Region-Based May-Happen-in-Parallel Analysis for C Programs

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Abstract—The C programming language continues to play an essential role in the development of system software. May-Happen-in-Parallel (MHP) analysis is the basis of many other analyses and optimisations for concurrent programs. Existing MHP analyses that work well for programming languages such as X10 are often not effective for C (with Pthreads).

This paper presents a new MHP algorithm for C that operates at the granularity of code regions rather than individual statements in a program. A flow-sensitive Happens-Before (HB) analysis is performed to account for fork-join semantics of Pthreads on an interprocedural thread-sensitive control flow graph representation of a program, enabling the HB relations among its statements to be discovered. All the statements that share the same HB properties are then grouped into one region. As a result, computing the MHP information for all pairs of statements in a program is reduced to one of inferring the HB relations from among its regions.

We have implemented our algorithm in LLVM-3.5.0 and evaluated it using 14 programs from the SPLASH2 and PARSEC benchmark suites. Our preliminary results show that our approach is more precise than two existing MHP analyses yet computationally comparable with the fastest MHP analysis.

Keywords—MHP; May-Happen-in-Parallel; concurrent program; multi-threading; static analysis;

I. INTRODUCTION

May-Happen-in-Parallel (MHP) analysis determines statically whether a given pair of statements in a concurrent program may be executed in parallel or not. This analysis serves as a cornerstone of many other static and dynamic analyses on detecting, for example, data races [1], [2] and deadlocks [3]. However, determining precisely whether all pairs of statements in a concurrent program may happen in parallel or not is NP-complete [4]. As a result, most of previous MHP algorithms either achieve precision by taking advantage of some language features in a particular programming language or sacrifice precision by computing approximated results.

The X10-like languages provide structured language features to simplify parallel programming. Their concurrency control constructs, async and finish, supports async-finish parallelism, by avoiding arbitrary uses of joins to make stronger scheduling guarantees. Unstructured languages such as C/C++ and Java remain mainstream in modern software development. Unlike structured language constructs, unstructured and low-level fork-join constructs allow programmers to express rich and complicated patterns of parallelism. However, such flexible non-lexically-scoped parallelism poses a major challenge to scalable and precise MHP analysis. The techniques developed for structured languages [5], [6], [7], [8] cannot be directly applied to unstructured languages. In C programs, for example, a thread may outlive its spawning thread or can be joined partially along one program path (a partial join) or indirectly in one of its child threads (a nested join). Thus, a sophisticated interprocedural analysis is needed to capture the MHP relations in C programs.

Previously, a MHP analysis for Java [9] introduces an abstract thread structure analysis to capture the fork and join interactions among threads. However, this analysis ignores partial and nested joins, which are some limitations to be overcome in this paper.

In this paper, we present a new MHP algorithm to analyse C programs. We perform a flow-sensitive Happens-Before (HB) analysis for a program by considering the fork-join semantics of Pthreads on an interprocedural thread-sensitive control flow graph representation of the program. All the statements that share the same HB properties in the program are grouped into one region, so that computing the MHP information for all pairs of statements in the program is reduced to one of inferring the HB relations from among its regions.

Our contributions are summarised as follows:

• We introduce a new MHP analysis that models the fork-join semantics of Pthreads in a C program by performing an interprocedural flow-sensitive analysis on a thread-sensitive control flow graph representation of the program.

• We present a region partitioning algorithm to build a Region Relation Graph (RRG) for a program in order to compute effectively the MHP information for the program by operating at the granularity of its code regions rather than individual statements.

• We have implemented our algorithm in LLVM-3.5.0 and evaluated it using 14 programs from the SPLASH2 and PARSEC benchmark suites. Our preliminary results show that our approach is more...
precise than two existing MHP analyses yet computationally comparable with the fastest MHP analysis.

II. STATIC THREAD MODEL

A. Abstract Thread

An abstract thread\(^1\) refers to a call of \texttt{pthread_create()} at a fork site during the analysis. Abstract threads are modelled context-sensitively so that a thread \(t\) always refers to a context-sensitive fork site, i.e., a unique runtime thread unless \(t\) is multi-forked, in which case, \(t\) may represent more than one runtime thread.

**Definition 1** (Multi-Forked Threads). A thread \(t\) is a multi-forked thread if its fork site \(f_{tm} \rightarrow t\) resides in a loop, recursion or its spawner thread \(t_m\) is multi-forked.

For a non-multi-forked thread, its context-sensitive fork site is cloned for its different calling contexts so that the thread uniquely identifies one single runtime thread.

We use \(f_{tm} \rightarrow t\) to denote a fork site, where \(t_m \rightarrow t\) represents a spawning relation such that a spawner thread \(t_m\) creates a spawnee thread \(t\). Similarly, \(j_{tm} \rightarrow t\) denotes a join site, where \(t_m \rightarrow t\) represents a joining relation such that a spawnee \(t\) is joined by its spawner \(t_m\). For a thread \(t\), we write \(S_t\) to stand for the start procedure of \(t\), where the execution of \(t\) begins.

B. Thread-Sensitive Control Flow Graph

Given a program, its interprocedural control flow graph (ICFG [10]) is a directed graph. A node represents a basic block containing a sequence of statements. An intraprocedural edge from one block to another represents the flow of control between the two blocks. All interprocedural edges represent the calling relations across the procedures. Indirect calls can be found using Andersen's pointer analysis [11], [12], [13].

An ICFG can be augmented to yield a thread-sensitive interprocedural control flow graph (TCFG) by adding fork and join edges to represent their thread spawning and joining relations, respectively, as highlighted by the dashed arrows in Figure 1. For a thread \(t\), we write \(G_t\) to represent the subgraph of the TCFG corresponding to \(t\), from the entry of \(t\)'s start procedure \(S_t\) to the exit of \(S_t\), including all reachable callees of \(S_t\) but excluding the statements in any spawnee thread of \(t\).

C. Modeling Thread Joins

To handle joins effectively, we distinguish direct (or immediate) and indirect (or nested) joins. In particular, indirect joins are recursively defined below.

**Definition 2** (Direct and Indirect Joins). A join site \(j_{tm} \rightarrow t\) represents a direct join of \(t\) in \(t_m\). In addition, a join site \(j_{tm} \rightarrow t'\) represents an indirect join of \(t\), where \(t \neq t'\), if every execution path in \(t'\) contains a join site \(j_{tm} \rightarrow t\), which is either a direct or indirect join of \(t\) in \(t'\).

Therefore, a join site \(j_{tm} \rightarrow t'\) that represents a join for a thread \(t\) is direct if \(t = t'\) and indirect otherwise. Figure 2 illustrates four different join patterns to be explained below. Each \(Join(t) (Join(t'))\) represents a direct join for \(t\) (\(t'\)). In addition, as illustrated in Figure 2(c), \(Join(t')\) represents an indirect join of \(t\) in \(t_m\).

In C programs, a thread can be joined fully along all program paths or partially along some but not all paths. Both cases need to be handled precisely.

**Definition 3** (Full and Partial Joins). A join site \(j_{tm} \rightarrow t'\) that represents a join of a thread \(t\) (where \(t\) and \(t'\) may or may not be the same) is a full (partial) join of \(t\) in \(t_m\) if it is reachable by its corresponding fork site \(f_{tm} \rightarrow t\) along all (some but not all) program paths.

Existing MHP analyses [9], [14] handle a join site conservatively. A join site \(j_{tm} \rightarrow t\) is considered only if \(j_{tm} \rightarrow t\) post-dominates its corresponding fork site \(f_{tm} \rightarrow t\) (as in the case of Figure 2(a)) but ignored otherwise (as in the more complex join cases illustrated in Figures 2(b) – (d)). In Figure 2(b), \(t\) is joined fully in \(t_m\) at two different join sites in the two branches. In Figure 2(c), \(t_m\) creates two threads \(t\) and \(t'\), with \(t\) being joined fully with \(t_m\) via a join site in \(t'\) in an indirect manner. In Figure 2(d), \(t\) can outlive its spawner \(t_m\) via a partial join in the \texttt{if} branch. If the \texttt{if} branch is taken, \(t\) terminates after the partial join. If the \texttt{else} branch is taken, \(t\) may still be alive even after \(t_m\) has finished its execution.

Conservatively handling the above join behaviours may lead to imprecise MHP results. Figure 3 shows a partial join from \texttt{x264} in the PARSEC benchmark suite, where the thread identified by \(h \rightarrow \text{thread\_handle}\) is joined.
Figure 2: Full and partial join patterns. In (c), $\text{Join}(t')$ is not only a direct join of $t'$ but also an indirect join of $t$.

// file encoder/encoder.c
1312 static int x264_slices_write (x264_t *h){
1313    static int x264_stack_align (x264_slice_write, h);
1314    h->out nal[h->out.i_nal-1].i_payload;
1315 }  
1316 int x264_encoder_encode (...){
1317    if(h->param.i_threads > 1)
1318 {  
1319       pthread_create(&h->thread_handle,  
1320            NULL,( void *) x264_slices_write ,h);
1321       h->b_thread_active = 1;
1322  }
1323 }  
1324  
1325 static void x264_encoder_frame_end  
1326   (x264_t *h,...){
1327    if(h->b_thread_active)
1328 {  
1329       pthread_join (h->thread_handle,NULL);
1330       h->b_thread_active = 0;
1331  }
1332 }  
1333 
1334 Figure 3: A partial join in PARSEC.x264.

partially inside an if branch in line 1707. Thus, the statements from line 1708 after the join site to the end of the if branch do not happen in parallel with any statement in the start procedure x264_slice_write of $h->\text{thread}\_\text{handle}$. However, ignoring this join site will result in spurious MHP statement pairs.

Following [9], [15], we presently conduct a may-alias analysis [11], [12], [13] to approximate the set of abstract threads joined at a join site. This can be unsound as a may-analysis is conservative. In general, handling all join sites both soundly and precisely in the presence of multi-forked threads (Definition 1) is difficult. However, it is possible to do so in some common usage scenarios. In Figure 7(a), a “fork” loop is first used to spawn a fixed number of threads (lines 18 – 20) and then a “join” loop is used later to join all these threads (lines 22 – 24). Such a usage pattern for multi-forked threads can be analysed by taking advantage of LLVM’s high-level loop optimiser, Polly, which uses polyhedral abstractions to analyze in-loop memory access patterns. The results computed by Polly can assist our analysis to determine if a multi-forked thread can be joined soundly.

III. REGION-BASED MHP ANALYSIS

We first perform a flow-sensitive analysis on TCFG to discover the statement-level Happens-Before information by considering the order in which threads execute. We then partition the statements in the program into regions, so that the statements with the same HB properties are grouped together to reduce the overhead incurred in computing all-pair MHP statements.

A. Thread Order Properties

For each context-sensitive abstract thread $t$ spawned at its fork site $f_{t_m \rightarrow t}$, we classify the statements (excluding fork and join sites) contained in both $G_t$ and $G_{t_m}$ into five categories to approximate the runtime thread execution order between $t$ and its spawner $t_m$.

Definition 4 (Thread Order Properties). Let $f_{t_m \rightarrow t}$ be a fork site. The statements in $G_t$ and $G_{t_m}$ are classified, by considering direct and indirect joins of $t$ in $t_m$:

- **BEF** (BEFORE): statements in $G_{t_m}$ that may be executed before the fork site $f_{t_m \rightarrow t}$
int gvar; // global variable
void *S(void *x) { gvar = 9; }

void main() {
    pthread_t t;
    gvar = 1;
    if (true) {
        gvar = 2;
        for(int i = 0; i < 2; i++) {
            gvar = 3;
            pthread_create(&t, NULL, S, NULL);
            gvar = 4;
            pthread_join(t, NULL);
            gvar = 5;
        }
        gvar = 6;
    } else {
        gvar = 7;
    }
    gvar = 8;
}

(a) Code

Figure 4: An example on classifying statements with different thread execution properties. Given $t_m$ as the main thread and $t$ as the multi-forked thread created inside the loop, we have: $P_{t_m \rightarrow t}(1) = P_{t_m \rightarrow t}(2) = BEF$, $P_{t_m \rightarrow t}(6) = P_{t_m \rightarrow t}(8) = AFT$, $P_{t_m \rightarrow t}(3) = P_{t_m \rightarrow t}(4) = P_{t_m \rightarrow t}(5) = FKJ$, $P_{t_m \rightarrow t}(7) = DPP$, and $P_{t_m \rightarrow t}(9) = SLA$.

- **AFT (AFTER):** statements in $G_{t_m}$ that may be executed after a join site $j_{t_m \rightarrow t'}$ that represents a (direct or indirect) join of $t$ in $t_m$ (if it exists);
- **FKJ (FORK-JOIN):** statements that appear in some execution path from the fork site $f_{t_m \rightarrow t}$ to a corresponding join site $f_{t_m \rightarrow t'}$ that represents a join of $t$ (if it exists) or to the exit of $G_{t_m}$ (otherwise);
- **DPP (DISJOINT PROGRAM PATHS):** statements in $G_{t_m}$ that do not appear in any common execution path as the fork site $f_{t_m \rightarrow t}$; and
- **SLA (SLAVE):** statements in $G_t$ of the spawnee $t$.

In what follows, we write $P_{t_m \rightarrow t}(s)$ to represent a function mapping a statement $s$ in $G_{t_m}$ and $G_t$ to \{BEF, AFT, FKJ, DPP, SLA\} with respect to one spawning relation $t_m \rightarrow t$.

Let us consider an example in Figure 4, where $t_m$ represents the main thread and $t$ a multi-forked thread created inside a loop. Statements $\Box$ and $\blacklozenge$ are annotated with BEF since both may be executed before $t$ is created, while statements $\lozenge$ and $\blacktriangle$ are annotated with AFT since both may be executed after the join site. However, statements $\blacktriangle$ and $\blacklozenge$ reside in a loop, causing each to possess both BEF and AFT, and are thus annotated with FKJ. Statement $\Box$ lies on a path between the fork site and join site and is thus labelled with FKJ. Statement $\bigcirc$ is annotated with DPP since the executions of this statement and the fork site are mutually exclusive.

Finally, statement $\bigcirc$ in $G_t$ is annotated with SLA.

B. Flow-Sensitive Static Happens-Before Analysis

In Algorithm 1, we present our flow-sensitive analysis for annotating the statements in a program with their thread order properties. Our algorithm works by considering all thread spawning relations individually (lines 1 and 2). For a spawning relation $t_m \rightarrow t$ created at a fork site $f_{t_m \rightarrow t}$, we first mark every statement $s$ in $G_t$ as SLA: $P_{t_m \rightarrow t}(s) = SLA$ (lines 3 and 4). We then mark each statement $s$ in $G_{t_m}$ so that $P_{t_m \rightarrow t}(s) \in \{BEF, AFT, FKJ, DPP\}$ by Definition 4 (lines 5 – 24).

We do so by first partitioning $G_{t_m}$ into two subgraphs, $G^R_{t_m}$ that contains all statements reachable by the fork site $f_{t_m \rightarrow t}$ along some program paths either forwards or backwards and $G^N_{t_m}$ that contains the remaining unreachable statements (line 5). This is achieved by solving a data-flow problem but omitted here.

For every statement $s$ in $G^N_{t_m}$, we set $P_{t_m \rightarrow t}(s) = DPP$ (lines 6 and 7). For the statements in $G^R_{t_m}$, we solve a forward data-flow problem $(V, \cap, F)$ (lines 8 – 24). We use the semilattice shown in Figure 5, where $V = \{BEF, AFT, FKJ, T\}$ and $\cap$ is the meet operator. Note that if a fork site and its corresponding join site appear in recursion or a loop, a statement can have both BEF and AFT properties, which will be combined into FKJ. $F$ represents the set of transfer functions used for the statements in $G^R_{t_m}$, given in lines 18, 20 and 22. Note that
Algorithm 1: Annotating Thread Order Properties

1. $F \leftarrow \text{set of all fork statements in the program}$
2. foreach $t_m \rightarrow t \in F$ do
3.     foreach statement $s$ in $G_t$ do
4.         $P_{t_m \rightarrow t}(s) \leftarrow \text{SLA}$
5. Partition $G_{t_m}$ into $G_{t_m}^R$ that contains the statements reachable by $f_{t_m \rightarrow t}$ either forwards or backwards along some paths in $G_{t_m}$ and $G_{t_m}^R$ that contains the remaining statements
6. foreach statement $s$ in $G_{t_m}^N$ do
7.     $P_{t_m \rightarrow t}(s) \leftarrow \text{DPP}$
8. foreach statement $s$ in $G_{t_m}^R$ do
9.     $P_{t_m \rightarrow t}(s) \leftarrow \top$
10. $W \leftarrow \text{set of statements in } G_{t_m}^R$
11. Let $s_{\text{entry}}$ be the entry statement in $G_{t_m}^R$
12. $W = W \cup \{s_{\text{entry}}\}$
13. $P_{t_m \rightarrow t}(s_{\text{entry}}) \leftarrow \text{BEF}$
14. while $W \neq \emptyset$ do
15.     $s = \text{a statement removed from } W$
16.     foreach $s' \in \text{succ}(s)$ in $G_{t_m}^R$ do
17.         if $s'$ is the fork site $t_m \rightarrow t$ then
18.             $P_{t_m \rightarrow t}(s') = P_{t_m \rightarrow t}(s') \cap \text{FKJ}$
19.         else if $s'$ is a join site $j_{t_m \rightarrow t'}$ representing a join of $t$ then
20.             $P_{t_m \rightarrow t}(s') = P_{t_m \rightarrow t}(s') \cap \text{AFT}$
21.         else
22.             $P_{t_m \rightarrow t}(s') = P_{t_m \rightarrow t}(s') \cap P_{t_m \rightarrow t}(s)$
23.     if $P_{t_m \rightarrow t}(s')$ has changed then
24.         $W = W \cup \{s'\}$

$succ(s)$ denotes the set of successors of a statement $s$ in $G_{t_m}^R$. To compute $P_{t_m \rightarrow t}(s)$ iteratively for each statement $s$ in $G_{t_m}^R$, we first perform the standard initialisation in lines 8 and 9. We then perform a forward data-flow analysis to annotate each statement $s$ in $G_{t_m}^R$ with $\text{BEF}$, $\text{AFT}$ or $\text{FKJ}$ (lines 10 – 24). Three different transfer functions are applied when processing three kinds of statements: (1) the (unique) fork statement $f_{t_m \rightarrow t}$ (lines 17 and 18), (2) its corresponding join statements $j_{t_m \rightarrow t'}$ for joining $t$ (if any) (lines 19 and 20), and (3) the remaining statements (lines 21 and 22).

C. Region Relation Graph

After having annotated all the statements in a program with their thread-order properties, we proceed to partition the program into regions so that the statements in the same region share the same thread-order properties. We achieve this by considering each $G_{t_m}$ individually for all spawning relations $t_m \rightarrow t$ created in $t_m$. Two statements $s_1$ and $s_2$ in $G_{t_m}$ are grouped in the same region if and only if $P_{t_m \rightarrow t}(s_1) = P_{t_m \rightarrow t}(s_2)$ for every possible thread $t$ spawned by $t_m$. Note that $P_{t_m \rightarrow t}(s) = P_{t_m \rightarrow t'}(s)$ may not necessarily hold when $t \neq t'$. For every region $r$ thus obtained from $G_{t_m}$, we abuse our notation by writing $P_{t_m \rightarrow t}(r)$ to mean $P_{t_m \rightarrow s}(s)$ for some $s \in r$ (since $P_{t_m \rightarrow t}(s_1) = P_{t_m \rightarrow t}(s_2)$ for $s_1, s_2 \in r$). For every thread $t$ spawned by $t_m$, we assume that $G_t$ has been eventually partitioned into $n$ regions (when $G_t$ is processed), $r_1, \ldots, r_n$. By Definition 4, we know that $P_{t_m \rightarrow t}(r_1) = \cdots = P_{t_m \rightarrow t}(r_n) = \text{SLA}$.

Given a program, its region relation graph (RRG) is a directed graph, where each node represents a region and each edge between two regions represents an inter-thread HB relation. We apply the rules given in Figure 6 to construct the inter-thread HB relations for a RRG. We distinguish two types of edges, denoted by $\rightarrow$ and $\leftarrow$, which represent unconditional and conditional HB relations, respectively. [FORK] models the HB relations established due to thread creation. [JOIN] models the HB relations due to full and partial thread joins. For a full join, $r' \leftarrow r$ represents the standard HB relation, which happens unconditionally between $r$ and $r'$. For a partial join, $r' \leftarrow r$ represents a conditional HB relation, which happens only conditionally between $r$ and $r'$ when the partial join actually takes place.

Let us now examine the last rule in Figure 6. In [DISJOINT-PATHS], we deal with the case when a region...
r in $t_m$ never appears on the same execution path as the fork site $f_{m \rightarrow j}$ in $t_m$. We postulate the existence of $r' \xleftarrow{} r$ (rather than $r \leftarrow r'$) in order to achieve better precision in practice. This is because for every spawning relation $t_m \rightarrow t$, there usually exist a region $r$ in $t_m$ (where $P_{t_m \rightarrow t_m}(r) = BEF$) and a region $r'$ in $t$ (where $P_{t_m \rightarrow t}(r) = SLA$) such that $r' \xleftarrow{} r$. This can always happen if the entry node of every sub-TCFG is assumed to contain a no-op, i.e., skip statement.

D. Computing MHP Relations

We are now ready to describe how to compute MHP regions and statements in a program.

**Definition 5 (Multi-Forked Regions).** A region in $G_t$ is a *multi-forked region* if $t$ is a multi-forked thread.

Let $t$ and $t'$ be two distinct threads. Let $r$ be a region in $G_t$ and $r'$ be a region in $G_{t'}$. We say that $r$ happens before $r'$ and write $r' \xleftarrow{} r$ if there exists a directed path from $r$ to $r'$ in the RRG of the program such that the path starts with a sequence of zero or more unconditional (i.e., traditional) HB edges $\leftarrow$, followed optionally by one conditional HB edge $\leftarrow$ at the end.

Two regions $r$ and $r'$ may happen in parallel, denoted $r \# r'$, if one of the following two conditions holds: (1) both $r$ and $r'$ are multi-forked regions and (2) neither $r' \xleftarrow{} r$ nor $r \xleftarrow{} r'$ holds. Recall that if a spawner thread is multi-forked, its spawnee threads will also be multi-forked, but the converse is not true (Definition 1).

Given two regions $r_i$ and $r_j$, $s_i \in r_i$ and $s_j \in r_j$ may happen in parallel if either (1) $r_i \# r_j$ when $i \neq j$ or (2) $r_i$ is a multi-forked region when $i = j$.

E. Example

Let us apply our MHP analysis to an example in Figure 7. In the code shown in Figure 7(a), there are three spawning relations, $t_m \rightarrow t_1$, $t_m \rightarrow t_2$ and $t_2 \rightarrow t_3$. The main thread $t_m$ creates $t_1$ in line 14 and joins it partially in line 28. In addition, $t_m$ also forks a multi-forked thread $t_2$ in line 19 and joins it fully in line 22. The child thread $t_2$ creates $t_3$ in line 6 and joins it in line 8. Figure 7(b) depicts the TCFG for the program.

For each spawning relation, we apply Algorithm 1 to annotate program statements with thread-order properties (Figure 7(c)) and partition the statements into regions (Figure 7(d)). Given the partitioned regions, we construct the RRG (Figure 7(e)) according to rules in Figure 6. Finally, we obtain the region pairs that may happen in parallel (Figure 7(f)). All MHP statement pairs can thus be obtained as described in Section III-D.

IV. Evaluation

We have implemented our MHP analysis in LLVM (version 3.5.0). For evaluation purposes, we have selected a set of 14 C programs, including 11 SPLASH2 benchmarks and 3 PARSEC benchmarks, as shown in Table I. All our experiments were conducted on a platform consisting of a 3.00GHz Intel Xeon(R) Quad E5450 processor with 16 GB memory, running Ubuntu Linux (kernel version 3.11.0).

The source code of each program is compiled into bit code files using clang and then merged together using LLVM Gold Plugin at link time stage (LTO) to produce a whole-program bc file. The compiler option `mem2reg` is turned on to promote memory into registers. Andersen’s pointer analysis is used to resolve indirect function calls and identify the threads joined at a join site.

To evaluate precision and efficiency of our analysis, we have implemented two previous solutions also in LLVM, one recent MHP analysis, named PCG (Procedural Concurrency Graph [14] and one more precise MHP analysis named as TCT (Thread Creation Tree) [9].

- PCG computes the MHP relations at the granularity of procedures instead of statements. As a result, this analysis is fast but imprecise.
- TCT computes the MHP relations at the granularity of statements based on a thread creation tree. So TCT is more precise but slower than PCG. However, the TCT analysis does not model precisely some complex fork-join behaviours, such as multi-forked threads, partial joins and nested joins.

A. Precision

Table I presents the results for PCG, TCT and our MHP analysis referred to as RRG. For each benchmark, we list its code size, the number of memory access statements, i.e., stores/loads, and the number of MHP statements found by each analysis. A statement executed in one thread is classified as a *MHP statement* if it may-happen-in-parallel with at least one statement in another thread. The number of MHP statements for each analysis is obtained by examining all pairs of statements.

Our RRG analysis can identify an average of 30.02% fewer MHP statements than PCG (achieving 48.15% at raytrace) and an average of 1.45% fewer MHP statements than TCT (achieving 4.70% at 1u_ch). RRG
```c
1: #include <pthread.h>
2: #include <stdio.h>

3: void *S3(void *x) { gvar = 300; }
4: void *S2(void *x) { gvar = 200; }
5: void main() {
6:   gvar = 1;
7:   pthread_create(&t1, NULL, S1, NULL); //t1: partially joined
8:   gvar = 2;
9:   if (gvar<4){
10:     gvar = 5;
11:     for(int j=0; j<5; j++){
12:       pthread_create(&t2[j], NULL, S2, NULL); //t2: multi-forked
13:     }
14:     gvar = 6;
15:     for(int j=0; j<5; j++){
16:       pthread_join(t2[j], NULL);
17:     }
18:   } else{
19:     gvar = 3;
20:     pthread_join(t1, NULL);
21:     gvar = 4;
22:   }
23:   gvar = 8;
24: }
```

**Figure 7: An illustrating example.**

(a) Code
(b) TCFG
(c) Statements with its thread-order properties
(d) Regions
(e) RRG
(f) MHP statement pairs marked with a "√"
Table I: The MHP statements found by PCG, TCT and RRG.

<table>
<thead>
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<th>Benchmark</th>
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<th>Number of MHP Statements</th>
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is slightly more precise than TCT for the set of benchmarks considered since RRG handles some complex fork-join behaviours, such as partial joins as illustrated in Figure 3, more precisely. Figure 8 shows some code snippets from ocean_ncp in the SPLASH2 benchmark suite, where a fixed number of threads are forked and joined in two "symmetric" loops. By performing the Polly loop analysis in LLVM, our RRG analysis can identify precisely that any statement in a slave thread does not happen in parallel with the statements after the second loop executed in the main thread. However, TCT handles this scenario conservatively by ignoring the join site in line 1101, resulting in more spurious MHP statements as shown in Table I.

B. Efficiency

Figure 9 shows a percentage distribution of RRG’s analysis time in each of its three stages: (1) pre-processing (points-to analysis and call graph construction), (2) HP analysis (happens-before analysis and RRG construction) and (3) MHP computation.

To compare RRG with PCG and TCT in terms of efficiency, we examine separately the overheads incurred in building various data structures, e.g., graphs and trees, used by these analyses and the times spent on generating the MHP statements. In the former case, Figure 10 shows that RRG is slightly more efficient than TCT but both RRG and TCT are apparently more costly than PCG. In the latter case, Figure 11 shows that PCG is the fastest (as it is the least imprecise as shown in Table I), and RRG, which operates at the granularity of regions, is 2.1x faster on average than TCT, which operates at the granularity of statements.

V. RELATED WORK

There has been a lot of studies on MHP analysis. Bristow et al. [16] build an inter-process precedence graph to indicate the synchronisation-imposed execution ordering among processes. Taylor [17] models a concurrency graph based on a reduced flow graph representation of every task. Recently, as parallel platforms become increasingly prevalent, a number of studies have appeared, introducing a variety of advanced techniques...
for discovering MHP statements in a program.

When it comes to the programming languages with restricted structures, the MHP analysis turns to be more effective due to the simplified problem. Targeting the X10 language, desirable effectiveness can be achieved by an intra-procedural MHP analysis, where simple path traversals are applied in a Program Structure Tree [5]. For improved precision, Lee and Palsberg [7] present a type system that solves a context-sensitive MHP analysis for X10-like structured languages. X10’s async-finish parallelism model simplifies the inference of escape information, since the finish construct ensures that all methods called within its scope terminate before the execution continues to the next instruction. In contrast to these MHP analyses for structured languages, our work focuses on C with Pthreads so that unstructured parallelism is supported. As a result, the presence of more flexible multi-threading patterns renders MHP algorithms for X10-like languages ineffective.

The research for computing MHP information for Java programs is rich in the literature. Based on Parallel Execution Graphs (PEGs), a MHP analysis is applied to Java programs [15], and its scalability was improved later [18]. A drawback with PEGs is that by combining the CFGs of individual threads, a bound on the number of coincident threads modelled is required for the analysis, since the PEGs may potentially grow in size otherwise. To simplify this thread model, Barik [9] describes an efficient MHP algorithm based on a Thread Creation Tree (TCT) that distinguishes threads by their

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**Figure 10:** Overheads on building the data structures required (normalised with respect to PCG).

**Figure 11:** Times spent on generating the MHP statements (normalised with respect to PCG).
creation sites. However, this analysis is based on the assumption that a parent thread is executed in parallel with each child thread. As a result, many join patterns, e.g., nested joins, are ignored. In this paper, fork and join behaviours are more precisely handled. In [19], a flow- and context-sensitive MHP analysis is discussed for the purposes of detecting concurrent errors in Java programs, without considering fully the join behaviour.

In the case of C programs (written with Pthreads), the MHP analysis is confronted with substantial challenges. Due to the lack of lexical-scope-based synchronisation and the presence of complex pointer/aliasing relations, both flow- and context-sensitivity are needed. Joisha et al. [14] present a coarse-grained analysis based on Procedural Concurrency Graphs (PCGs) to detect MHP information at the level of procedures. Chen et al. [20] introduced a graph-based MHP algorithm with a context-insensitive thread model. Compared to these, our fine-grained analysis achieves improved precision.

VI. Conclusion

This paper presents a new region-based MHP analysis for C programs. By modelling thread joins (nested and partial joins) more precisely than before and reasoning about happens-before relations at the level of regions (instead of statements), our analysis can achieve better precision than existing MHP analyses while being computationally efficient. As MHP analysis is an important analysis, its improved precision can provide benefits to many client applications, such as program optimisers, bug detectors and security analysers.

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References


