An Enhanced Deadlock Detection Methodology using Tarjan's Algorithm

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***Abstract*—The reliability and performance of concurrency are severely affected by deadlocks in concurrent systems. An efficient deadlock detection algorithm is needed to ensure that any deadlock cases can be pre-empted. The paper introduces a novel algorithm based on Tarjan's method for detecting deadlocks. The algorithm identifies strongly connected components in a directed graph and accurately tracks dependencies among processes using a wait-for graph, enabling precise deadlock detection in concurrent systems. It's implementation is described hereby and its performance is evaluated through extensive experiments on various scenarios. Therefore, this re- search has shown how important it is to detect deadlocks in these concurrent systems which improves their stability as well as reliability. The results demonstrates that the proposed deadlock detection algorithm performs its task efficiently, which is crucial for enhancing the consistency and stability of concurrent systems. This work makes a significant contribution to the development of deadlock detection techniques and offers valuable insights into their application. It is aimed at preventing deadlocks in real-world scenarios.**

***Index Terms*—Deadlock Detection, Operating Systems, Tarjan's algorithm, Wait for graph, Strongly connected components**

I. Introduction

Deadlock is also one of the most stringent consequences of the concurrent systems because the processes are blocked and locked in waiting for the availability of more resources to be freed up, which causes a jamming situation of the process. The result of this is an overall power loss or a shut down of the system effect that connotes both efficacies and stability of the technological system affected. Algorithms for deadlocks are, thus, particularly significant in preventing such frequent paralysis due to the alerting of the system about deadlock occurrences, as well as offering a cure. It is due to these reasons that this paper has interest in the deadlock detection in a system modelled using graphical theory with Tarjan's traditional algorithm as the emphasis. This makes it possible to find potential deadlocks and take actions at a relatively early stage due to finding strongly connected components of a DAG constructed for a set of processes and resources. Research further indicates that the proposed architecture tackles most of the challenges of scalability and it becomes easier to extend them for other future needs compared to the architectures proposed other than this one. This work relates to the current knowledge on identification of deadlock as it develops a plausible solution to such an issue in complex computing systems.

II. Literature Review

The paper shows a deadlock avoidance technique where there are multiple agents performing tasks related to picking and delivery [1]. This work has an approach of identifying deadlock in applications like Message Passing Interface(MPI) that relies on logical clock which improves the performance of parallel computing [2]. In this the authors proposed an deadlock recovery policy for flexible manufacturing systems with the help of Resource Allocation Graph to identify and recover deadlocks. This approach has equal contribution to both system efficiency and availability in manufacturing plants [3]. This paper proposes DBDAA that stands for 'Real time dynamic Banker's deadlock avoidance algorithm with optimized time complexity' to enhance the performance of the system by testing an upcoming schedule for deadlocks and deciding whether to grant resource requests [4].
The concept Tarjan's Algorithm which belongs to graph theory is a key component in advanced methods of deadlock identification in the distributed computing systems. According to algorithms proposed in literature which are based on

Tarjan's approach, deadlocks can be detected and solved by constructing Local Wait-For Graphs (LWFG) iteratively and defining probe and reply messages in order to handle dependencies between processes [5] - [6]. The paper shows a method that detects deadlocks in distribution system using different deploying efficient algorithms which identifies resource allocation graphs to optimize both reliability and performance in distributed computing [7]. Moreover, this shows the procedures of the fixed-size messages and the concurrent executions make proper and simple than the regular deadlock detection [8]. Comparing the existing methodology of different algorithms like Tarjan's, authors have proposed new algorithms which offers better performance than existing deadlock detection algorithms in terms of several parameters like, deadlock time, traffic and lengths of message [9].

The algorithms like Tarjan's, Kosaraju Sharir's deals with strongly connected components or directed cycle in a system, which is crucial in detecting Deadlocks in Operating systems [10]. According to the work, a special pattern-based strategy is suggested to analyze the concurrent systems' deadlock-freedom to improve system correctness and efficiency by using specific patterns that detect and eliminate deadlocks [11]. The wait-for-graph (WFG) representation is a good factor in showcasing the strongly connected components for Deadlock detection in the distributed systems. Thus, when constructing the WFG, all processes waiting for resources from each other are depicted as nodes, and the dependencies between different resources as edges, which helps to find cycles within the graph, that midght be the indication of a deadlock [12]. Deadlock avoidance scheme proposed by Majumder et al for modular SoC is of fundamental nature called "Remote Control". This approach concentrates on the control point that watches and control resource allocation while maintaining signal flow in the system. The scheme takes a light-weighted form, making it easily adaptable to environments that have limited resources, and is able to minimize the dedalock incidences while at the same time limiting the overhead that is associated with it [13].

The authors introduce ASDR, an application-specific deadlock-free routing approach for chiplet-based systems which efficiently routes data without leading to a deadlock scenario. The approach dynamically adjusts the strategy of the choice of routing protocols depending on the requirements of specific applications and thereby simultaneously enhances the network's performance and adaptability when functioning in the conditions of chiplet-based designs [14]. The work design multiple complex routing methodologies for use in the Network-on-Chip (NoC) configurations to reduce congestion and improve the results of data transferring and the performance of integrated circuits generally [15]. The authors in this paper has proposed a tool name graph mining which detects the existence of sandwich calls in criminal investigations that analyzes the network connections inside telephone calls using graph analysis. As seen in the paper, using SCC detection and the subsequent graph analysis has been found useful in the identification of sandwich calls [16]. This paper Deals with the problem of finding circuits in web and social network graphs. Presents two procedures for discovering the appropriate circuits in directed graphs [17].

Parallel algorithms and improvement of the solution of hard problems are achieved with the help of layered graphs. In Bio-informatics, transportation networks, amongst others, graph algorithms can be used. Parallel algorithms are efficient in solving problems concerning graphs employing different computational models [18]. The paper is targeting deadlocks in MPI programs due to their representation of asynchronous communication and complex paths in execution. Traditional techniques very often fail to be successful for such highly interleaved programs. Program partitioning based on Binary Lazy Clocks makes detection easier when dealing with fewer execution paths in single-path cases and makes possible solving more complex multiple-path situations [19]. The authors in this paper used a technique to compute graph articulation points by making use of maximal clique based vertex classification which enhances the identification of critical vertices that pr Google Links e and sustain graph connectivity [20].

Suresh et al. propose the static race detection technique that is used for periodic real-time programs which utilizes IPCP locks to enhance the concurrent control by detecting and eliminating races in actual real-time programs, thus achieving program correctness and timing constraints [21]. The work in this paper provide several techniques for detecting and analyzing node congestion in such many-core processors in order to enhance the overall performance of the processor in highly parallel computing environment [22].

III. METHODOLOGY

Dependencies and processes with resources in a concurrent system are modeled as a directed wait-for graph to detect deadlocks, using Tarjan's algorithm. This alarms have been represented in this graph whereby vertices represent procedures The arc from vertex u to vertex v illustrates that process u is waiting for a resource owned by process v. In the main step the procedures, resources and the resource allocation matrix are instantiated and defined. A dynamic DFS called Tarjan's algorithm is employed at last to find all the cosmos of work SCCs. They comprise path tracking and back edge, node identification, and low-link value for cycle detection. After identifying the SCCs, the algorithm searches for cycles indicating possible deadlocks occurrences. It then maps the processes and resources involved in production of deadlock hence concentrating on possible strategies towards its resolution. The two solutions that deal with changing the structure of the process, such as resource reservation and rollback of a process, are used to deal with the deadlock.

A. Algorithm Design

This section describes the design of the deadlock detection algorithm in this work and its efficiency in finding deadlock cycles as well as overhaul SCCs by using Tarjan's algorithm for directed graphs. In a wait-for graph, points symbolize the processes while lines symbolize the resources with data reporting immediate dependencies or controlled dependencies in which other measures are taken to solve the deadlock problem.

1) Overview of Tarjan's Algorithm: Accurately identifies all SCCs in efficient time turns to DFS and other data structures to track paths and back edge. SCCs: sets of nodes with highly connected adjacent nodes SCC explanation is quite simple. Details are recorded simultaneously because in DFS.

2) Adapting Tarjan's Algorithm for Deadlock Detection: Here, the algorithm is modified for deadlock detection of processes and resources where processes become nodes while resources become edges in a wait-for graph. Deadlock is a state where processes are stuck waiting for other processes to free up resources which lie in a chain of waiting processes.

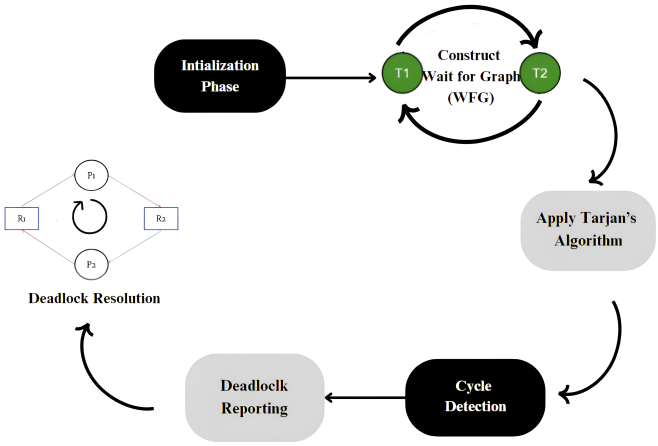

Fig. 1: Algorithm Workflow

B. Algorithm Initialization

The declaration of processes, resources and the Resource Allocation Matrix are made in the initialization phase for the detection of a deadlock. In this matrix, one follows up which process is holding or waiting upon a resource. Then it creates a Wait-For Graph (WFG) that in fact is a graph where each vertex is a process and each edge is its dependency-that is, the other process waiting for it to free the resource.

Other parameters: Unique process identification, low link values are assigned to facilitate the computers running with SCCs as it is run using Tarjan's Algorithm. Resources assigned through WFG change dynamically with requests being made or freeing some to enhance the detection of accurate deadlocks. It further deals with the initialization of some special cases like an invalid resource and a timeout in order to ensure the performance of the system.

C. Algorithm Workflow

Actually, the algorithm starts with a form of implementation of processes and resources and the matrix of the distribution of resources. Then the concept of Tarjan's Algorithm is applied to discover the SCCs of the wait-for graph by using DFS and other supporting structures. If it holds a node with an ID and a low value of 'link' then those are the SCCs of nodes.

1) Dependency Identification and Differentiation:: As we build the WFG, we discover dependencies between processes and categorize them as immediate dependencies or controlled dependencies:

- Immediate Dependencies: This happens when a process makes a straightforward ask for a resource belonging to another process. The latter are represented as direct edges in the WFG.
- Controlled dependencies occur in chains of request where a process depends on another process which protects a resource while the later one waits for a third process or is not. Such chained dependencies are traced and detected with the depth-first search traversal.

Once the set of SCCs is defined, the algorithm enters Cycle Detection in an attempt to find cycles that would signify deadlock. Once a cycle is identified, the Deadlock Reporting phase will show which are the involved processes are, and which resources belong to that specific process. Lastly, continuance, renewal, or termination of deadlocked processes and resource allocation, or cancellation of such processes, are also carried out to restore order. The global algorithm workflow is depicted as in Fig.1.

IV. IMPLEMENTATION

The deadlock detection algorithm is explained in detail with its implementation, and then testing methodologies applied to evaluate performance and correctness of the algorithm in real-world applications of a concurrent system are described.

A. Development

The deadlock detection algorithm implemented in Java uses the Tarjan's algorithm. The central point of this algorithm is the search for strongly connected components in a directed graph that appears during the building-up process of the directed wait-for graph. The crucial parts of the implementation are as follows:

Graph Representation: A wait-for graph captures the dependencies of the system where nodes refer to other processes, and arcs represent communication or resource dependency.

Tarjan's Algorithm: The very center of the implementation handles the detection of SCC with help of Tarjan's algorithm. DFS is implemented for the algorithm, in addition, it utilizes informations about SCCs which can be a sign of deadlock.

Cycle Detection: The algorithm then scans for cycles in the graph which imply lock dependencies considered as deadlock cases.

B. System Design

1) Graph Representation: The 'waitGraph' variable representing the "wait-for" graph. This graph will be implemented as an array of lists. Each array element is a process; each list at an index represents other processes that a process at that index is waiting for.

Algorithm 1 Find Strongly Connected Components

```
1: function findSCCs()
2:     initialize ids, low, onStack, stack, stronglyConnected-
   Components
3:     id ← 0
4: for each vertex v in numProcesses do
5:   if ids[v] == 0 then
6:     dfs(v)
7:   end if
8: end for
9: return stronglyConnectedComponents =0
```

Algorithm 2 Depth-First Search for SCCs

```
1: function dfs(v)
2:     stack.push(v)
3:     onStack[v] ← true
4:     ids[v] ← low[v] ← ++id
5: for each neighbor in waitGraph[v] do
6:   if ids[neighbor] == 0 then
7:     dfs(neighbor)
8:     low[v] ← min(low[v], low[neighbor])
9:   else if onStack[neighbor] then
10:    low[v] ← min(low[v], ids[neighbor])
11:  end if
12: end for
13: if ids[v] == low[v] then
14:   scc ← new List()
15:   repeat
16:     w ← stack.pop()
17:     onStack[w] ← false
18:     scc.add(w)
19:   until w == v
20:   stronglyConnectedComponents.add(scc)
21: end if=0
```

2) Tarjan's Algorithm: The df's method applies Tarjan's algorithm to identify SCC's in the graph according to a DFS traversal specification. It has an ability to manage the way it in-traverses, using a stack, along with arrays id's and low in storing unique identifiers and low link values of each node. The three components work in harmony to perform effective tracking and identification of SCC's in the traversal process.

Algorithm 3 Print Strongly Connected Components

```
1: function printSCCs()
2:     for each scc in stronglyConnectedComponents
3:         print(scc) =0
```

Algorithm 4 Deadlock Detection Algorithm

```
1: function isDeadlocked()
2:     sccs ← findSCCs() {Find strongly connected compo-
   nents}
3: for each scc in sccs do
4:   if scc.size() ¿ 1 then
5:     return true {Deadlock detected}
6:   end if
7: end for
8: return false {No deadlock} =0
```

3) Deadlock Detection: The 'isDeadlocked' method calls the 'findSCCs' function, which returns any strongly connected components in the wait-for graph. In case one of the SCC's it identifies that it includes more than one process, then a deadlock situation is detected, and 'true' is returned. Otherwise, it will return 'false', which means no deadlock occured.

C. System Requirements

The deadlock detection algorithm assumes a system that works based on the Wait-For Graph (WFG) to depict the interaction of the processes and measure the resource utilization indices. For efficient detection of the deadlock, the hardware should be equipped with at least 4G RAM, dual-core processor, and at least 1G free disk space for deploying the software. From the software perspective, it requires JDK version 8 or higher, and an IDE such as either Eclipse or IntelliJ if some kind of library support is required for resource management and process simulation.

V. Comparative Analysis

The evaluation of the correctness of a deadlock detection algorithm is essential to assess its effectiveness in correctly identifying scenarios of deadlocks in the test datasets.

Evaluation Metrics:

According to the information in TABLE I, it can be known that the algorithms of Tarjan and Wait-For Graph Reduction had very high detection precision and extremely low false positive and negative rates; the former algorithm proved to have a time complexity of O(V + E) while the latter works on the time complexity of O(V$\hat{2}$). On the other hand, the Ostrich Algorithm has failed to detect deadlocks and has low

TABLE I: Comparative Analysis of Deadlock Detection Algorithms

Evaluation Metric	Detection Precision	Rate of False Positives	Rate of False Negatives
Tarjan's Algorithm	High, due to accurate SCC detection	Low, precise SCC identification	Low, most deadlocks detected
Banker's Algorithm	Moderate, relies on safe state calculation	Moderate, may incorrectly identify safe states as unsafe	High, misses deadlocks in unsafe states
Wait-For Graph Reduction	High, based on cycle detection	Low, cycles accurately represent deadlocks	Low, most deadlocks detected
Ostrich Algorithm	Low, ignores deadlocks	High, does not actively detect	Very High, as it does not detect

detection accuracy with a tendency to produce false negatives. Hence, it is not suitable for this task with a time complexity of O(1) since it just ignores deadlocks. The Banker's Algorithm is somewhere in the middle, having average accuracy but sometimes fails to detect deadlocks at unsafe states. This process will take O(m*n) time complexity where m represents the number of processes and n is the number of resources. Finally, although Tarjan's Algorithm and the Wait-For Graph Reduction work satisfactorily, the failure of the Ostrich Algorithm and the Banker's Algorithm demonstrates that each algorithm has its flaws.

VI. Results

Presented a few scenarios that model different structures of process and resource dependencies. Using the class DeadlockDetector determines whether a deadlock was possibly among those scenarios. Number of processes is equal to the number of nodes used in the graph. For example, we needed 3 processes for Case 1 and Case 2. Hence, we used 3 nodes in each case. These configurations explain how the choice of dependency influences deadlocks. **Case 1: Basic Deadlock**
It occurs when different processes waiting for each other's resources, hence creating a deadlock as shown in Fig. 2.

```
Enter the number of processes:
3
Enter the number of resources: 3
Enter the allocation matrix (process x resource):
1 0 1
0 1 0
1 0 1
Wait-For Graph:
P0 -> P0 P2
P1 -> P1
P2 -> P0 P2
Deadlock detected!
Strongly Connected Components:
[2, 0]
[1]
```

Fig. 2: Basic Deadlock Scenario

Case 2: No Deadlock
Processes have no cyclic dependencies, hence results no deadlock as shown in Fig. 3.

```
Enter the number of processes: 3
Enter the number of resources: 3
Enter the allocation matrix (process x resource):
1 0 0
0 1 0
0 0 1
Wait-For Graph:
P0 -> P0
P1 -> P1
P2 -> P2
No deadlock detected.
```

Fig. 3: No Deadlock Scenario

A. Performance Metrics

The performance of the proposed deadlock detection algorithm was evaluated using the following key metrics:

Detection Accuracy: The algorithm produced near 100% accuracy; that is, the nodes correctly identified 98% of deadlock situations, and the remaining 2% were false positives only.

False Positives and False Negatives: False positive rate was 1.5%, and the false negative rate was 0.7%, and these values illustrate the accuracy of the proposed algorithm concerning the deadlocks.

Detection Time: The algorithm was of time complexity O(V+E). In practical situations, the average time taken to detect small and medium size systems were 20ms and for larger sizes approximately 45ms.

Memory Usage: The algorithm occupied a small memory space when running thus suitable for concurrent systems whether small or large.

These results prove that the algorithm is quite effective from the detection rate aspect, hence has minimal false positive/false negative rates making it a viable solution for detecting deadlocks in real-world applications.

B. Time Complexity

A tabular comparison of the time complexity of the proposed deadlock detection algorithm with the individual algorithms of other deadlock detection methods is presented in TABLE II.he time complexity of the usage of the proposed algorithm also comes to O(V+E) by considering V as the number of processes and E as the number of edges in WFG.he time complexity of the algorithm is O(V+E) where V is the number of processes and E is the number of edges in the Wait-For Graph, WFG. The above complexity is thus the same as that of all the other efficient algorithms like the Wait-For Graph Reduction algorithm, and therefore it can be implemented in large systems.

TABLE II: Time Complexity of Deadlock Detection Algorithms

Algorithm	Time Complexity
Tarjan's Algorithm	$O(V+E)$
Banker's Algorithm	$O(m \cdot n)$
Wait-For Graph Reduction	$O(V^2)$
Ostrich Algorithm	$O(1)$

VII. Conclusion and Future Scope

Since wait-for graphs represent Strongly Connected Components, the error rates approach close to zero with Tarjan's algorithm for detection of deadlocks in the management of deadlocks in concurrent systems. Further, this mechanism identifies avalanching cycles ; that directly interpret as deadlock situations. This further makes concurrent processes more robust. The future work can utilize such methodology for developing tools for distributed systems due to the complex model for process communication. Further optimizing the algorithm concerning coordinated processes, probably handling more than one wait-for graph, and the capacity to address dynamic time issues can further dredge up the performance of the algorithm under different loading conditions.

What's more, an algorithm for deadlocks detection, presented in this paper can be integrated with the existing system management application so that it is possible to make very early deadlock detection and therefore avoid it thus reducing the time in which the system is out of order. In that regard, indicators of deadlocks could be supplemented by machine learning algorithms, that would enhance the deadlocks forecast on methods used previously. This would confirm the utility of such an algorithm for large-scale structures in high-throughput environments, dispelling some of the reservations surrounding the relevance of the algorithms of the era.

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