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Title
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Permalink
https://escholarship.org/uc/item/7sj9767p

ISBN
9781595936677

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Publication Date
2007

DOI
10.1145/1248377.1248416

Peer reviewed
Deadlock-Free Scheduling of X10 Computations with Bounded Resources

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ABSTRACT
In this paper, we address the problem of guaranteeing the absence of physical deadlock in the execution of a parallel program using the async, finish, atomic and place constructs from the X10 language. First, we extend previous work-stealing memory bound results for fully strict multithreaded computations to terminally strict multithreaded computations in which one activity may wait for completion of a descendant activity (as in X10’s async and finish constructs), not just an immediate child (as in Cilk’s spawn and sync constructs). This result establishes physical deadlock freedom for SMP deployments. Second, we introduce a new class of X10 deployments for clusters, which builds on an underlying Active Message network and the new concept of Doppelgänger mode execution of X10 activities. Third, we use this new class of deployments to establish physical deadlock freedom for deployments on clusters of uniprocessors.

Together these results give the user the ability to execute a rich set of programs written with async, finish, atomic and place constructs without worrying about the possibility of physical deadlock due to computation, memory and communication resources. A major open topic for future work is to extend these results to deployments on clusters of SMPs.

Categories and Subject Descriptors
D.1.3 [Programming Techniques]: Concurrent Programming—distributed programming, parallel programming

General Terms
Algorithms, Languages, Theory

Keywords
X10, Deadlock-free scheduling, Active Messages

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SPAA’07, June 9–11, 2007, San Diego, California, USA.
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1. INTRODUCTION

Driven by the ever-increasing levels of hardware parallelism and the need to mask memory and network latencies, the DARPA HPCS languages all combine dynamic parallelism with locality control. This raises the question of how to map dynamic parallelism onto a fixed set of processor and memory resources while obeying the locality properties of the program. X10 is a novel object-oriented programming language designed for high-performance, high-productivity programming of parallel computers [6] as part of the DARPA HPCS program. X10 differentiates itself from multithreaded programming models such as Cilk [7] through its explicit reification of locality in the form of places, which serve as virtual locations for distributed activities and data. X10 also differentiates itself from Partitioned Global Address Space (PGAS) languages [10, 14, 16] and other Single Program Multiple Data (SPMD) programming models through its integration of loop parallelism, task parallelism, and asynchronous communication in a single unified execution model.

X10 creates parallel activities using an async statement, forces their completion with finish, supports mutual exclusion with atomic, and provides a generalized form of barrier synchronization called clocks. The async statement generalizes other dynamic threading models by allowing the programmer to specify a place at which the computation should be performed. In past work [15], it was shown that X10 programs written with async, finish, atomic and clocked are guaranteed to be free of logical deadlock i.e., they are guaranteed to never deadlock when executed with unbounded computation, memory, and communication resources.

This paper studies the problem of deadlock-free scheduling of X10 programs on physical nodes with bounded computation, memory, and communication resources. For simplicity, we focus on a core subset of the X10 language consisting of async, atomic and finish. In general, physical nodes have bounded computation resources (which limit the maximum number of activities that can execute simultaneously), bounded memory resources (which limit the number of live activities that can be suspended), and bounded communication resources (which limit the maximum number of entries in a node’s input/output communication queue).
In Section 2, we restrict our attention to single-place X10 computations which correspond to SMP deployments for which communication resource bounds do not apply. We address the use of bounded computation and memory resources for this case through the use of work stealing and show that for an SMP with \(P\) processors, X10 programs written with \texttt{async} and \texttt{finish} will use space no greater than \(S_1 + P\), where \(S_1\) is the space used by a single processor execution. This generalizes previous work-stealing results for the Cilk language [3] to admit more general synchronization patterns in which one activity may wait for completion of a descendant activity, not just an immediate child as in Cilk.

In Section 3, we introduce the notion of X10 deployments which formalize the mapping of virtual places to physical nodes by adding bounded communication resources. Unfortunately, a simple one-to-one mapping from places to nodes for data and activities may lead to physical deadlock due to the bounds on stalled activities and communication queues. To address this problem, we propose a communication framework built on Active Messages and an extension of X10 deployments with a Doppelgänger capability (Section 3.3), which enables an X10 activity to run on a node other than the node specified by the programmer. Doppelgänger mode enables us to create deployments for clusters of uniprocessors that are guaranteed to never exhibit physical deadlock by exploiting deadlock-free communication protocols such as Active Messages.

In Section 4, we discuss a set of scheduling algorithms for multi-place X10 computations using \texttt{async}, \texttt{finish} and \texttt{atomic} that are proved to a) never exhibit physical deadlock, and b) stay within the memory bounds of work stealing algorithms. The scheduling algorithms include heuristics that attempt to obey the place directives provided by the X10 programmer as far as possible, and only ignore them by entering Doppelgänger mode when necessary to satisfy a) and b).

Finally, Sections 5 and Section 6 summarize related work and the conclusions, and Appendix A includes proofs and additional technical details.

2. BOUNDED-MEMORY SCHEDULING OF X10 PROGRAMS ON SMP'S

In this section, we show how a single place deployment of an X10 program on an SMP with \(P\) physical processors can be executed in a deadlock-free manner, while satisfying per-processor memory bounds. Recall that inter-processor communication resources are not an issue in this single place scenario.

2.1 X10 computations

As in Cilk [3], an X10 computation can be represented as a dag in which each node corresponds to a dynamic execution instance of an X10 instruction/statement, and each edge defines a precedence constraint between two nodes. The first instruction of the main activity \(^1\) serves as the root node of the dag (with no predecessors). Any instruction which spawns a new activity will create a child node in the dag with an edge from the spawn instruction to the first instruction of that child activity. These edges are called spawn edges. In addition, execution instances of instructions from the same activity are sequenced in the dag by the use of \texttt{continue} edges.

X10 activities may wait on descendant activities by executing a \texttt{finish} statement. We model these dependencies by introducing \texttt{start fin} and \texttt{end fin} nodes in the dag for each instance of a \texttt{finish} construct and then create dependence edges from the last instruction of the spawned activities within the scope of \texttt{finish} to the corresponding \texttt{end fin} instruction. Figure 1 shows an example X10 code fragment and its computation dag.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{dag.png}
\caption{X10 computation dag}
\end{figure}

While there are many similarities between an X10 computation dag and a Cilk computation dag, there are also some interesting differences. For example, the direct dependence edge from activity \(G_2\) to activity \(G_0\) in Figure 1 is not allowed in Cilk because \(G_0\) is not \(G_2\)'s parent in the dag. The only way to establish such a dependence in Cilk is via \(G_1\). In X10 it is also possible for a descendant activity (e.g., \(G_2\)) to continue executing even if its ancestor activity (e.g., \(G_1\)) has terminated. This degree of asynchrony can be useful in parallel divide-and-conquer algorithms so as to permit sub-computations at different levels of the divide-and-conquer tree to execute in parallel without forcing synchronization at the parent-child level.

We now show how the Work-Stealing Algorithm from [3] for \texttt{fully strict} multithreaded computations can be extended to \texttt{terminally strict} multithreaded computations in which one activity may wait for completion of a descendant activity.

2.2 Work-Stealing Algorithm: Overview

In this section, we summarize key definitions and results from [3] that provide relevant background for our paper.

- An execution schedule, denoted by \(\mathcal{X}\), for a multi-threaded computation determines which processors of a parallel computer execute which instructions at each step.
- The space required by a P-processor execution schedule, \(\mathcal{X}\), is denoted by \(S(\mathcal{X})\).
- The space required by a 1-processor execution schedule is denoted by \(S_1\).

\(^1\)The terms “activity” and “thread” are used interchangeably in this paper.
2.3 Extending Work-Stealing for X10

The difference between Cilk and X10 computations is that unlike Cilk, X10 does not fall into the class of fully strict multithreaded computations and, therefore, we cannot directly apply the result from Theorem 2.3. However, X10 computations fall in the class of strict multithreaded computations because dependence edges can only occur from descendants to ancestors. Further, X10 computations that use async, finish and atomic constructs form a proper subset of strict computations that we refer to as terminally strict multithreaded computations. We use “terminally” to emphasize the fact that dependencies from descendants to ancestors only occur on termination of descendant activities, as determined by X10’s finish construct.

Specifically, a terminally strict multithreaded computation must satisfy the following properties, where \( \Gamma_0, \Gamma_1, \Gamma_2, \ldots, \Gamma_n \) represents a chain of activities such that \( \Gamma_{j+1} \) is a child of \( \Gamma_j \) for \( j = 1 \ldots n \):

1. In case of dependencies on descendants of a child, it is always the case that a dependency on the child also exists.
2. All the descendants created within the immediate scope of finish will have a dependence edge going to the end fin node of that finish.
3. There can be at most one outgoing dependence edge from a node. Note that in absence of dependence edge between two activities, they can complete in any order.

4. When an activity, say \( \Gamma_0 \), with an outgoing dependence edge completes, the dependency on \( \Gamma_0 \) is resolved. An activity with incoming dependence edges can progress only when all the edges get resolved. For example, in Figure 1, \( \Gamma_0 \) can progress past its end fin instruction only when \( \Gamma_1 \) and \( \Gamma_2 \) complete. Note that \( \Gamma_1 \) and \( \Gamma_2 \) can complete in any order.

5. A finish block completes only when all its descendant activities complete. In case of nested finish blocks, this will imply transitive dependency.

The Work-Stealing algorithm for scheduling X10 computations provably uses bounded space and can be shown not to have any cyclic dependencies thus guaranteeing that computation will not exhibit deadlock due to resource constraints. Furthermore, the overall space bound will be demonstrated to scale no greater than linearly with increasing processor count, which is generally a precondition for practical implementation.

Each processor maintains a ready deque data structure of threads. The ready deque has two ends: a top and a bottom. Threads can be inserted in the bottom and removed from either end. A processor treats its ready deque like a call stack, pushing and popping from the bottom. Threads that are migrated to other processors are removed from the top.

In general, a processor obtains work by removing the thread at the bottom of its ready deque. It starts working on the thread, call it \( \Gamma_a \), and continues executing \( \Gamma_a \)'s instructions until \( \Gamma_a \) spawns, blocks, dies, or enables a blocked thread, in which case, it performs according to the following rules:

1. Async: If the thread \( \Gamma_a \) spawns an async child \( \Gamma_b \), then \( \Gamma_a \) is placed on the bottom of the ready deque, and the processor commences work on \( \Gamma_b \).
2. Blocks: If the thread \( \Gamma_a \) blocks due to a finish construct, its processor begins work stealing. A thread can block if there exists some live descendants from which it has incoming dependence edges. The only possible reason that this thread got separated from its descendants is that it was stolen.
3. Terminates: If the thread \( \Gamma_a \) terminates, it first checks if it enables thread \( \Gamma_a \) i.e., if \( \Gamma_a \) is the last dependency for \( \Gamma_a \)'s finish operator. If so, \( \Gamma_a \) is inserted as the bottommost thread in deque of \( \Gamma_a \)'s processor. Next, \( \Gamma_a \)'s processor checks its ready deque. If the deque contains any threads, then the processor removes and begins work on the bottommost thread. If the ready deque is empty, the processor begins work stealing: it steals the topmost thread from the ready deque of a randomly chosen processor and begins work on it.

Having outlined the rules of work stealing on a thread (activity) in X10 we now arrive at the space bound in the following manner. We apply the rules of work stealing for fully-strict computations in [3] to terminally-strict X10 computations without much modification, and obtain an analogous space bound.

**Lemma 2.4.** In the execution of any terminally-strict (X10) computation by the Work-Stealing Algorithm, let us consider any processor \( p \) and at the beginning of a given time step let there be \( k \) number of activities in \( p \)'s ready deque. Let \( \Gamma_0 \) be the activity that \( p \) is working on. Let \( \Gamma_1, \Gamma_2, \ldots, \Gamma_k \) denote the \( k \) activities ordered from bottom to top, that is, \( \Gamma_1 \) is
the bottommost and $\Gamma_k$ is the topmost. If $k > 0$, then the activities in $p$’s ready deque satisfy the following properties:

1. For $i = 1, 2, \ldots, k$, activity $\Gamma_{i-1}$ is the child of $\Gamma_i$.
2. For $i = 1, 2, \ldots, k$, activity $\Gamma_i$ has not been worked upon since it spawned $\Gamma_{i-1}$.

See section A.1 in appendix for proof.

**Lemma 2.5.** The Work-Stealing Algorithm for terminally-strict X10 computations preserves the busy-leaves property. See section A.1 in appendix for proof.

**Theorem 2.6.** For an X10 computation, which is a terminally-strict multithreaded computation, with stack depth $S_1$, the Work-Stealing Algorithm run on a computer with $P$ physical processors uses at most $S_1 \cdot P$ bytes for the deque per processor. That is, it uses total space of $S_1 \cdot P$ bytes.

**Proof.** Follows from Lemma 2.5 and 2.2. $\square$

This theorem states clearly that given bounded space we can handle any terminally-strict computation, provided that computation requires finite stack depth. This result implies that given $S_1 \cdot P$ space in our system, we can guarantee the progress of the X10 computation using the Work-Stealing Algorithm and will not observe any deadlocks due to insufficient activity memory resources.

### 3. X10 Deployments, Active Messages, DoppeLGanger Mode

#### 3.1 X10 Deployments

As described in [6], a key feature of the X10 programming model is the concept of a place which establishes a binding between a set of activities and a set of shared mutable locations in a partitioned global shared address space. Places are a virtual concept. The mapping of places to physical processors and memories is called a deployment, as shown in Figure 2. A deployment for an X10 program execution is specified separately from the X10 program – it may be specified by the programmer or application end-user through the run-time environment, or it may be selected automatically by an X10 implementation. Though objects and activities do not migrate across places in an X10 program, an X10 implementation is free to adaptively optimize a deployment at run-time by migrating places across physical locations as it sees fit.

In this section, we focus our attention on the case where the deployment target is a cluster of uniprocessors interconnected with a communication network. Even though this case represents a restricted subset of potential X10 deployment targets, it serves as a good foundation for establishing deadlock avoidance in the presence of bounded resources. Figure 3 outlines a standard cluster deployment where there is a one-to-one mapping of activities and data from places to nodes.

#### 3.2 Deadlock Freedom in Active Messages

In this section, we show how Active Messages can be implemented with provable deadlock freedom and bounded re-
source utilization by using two virtual networks, one for AM Requests and one for AM Replies. Virtual networks [8] provide independent communication channels, ensuring that resource starvation (e.g., lack of buffer space) on one virtual network does not prevent communication progress on the other virtual network. Virtualization is often implemented by multiplexing over a single physical network and maintaining logically independent buffers, but other strategies are possible. The buffer space required by each virtual network is assumed to be fixed and usually established at program initiation.

Generalizing, we define an AM(N) communication protocol to be a handler-based communication protocol which delivers messages of a bounded size and is implemented using a fixed number of virtual networks V₀, . . . , Vₙ₋₁ of increasing priority, and adheres to the following rules:

- All message injection operations executed outside the dynamic context of a handler inject messages on the lowest priority virtual network V₀.
- A handler running in response to a message received on Vᵢ can only inject messages on the next-higher priority network Vᵢ₊₁.
- Handlers running in response to a message received on the highest-priority virtual network, Vₙ₋₁ may never inject messages.
- Message injection is the only blocking operation permitted within a handler. Handlers are otherwise never permitted to block indefinitely (e.g., to await resources or communication arrival) — they must run to completion independently of other system activities, consuming a bounded amount of resources and issuing a bounded number of message injections.
- Message injection operations block until resources are available to accept the message, and any attempt to inject a message on Vᵢ which cannot complete immediately (e.g., due to resource starvation on that network) must service any incoming messages on Vᵢ₊₁, Vᵢ₊₂, . . . , Vₙ₋₁ while blocking. Incoming messages are otherwise never serviced from within handler context.
- Each virtual network makes independent progress on message delivery and consumes bounded resources.

**Theorem 3.1.** An AM(N) protocol can be implemented without deadlock and with bounded resource utilization.

See Section A.2 in appendix for proof.

**Corollary 3.1.1.** Active Messages can be implemented without deadlock and with bounded resource utilization.

**Proof.** Active Messages is just a special case of Theorem 3.1 where N = 2:

- All AM Request messages travel on virtual network 0 (low priority network)
- All AM Reply messages travel on virtual network 1 (high priority network)
- AM Request handlers may inject at most one AM Reply, and otherwise may never block.
- AM Request injections poll both networks, AM Reply injections poll only the AM Reply network. 
- AM Reply handlers may never inject messages or block.

**3.3 Physical Deadlock and Doppelganger Mode**

We now move from Active Messages to more general X10 activities. To illustrate the possibility of a physical deadlock with a simple one-to-one mapping from places to nodes, consider the dynamic activity creation tree in Figure 4, for an execution of the X10 code fragment shown in Figure 5 on two places named P₀ and P₁. In this scenario, the p.next() operator alternates between places P₀ and P₁. Assume that each node has M slots available in its incoming message queue (each of which can hold one activity while it is being pushed over the network from a peer) and furthermore that each node has M slots in local memory which can hold a stalled activity while it awaits a response from a child activity pushed to a remote node. For the sake of concreteness, assume that I = M = 2 in this example.

The dynamic activity creation tree for this X10 program is shown in Figure 4. We assume that this simple deployment has no support for throttling the creation of remote activities. Initially P₀ starts the execution of activity A₀ created in the main() method (Statement 11) with 2 empty slots for I and M each. A₀ then creates two child activities at P₁ and subsequently waits for its completion. At Level 1, P₁ now has 2 incoming activities (A₁ and A₂), each of which again creates 2 child activities at P₂ and P₃ for the sake of concreteness, assume that I = M = 2 in this example.

The dynamic activity creation tree for this X10 program is shown in Figure 4. We assume that this simple deployment has no support for throttling the creation of remote activities. Initially P₀ starts the execution of activity A₀ created in the main() method (Statement 11) with 2 empty slots for I and M each. A₀ then creates two child activities at P₁ and subsequently waits for its completion. At Level 1, P₁ now has 2 incoming activities (A₁ and A₂), each of which again creates 2 child activities at P₂ and P₃. A₀ and A₂ created at Level 2 subsequently create 8 activities at P₃. Thus the number of empty slots for I and M now becomes 0 at P₀. These 8 activities recursively create 16 activities at P₁ and make the number of empty slots in I and M also equal 0 at P₁. At this point the system is deadlocked - all incoming queues are full of non-leaf activities, and there is no remaining memory for non-leaf activities to stall while waiting for remote children to terminate. Both nodes are attempting to inject newly-created activities and there is nowhere for them to go, and none of the existing activities can be drained or retired.

Consider an activity, Aᵢ, that was created at place Pᵢ in an X10 program. Note that the physical deadlock scenario in Figure 5 arose for the case of a standard cluster deployment in which activity Aᵢ must be scheduled at the physical node, Nᵢ, corresponding to Aᵢ’s place. We will now consider a modified cluster deployment in which activity Aᵢ is executed on some other physical node, Nⱼ, while still preserving the illusion that Aᵢ is executing at its designated place Aᵢ ∈ Pⱼ. For the sake of concreteness, assume that I = M = 2 in this example. **Figure 5: Example X10 Code Fragment for Physical Deadlock Scenario**

```java
void foo (place p, ...) {
  if (...) {
    ... // recursion termination condition
  } else {
    11: finish {
      12: async (p.next()) { foo (here, ...); } 
      13: async (p.next()) { foo (here, ...); } 
      14: }
    } ...
    // Other computation

  void main () {
    15: finish async { foo (here, ...); }
  }
}
```
will attempt to Figure 3.2. As shown in Figure 6, this kind of deployment works by allowing activities to execute in Doppelgänger Mode. As indicated by the dotted arrow in Figure 6, when an activity executes in Doppelgänger Mode, it is permitted to run on a different node from the one where its place’s data is located. Doppelgänger Mode only impacts the mapping of activities to nodes; the mapping of data from places to nodes remains unchanged from Figure 3 to Figure 6. Note that the mapping of activity $A_i$ to remote node $N_k$ is a deployment step that does not impact the logical identity of $A_i$’s place in the X10 program. In particular, the expression, here, will continue to refer to place $P_j$ for activity $A_i$, even when $A_i$ is executing on node $N_k$. Further details on Doppelgänger mode are discussed in Section 3.3.

We now briefly discuss the four cases that can lead to inter-node communication in Doppelgänger mode:

**Place-local data accesses (Case 1).**

All place-local data accesses in $A_i$ executing at node $N_k$ (i.e., accesses to data in place $P_j$, which will be located at node $N_j$) will have to be performed remotely via the Active Message network since $A_i$ is not running on node $N_j$. For example, a read operation on an object field $p.x$ or array element $A[i]$ that could have been performed locally if $A_i$ was executing on $N_j$ will now have to be performed remotely. Since the extra number of remote messages may degrade performance, the heuristic algorithm in Section 4 uses Doppelgänger mode as a last resort for deadlock avoidance. Note that all activity-local data for $A_i$ can be allocated and accessed at node $N_k$ without requiring any remote communication.

**Activity creation (Case 2).**

When $A_i$ creates a child activity, the destination place ($P_x$, say) for the activity is specified by the X10 program’s semantics. The heuristic algorithm in Section 4 will attempt to create the activity at node $N_x$. However, if resource constraints do not permit this inter-node communication for activity creation, then the heuristic algorithm will instead create the activity at node $N_k$ so that it too will execute in Doppelgänger mode if $N_x \neq N_k$.

**Finish notification (Case 3).**

If activity $A_i$ enters a finish statement, the fact that $A_i$ is executing on node $N_k$ will be propagated to all descendant activities created in the scope of the finish so that their termination notifications will be sent to node $N_k$ rather than node $N_j$.

**Atomic blocks (Case 4).**

Atomic blocks need special handling in Doppelgänger Mode. If activity $A_i$ contains an atomic statement, the implementation needs to ensure that its combination of operations on activity-local data (on node $N_k$) and place-local data (on node $N_j$) is performed atomically. This can be accomplished by the following steps:

1. **Copy-in:** Activity $A_i$ makes a copy of all activity-local variables that may be read in the atomic statement, for transmission from node $N_k$ to node $N_j$.

2. **Active Message request:** $A_i$ then sends a request message to node $N_k$ with a copy of the local variables from Step 1 and a pointer to the code for the atomic statement, and blocks waiting for the reply. Atomic statements in X10 are guaranteed to satisfy all the constraints for active message handlers outlined in Section 3.2, including no place-remote accesses.

3. **Active Message reply:** After completion of the active message handler for the atomic statement, node $N_j$ sends a reply to node $N_k$ with a copy of all activity-local variables that may have been written in the atomic statement.

4. **Copy-out:** Activity $A_i$ copies values of the local variables received in the reply message, and then resumes execution.
4. DEADLOCK-FREE SCHEDULING OF MULTI-PLACE X10 COMPUTATIONS

The multi-place scheduling algorithm (outlined in Figure 7) is a novel distributed algorithm that governs the scheduling of X10 activities at multiple places, while maintaining provable bounds on resource utilization at each place. In this paper, we restrict our attention to the case where there is exactly one processor per place, which corresponds to a cluster of uniprocessors. Furthermore, for simplicity, we assume the multi-place algorithm never performs work-stealing across the cluster — once created, activities run to completion on a given processor, although that processor may or may not correspond to the place expression (depending on the decisions made by the scheduling algorithm at activity creation). Future work includes expanding the multi-place algorithm to allow work-stealing while still maintaining provable resource utilization bounds per place. The complete details of the algorithm cannot be covered here due to space restrictions, so we shall focus on the portions relevant to the proof of bounded resource utilization.

X10 supports dynamic creation of activities, and in general the values of the place expressions associated with activity creation are only discovered at runtime as the computation unfolds — therefore scheduling decisions are made online using a greedy heuristic. We shall use the terms local activity and remote activity to indicate an activity which is spawned with a place expression which respectively equals or differs from the place of the processor executing the parent activity.

By default, the heuristic assigns activities to the processor hosting their semantically-specified place — local activities are always executed on the local place, and remote activities are pushed to their target place upon creation. Once a remote activity is successfully pushed to a remote place, the local processor is free to continue executing the parent activity and servicing its local deque, as the depth-first exploration of the remote activity subtree has effectively been handed off to the remote processor. When there is resource contention at the source or target place, the heuristic exercises flow control by running remote activities on the local processor in Doppelgänger mode.

As in the single-place scheduling algorithm, each processor has an associated ready deque of activities which govern the order in which the activities are processed. One important difference we shall see is this deque allows for insertion at a well-defined point in the middle, although this paper will still refer to the data structure as a deque for consistency with existing literature. Except where otherwise noted, the processor services the deque as described in section 2.3 — in the absence of remote async operations, activities are serviced by the processor in depth-first order.

Additionally associated with each processor is a stalled activity buffer (SAB), an area of memory which holds activities that have stalled upon a finish operation waiting for the completion of a descendant activity. Due to the depth-first nature in which local activities are processed, an activity can only enter the SAB if it has stalled awaiting the completion of a descendant activity that has been pushed to a remote processor, but not yet completed.

At all times, every live activity in the system will reside in exactly one of three areas: the processor (which executes at most one activity at a time), the deque (where it awaits servicing by the processor) or the SAB (where a stalled activity awaits to be reenabled by one or more remote descendant activities). The scheduling algorithm manages the movement of activities between these locations at each node, and the system resource utilization at each node can be captured by summing the contributions of activities in each area.

4.1 Useful Notations

Some useful notations as used by the algorithm in Figure 7 are defined here.

- \( A_i \) where \( i \in \{1, 2, \ldots\} \) stands for an activity.
- \( \text{finish}(A_i) \) denotes the activity that contains the finish instruction to which \( A_i \) must report completion.
- \( P_i \) denotes a place, \( N_i \) denotes a node.
- \( \text{node}(A_i) \) denotes the node hosting the activity \( A_i \).
- \( \text{node}(P_i) \) denotes the place hosting the place \( P_i \).
- \( \text{deque}(N_i) \) SAB \( SAB(N_i) \) denote the deque and Stalled Activity Buffer respectively for node \( N_i \).
- \( \text{Count}^\text{in}(N_i) \) denotes the counter which keeps track of the bound \( R \) on fresh activities in the deque.\( \text{Count}^\text{out}(N_i) \) checks for the bound \( R \) on the stalled activities in the SAB.
- The predicate \( \text{Fresh}(A_i) \) is set if \( A_i \) is a fresh activity and it is initialized to false.

4.2 Algorithm Outline

The algorithm in Figure 7 is based on the following ideas. Consider an activity \( A_1 \) at place \( P_j \) executing at node \( N_j \).

At an execution step, any one of the following is possible.

1. \( A_1 \) creates a local activity \( A_2 \) at \( P_j \). Following the depth-first execution rule, \( A_1 \) will be pushed to bottom of the local deque at \( N_j \) and \( A_2 \) will start executing.
2. \( A_1 \) creates a remote activity \( A_2 \) to be executed at \( P_r \) (where \( r \neq j \)). There are two possibilities in this case: either the system has enough resources for \( N_r \) to accept \( A_2 \) or it does not have. In case it has enough resources, \( A_2 \) is pushed to the top of \( N_r \)’s deque. Otherwise, \( A_2 \) is executed at \( N_r \) in Doppelgänger mode.
3. \( A_1 \) stalls because of a \text{finish} instruction which is waiting for a descendant activity to complete. Note that due to the depth-first processing of local activities, this can only occur when some descendant was pushed to a remote node. In this case, \( A_1 \) is moved to the SAB.
4. \( A_1 \) completes its execution. It sends a completion notification to activity \( A_2 = \text{finish}(A_1) \). If \( A_1 \) was the last dependency for the \text{finish} in \( A_2 \), then \( A_2 \) is enabled and moved out from SAB to the middle-insertion point of the deque at the corresponding processor.
5. \( A_1 \) performs a finite computation.

It is clear that at any node, the deque and SAB structures are manipulated for managing the activities. Therefore, to show that the X10 computation needs bounded resources assuming bounded \( S_1 \) and \( S_{\text{max}} \) as defined in section 2, we should show that we will never require the deque or the SAB to be unbounded. In the following, we outline the ideas incorporated in the algorithm to keep the deque and the SAB bounded.

- A deque at any node consists of activities that have been either created locally or pushed by remote nodes.
In case of locally created activities, they follow depth-first execution rules thus ensuring that a bounded deque suffices for local activities. However, we need to limit the activities being pushed by remote nodes, otherwise remote nodes could go on pushing activities without regard to resource limitations at the target. The way to handle incoming activities from remote nodes is that the activities in the deque are distinguished as fresh or worked-on based on the follow definition: an activity is considered fresh if it has not moved to the processor even once, otherwise it is considered worked-on. The middle-insertion point is defined to be the point below the bottommost fresh activity (if any) and the topmost worked-on activity (if any). The activities from the SAB that are inserted at this middle-insertion point fall in the class of worked-on activities. Incoming activities are accepted if and only if the number of fresh activities is less than or equal to \( R \), where \( R \) is a predefined constant positive integer. In case an activity is not accepted by this node, then the activity will run in Doppelgänger mode at the remote source node. This is taken care of by parts (B) and (D) of the algorithm in Figure 7.

- The SAB for a node contains the stalled activities, and therefore if we do not limit the movement of activities to SAB, we may need an unbounded SAB. To bound the SAB, we bound with \( R \) the number of activities that are waiting for the completion of remote activities (activities that were pushed to remote nodes). Note that they should not be waiting for completion of any local activity. These activities exactly correspond to those activities rooting a spawn subtree that executed one or more remote push operations and contain the innermost finish instruction for those remote pushes. Whenever there are \( R \) such activities in SAB and a remote activity is created within a local finish scope, then the node resorts to Doppelgänger mode. This is incorporated in parts (A), (C), and (F) of the algorithm in Figure 7.

- Finally, we have to consider the case when an activity is moved to the middle-insertion point of the deque from SAB after getting enabled. The decision of putting the activity at the middle-insertion point ensures that the deque cannot process any fresh activity until all the worked-on activities at that processor have either stalled or completed. This ensures no extra demand on the resources deque or SAB.

The only thing left to be shown is that no deadlock can arise, if we hit the resource bounds by following the multi-place algorithm as in Figure 7. As we have seen, whenever the bound \( R \) is reached on deque or SAB, it is appropriately handled by using the Doppelgänger mode where deadlock-free Active Messages are used to perform any place-local data accesses using fine-grained messages. Thus progress is always ensured and no deadlock can arise in spite of the bounded resource setup.

**Theorem 4.1.** The multi-place algorithm in Figure 7 uses at most \( 2 \times R \times S_{\text{max}} + R \times S_1 + S_1 \) bytes of space per node and ensures deadlock freedom.

See Section A.3 in appendix for proof.

5. RELATED WORK

While UPC [16], Titanium [10] and Co-Array Fortran [14] follow an SPMD style control-flow model where all threads execute the same code [9], Cilk [7], Chapel [11], Fortress [1] and X10 choose a more flexible model and allow more general forms of control flow among concurrent activities. This flexibility removes the implicit co-location of data and processing that is characteristic of the SPMD model. X10’s async and finish are conceptually similar to Cilk’s spawn and sync constructs. However, X10 is more general than Cilk in that it permits a parent activity to terminate while its child/descendant activities are still executing, thereby enabling an outer-level finish to serve as the root for exception handling and global termination. Fortress offers library support that enables the runtime system to distribute arrays and to align a structured computation along the distribution of the data. X10 is somewhat different, in that it introduces places as a language concept and abstraction used by the programmer to explicitly control the allocation of data and processing. A place is similar to a locale in Chapel and a site in Obliq [5]. Like X10, each object in Obliq is allocated and bound to a specific site and does not move; objects are accessed through “network references that can be transmitted from site to site without restrictions” [5]. In Obliq, arrays cannot be distributed across multiple sites. Chapel’s model of allocation is different from X10 and Obliq because Chapel does not require that an object be bound to a unique place during its lifetime or that the distribution of an array remain fixed during its lifetime.

The Cilk-NOW project [2] explored the use of work-stealing algorithms in a distributed-memory environment, with adaptive parallelism and fault-tolerance. In that system task migration was entirely pull-based (via a randomized work stealing algorithm), in contrast to our algorithm which pushes work to specific places guided by linguistically-explicit locality expressions (which Cilk lacks). To the best of our knowledge, no formal proof for the deadlock-freedom or resource utilization properties in the distributed version of Cilk has been published thus far.

The concept of Active Messages was first introduced in [17] and later standardized in the AM-2 specification [12], and the ideas have subsequently appeared in various forms in a number of systems. One recent example is the GASNet communication system [4], which serves as the communication layer for several global-address-space language compilers. GASNet includes an Active Message interface modeled on AM-2, and augmented with extensions to allow handler concurrency through explicit atomicity control (handler-safe locks and no-interrupt sections). The deadlock-freedom guarantee from Section 3.2 can be extended to other, more general variants of Active Messages as well.

There is extensive literature on deadlock-freedom in routing algorithms for interconnect hardware and the use of virtual networks - see [13] for a good survey. Proofs of deadlock-freedom in routing algorithms rely upon the assumption that messages arriving at a destination node are eventually consumed – our proof can be seen as a verification that this property is always maintained under an AM(\( N \)) protocol, which still maintains bounded resource utilization.
(A) Activity $A_1$ at node $N_1$ creates activity $A_2$:
1. $FA := \text{finish}(A_2)$; $FN := \text{node}(FA)$;
2. if node($A_2$) == $N_1$ then \(/ / \text{local activity}
   (a) Create $A_2$ at $N_1$, Push $A_1$ to bottom of $\text{deque}(N_1)$ and start executing $A_2$.
else \(/ / \text{remote activity}
   (a) \text{// Initialize doPush to true if local conditions permit a remote push operation for creating $A_2$
      doPush := (FN \neq N_1) \text{ || hasRemoteChildren}(FA) \text{ || } (\text{Count_out}(N_1) \leq R);
   (b) if doPush then
      i. Send \text{AM request} to create $A_2$ as a fresh activity on node($A_2$)
   ii. Block to await \text{AM reply}; \text{(see (B))}
   iii. if reply == failure then doPush := false;
   (c) if doPush then hasRemoteChildren($FA$):= true; \text{// Remember a child activity was pushed to remote node else Execute}
   activity $A_2$ at node $N_1$ in Doppelgänger mode

(B) Node $N_2$ receives an AM request to create $A_2$:
1. if $\text{Count_in}(N_2) < R$ then
   (a) $\text{Count_in}(N_2)++$; Fresh($A_2$) := true; \text{Put activity $A_2$ at the top of $\text{deque}(N_2)$ ;}
   (b) $\text{Send success}$ reply in response to AM request.
else $\text{Send failure}$ reply in response to AM request.

(C) Activity $A_1$ at $N_1$ stalls to wait for descendants to complete:
1. if hasRemoteChildren($A_1$) then $\text{Count_out}(N_1)++; \text{// }A_1$ is innermost finish for remote push
2. Move $A_1$ to SAB($N_1$).

(D) Activity $A_2$ is removed from the deque by the processor to work on:
1. if Fresh($A_2$) then $\text{Count_in(node}(A_2))--$; \text{// Allow more incoming activities to be accepted.}
2. Fresh($A_2$) := false;

(E) Activity $A_2$ completes, and is the last living local activity in a subtree pushed from a remote node:
1. $FA:= \text{finish}(A_2)$; $FN:= \text{node}(FA)$;
2. Send completion notification for $A_2$ to activity $FA$ on node $FN$.

(F) Activity $FA$ at Node $FN$ receives completion notification for $A_2$:
1. if $FA$ is enabled then
   (a) hasRemoteChildren($FA$):= false; \text{// $FA$ is enabled means that all its descendants have completed.}
   (b) Move $FA$ to middle-insertion point of $\text{deque}(FN)$ ;
   When the processor next picks up $FA$ to work on, it will do $\text{Count_out}(FN)--$

Figure 7: Multi-place Deadlock-free Heuristic Scheduling Algorithm

6. CONCLUSIONS
X10 provides a general dynamic parallelism model in the setting of a virtualized partitioned memory model, and therefore gives programmers the ability to have dynamic parallelism along with locality control. The X10 runtime system is responsible for resource management and, as shown in this paper, there are potential pitfalls that can lead to physical deadlock due to unbounded resource consumption.

We addressed the problem of guaranteeing the absence of physical deadlock in the execution of a parallel program using the X10 async, finish and atomic constructs. We extended previous work-stealing memory bound results for the Cilk language [3] for a single-place execution on an SMP to admit more general synchronization patterns in which one activity may stall for completion of a descendant activity, not just an immediate child as in Cilk. We introduced a new heuristic multi-place algorithm (with a Doppelgänger mode) for deployment on a cluster of uniprocessors that guarantees the absence of physical deadlock in the presence of bounded communication resources. While several language groups have proposed constructs for combining locality control with dynamic threading, we believe that this paper contains some of the first results guaranteeing deadlock-free execution in the presence of bounded resources. For future work, we plan to combine both results to obtain a physical-deadlock-freedom guarantee for deployments on clusters of SMPs.

7. REFERENCES
A. APPENDIX: TECHNICAL DETAILS

A.1 Deadlock Free Scheduling for Single Place X10 Computations (Section 2)

Lemma A.1. In the execution of any terminally-strict (X10) computation by the Work-Stealing Algorithm, let us consider any processor \( p \) and at the beginning of a given time step let there be \( k \) number of activities in \( p \)'s ready deque. Let \( \Gamma_0 \) be the activity that \( p \) is working on. Let \( \Gamma_1, \Gamma_2, \ldots, \Gamma_k \) denote the \( k \) activities ordered from bottom to top, that is, \( \Gamma_1 \) is the bottommost and \( \Gamma_k \) is the topmost. If \( k > 0 \), then the activities in \( p \)'s ready deque satisfy the following properties:

1. For \( i = 1, 2, \ldots, k \), activity \( \Gamma_{i-1} \) is the child of \( \Gamma_i \).
2. For \( i = 1, 2, \ldots, k \), activity \( \Gamma_i \) has not been worked upon since it spawned \( \Gamma_{i-1} \).

Proof. We focus on the case where a stalled activity is enabled in a terminally-strict (X10) computation, since the other cases have already been addressed in the proof of Lemma 4 in [3].

If \( \Gamma_0 \) enables a stalled activity \( \Gamma_x \), then either \( k = 0 \) or the bottommost activity in \( p \)'s ready deque is \( \Gamma_x \). This is because an activity can be enabled only when all the dependencies on descendants are resolved. A dependency is resolved only when the activity from which there is a dependency edge completes (dies). Thus, if \( \Gamma_0 \) enables \( \Gamma_x \), it means that all ancestors, if any, of \( \Gamma_0 \) between itself and \( \Gamma_x \) have completed. If \( \Gamma_0 \) and \( \Gamma_x \) are in same \( p \) and \( \Gamma_0 \) enables \( \Gamma_x \), then by induction we conclude that \( \Gamma_x \) must be the parent of \( \Gamma_0 \) and also the bottommost. If \( \Gamma_0 \) and \( \Gamma_x \) do not belong to same \( p \) and \( \Gamma_0 \) enables \( \Gamma_x \), then by induction the deque should have \( k = 0 \). These two statements imply that either \( k = 0 \) or \( \Gamma_x \) is parent and bottommost. Note that since \( \Gamma_0 \) can enable \( \Gamma_x \) only after completing its last instruction (due to terminally-strict property), by the end of this time step, \( \Gamma_x \) would have been brought to \( p \) according to the rules of the Work-Stealing Algorithm.

These conditions on the deque derived for terminally-strict computation exactly correspond to that for fully-strict computation. Therefore, we claim that the Property (1) and (2) of the lemma are preserved for terminally-strict computations in the case when an activity is enabled. □

Lemma A.2. The Work-Stealing Algorithm for terminally-strict X10 computations preserves the busy-leaves property.

Proof. The proof is straightforward induction on execution time. Let \( k, \Gamma_0, \Gamma_1, \ldots, \Gamma_p \) be as defined in Lemma A.1. For \( k = 0 \), the lemma is vacuously true at the outset. Let \( \Gamma_k' \) denote the activity being worked on by \( p \) after the step. Let \( \Gamma_1', \Gamma_2', \ldots, \Gamma_k' \) denote the \( k' \) activities in \( p \)'s ready deque after the step. We now use Lemma A.1 and the rules of Work-Stealing Algorithm to prove that lemma is preserved. That is, we will show either \( k' = 0 \) or the property holds.

If \( \Gamma_0 \) spawns a child, then \( p \) pushes \( \Gamma_0 \) onto the bottom of the ready deque and commences work on the child. \( \Gamma_0 \) denotes the child which is being worked upon. By Lemma A.1, \( \Gamma_0 \) is the leaf node of the current span subtree and thus busy-leaves property is maintained.

If \( \Gamma_0 \) stalls, then we know that \( \Gamma_0 \) was the only activity running on processor and \( k = 0 \). Therefore, the processor commences work stealing. The busy-leaves property is maintained by default.

If \( \Gamma_0 \) dies, then we have to consider two cases. If \( k = 0 \), then the ready deque is empty, so the processor commences work stealing and when it steals and commences work on an activity, we have \( k' = 0 \). Thus the lemma holds in this case. If \( k > 0 \), the ready deque is not empty, so the processor pops the bottommost activity off the deque and commences work on it. Thus, by virtue of being bottommost, we can deduce from Lemma A.1, that this is the leaf node of current span subtree and hence the busy-leaves property holds.

If \( \Gamma_0 \) enables a stalled activity \( \Gamma_x \), then either \( k = 0 \) or the bottommost activity in \( p \)'s ready deque is \( \Gamma_x \). This is because an activity can be enabled only when all the dependencies on descendants are resolved. A dependency is resolved only when the activity from which there is a dependency edge completes (dies). Thus, if \( \Gamma_0 \) enables \( \Gamma_x \), it means that all ancestors, if any, of \( \Gamma_0 \) between itself and \( \Gamma_x \) have completed. This in conjunction with Lemma A.1 implies that either \( k = 0 \) or \( \Gamma_x \) is bottommost.

If \( \Gamma_0 \) is the bottommost activity in \( p \)'s ready deque, this implicitly means that \( \Gamma_0 \) was the last descendant with a dependency edge to \( \Gamma_x \)'s next instruction. Thus, when \( \Gamma_x \) is enabled it does not have any living descendants and thus the busy-leaves property holds true. If \( k = 0 \), then the enabled activity \( \Gamma_x \) is brought to the \( p \)'s ready deque and made the bottommost in the deque. This means that \( \Gamma_x \) starts executing from next step, thus maintaining the busy-leaves property.
It is clear that all living activities for which there are no living descendants are getting worked upon by some processor. Thus we prove the busy-leaves property.

A.2 Deadlock Freedom in Active Messages (Section 3.2)

Theorem A.3. An AM(N) protocol can be implemented without deadlock and with bounded resource utilization.

Proof. By definition, deadlock occurs when two or more processes are blocked with no ability to make progress. The only blocking operation permitted in an AM(N) protocol is message injection, therefore it suffices to prove deadlock cannot occur when two or more processes are blocked while injecting messages.

The proof is by induction on decreasing virtual network number, with the base case of $V_{N-1}$. All message injection operations that block must service incoming messages on $V_{N-1}$, and handlers running in response to messages received on $V_{N-1}$ must execute and complete without consuming additional messaging resources. Therefore, by the independent progress guarantee of virtual networks, $V_{N-1}$ is guaranteed to eventually make progress, allowing injection operations on $V_{N-1}$ to eventually succeed, proving the base case. For the inductive case, handlers executing in response to messages received on $V_{i}$ may only block while injecting a message on $V_{i+1}$. By the inductive hypothesis, that injection operation will eventually succeed allowing the handler to make progress towards completion, ensuring that it will eventually retire and allow progress on injections into $V_{i}$. Therefore, all message injection operations are guaranteed to eventually make progress, implying deadlock cannot occur.

The resource utilization of an AM(N) protocol is comprised of the resources needed to implement virtual networks $V_0, \ldots, V_{N-1}$, plus the resources needed for any handlers simultaneously active on the program stack of each process. The resource utilization of each virtual network is assumed to be bounded at a fixed value. Handlers for messages on $V_i$ inject messages on $V_{i+1}$ and therefore may only be preempted to service incoming messages on higher-priority networks $V_{i+1}, \ldots, V_{N-1}$ — therefore at most $N$ handlers may be active on the program stack at any time. Each such handler consumes bounded resources, therefore the total resource utilization of the AM(N) protocol is bounded.

A.3 Space Bounds for Multi-Place Algorithm (Section 4)

Lemma A.4. A fresh activity is picked by a processor at a node from the deque only when all the worked-on activities in that node until that instant are either completed or stalled.

Proof. To begin with, let us recall what is a fresh activity. A fresh activity is a term associated with an activity that has been pushed on the deque by a remote node and has not been executed by the processor even once. When an activity is picked by a processor to work on, then the spawn subtree rooted at this activity is explored in a depth-first manner.

Note that the activities created locally during the course of processing the spawn subtree are regarded as worked-on and not fresh. The activities in SAB automatically fall in the class of worked-on by definition.

Suppose at some instant in time at a node $n$, the deque has some fresh activities denoted by set $F$ and some worked-on activities denoted by $W$. Note that fresh activities are pushed onto the top of the deque. Therefore, the set $F$ is placed above the set $W$ in the deque. Another point to note is that the activities in SAB upon getting enabled are inserted between $F$ and $W$ in the deque and are added to the set $W$.

Let us now see the progress at node $n$ from this instant onwards. As mentioned earlier, the processor picks activities from the bottom of deque which implies that in our case it will pick an activity $w$, where $w \in W$. The case where $W$ is empty is similar to Case 1 below. The case $F = \phi$ vacuously holds for all the following cases. Let $W' = W \setminus w$.

The possible cases that may arise are as follows:

1. $w$ completes and $W' = \phi$ and no activity moves to deque from SAB: In this case, an activity in $F$ becomes bottommost in the deque and is picked by the processor.
2. $w$ completes and $W' \neq \phi$: In this situation, the bottommost activity will be from $W'$. Hence, a worked-on and not fresh activity will be picked by the processor.
3. $w$ stalls and $W' = \phi$ and no activity moves to deque from SAB: Here, $w$ is moved to SAB and an activity from $F$ is picked to work on.
4. $w$ stalls and $W' \neq \phi$: In this case, $w$ is moved to SAB and an activity from $W'$ is picked to work on.
5. $w$ spawns a child say $w_c$: The activity $w$ is pushed to the bottom of deque and added to set $W$ if it is not a member already. The processor starts executing the child activity $w_c$.

All the cases above show that a fresh activity is picked by a processor only when the worked-on activities in deque get completed or stalled.

Lemma A.5. The algorithm requires at most $R + S_1$ bytes of space per node for the SAB.

Proof. For a node $N$, the value of $Count_{out}(N)$ is incremented whenever an activity has to stall waiting for completion of its descendants at remote nodes. Note that $Count_{out}$ never exceeds $R$ as can be seen from the algorithm. This implies that at any point in time, we can have at most $R$ activities that are waiting for completion of their remote descendants.

A stalled activity in SAB may also have its ancestors in that SAB. Suppose $A$ is an activity in the SAB at $N$ such that it has some ancestors in the SAB too. Then the oldest such ancestor in the SAB will be referred to as root of $A$ or root($A$). The ancestors may also have immediate remote children in which case they will contribute to $Count_{out}$, otherwise if they are in SAB because of their descendants that are waiting for remote children to finish, then they do not contribute to $Count_{out}$.

As we have seen, an upper bound of $R$ has been enforced on the number of activities in $N$ that have remote descendants. The fact that $Count_{out}$ gets decremented only when an enabled activity that had moved to deque reaches the processor ensures this bound. We now have to bound the activities that reside in the SAB but do not have remote descendants. We have the following cases to consider:

1. $Count_{out} = R$ and for all $R$ activities in SAB at $N$, their root is different: In the worst possible case, the stack depth for each of the $R$ activities in SAB is $S_1$, (since the stack depth can have the maximum size of $S_1$ bytes by definition.) Since $Count_{out} = R$, no new activities will be moved to SAB as per the algorithm.
and, therefore, the upper bound in this case is $R \times S_1$ bytes.

2. Count\textsubscript{out} = $R$ and some activities among the $R$ activities share their root. In this case, the total number of root activities for these $R$ activities will be less than $R$. Then by an argument similar to Case 1, it is clearly seen that the upper bound on the size of SAB is smaller than $R \times S_1$ bytes.

3. Count\textsubscript{out} < $R$: It is straightforward to see in this case that the size of SAB is less than $R \times S_1$ bytes.

These cases cover all possibilities and therefore, the upper bound on size of SAB at a node is $R \times S_1$ bytes.

**Lemma A.6.** The size of the worked-on activities in the deque is bounded by $S_1 + R \times S_{\text{max}}$ bytes per node.

**Proof.** According to the algorithm, there are three sources of worked-on activities in the deque at a node:

1. SAB
2. The activities spawned by worked-on activities are also considered worked-on.
3. A fresh activity gets picked by a processor and, therefore, its status changes to worked-on.

Let us first consider the source of SAB. Any activity that moves to deque from SAB after getting enabled, is pushed at the top of current set of worked-on activities at that node. These enabled activities can enable their ancestors in SAB only when they are picked by processor at that node. We know that a SAB can have a maximum of $R \times S_1$ size, that is at most $R$ leaf activities. This implies that there can be no more than $R$ such activities in the deque that have moved from SAB to deque but have not been picked by processor. This implies that the size required by this set of activities is bounded by $R \times S_{\text{max}}$.

Now let us consider the remaining two sources (2 and 3) above. The processor picks the bottommost activity in the deque. It can be either a worked-on activity or a fresh activity in case the condition of lemma A.4 is met.

During exploration of the spawn subtree rooted at bottommost activity, the size of deque can grow by at most $S_1$ bytes which is the maximum possible depth of the spawn subtree. The Count\textsubscript{out} value at the instant when exploration begins decides the number of activities that can be pushed to SAB. If Count\textsubscript{out} value reaches $R$, then the node switches to Doppelgänger mode. Thus, we see that in all situations, sources 2 and 3 above require a maximum of $S_1$ bytes.

We thus conclude that the space required by worked-on activities is bounded by $S_1 + R \times S_{\text{max}}$.

**Theorem A.7.** The multi-place algorithm in Figure 7 uses at most $2 \times R \times S_{\text{max}} + R \times S_1 + S_1$ bytes of space per node and ensures deadlock freedom.

**Proof.** We need to account for following activities in a node:

1. Fresh activities in deque
2. Worked-on activities in deque and SAB

There is an upper bound of $R$ on the number of fresh activities in a deque and the size of each activity has been bounded by $S_{\text{max}}$. Therefore, the space required by fresh activities in the deque is bounded by $R \times S_{\text{max}}$.

Let us consider the worked-on activities now. As shown in lemma A.6, they are bounded by $S_1 + R \times S_{\text{max}}$. According to Lemma A.5, they are bounded by $R \times S_1$ in SAB. Hence, we prove the total bound of $2 \times R \times S_{\text{max}} + R \times S_1 + S_1$ per node.

The multi-place scheduling algorithm ensures freedom from deadlocks that may arise due to resource bounds in case of normal scheduling. This assurance comes from the Doppelgänger mode by which we ensure that a node does not wait on another node to accept its remote activity. Since there is no such wait involved at any node, an activity that has been spawned already is guaranteed to complete either normally or by using Active Messages (which have also been shown to be deadlock free).