A Conservative Data Flow Algorithm for Detecting All Pairs of Statements that May Happen in Parallel

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ABSTRACT
Information about which pairs of statements in a concurrent program can execute in parallel is important for optimizing and debugging programs, for detecting anomalies, and for improving the accuracy of data flow analysis. In this paper, we describe a new data flow algorithm that finds a conservative approximation of the set of all such pairs. We have carried out an initial comparison of the precision of our algorithm and that of the most precise of the earlier approaches, Masticola and Ryder’s non-concurrency analysis [8], using a sample of 159 concurrent Ada programs that includes the collection assembled by Masticola and Ryder. For these examples, our algorithm was almost always more precise than non-concurrency analysis, in the sense that the set of pairs identified by our algorithm as possibly happening in parallel is a proper subset of the set identified by non-concurrency analysis. In 132 cases, we were able to use reachability analysis to determine exactly the set of pairs of statements that may happen in parallel. For these cases, there was a total of only 10 pairs identified by our algorithm that cannot actually happen in parallel.

1. INTRODUCTION
As the number and significance of parallel and concurrent programs continue to increase, so does the need for methods to provide developers with information about the possible behavior of those programs. In this paper, we address the problem of determining which pairs of statements in a concurrent program can possibly execute in parallel. Information about this aspect of the behavior of a concurrent program has applications in debugging, optimization (both manual and automatic), detection of synchronization anomalies such as data races, and improving the accuracy of data flow analysis [8].

The problem of precisely determining the pairs of statements that can execute in parallel is known to be NP-complete [12]. Most work in the area has therefore focused on finding methods for computing a conservative approximation to the set of pairs that can execute in parallel, that is, computing a set of pairs of statements that contains all the pairs that can actually execute in parallel but may also contain additional pairs. The goal is to find a useful tradeoff between precision and cost.

Several approaches have been proposed. Callahan and Subhlok [1] proposed a data flow algorithm that computes for each statement in a concurrent program the set of statements that must be executed before this statement can be executed (B4 analysis). Duetschwald and Soffa [2] applied this approach to the Ada rendezvous model and extended B4 analysis to be interprocedural. Masticola and Ryder proposed an iterative approach they called non-concurrency analysis [8] that computes a conservative estimate of the set of pairs of communication statements that can never

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flow graphs (CFGs), one for each concurrent process, or task, in the program, with nodes and edges added to represent intertask communications. (If the code region represented by node \( n \) in one task contains a synchronization statement that can correspond to one represented by node \( m \) in another task, a new node is added with incoming edges from \( n \) and \( m \) and outgoing edges to all successors of \( n \) and \( m \). This is illustrated in the figures.)

The TFG model deliberately does not specify exactly what kind of region in the task each CFG node represents, imposing only the weak restrictions that a region cannot contain more than one synchronization statement and that, if a region contains a synchronization statement, it must be the last statement in this region. This underspecification provides for greater flexibility of the model. For example, a CFG node can represent a single machine level instruction, a basic block, or even a set of paths from one synchronization point to another. We also add a unique initial node that has no incoming edges and has outgoing edges to the start nodes of all CFGs and a unique final node that has no outgoing edges and has incoming edges from the end nodes of all CFGs.

Formally, a TFG is a labeled directed graph \((N, E, n_{\text{initial}}, n_{\text{final}}, \mu)\), where \( N \) is the set of nodes, \( E \subseteq N \times N \) is the set of edges, \( n_{\text{initial}}, n_{\text{final}} \in N \) are unique initial and final nodes, and \( \mu \) is a mapping from nodes to regions of code within tasks. The set of all nodes from the CFGs for all tasks forms the set of local TFG nodes, \( \text{LOCAL} \). The elements of the set of non-local nodes, \( \text{COM} = N \setminus \{\text{LOCAL} \cup \{n_{\text{initial}}, n_{\text{final}}\}\} \), are communication nodes, which represent task rendezvous. In building a TFG from a collection of CFGs, the communication nodes are obtained by syntactic matching of synchronization statements. As a result, some nodes in \( \text{COM} \) may be unreachable, but our algorithm is capable of detecting some of these. For each node \( n \), we let \( \text{Pred}(n) \) and \( \text{Succ}(n) \) be the sets of (immediate) predecessors and successors of \( n \), respectively.

Figure 1(a) shows a program that consists of two communicating Ada tasks, Figure 1(b) shows the corresponding CFGs with nodes labeled with the corresponding Ada program statements, and Figure 1(c) gives the corresponding TFG. The local nodes in this TFG have the same labels as the corresponding nodes in the CFGs. Nodes 1 and 2 are communication nodes; node 1 represents the communication between the tasks at entry call \( T2.E1 \), and node 2 represents the communication at entry call \( T2.E2 \).

The TFG model offers a compact representation of the program’s behavior. The number of local nodes in the TFG is linear in the number of program state-

2. THE MHP ALGORITHM

2.1. Program representation

The program representation used in this work is the trace flow graph (TFG) introduced by Dwyer and Clarke [3,4]. This representation is conservative in the sense that it models a superset of all feasible program
ments. A communication node is created for every syntactically matching pair of call and accept statements, so, for example, the local node corresponding to a single call(T2.E) statement in task T1 would share a separate communication node successor with each accept E statement in task T2. In the worst case, this results in the number of communication nodes being quadratic in the number of program statements. However, this blow-up in the number of communication nodes does not seem common in practice. Our experimental results support this hypothesis.

Given a pair (m,n) of nodes in a TFG, we are interested in determining whether, on some computer system, the program represented by the TFG has an execution in which code corresponding to a statement in the task region represented by m executes at the same time as code corresponding to a statement in the task region represented by n. (For the sake of brevity, in the rest of the paper we will use the phrase “node n executes” to mean “an instruction from the task region represented by node n executes”.) If there is such an execution, we say that m and n may happen in parallel, and define $MHP_{\text{perf}}(m,n)$ to be true. This definition of the $MHP_{\text{perf}}$ relation identifies the “ideal” set of pairs of statements that may execute in parallel. The algorithm presented in this paper computes a conservative approximation $MHP$ to $MHP_{\text{perf}}$.

2.2. The MHP algorithm

In this section we give the detailed description of the MHP algorithm and state the major results about its termination, conservativeness, and worst-case time bound. Rather than using the lattice/function space view of data flow problems [5], we give data flow equations for TFG nodes. This is done for two reasons. First, it makes explanations and especially proving properties of this algorithm more intuitive. Second, one aspect of the algorithm precludes its representation as a purely forward- or backward-flow data flow problem or even as a bidirectional [10] data flow problem. We conclude the description of the algorithm by giving pseudo-code for its worklist version.

Our algorithm associates three sets with each node n of the TFG: $GEN(n)$, $IN(n)$, and $M(n)$. The set $M(n)$ is the current approximation to the set of nodes that may happen in parallel with n, while $GEN(n)$ represents the nodes we can place in the approximation based on information local to n and $IN(n)$ represents the nodes we can place in the approximation using information propagated from the predecessors of n. Initially, all three sets for all nodes are empty. These sets are repeatedly recomputed until the algorithm reaches a fixed point and the sets do not change. At this point set $M(n)$ represents a conservative overestimate of nodes with which node n may execute in
parallel.

In addition to these three sets, we assign a Reach bit to each communication node. This bit is initially set to false. Its value is set to true if, on some iteration, each of its two local predecessors belongs to the M set of the other. Intuitively, a task rendezvous represented by a communication node can take place only if both tasks are ready to participate in it. Until the Reach bit of a communication node is set to true, the algorithm assumes that the task synchronization represented by this node is not possible. If the Reach bit of a communication node is still false after the algorithm reaches a fixed point, this means that the task communication represented by it is not possible on any execution of the program.

The sets GEN and IN are computed on each iteration of the algorithm as follows. If n is a local node, let P be the set consisting of ninitial, if n is a successor of ninitial, and all communication nodes C that have n as a successor and have Reach(C) set to true. Then \( \text{GEN}(n) = \left( \bigcup_{p \in P} \text{Succ}(p) \right) \setminus \{m \mid m \text{ is in the same task as } n \} \). Informally, GEN(n) is the set of local nodes m such that m and n are both successors of a reachable communication node, or of the initial node. The idea is that, if a local node is a successor of a reachable communication node, it may happen in parallel with other successors of this communication node since both tasks participating in the communication can execute immediately after the communication. For example, in Figure 2(a), after rendezvous C1 is executed, nodes m1 and n may happen in parallel. If n is a communication node, \( \text{GEN}(n) = \emptyset \).

For a local node n, we put \( \text{IN}(n) = \bigcup_{p \in \text{Pred}(n)} M(p) \), while if n is a communication node, we put

\[
\text{IN}(n) = \begin{cases} \bigcap_{p \in \text{Pred}(n)} M(p) & \text{if Reach(n)} \\ \emptyset & \text{otherwise.} \end{cases}
\]

Here the idea is that, since tasks can execute at varying rates, a local node that may execute in parallel with another node may also execute in parallel with all local successors of that node. A communication node, however, can execute only when both of its predecessors have executed, and so may not execute in parallel with a node that cannot execute in parallel with both of its predecessors. Figure 2(b) provides an illustration. Suppose that nodes n and p may happen in parallel (i.e., that node C is reachable), and nodes m and p may not happen in parallel. Since node L can happen only after both m and n happened, it may not happen in parallel with node p. Note that by construction a communication node can never have nodes in its IN set from the two tasks whose rendezvous it represents.

On each iteration, we set \( M(n) = \text{IN}(n) \cup \text{GEN}(n) \). Up to this point the algorithm is a standard forward-flow data flow algorithm [5]. However, after computing GEN, IN, and M sets for each node, we have to take an additional step to ensure the symmetry \( n_1 \in M(n_2) \iff n_2 \in M(n_1) \) by adding \( n_2 \) to \( M(n_1) \) if \( n_1 \in M(n_2) \). Figure 2(c) illustrates this necessity: without this additional step the M sets of nodes \( n_1 \) and \( m_1 \) are \( \{n_2\} \) (\( \text{GEN}(m_1) = \{n_2\} \) and \( \text{IN}(m_2) = \{n_2\} \)), but the M set of \( n_2 \) is \( \{n_1\} \) (\( \text{GEN}(n_2) = \{n_1\} \)). Thus, \( n_2 \in M(m_1) \) holds but \( m_1 \in M(n_2) \) does not and so the symmetry step in necessary to put \( m_1 \) in \( M(n_2) \).

In Figure 3, we give a worklist version of the MHP algorithm. Although steps (12)-(14) do not allow cast-
Theorem 4 (Polynomial-Time Boundedness). The worst-case time bound for computing MHP sets for all nodes in the TFG is $O(|N|^3)$.

To prove this, we construct an optimized version of the worklist algorithm which limits the amount of information passed among the nodes in the TFG by sending each node from the $M$ set of a given node to each of its successors only once. Then we prove that this efficient algorithm computes exactly the same information as the MHP algorithm in Figure 3 and show that the complexity of the efficient algorithm is $O(|N|^3)$.

The idea of the efficient algorithm is that, if node $m$ is one of control predecessors of node $n$, each node in $M(m)$ should only be inserted in $M(n)$ once. This is achieved by defining an additional set $OUT$ for each node. A node is placed in $OUT(m)$ if and only if it is in $M(m)$ and has never been placed in $OUT(m)$ before. The $IN$ set for a local node is set equal to the union of the $OUT$ sets of all its predecessors. Since each local node has $O(|N|)$ predecessors, and the number of nodes that can be put in the $OUT$ set of each of the predecessors in the course of the algorithm is $O(|N|)$, the number of times a node is added to the $IN$ set of each local node is $O(|N|^2)$. Combined over all local nodes, there are at most $O(|N|^3)$ insertions in $IN$ (and thus $M$) sets. Because each of the communication nodes in the graph has exactly two predecessors, computation of $IN$ sets for communication nodes can be based on the $M$ sets of their predecessors, exactly as in the algorithm in Figure 3, and thus takes $O(|N|)$ operations. Each node in the graph may be placed on the worklist at most $O(|N|^2)$ times, and so the overall
The GEN sets for all nodes in the graph can be largely precomputed and only modified in the course of the algorithm as communication predecessors of local nodes become reachable. This precomputation takes $O(|N|^3)$ and the modification is $O(|N|)$ for each local node for the course of the algorithm.

Combining the complexities for the parts of the algorithm, we obtain the cumulative complexity of $O(|N|^3)$.

We note that, in the worst case $|N|$ is itself quadratic in the number of statements in the program (due to the introduction of communication nodes). In practice, however, $|N|$ is usually a small multiple of the number of program statements. In Section 4, we report on the relation between the number of TFG nodes and the size of the program for our sample of 159 programs.

3. COMPARING NON-CONCURRENcy ANALYSIS WITH THE MHP ALGORITHM

This section introduces the most precise of the previous approaches for computing the MHP information, Masticola and Ryder’s non-concurrency analysis. Since the program model used by this approach is different from TFG, we describe the technique for creating TFGs automatically from the non-concurrency graphs. Finally, since the MHP algorithm computes pairs of nodes that may happen in parallel and non-concurrency analysis computes pairs of nodes that cannot happen in parallel, we present a mapping between these two sorts of data. This mapping allows us to compare the information computed by the two approaches.

3.1. Non-concurrency Analysis

Non-concurrency analysis computes can’t happen together (CHT) information, which is the opposite of what the MHP algorithm computes. The model of the program used in this approach is the sync graph, where each node represents a number of control paths in a task that end in a single synchronization point. Possible rendezvous are represented as hyperedges, connecting the synchronizing paths. Initially it is assumed that a given node can happen together with any of the nodes in the other tasks. Four CHT refinements are then applied, in arbitrary order, until a fixed point is reached. The four refinements are pinning analysis, $B^4$ analysis, RPC analysis, and critical section analysis. The complexity of each of the four refinements is $O(|N_{sync}|^2)$, and the complexity of the overall approach is $O(|N_{sync}|^5)$, where $N_{sync}$ is the set of sync nodes.

3.2. Deriving TFGs from Sync Graphs

In order to compare information computed on sync graphs and TFGs, we construct a special restricted trace flow graph (RTFG) from a sync graph. Here we give only a sketch of this construction. We create a single local RTFG node for each sync graph node, except for those nodes in the sync graph that represent entry calls to accept statements with bodies, for which two local RTFG nodes are constructed. One RTFG node represents the execution of the caller task before the callee task accepts the call. The second RTFG node represents the state of the calling task while the accept body executes. Similarly, a single communication RTFG node is created for each hyperedge that models an entry call to an accept statement without a body and two communication nodes are created for each hyperedge that models an entry call to an accept statement with a body.

Figure 4 gives an example. The sync graph in Figure 4(b) models the communication structure of the simple program in Figure 4(a). The hyperedge representing the call to entry E, made by task T1, is shown as a dashed line, and the wavy line represents the subgraph corresponding to the body of the accept statement in T2. The RTFG derived from this sync graph is shown in Figure 4(c). The matching sync graph and RTFG nodes are labeled with the same numbers. The node labeled 1’ in the RTFG represents the second local node created for the sync graph node 1.

3.3. Mappings between the information computed by the two approaches

The algorithm for constructing RTFGs from sync graphs provides us with a mapping $\mu : N_{sync} \rightarrow 2^N$, where $N_{sync}$ is the set of nodes in the sync graph and $N$ is the set of nodes in the corresponding RTFG. We define a function $\mu^{-1} : 2^N \rightarrow 2^{N_{sync}}$ by setting $\mu^{-1}(S) = \{ \mu(n) \mid n \in S \neq \emptyset \}$.

Using these mappings, we can “translate” the MHP information from the RTFG to the corresponding sync graph by mapping the MHP set computed for a node $n$ in the RTFG to the corresponding node in the sync graph. In cases where a sync graph node $\mu(n)$ has two corresponding RTFG nodes $n_1$ and $n_2$, $MHP(\mu(n))$ is defined as the union of the two translated sets $MHP(n_1)$ and $MHP(n_2)$. In general, $MHP(\mu(n)) = \bigcup_{n \in \mu^{-1}(\mu(n))} MHP(n)$.

The result is that each node in the sync graph has a CHT set and an MHP set associated with it. To compare these sets, we must take the facts that,
for each node $\hat{n}$ in the sync graph, $\hat{n} \notin MHP(\hat{n})$ and $\hat{n} \notin CHT(\hat{n})$ into account. For any function $A: N_{sync} \rightarrow 2^{N_{sync}}$, let $A^+(\hat{n}) = A(\hat{n}) \cup \{\hat{n}\}$. Then $CHT(\hat{n})$ computed by non-concurrency analysis corresponds to $MHP^+(\hat{n})$ computed by the MHP algorithm, where the bar indicates the complement. Thus, to compare the precision of the two techniques, we compare the sets $CHT(\hat{n})$ and $MHP^+(\hat{n})$. One technique is more precise than the other if, for each node $\hat{n}$, the set computed by the former contains the set computed by the latter.

3.4. Theoretical comparison

We compared the theoretical precision of information computed by the MHP algorithm and non-concurrency analysis. Specifically, we compared the MHP algorithm to each of the four refinements used by non-concurrency analysis, attempting to prove or disprove that our algorithm is more precise than this refinement. We say that the MHP algorithm subsumes a refinement if, given that the MHP information was at least as precise as the CHT information before the refinement (i.e., that $CHT(\hat{n}) \subseteq MHP^+(\hat{n})$ for all $\hat{n}$), that is still the case after the refinement. Due to space limitations, we briefly state the results of this comparison without proof.

We were able to prove that the MHP algorithm subsumes the pinning and B4 refinements of the non-concurrency approach. On the other hand, we found counterexamples showing that the MHP algorithm does not subsume the critical section and RPC refinements. The MHP algorithm can be improved to take advantage of critical section regions\footnote{In the TFG model the subgraph corresponding to the RPC structure is just a special case of the critical section structure. Therefore, this extension of the MHP algorithm also takes advantage of the information about remote procedure calls.}. However, the resulting algorithm is more complicated than the one presented in this paper and its worst-case complexity is $O(|N|^9)$. Our initial evaluation of the performance of the MHP algorithm, discussed in the next section, seems to indicate that the gain in precision may not warrant this added complexity. We plan to investigate these trade-offs in our future work.

4. EXPERIMENTAL RESULTS

We measure the precision of the information computed by a technique in terms of the set of pairs of nodes in the sync graph that this technique determined cannot happen in parallel. We write $P_{NCA}$ for the set of CHT pairs found by non-concurrency analysis and $P_{MHP}$ for the set of CHT pairs found by the MHP algorithm.

Stephen Masticola graciously provided us with his implementation of non-concurrency analysis, written in C. We used this for our experiments, together with our own implementation of the MHP algorithm, written in Java. In addition, we wrote a reachability tool to find all reachable program states of the RTFG model, also in Java. Although the reachability tool runs out of memory for some of our test programs, in the cases where it ran successfully, it determined the “ideal” set of pairs of nodes that can happen in parallel. Assuming that no data sharing and no unreachable code exists in the program, this set is equal $MHP_{perf}$. Given this set, we computed $CHT_{perf}$, the “ideal” set of pairs
of nodes that cannot happen together. We ran the non-concurrency tool on a Sun Sparc 10 with 32 MB of memory, and the MHP tool and the reachability tool on an AlphaStation 200 with 128 MB of memory. (The non-concurrency tool could not be compiled on the AlphaStation, which is our primary platform.)

We used a sample of 159 Ada programs, including the suite of 138 programs Masticola and Ryder used in their experiments with non-concurrency analysis. Most of the remaining programs are examples drawn from the concurrency literature, such as the dining philosophers and the gas station. Of the 159 programs, 25 did not have loops. The sizes of the programs range from only a few lines of code to several thousand lines. This program sample contains several groups of programs representing different sizes and variations of the same basic example and actually contains approximately 90 significantly different examples. It is, of course, unlikely that this sample of relatively small programs is representative of concurrent Ada programs in general, but our results provide some initial data indicating that the MHP algorithm is very often more precise than non-concurrency analysis.

In the following discussion of the results, we separate the program sample into three subsets, which we discuss separately. First, we consider the 25 programs without loops. For all of these programs, which come from the Masticola-Ryder collection, the MHP algorithm found all the CHT pairs found by non-concurrency analysis. Second, we describe our results for the 9 programs in which non-concurrency analysis detected some CHT pairs not found by our MHP algorithm. Finally, we describe the results for the remaining 125 programs, those with loops for which the MHP algorithm found all the CHT pairs found by non-concurrency analysis. The focus of our discussion is on the detection of CHT pairs by the two approaches. We do comment briefly on the execution times for non-concurrency analysis and our MHP approach, but these times do not have much significance. Neither we nor Masticola and Ryder aimed to maximize the speed of the implementations. In addition, non-concurrency analysis was implemented in C, a compiled language, and the MHP algorithm was implemented in Java, an interpreted language. Finally, as mentioned above, the tools were run on different machines with different operating systems, clock speeds, and memory sizes. Thus, we view the comparison of the precision of the two approaches as the primary goal of this experiment.

### 4.1. Programs without loops

We realize that the programs without loops are not likely to be realistic examples, and so we consider them separately from other programs. The reachability analysis was completed successfully for all but one of the 25 programs without loops, and in all such cases the MHP algorithm found all pairs found by reachability (so \( P_{MHP} = CHT_{perf} \) for all RTFG nodes). In 8 cases, the MHP algorithm found a small number of pairs that non-concurrency analysis did not, with the average ratio \( |P_{MHP}|/|P_{NCA}| \) of 1.01. The average timing ratio (NCA time)/(MHP time) was 1.82, with most running times for both tools well under a second.

### 4.2. Programs where non-concurrency analysis found pairs that the MHP algorithm did not

Non-concurrency analysis found some CHT pairs not found by the MHP algorithm in 9 of the 159 cases we ran. The complete data for these cases are presented in Table 1. The first column of this table shows the program size in terms of the number of nodes in the sync graph. The next three columns give the number of pairs of nodes that cannot happen together, as found by the three different methods. The fifth column gives the number of pairs found by the MHP algorithm that were not found by non-concurrency analysis, while the sixth column gives the number of pairs found by non-concurrency analysis but not by the MHP algorithm. The seventh and eighth columns give, for the 5 cases that our reachability tool could handle, the number of pairs in CHT_{perf} that were not found by non-concurrency analysis and by the
columns show the time used by each of the analysis methods; times are in seconds and include both user and system time. An interesting observation is that, for the 5 cases in which our reachability tool could determine $CHT_{\text{perf}}$, although neither the $MHP$ algorithm nor non-concurrency analysis found all possible pairs, the combination of the two approaches was as precise as reachability.

Figure 5 compares the precision of the two approaches by comparing the total number of $CHT$ pairs found by each of them to the number of $CHT$ pairs in the union $P_{NCA} \cup P_{MHP}$. As just noted, this union is equal to $CHT_{\text{perf}}$ in the 5 cases that our reachability tool could handle. Note that in all cases the $MHP$ algorithm outperformed non-concurrency analysis in terms of the total number of $CHT$ pairs found.

4.3. The other 125 programs

The remaining 125 programs are those that have loops and where the $MHP$ algorithm found all $CHT$ pairs that non-concurrency analysis did. Of these, the reachability tool ran in 102 cases. For all of these 102 cases in which we were able to determine $CHT_{\text{perf}}$, the $MHP$ algorithm found all the pairs in $CHT_{\text{perf}}$. Non-concurrency analysis found all the pairs in $CHT_{\text{perf}}$ in only 22 cases.

Of these 125 programs, there were 101 cases in which the $MHP$ algorithm found some pairs that were not found by non-concurrency analysis (in the remaining 24 cases, the $MHP$ algorithm and non-concurrency analysis found exactly the same pairs). Figure 6 plots the ratio $|P_{MHP}|/|P_{NCA}|$ against the program size, measured as the number of nodes in the sync graph. The average precision ratio $|P_{MHP}|/|P_{NCA}|$ was 1.41 and the average timing ratio $\text{NCA time}/\text{MHP time}$ was 2.94. The running times of both tools were under 4 minutes for all programs.

4.4. The number of RTFG nodes

In addition to comparing the performance of the two approaches, we examined the question of potential quadratic blow-up in the number of RTFG nodes. We plot the number of sync graph nodes against the number of RTFG nodes in Figure 7. The figure also shows the least-squares regression line, which has a slope of 1.84. The correlation coefficient is .984. This sample of programs thus offers strong support for the hypothesis that, in practice, the number of RTFG nodes depends linearly on the number of sync graph nodes. Since the size of the sync graph is linear in the number of program statements, the same appears to be true for RTFGs.

5. CONCLUSION

Information about which pairs of statements may execute in parallel has important applications in optimization, detection of anomalies such as race conditions, and improving the accuracy of data flow analysis. Efficient and precise algorithms for computing this information are therefore of considerable value. In this paper, we have described a data flow method for computing a conservative approximation of the set of pairs of statements in a concurrent program that may execute in parallel. Theoretically, neither non-concurrency analysis nor our $MHP$ algorithm has a clear advantage in precision. However, based on our experimental data, the $MHP$ algorithm often is able to determine the pairs of statements that may execute in parallel more precisely than non-concurrency analysis.

As a part of our experiments, we compared the precision of the $MHP$ algorithm with the precision of a technique based on the exhaustive exploration of the program state space. While this reachability technique, being exponential in the program size, is not practical in general, with its help we were able to compute "perfectly" precise information for many examples. For these examples, the information computed by the $MHP$ algorithm was remarkably close to that of the reachability technique.

At present, the $MHP$ algorithm is being used as part
Figure 5: Precision comparison for the 9 cases where non-concurrency analysis found some pairs that the MHP algorithm did not

Figure 6: The precision ratio $|P_{MHP}|/|P_{NCA}|$ for the 125 programs with loops where the MHP algorithm found all CHT pairs found by non-concurrency analysis


In the future, we plan to extend the MHP algorithm to apply to programs containing procedure and function calls without using inlining. Even in its current form, the MHP algorithm can be easily used to support a limited form of interprocedural MHP analysis, with the restriction that procedures may not contain task entry calls. Under this restriction, the MHP sets computed for procedure call nodes are sufficient to determine the MHP sets for all nodes in this procedure. Thus, if $n$ is a call node for procedure $P$, then any node in the body of $P$ may happen in parallel with any node in $MHP(n)$, computed the MHP algorithm. Special care must be taken when there is a possibility that a procedure may be called by more than one task, in which case executions of multiple instances of this procedure may overlap in time. In this case, unlike task nodes, the MHP sets of nodes from the procedure will contain other nodes from the same procedure. To determine whether this might happen, we have to check
of any of the other call nodes to this procedure (this has to be done recursively for nested procedure calls), in which case the MHP sets of all nodes in $P$ must contain all nodes in $P$.

In the case of procedures containing entry calls, we plan to use a context-sensitive approach, extending the TFG model to include procedure call and return edges, similar to the approach of [6], and modifying the MHP algorithm accordingly.

In addition, we plan to implement an algorithm that improves the precision of the MHP algorithm by taking advantage of information about regions in the program that can only execute in a mutually exclusive fashion, in a way similar to the critical section analysis refinement of non-concurrency analysis. Then we plan to carry out a careful comparison of the performance of this improved algorithm with that of the algorithm presented in this paper and of the non-concurrency approach. The initial hypothesis, which seems to be supported by this work, is that in practice the improved algorithm will be only marginally more precise than the current algorithm. We hope to perform these experiments for a larger program sample with more realistic programs and to evaluate the trade-offs of precision and cost added by the improved algorithm.

Finally, we are working on an MHP algorithm for concurrent Java programs. The differences in the way communications between threads of control are realized in Ada and Java imply different program models. While we are able to use the same general principle for Java as the one we introduce in this paper for Ada, there are a number of significant changes in the data flow equations used by the algorithm for Java. It will be interesting to see if the practical precision of the MHP algorithm depends on the differences in communication mechanisms of the different concurrent languages.

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