Optical Transpose Interconnection System(OTIS)

## Definition (Marsden et al.- 1993)

- OTIS is a widely studied interconnection network topology
- In this architecture, processors are divided into groups (called clusters)
- Processors within the same group are connected using electronic interconnects, while optical interconnects are used for intercluster communication.
- Power consumption is minimized and the bandwidth rate is maximized when the number of processors in a cluster equals the number of clusters

# OTIS Arrangement

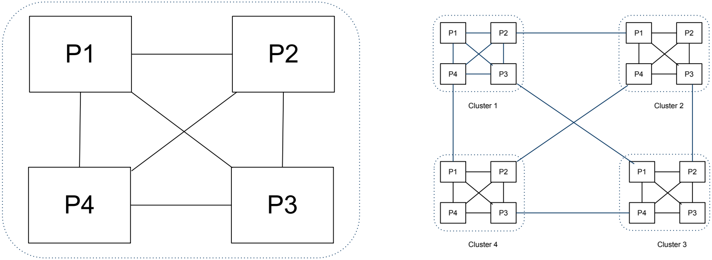


Figure: (a) Base Network(b) OTIS network

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# The Hamiltonian Cycle problem

## The problem

A Hamiltonian cycle is a spanning cycle in a graph, i.e., a cycle through every vertex, and a Hamiltonian path is a spanning path. A graph containing a Hamiltonian cycle is said to be Hamiltonian.

## Importance

- Hamiltonicity is important to ensure deadlock freedom in some routing algorithms and to allow efficient emulation of linear-array and ring algorithms.
- All-to-all broadcasting or total exchange algorithms relies on a Hamiltonian cycle for its efficient execution.
- Hamiltonicity is closely related to fault tolerance.

# Fault Tolerance and Independent Spanning Tree

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## Major Faults in Distributed Systems

- Dead processor fault(due to failure of processor or support chip).
- Dead interprocessor communication(due to failure of communication hardware).
- Independent Spanning Trees ensure the presence of parallel, node-disjoint paths between nodes of the network.

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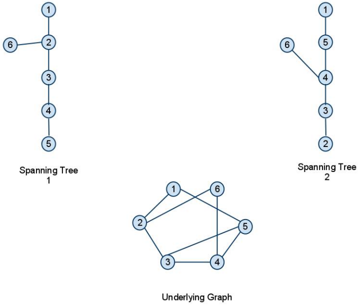


Figure: Illustration

# Hamiltonian Cycle and IST count



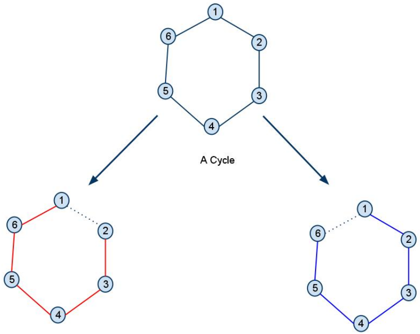


Figure: Illustration

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# Previous Work done

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## Hamiltonicity of OTIS graphs

- Parhami proved that OTIS networks built of Hamiltonian basis networks are Hamiltonian.
- Hoseinyfarahabady et al. showed that the OTIS-Network is Pancyclic and hence Hamiltonian, if its base network is Hamiltonian-connected.

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## Workdone

- We prove that Hamiltonicity of base graph is not a necessary condition for the OTIS to be Hamiltonian.
- We further prove that it is not sufficient for the base graph to have Hamiltonian path, for the OTIS to be Hamiltonian.
- We consider the generalization of this butterfly/bowtie graph, $BF(n, m)$ as base network, give constructive proofs for Hamiltonicity, on Bowtie-OTIS of $BF(2m+1, 2n+1)$ and $BF(2m+1, 2k)$, where $m, n, k \in \mathbb{N}$.
- This construction leads to an efficient alternate linear time rooted Independent Spanning Tree construction algorithm on this class of Bowtie-OTIS graphs.

# Butterfly/Bowtie Base Graph and OTIS



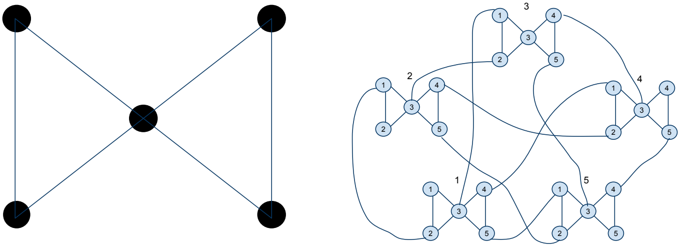

Figure: (a) Butterfly or Bowtie Graph $BF(3,3)$ (b) OTIS on $BF(3,3)$

# Hamiltonian OTIS on Non-Hamiltonian Base Graphs

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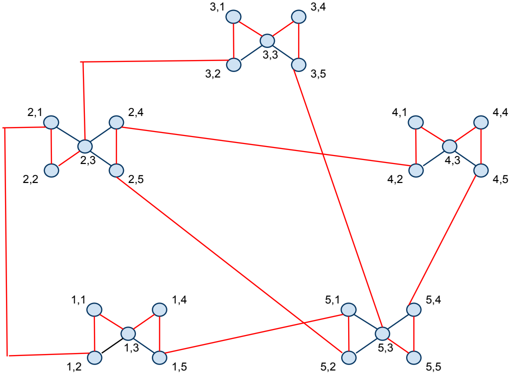


Figure: Hamiltonian edges shown in red

# Hamiltonian Path on Base Graph does not gurantee Hamiltonian Cycle on OTIS



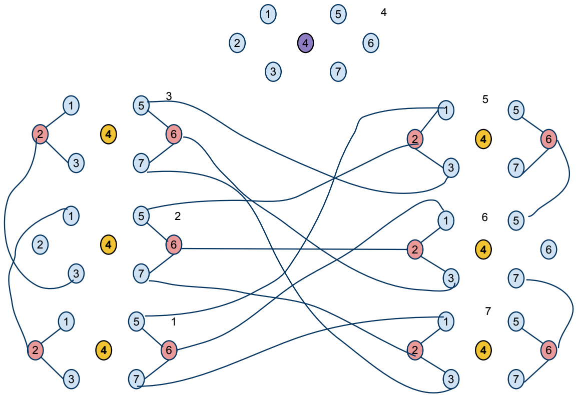


Figure: Total number of edges in $OTIS(BF(4,4))$ is $\frac{\sum_{i=1}^{n} d_i}{2} = 77$.

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# Inference Rules

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## Inference Rules

IR 1: If a vertex of degree $\geq 3$, gets saturated, the rest of its edges, not used in the saturation, becomes Non-Hamiltonian edges and are deleted from the graph.

IR 2: If $(\langle g_1, u\rangle, \langle g_2, v\rangle)$ is an edge between the vertices $\langle g_1, u\rangle$ and $\langle g_2, v\rangle$, both of degree $3$, and if the edge $(\langle g_1, u\rangle, \langle g_2, v\rangle)$ is identified as Non-Hamiltonian, then all other edges incident to the vertices $\langle g_1, u\rangle$ and $\langle g_2, v\rangle$ are forced to be Hamiltonian.

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## Algorithm

1: We identify the key Non-Hamiltonian edges whose endpoints lies within the same cluster, explicitly and delete them.

2: In this process some vertices becomes saturated; we apply IR 1 on these vertices.

3: The previous step, in turn decides Hamiltonian edges of the remaining vertices(due to IR 2).

# Construction for $OTIS(BF(3, 2k))$

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## Step 1:

Cluster 1: $(3, 2), (3, 4), (3, i)$

Cluster 2: $(3, 1), (3, 4)$ And the set $S_2 = \{(5, 6), (7, 8), \ldots, (i-1, i)\}$

Cluster 3: $(3, 1), (3, 4)$

Cluster 4: $(3, 1), (3, 2), (3, i)$

Cluster $5, 6, \ldots, (i-1)$: $(3, 2), (3, i)$

Cluster $i$: $(3, 1), (3, 2)$ and the set $S_i = \{(4, 5), (6, 7), \ldots, (i-2, i-1)\}$

# Illustration with $OTIS(BF(3, 2k)), k = 2$



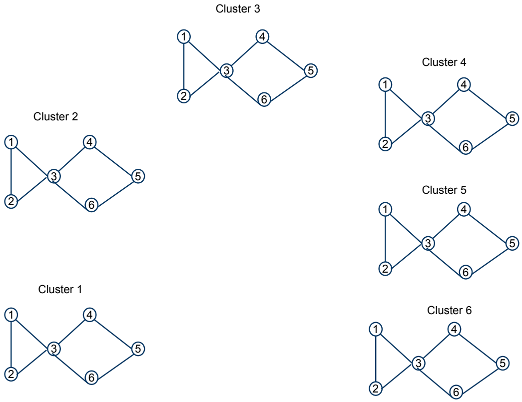


Figure: Illustration with $k = 2$

# Step 1

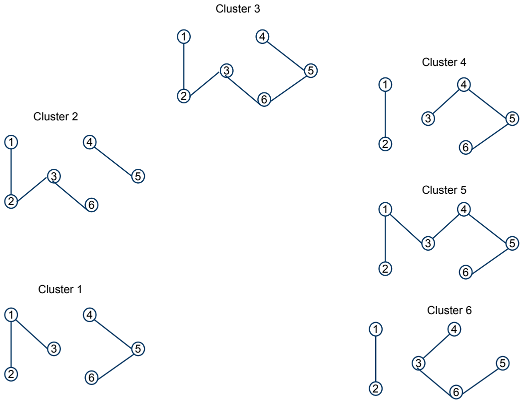


Figure: After execution of Step 1

# Step 2

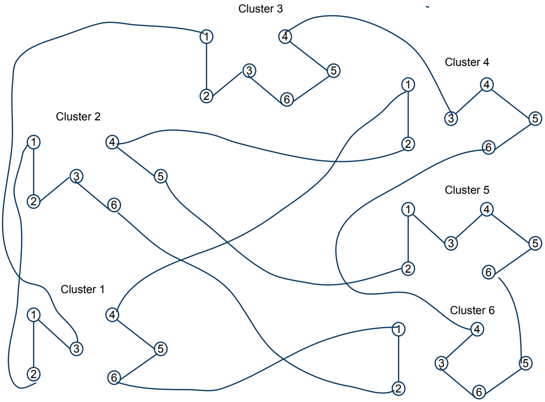


Figure: After execution of Step 2

# Independent Spanning Tree Construction

## IST Construction

- Pick any vertex as root and denote it as $r$
- Delete one edge incident to $r$. This gives a spanning Tree $T_1$
- Now, retain the edge previously deleted, and delete the other edge incident to $r$. This gives another spanning tree $T_2$

# Time Complexity

## Complexity Analysis

- Consider $OTIS(BF(2m+1, 2n+1))$ and $(OTIS(BF(2m+1, 2k))$; the number of intracluster edges, deleted per cluster, in these constructions, is of $O(m)$, assuming $m > n, m > k$
- Hence the Hamiltonian Cycle construction takes time $O(m|V_B|)$, which is of $O(m^2)$, i.e., linear in number of vertices of the OTIS graph.

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# A Polynomial Time Algorithm for Longest Paths in Biconvex Graphs

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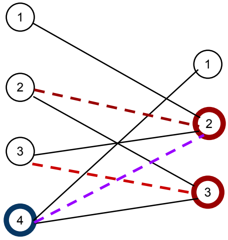
# Doubly Convex or Biconvex Graphs

**Definition (Glover-1967)**

A bipartite graph $G = (S \cup T, E)$ is *doubly convex* or *biconvex* if $\exists$ a numbering $1, 2, \ldots, |S|$ of the vertices in $S$ and a numbering of the vertices $1, 2, \ldots, |T|$ in $T$ such that $\forall v \in S \cup T$, $N(v)$ is a set of consecutive integers.

# Illustration



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# The Longest Path problem

## The problem

The longest path problem is the problem of finding a simple path of maximum length in a given graph.

## Importance

- The well-known Travelling Salesman problem and Hamiltonian Path problem are special cases of Longest Path problem.
- The longest path in program activity graph is known as critical path, which represents the sequence of program activities that take the longest time to execute.

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## Polynomial Solution for longest path problem on some graph classes

- Polynomial time algorithms for longest path exist for graph classes like Trees, Cacti, Ptolemic graphs, Bipartite Permutation graphs, proposed by Uehera et al.
- Recently polynomial time solutions for the longest path problem is proposed by Ioannidou et al. on interval graphs and cocomparability graphs.

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## Workdone

- We have proposed a $O(n^6)$ time algorithm to find the longest path on biconvex graphs, where $n$ is the number of vertices of the input graph.
- We have used Dynamic Programming approach.

# The Ordering

## Ordering the vertices

- Let $\pi_1 = (s_1, s_2, \cdots, s_{|S|})$ be the labeled vertices of partition $S$, and $\pi_2 = (t_1, t_2, \cdots, t_{|T|})$ be that of partition $T$
- Initialize $\sigma_S = \pi_1$.
- Update $\sigma_S$ as follows: For all $t_i$ in $\pi_2$, insert $t_i$ immediately after its rightmost neighbor.

# Illustration

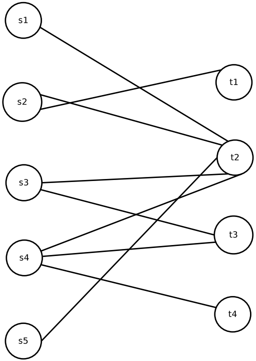


Figure: $\pi_1 = (s_1, s_2, s_3, s_4, s_5)$ and $\pi_2 = (t_1, t_2, t_3, t_4)$
$\sigma_s = (s_1, s_2, t_1, s_3, s_4, t_3, t_4, s_5, t_2)$

# Monotonic Path

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## Definition

A *S-Monotone* path of a Biconvex graph $G = (S \cup T, E)$ is a simple path $P = \{s_{\alpha_1}, t_{\beta_1}, s_{\alpha_2}, \ldots, t_{\beta_{j-1}}, s_{\alpha_j}, t_{\beta_j}\}$ such that $s_{\alpha_k} \prec_{\sigma_S} s_{\alpha_{k+1}} \forall$ k $\ni$ 1 $\leq$k$\leq j$.

Symmetrically, we define T-Monotone path.

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# Lemma

## Lemma

*Let*

- $P = \{s_{\alpha_1}, t_{\beta_1}, s_{\alpha_2}, t_{\beta_2} \ldots s_{\alpha_{j-1}}, t_{\beta_{j-1}}, s_{\alpha_j}, t_{\beta_j}\}$ *be a simple path of a biconvex graph* $G = (S \cup T, E)$.
- *Let* $P_{max}$ *denote the longest S-S sub path of* $P$.

*Then, the vertices on the path* $P_{max}$ *can be reordered to get a path* $P'_{max}$ *on the same set of vertices, which is S-Monotone.*

# Illustration

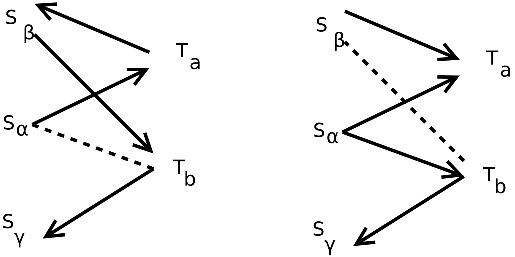


Figure: Case $\beta \prec \alpha \prec \gamma$
(a)*Non S-Monotone* Path (b)*S-Monotone* Path

# Case $\beta \prec \gamma \prec \alpha$

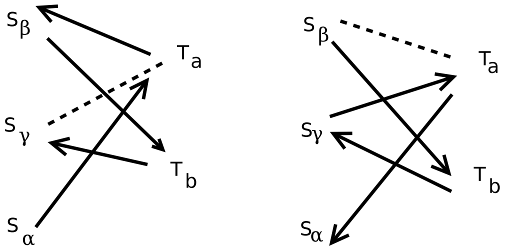


Figure: (a)*Non S-Monotone* Path (b)*S-Monotone* Path

# Proof Sketch


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## Inductive hypothesis:

For the longest S-S sub path of a simple path $P=\{s_{\alpha_1}, t_{\beta_1}, s_{\alpha_2}, \ldots, t_{\beta_{j-1}}, s_{\alpha_j}, t_{\beta_j}\}$, there exists a path $P' = \{s_{\gamma_1}, t_*, s_{\gamma_2}, \ldots t_*, s_{\gamma_j}\}$ satisfying the *S-Monotonicity* Property.

## Inductive Step

We prove the lemma by induction on $|S|$. Hence we consider a path $P_1=P \cdot s_{\alpha_{j+1}}$ and prove by principle of induction that the longest S-S subpath satisfying the S-Monotonicity property exists.

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# Algorithm Overview

## First Part of the Algorithm

Given the ordering $\sigma_S = (u_1, u_2, \cdots, u_n)$, for all $s_i, s_j$, where, $1 \leq i < j \leq |S|$, do the following:

- Choose the subsequence $\sigma_{Sij} = (u_k, u_{k+1}, \cdots, u_m)$ such that:
  - $u_k$ is the vertex $s_i$
  - $u_m$ is $s_j$, if $s_{j+1}$ immediately succeeds $s_j$ in $\sigma_S$.
  - Otherwise, $u_m$ is the rightmost T-vertex that lies between $s_j$ and $s_{j+1}$ in $\sigma_S$.
- Run the "Longest Path" routine and remember the maximum path length obtained over these iterations and all the paths of that maximum length.

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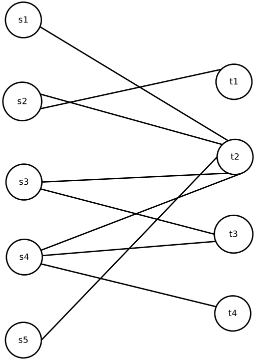


Figure: $\sigma_S = (s_1, s_2, t_1, s_3, s_4, t_3, t_4, s_5, t_2)$

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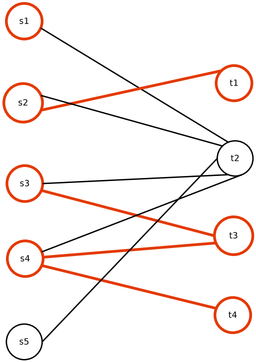


Figure: $\sigma_S = (s_1, s_2, t_1, s_3, s_4, t_3, t_4, s_5, t_2)$ and $\sigma_{S14} = (s_1, s_2, t_1, s_3, s_4, t_3, t_4)$

Longest S-Bimonotone Path is $P = \{s_3, t_3, s_4, t_4\}$

# Algorithm Overview(Cont.)

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## Second Part of the Algorithm

Symmetric to Part 1, this part is executed for vertices of T-partition with the initial ordering $\sigma_T = (u_1, u_2, \cdots, u_n)$.

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# Algorithm Overview(Cont.)

## Third Part of the Algorithm

- Choose the maximum of the two lengths obtained as output from the first and second part of the algorithms. Let us denote this length as $max$
- For all paths of length $max$, check if any of the end vertices have unvisited neighbor.
- If such a neighbor exists, extend the path till that neighbor and declare it as a longest path and $max + 1$ as longest path length.
- Else declare $max$ as the longest path length and all paths of this length as longest paths.

# The "Longest Path" Routine

## Description

1. Iterate through all the vertices of $\sigma_{S1n}$ from indices 1 to n
2. Initialize $P(u_i; i, i)$ with $u_i$ and $l(u_i; i, i)$ with 1.
3. For all $u_k$ , $i \leq k \leq j - 1$, which are S-vertices, initialize $P(u_k; i, j)$ with $P(u_k; i, j - 1)$ and $l(u_k; i, j)$ with $l(u_k; i, j - 1)$
4. If $u_j$ is also a S-vertex , initialize $l(u_j; i, j)$ with 1 and $P(u_k; i, j)$ with $u_j$
5. If $u_j$ is a T-vertex then execute $process(G(i, j))$
6. Compute the max$\{(u_k; 1; n) : u_k \in S(G)\}$ and the corresponding path $P(u_k; 1; n)$.

# The $process(G(i,j))$ subroutine



## $process(G(i,j))$

- For $y = f(u_j) + 1$ to $j - 1$, iterate through $x = f(u_j)$ to $y - 1$ if both $u_x$ and $u_y$ are S-vertices, then update the path as follows:
  - $w_1 \leftarrow l(u_x; i, j-1)$; $P'_1 \leftarrow P(u_x; i, j-1)$
  - $w_2 \leftarrow l(u_y; x+1, j-1)$; $P'_2 \leftarrow P(u_y; x+1, j-1)$

  If $w1 + w2 + 1 > l(u_y; i, j)$, then
  - $l(u_y; i, j) \leftarrow w1 + w2 + 1$;
  - $P(u_y; i, j) = (P'_1, u_j, P'_2)$;

Return the value $\{l(u_k; i, j)\}$ and the path $\{P(u_k; i, j), \forall u_k \in S(G(f(u_j) + 1, j-1))\}$

# Illustration

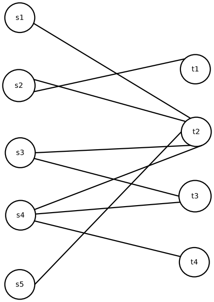


Figure: $\sigma_s = (s_1, s_2, t_1, s_3, s_4, t_3, t_4, s_5, t_2)$

# Illustration

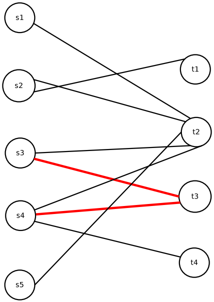


Figure: Path getting updated at call $process(G(4,6))$ and $x = 4, y = 5$

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Workdone
Algorithm and Complexity

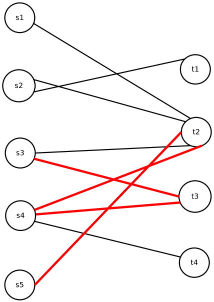


Figure: Path getting updated at call $process(G(1,9))$ with $x = 5, y = 8$

# Time Complexity

## Complexity Analysis

- Generating the ordering $\sigma_S$ and $\sigma_T$ will take $O(|S||T|)$ time.
- The subroutine process() takes O($n^2$) time and is executed at most once for each subgraph G(i, j) of G. Hence takes O($n^4$) time.
- Since the routine "Longest Path" is called for each ordered pair $s_i, s_j$ (and $t_i, t_j$), and there can be $O(n^2)$ such ordered pairs, so the total running time is $O(n^6)$.

# Publications from this Thesis

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- Esha Ghosh, N. S. Narayanaswamy, and C. Pandu Rangan. A Polynomial Time Algorithm for Longest Paths in Biconvex Graphs. To appear in: *Proceedings of Workshop on Algorithms and Computation(WALCOM) 2011*, pp.191-201, LNCS 6552, Springer-Verlag 2011.
- Esha Ghosh, Subhas K. Ghosh, and C. Pandu Rangan. On the Fault Tolerance and Hamiltonicity of the Optical Transpose Interconnection System of Non-Hamiltonian Base Graphs. under Review

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**THANK YOU**