An Operational Semantic Basis for OpenMP Race Analysis

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Abstract—OpenMP is the de facto standard to exploit the on-node parallelism in high performance computers. Despite its overall ease of use, even expert users are known to create OpenMP programs that harbor concurrency errors, of which one of the most insidious of errors are data races. OpenMP is also a rapidly evolving standard, which means that future data races may be introduced within unfamiliar contexts. A simple and rigorous operational semantics for OpenMP can help build reliable race checkers and ward off future errors through programmer education and better tooling. This paper’s key contribution is a simple operational semantics for OpenMP, with primitive events matching those generated by today’s popular OpenMP runtimes and tracing methods such as OMPT. This makes our operational semantics more than a theoretical formalization; it can serve as a blueprint for OpenMP event capture and tool building. We back this statement by summarizing the workings of a new data race checker for OpenMP being built based on this semantics. The larger purpose served by our semantics is to serve the needs of the OpenMP community with regard to their contemplated extensions to OpenMP, as well as future tooling efforts.

Index Terms—OpenMP; operational semantics; concurrency; formal definition; data race; data race detection tool; structured parallelism

I. INTRODUCTION

OpenMP is the de facto standard for on-node parallelism in high performance computing. While OpenMP is highly portable and easy to use, it is also error-prone. Data races are one of the major source of errors in OpenMP based HPC applications. Although many existing correctness checking tools support programmers in the detection and removal of data races, these tools rely on static and dynamic analyses that either may not fit well with the needs of practical OpenMP race checking [1], [2], [3], miss races, or incur high overheads. Even symbolic analysis methods for OpenMP suffer from these issues [4].

Our past work has successfully adapted static and dynamic analysis to OpenMP and offered a practical race checker called ARCHER that has caught data races in critical field applications [5]. However, ARCHER suffers from high memory overheads, and misses races in many cases due to its exclusive reliance on the happens before model. It is well known that the races caught under this model depend on the schedule actually played out. That is, races within alternate schedules may be missed.

Our approach is to follow the lead of those who have exploited structured parallelism to make race-checking simpler and more efficient—e.g., for OpenMP [6], Cilk [7], and X10 [8]. We define an operational semantics that models the concurrency structure of OpenMP programs, exploiting the tool API (OMPT) [9] of modern OpenMP runtimes to identify every OpenMP event in the execution. Our approach also has the flavor of combining the exploitation of structured parallelism with lock-set based race checking (see Section III-E for our lock handling rules). The result is a more precise and traceable data race checker based on a clear operational semantics that fits in one page over 10 rules (Section III-E), supported by some helper functions (Section III-D). We believe that our formalization will benefit designers who seek to model new data race detection techniques for structured parallelism (in particular OpenMP) and those seeking to build and understand new and existing data race checkers.

While Raman et. al.’s work in this area [10], [11] proposes techniques to exploit the structured parallelism on parallel programming models such as Cilk and X10, their techniques currently are focused on async/finish structured parallelism of X10 and Habanero-Java. This makes their technique not directly applicable to OpenMP at this point. To summarize, the main contributions of this work are:

• An operational semantics that model the concurrency structure of an OpenMP program matching the OMPT events, and an overview of a prototype race checker that demonstrates how such a semantics can be a workhorse for race checking.
• A set of rules that exploit the OpenMP structured parallelism to identify races.
• An extensible operational semantics that allows future OpenMP constructs to be captured and analyzed.

The remainder of this paper is structured as follows: Section II discusses limitations of existing techniques that our operational semantics can overcome; Section III illustrates the state machine that implements the operational semantics rules, the conventions used to define the operational semantics rules, how we model the OpenMP constructs in our concurrency model, and a real example to show the effectiveness of the operational semantics in identifying data races; Section IV...
gives some ideas of a possible implementation of the operational semantics in a real data race detection tool; Section V concludes the paper.

II. BACKGROUND

In this section we give an overview of the happens-before relation for dynamic data race detection analysis that underlies existing race detectors [5], [2], [12]. For our purposes, event \( a \) happens before \( b \) if (1) they occur in that order within the same thread, (2) if \( a \) is an unlock and \( b \) is a lock, or (3) they are synchronized otherwise (e.g., \( a \) is before a barrier and \( b \) happens after the barrier). A data race is a happens-before unordered pair of events where one event is a write. Vector-clocks [14], [15] and their adaptations [2] typically help realize happens-before. Happens-before is defined per thread schedule, thus making happens-before based race detectors miss races when they do not exercise all schedules. For example, in listing 1 we depict a parallel region with two threads. The main thread initializes \( a \) inside the master construct, and both threads write variable \( a \) within a critical section. Because the OpenMP master construct does not enforce an implicit barrier at its termination point, while thread 0 initializes \( a \), the thread 1 can simultaneously access \( a \) within the critical section, introducing a data race.

In Figure 1 we exhibit three different thread interleavings for the program in Listing 1. In the first two interleavings, the data race on \( a \) manifests itself. Indeed in Figure 1(a) first thread 2 reads and writes within a synchronization block, while thread 1 performs a non-synchronized write. As shown in the figure, the non-synchronized write from thread 1 can happen anytime, even though thread 2 is accessing \( a \) within a critical section. In Figure 1(b) first thread 1 performs a non-synchronized write and thread 2 reads and writes within a synchronization block. In both cases, the two threads access simultaneously \( a \) and the data race detection algorithm shows the absence of happens-before between the threads, catching the data race. On the other hand, in Figure 1(c) we have the typical situation where happens-before masks a race. Thread 1 executes both non-synchronized and synchronized accesses on \( a \) before thread 2 performs any other operation. The release of the lock by thread 1 creates a happens-before edge with the acquiring of the same lock by thread 2, masking the previous non-synchronized write by the first thread.

In our approach, races such as in Figure 1 are detected thanks to a global data structure that maintains relevant memory accesses information performed by the threads, along with other information such as operation type, thread id, and locks held while making accesses. At each barrier, the operational semantics verifies the presence of data races, analyzing all the memory accesses performed by the threads up to that point, ensuring no data race will be missed (details are in Section III).

Listing 1: Data race in OpenMP program that may not manifest at runtime.

```c
int a;

#pragma omp parallel shared(a) num_threads(2)
{
    #pragma omp master
    {
        a = 0;
    }
    #pragma omp critical
    {
        a += 1;
    }
}
```

A key property of our operational semantics is that it highlights the concurrency structure created by a particular OpenMP program. If a particular thread forks two different threads and these threads perform their own accesses, our semantics records these accesses not in terms of a particular interleaving, but as a pair of accesses at specific positions in the fork-join structure, together with the mutex locks held when making the access. We exploit the idea of offset span labels pioneered by Mellor-Crummey [10] to record “positions” within the concurrency structure. We believe that these mechanisms serve the dual purpose of (1) creating a concurrency representation that is general enough to “hang” on its future extensions to OpenMP’s concurrency structure, and (2) also efficient enough to support the creation of a dynamic race detector.
III. OPERATIONAL SEMANTICS

The basic idea behind the operational semantics is to advance a state machine along the execution of the program in response to OpenMP events, and update the concurrency structure held in our state representation. Typical events include fork/join events (begin/end of a parallel region), acquiring and releasing of locks that guard critical sections, loads, stores, etc. The capturing of the OpenMP events is enabled by the new OpenMP Tools API (OMPT) [9] that modern OpenMP runtime implements to facilitate the development of correctness and performance tools. The OMPT interface triggers a callback for each OpenMP event that happens at runtime so that tools can access important information including parallel regions creation, threads entering or exiting a critical section, barrier executions, etc. The operational semantics rules match the OMPT events to correctly represent the concurrency structure of the OpenMP program. Each thread maintains a label in terms of offset-span labels that marks its lineage in the concurrency structure defined by prior forks and joins. Figure 2 illustrates the concurrency structure of the code in Listing 2 where circles represent the starting point of threads, and vertical lines represent traces of a thread’s execution. Two or more diagonal lines that exit/enter the circles represent fork/join points in the program.

In our example, master thread 0 creates the first parallel region and the operational semantics records this event through one of its rules. The same happens for thread 1 and 2 when they create the two nested parallel regions. At this point, each thread starts the execution of the operations in the program. In both nested parallel regions, the threads acquire different locks to access the shared variables. This triggers specific operational semantic rules to record the operations in the history of each thread.

More specifically, in the left parallel region, threads 3 and 4 enter a global critical section, write on $x$ and exit from the
Listing 2: OpenMP program with nested parallel regions.

```c
#pragma omp parallel num_threads(2) 
{ 
    if (omp_get_thread_num() % 2 == 0) { 
        // Left-branch of the graph 
        #pragma omp parallel num_threads(2) 
        { 
            #pragma omp critical 
            { 
                x = 1; 
            } 
            #pragma omp barrier
            y = x; 
        } 
        #pragma omp critical(M1) 
        { 
            printf("Y: %d\n", y); 
        } 
    } else { 
        // Right-branch of the graph 
        #pragma omp parallel num_threads(2) 
        { 
            #pragma omp critical(M1) 
            { 
                y = y + 1; 
            } 
            #pragma omp barrier
            #pragma omp for 
            for (int i = 0; i < 10; i++) 
            { 
                #pragma omp critical 
                { 
                    x = x + 1; 
                } 
            } 
        } 
    } 
} 
```

critical section. At the same time, threads 5 and 6 in the nested parallel region on the right acquire a lock on M1, write on y and release the lock. Also, the loads and stores performed by threads trigger a rule that stores the information about the memory accesses in a global structure along with the thread id and the id of the mutexes previously acquired by the thread (if any).

In our example, threads 3 and 4 reach the barrier 1 eventually, while threads 5 and 6 reach barrier 2. When a parallel thread reaches a barrier (either implicit or explicit), it waits for all the other threads in the team; they then synchronize and proceed with the execution. The state machine triggers different rules at the barrier to model the thread synchronization—more importantly to perform the data race detection on the operations executed up to that point.

The data race detection rule first identifies all possible concurrent threads in the system, comparing their offset-span labels. Second, it compares, for a given thread, its memory accesses with the memory accesses of another concurrent thread. If the rule identifies two memory accesses to a common location, at least one write, and without synchronization (or different mutex ids), it reports the race.²

Let us suppose the threads 8 and 9 have reached the implicit barrier 4, while the threads 5 and 6 are waiting at the implicit barrier 6. (Notice how threads 3 and 4 already joined into thread 7 which generated a new nested parallel region with threads 8 and 9. The global data structure still contains all the operations performed during the program execution up to those barriers.) All of the threads trigger the data race detection algorithm through one of the barrier rules. Up to that point, the global structure that collects the memory accesses contains all the loads and stores executed by the threads and related mutex information used for the memory accesses. The data race algorithm has all the information to identify potential data races. As stated previously, the algorithm identifies and compares only the memory accesses of concurrent threads.

In our example, there are three data races, identified by R1, R2, and R3.

- **R1** happens within the same nested parallel region on shared variable y. This happens because both thread 3 and 4 (that are concurrent) write the shared location without any synchronization.
- **Race R2** manifests between the threads of the two nested different parallel regions. The involved threads are 3 and 4 from the parallel region on the left, and 5 and 6 from the right parallel region. All the threads are concurrent to each other: threads 5 and 6 write on y through the critical section M1 and they do not race with each other. However, the concurrent threads 3 and 4 write on the same shared variable without any synchronization racing with threads 5 and 6.
- **R3** is similar to thread R2 but on the shared data x.
- The data race detection algorithm identifies the races by comparing all the memory accesses in the global structure only for the possible concurrent threads. It is interesting to notice that the algorithm does not report any races on y between threads 3,4 and the threads 8,9. By comparing the offset-span labels, the algorithm recognizes that threads 3 and 4 have already terminated when threads 8 and 9 start their work, so they are not deemed concurrent.

We now detail our semantics, presenting each of its component building blocks in separate sections, followed by our semantic rules themselves.

### A. Predicates and Conventions

We first need to state our conventions. \( \mathbb{N} \) is the set of natural numbers, \( \{0, 1, 2, \ldots\} \). \( x \in \mathbb{N} \) can be treated as a set \( \{0, 1, 2, \ldots, x - 1\} \) as in set theory. Thus, \( 0 = \{\} \), \( 1 = \{0\} \), \( 2 = \{0, 1\} \), \( 3 = \{0, 1, 2\} \), etc. Whenever we treat a member of \( \mathbb{N} \) as a number as well as a set, we’ll make sure to provide a hint. \( t \in TID \) is a thread identifier for some \( TID \in \mathbb{N} \).

²While these comparisons can make race-checking inefficient, our implementation in progress splits the burden into online event logging and offline event analysis that employs parallelism, as elaborated in Section IV.
$ADDR \in \mathbb{N}$ is the range of memory addresses accessed by the threads.

B. Offset-Span Labels

We showed how the offset-span labels are used to identify whether two threads are concurrent, and apply the data race detection only in that case. The offset-span label mechanism was introduced in [16]. An offset-span label, $osl$ for short, labels each thread’s execution point with a sequence of pairs, marking its lineage in the concurrency structure defined by prior forks and joins. The domain for the offset-span labels is $OSL = (\mathbb{N} \times \mathbb{N})^3$, i.e. each member $osl \in OSL$ is a sequence of pairs:

$$[a_1, b_1][a_2, b_2], \ldots, [a_n, b_n].$$

Let us take two offset-span labels $osl_1, osl_2 \in OSL$, respectively associated to thread 1 and thread 2. These labels are sequential (hence the thread 1 and thread 2 are not concurrent) when:

- **case 1:** $\exists_P, S (osl_1 = P) \land osl_2 = PS$, where $P$ and $S$ are any non-null sequence of ordered label pairs.

- **case 2:** $\exists_P, S, osl_1 = P[o_x, s]S_x \land osl_2 = P[o_y, s]S_y \land (o_x < o_y) \land (o_y \mod s = o_x \mod s)$ where $P$, $S$, and $S_y$ are (possibly null) sequence of ordered pairs.

Otherwise, they are concurrent.

The offset-span label is an important piece of our concurrency model since it gives precious information regarding whether two given threads can actually race or not. For further details, please see [16].

C. System State

The state of the system consists of a global state $GS$ and a set of thread local states $TP$ (Thread Pool). The total state $ts$ of any system is a pair “Global State, Thread Pool”. A specific total state $ts$ is:

$$ts = \langle gs, tp \rangle$$

Each total state $ts$ originates from the domain $TS$, where $TS = GS \times TP$.

Each global state $gs$ is a 4-tuple:

$$\langle bm, m, rw, \sigma \rangle$$

Each global state $gs$ originates from the domain $GS$, where $GS = BM \times M \times RW \times \Sigma$

where:

- The domain $BM = ParRegID \mapsto (\mathbb{N} \times \mathbb{N})$. Thus, for each $bm \in BM$, we have $bm : ParRegID \mapsto (\mathbb{N} \times \mathbb{N})$. Given a $p \in ParRegID$, $bm$ returns a pair of natural numbers $(a, b)$, where $a$ is the “current Barrier Count” and $b$ is the “target Barrier Count.” When a thread $t$ with offset-span label $osl$ executes a $ParBegin(N)$ instruction, $N$ threads are created, and an entry $\langle osl, (0, N) \rangle$ is added to function $bn$. The first field $a$ is incremented each time a thread hits a barrier. When the value reaches the number of threads in the team, it signals that all threads have synchronized at the barrier and the program can continue its execution.

- “Mutex” $m$ comes from domain $M$ where $M = Names \mapsto (\{-1\} \cup TID)$. That is, given a mutex name $m \in Names$, $M[m] = -1$ means that this mutex is free. Otherwise, $M[m] = t$, recording the fact that this mutex is held by the task associated to thread $t$. We use the value $\mu$ to indicate a mutex that has no name associated. A mutex with no name is usually the common case in an OpenMP program and it refers to any global critical section or lock (e.g. #pragma omp critical).

- Let memory access-type $MAT = \{R, W\}$ indicates a read or a write operation of a memory access.

- $rw \in RW$ is a tuple (data structure) that maintains all the memory accesses of each thread in the system. We have $RW = TID \times OSL \times N \times ADDR \times MAT \times M$. Each memory access performed by thread $t$ is recorded as the tuple

$$\langle tid, osl, bl, addr, mat, mutex \rangle$$

where:

- $tid \in TID$ is the thread ID;
- $osl \in OSL$ is the offset-span label;
- $bl \in \mathbb{N}$ is the barrier label of the last barrier seen by the thread $t$;
- $addr \in ADDR$ is the memory address;
- $type \in \{R, W\}$ records reads or writes;
- $mutex$ is the synchronization state (value of $M$ in $GS$) at the time of the access;

- $\sigma \in \Sigma$ is the data state of the system, as described earlier.

The local state $TP$ is the thread pool that contains a list of 3-tuples, each one of which is the local state of a thread:

$$\langle tid, osl, bl \rangle$$

The domain $TP = 2^{TID \times OSL \times N}$

where:

- $t \in TID$ is the id of the thread;
- $osl \in OSL$ is an offset-span label;
- $bl \in \mathbb{N}$ is the label of the barrier the thread has witnessed last. We assume that each barrier instruction is of the form $bar(L)$ where $L \in \mathbb{N}$ carries the barrier number. A thread crossing a barrier sets its $bl$ to the value $L$.

D. Helper Functions and Predicates

We define some helper functions to support the operational semantics rules. They can be operators or functions that receive some arguments in input and return a certain result

3Recall that functions are single-valued relations, or sets of pairs with unique second component for each given first component. Thus, $\{(osl, (0, N))\}$ is a function. We allow functions to evolve, i.e. undefined for items explicitly added.
Fig. 3: OpenMP Concurrency Operational Semantics

**Operational Semantics State**

\[ gs \text{ as } (bm, m, rw, \sigma) \in GS \]
\[ te \text{ as } (tid, osl, bl) \in TP \]

**Operational Semantics Rules**

\[ \text{ParallelBegin}(N) \]
\[ at(tid, \sigma, \text{ParBegin}(N)) \land tp' = (tp - \{ te \} \cup \text{SpawnChildren}((tid, osl, bl), \sigma, N)) \land \]
\[ bm' = bm \cup \{(osl, \{0, N\})\} \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm', m, rw, \sigma' \rangle, tp' \rangle \]

\[ \text{ParallelEnd}(N) \]
\[ tp' \subseteq tp \land at(tid, \sigma, \text{ParEnd}(N)) \land \]
\[ \sigma' = \text{nxt}(\sigma, tid) \land tp'' = tp - tp' \cup \text{GetChildJoin}(tp') \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm, m, rw, \sigma' \rangle, tp'' \rangle \]

\[ \text{ImplicitTaskBegin()} \]
\[ at(tid, \sigma, \text{ImplicitTaskBegin}()) \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm, m, rw, \sigma' \rangle, tp \rangle \]

\[ \text{ImplicitTaskEnd()} \]
\[ at(tid, \sigma, \text{ImplicitTaskEnd}()) \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm, m, rw, \sigma' \rangle, tp \rangle \]

\[ \text{LoadStore()} \]
\[ rw' = \text{ADDR} - \text{RW}(\text{tid}, osl, bl, addr, mat, \text{mutex}) \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm, m, rw', \sigma' \rangle, tp \rangle \]

\[ \text{AcquireMutex(name)} \]
\[ at(tid, \sigma, \text{AcquireMutex(name)}) \land m[name] = \emptyset \land m' = m[name \rightarrow tid] \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm, m', rw, \sigma' \rangle, tp \rangle \]

\[ \text{ReleaseMutex(name)} \]
\[ at(tid, \sigma, \text{ReleaseMutex(name)}) \land m[name] = tid \land m' = m[name \rightarrow \emptyset] \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm, m', rw, \sigma' \rangle, tp \rangle \]

\[ \text{Barrier(bid)} \]
\[ at(tid, \sigma, \text{Barrier(bid)}) \land \text{Full}(bm, \text{most}(osl)) \land bm' = bm - \{ (osl, \ast) \} \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm', m, rw, \sigma' \rangle, tp \rangle \]

\[ \text{Barrier(bid)} \]
\[ at(tid, \sigma, \text{Barrier(bid)}) \land -\text{Full}(bm, \text{most}(osl)) \land bm[\text{most}(osl)] \text{ as } (\text{count}, N) \land\]
\[ tc' \text{as }(tid, osl, bid) \land tp' = tp - te \cup \{ te' \} \land bm' = bm \cup \{ (osl, (\text{count} + 1, N)) \} \land \sigma' = \text{nxt}(\sigma, tid) \]
\[ \langle gs, tp \rangle \rightarrow \langle gs' \text{ as } \langle bm', m, rw, \sigma' \rangle, tp' \rangle \]

\[ \text{Barrier(bid)} \]
\[ tc_1 \text{ as } (tid_1, osl_1, bl_1) \in tp \land tc_2 \text{ as } (tid_2, osl_2, bl_2) \in tp \land (tid_1 \neq tid_2) \land \]
\[ \text{Concurrent}(osl, tid_1, tid_2) \land i \in \text{rw[tid}_1] \land j \in \text{rw[tid}_2] \land\]
\[ (\text{rw[tid}_1][i].\text{addr} == \text{rw[tid}_2][j].\text{addr}) \land\]
\[ (\text{rw[tid}_1][i].\text{mat} == W) \land (\text{rw[tid}_2][j].\text{mat} == W) \land\]
\[ (\text{rw[tid}_1][i].\text{mutex} \cap \text{rw[tid}_2][j].\text{mutex} == \emptyset) \land\]
\[ (\text{rw[tid}_1][i].bl == \text{rw[tid}_2][j].bl) \land (\text{rw[tid}_1][i].bl || \text{rw[tid}_2}[j].bl) \]
\[ \langle gs, tp \rangle \rightarrow \text{RaceFail}(\sigma, addr, tid_1, tid_2) \]
or state useful for the rule execution. The helper functions are the following:

- \( \text{as:} \) is used as in Ocaml (it allows a name for a whole structure, as well as helps us refer to the inner details of the structure).
- \( \text{most(\text{lst})}: \) we define \( \text{most} \) as a function that returns the same list given in input except the last element (i.e. in Python \text{lst[:-1]})
- \( ||: \) This operator is used to describe that two different threads are concurrent. In particular, given two offset-span labels \( \text{osl}_1 \) for thread \( T_1 \) and \( \text{osl}_2 \) for thread \( T_2 \), \( \text{osl}_1 \parallel \text{osl}_2 \) (read \( \text{osl}_1 \) and \( \text{osl}_2 \) are concurrent) means that the threads \( T_1 \) and \( T_2 \) may race.
- \( \text{SpawnChildren}(\langle \text{ptid}, \text{osl}, \text{pbl} \rangle, \sigma, N): \) Given the parent’s thread id \( \langle \text{ptid}, \sigma \rangle \), offset-span label \( \langle \text{osl} \rangle \) and barrier label \( \langle \text{pbl} \rangle \), this function creates a pool of \( N \) threads — specifically, the local states of these threads \( \langle \text{tid}, \text{osl}, \text{bl} \rangle \). It initializes the offset-span label \( \text{osl} \) for each thread created (e.g. at the beginning of a parallel region), by extending \( \text{posl} \) with pairs \([0, N]\) through \([N-1, N]\). The \( \text{bl} \) is set to \( \text{pbl} \). The threads id are somehow uniquely generated.
- \( \text{GetChildJoin}(\text{tp}): \) returns the single thread-state triple that result from fusing all the threads in the thread pool \( \text{tp} \).
- \( \text{Concurrent}(\text{osl}, t_1, t_2) \) is the function that compares the offset-span labels as described in Section \( \text{III-B} \)
- \( \text{AddRW}(\langle \text{tid}, \text{osl}, \text{bl}, \text{addr}, \text{mat}, m, n \rangle) \) adds the access into the \( \text{rw} \) structure. The record says “an access by \( \text{tid} \) with offset-span label \( \text{osl} \) and barrier label \( \text{bl} \) is performed at address \( \text{addr} \) with memory access type \( \text{mat} \), when the mutex state is \( m \)”
- \( \text{Full}(\text{bm}, \text{osl}): \) This predicate keeps the count of the number of threads that have reached a \( \text{ParEnd}(N) \) (or a \( \text{Barrier(bid)} \) construct. In order to count the threads, it uses the structure \( \text{bm} \) which is indexed by the \( \text{ParRegID} \) represented by the offset-span label \( \text{osl} \). In other words, the predicate \( \text{Full} \) means that other threads have reached the construct and have incremented the counter in the \( \text{bm} \) structure. From a functional language point of view \( \text{Full} \) would look like:

\[
\begin{align*}
\text{let } & \quad \text{Full}(\text{bm}, \text{osl}) = \\
\text{let } & \quad (\text{count}, N) = \text{bm}[\text{osl}] \\
\text{in } & \quad (\text{count} == N - 1)
\end{align*}
\]
- \( \text{WaitAtBarrier}(\text{bid}): \) This predicate is used for the example in Section \( \text{III-F} \) to indicate that a thread already encountered a barrier and it is waiting for the other threads in the team.
- \( \text{RaceFail}(\text{state}, \text{addr}, t_1, t_2): \) This helper function is used to report the race found on \( \text{addr} \), between thread \( t_1 \) and thread \( t_2 \).

E. Operational Semantics Rules

Now, we explain the rules in Table \( \text{III} \) one by one. While each rule models a different behavior, all rules update the system state incrementing the program counter to point to the next instruction.

- Parallel Region Begin: The ParallelBegin rule models the creation of the team of threads for the encountered parallel region and initializes the offset-span labels for each thread.
- Parallel Region End: The ParallelEnd rule models the end of the parallel region. It terminates the threads in the team except the master thread which resumes its execution.
- Implicit Task Begin: The ImplicitTaskBegin rule fires when a thread, after its creation, begins the associated implicit task which performs the work within the parallel region. This rule is a helper transition to initialize the thread and its implicit task state.
- Implicit Task End: The ImplicitTaskEnd fires when a thread exits the implicit barrier and the parallel region is terminating. It also resets the thread state.
- Load Store: The LoadStore rule triggers every time a thread performs a read or a write operation. Its task is to store the information about the current memory accesses of a thread along with other information such as the current locks held by the task, offset-span label, etc. The information about a load or a store are kept in a data structure shared among all threads.
- Acquire Mutex: The rule AcquireMutex fires when a thread encounters a synchronization construct, such as a critical section. It stores the id (\( \mu \) in case of global critical section) of the synchronization construct into a data structure for the given thread. All the following memory accesses are stored with the information that they happened within the given synchronization region.
- Release Mutex: The rule Release Mutex instead fires when a thread encounters the end of a critical section or releases a lock. It removes, from the thread’s data structure, the id of the synchronization construct.
- Barrier: The Barrier rules are of extreme importance since they implement the data race detection algorithm. The first two rules make sure that all threads in a team reached the barrier and update the information in the global state. Once all threads have hit the current barrier the third rule triggers and perform the race check. The data race check consists of searching for memory accesses conflicts between each given pair of concurrent threads. First, the rule checks if the pair contains two concurrent threads, either checking if they belong to the same barrier interval or comparing the offset-span labels. In the event the threads are concurrent, the rule applies the other checks to search for data races. It looks into the loads/stores data structures for memory accesses with the same address, checks if at least one of them is a write and they do not have any synchronization regions in common. In case all these checks are positive the rule triggers a RaceFail event to report the data race.

F. Operational Semantics Example

In this section we show an application of the operational semantics in an OpenMP example. We show how each rule is triggered according to the operations performed by the program. We also provide a transition table to illustrate the
system state and how it changes under the execution of each rule. The example we use is the OpenMP program shown in Listing 1. Initially we have only the main thread, the total state of the system is therefore the following:

\[\text{init} = (gs, tp)\]

with:

\[gs = (bm, m, rw, \sigma) \in GS\]

\[tp = (tid, osl, bl) \in TP\]

where:

\[gs = (\emptyset, \emptyset, \emptyset, \sigma)\]

\[tp = ((0, 0, 1], 0)\]

The Table I illustrates the transition table of the system for the example in Figure 4. Each thread in the table is represented by its thread id and offset-span label.

The row 0 of the transition table shows the initial state of the system. The first fired rule is \texttt{ParBegin(2)} (Row 1) when the thread 0 hits the parallel construct. This rule models the beginning of the parallel region and the creation of the team of threads. In the example, the master thread creates one more thread to make a team of two. Both threads in the system trigger the \texttt{ImplicitTaskBegin} rule (Row 2 and 3) to initialize their status (e.g. offset-span labels, state, barrier counts, etc.). Now the threads start their parallel work. Thread 0 triggers the \texttt{LoadStore} rule (Row 4) when it accesses the master construct and initializes the variable \(a\). The rule adds the memory access information inside the \(rw\) data structure and points to the next instruction. In the next instruction, thread 0 acquires the mutex which triggers the \texttt{AcquireMutex} rule (Row 5) and updates the thread state with the synchronization information. Thread 0 accesses again variable \(a\) and the \texttt{LoadStore} rule (Row 6) adds the new memory access to \(rw\) along with the synchronization information acquired by the previous operation. The thread 0 releases the mutex triggering the \texttt{ReleaseMutex} rule (Row 7) and reaches the implicit barrier at the end of the parallel region. The triggering of the \texttt{Barrier} rule (Row 7) keeps thread 0 on waiting for thread 1 to reach the barrier.

Thread 1 triggers respectively \texttt{AcquireMutex}, \texttt{LoadStore}, and \texttt{ReleaseMutex} (Row 9, 10, 11), which add a new synchronized memory access into the \(rw\) data structure. Now thread 1 reaches the implicit barrier triggering the \texttt{Barrier} rule (Row 12). The \texttt{Barrier} rule performs the data race detection which identifies the data race between the non-synchronized access from thread 0 \(((0, 0, 1][0, 2], [0, 1][0, 2][0], x, W, 0))\) and the synchronized

### Table I: State machine transitions for the example in Listing 1

| # | tid - osl | rule          | bm    | rw | tp        | Next State                                         |
|---|-----------|---------------|-------|----|-----------|----------------------------------------------------|
| 0 | init      |               | 0     | \emptyset | \emptyset | (0, [0, 0), ) ParBegin(2) |
| 1 | 0 − [0, 1] | \texttt{ParBegin(2)} | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0), (1, 0, 1, 2), 0) AcquireMutex() |
| 2 | 0 − [0, 1][0, 2] | ImplicitTaskBegin() | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0, 2) LoadStore(x, W) |
| 3 | 1 − [0, 1][1, 2] | ImplicitTaskBegin() | [0, 1] = (0, 2) | \emptyset | \emptyset | (1, 0, 1, 1, 2), 0) ReleaseMutex() |
| 4 | 0 − [0, 1][0, 2] | LoadStore(x, W) | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0, 2), (0, 1, 0, 2), 0) Barrier(1) |
| 5 | — | AcquireMutex() | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0, 2), (0, 1, 0, 2), 0) WaitAtBarrier(1) |
| 6 | — | LoadStore(x, W) | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0, 2), (0, 1, 0, 2), 0) RaceFail(σ, x, 0) |
| 7 | — | ReleaseMutex() | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0, 2), (0, 1, 0, 2), 0) ParEnd(2) |
| 8 | — | Barrier(1) | [0, 1] = (0, 2) | \emptyset | \emptyset | (0, [0, 1], 0, 2), (0, 1, 0, 2), 0) ParEnd(2) |
access from thread 1 (⟨[1, 0, 1][0, 2], [0, 1][0, 2][0], x, W, μ⟩).
The two accesses are performed by two different threads in the same memory location, both happen in the same barrier interval (concurrently according to offset-span label), at least one of the operations is a write, and one of them happens outside the critical section μ. The system reports the race through the RaceFail helper function.

The execution of the program continues triggering the ImplicitTaskEnd rule (Row 13 and 14) by both threads. Thread 1 terminates immediately, while thread 0 reaches the end of the parallel region and terminates with the end of the program.

G. Lowering OpenMP constructs

Our operational semantics models the concurrency structure of an OpenMP program that uses a subset of the entire OpenMP specification. We target OpenMP parallel directives and all related constructs except explicit tasks and target devices that we leave to future works. Our formalization lowers every OpenMP directive into basic underlying synchronization structures such as barriers and mutexes. In the following paragraphs, we show how each of these directives can be simplified and modeled by the operational semantics.

a) parallel Construct: The first five rules in Figure 3 model the begin/end of a parallel construct including the creation and destruction of the implicit task associated to the threads. The threads within the parallel region trigger the other rules based on the work they are performing: accessing shared or private memory, acquiring/releasing mutexes, synchronizing to an implicit/explicit barrier. The data race detection algorithm performed at the barrier (either implicit or explicit) catches the potential race(s). The clauses related to the parallel region constructs do not influence the data race detection. For example, in presence of the private clause or similar, when the threads access their own private memory, the memory addresses of the locations are different for each thread, thus no race is reported.

b) worksharing Constructs: The worksharing constructs such as for, section, single, and workshare are also supported by the operational semantics. These constructs add an implicit barrier at the end, so the race detection algorithm runs when the thread synchronizes, identifying any potential race within the barrier interval. In the presence of a nowait clause, the operational semantics models the specific constructs as an extension of the parallel work until the next barriers. Let us take the example in Listing 3. The snippet of code shows two consecutive parallel for-loops with the nowait clause. The clause removes the implicit barrier at the end of the first parallel loop, introducing a data dependency between the write on a[i] in the first loop and the read on a[i] and a[i-1] in the second loop. Consequently, all memory accesses performed by the threads in both loops happen in the same barrier interval. Only at the end of the second loop, when the threads encounter the implicit barrier, the state machine triggers the data race detection analysis (Rule 12). In detail, the state machine stores information about the memory locations accessed by the threads in both loops. Because of the data dependency between the loops, the race check identifies two common non-synchronized memory accesses, in the rw data structure, from two different threads. Since one of the accesses is a write, the operational semantics reports the data race.

Listing 3: Data race on array a because of nowait clause and data dependency between two for loops.

```c
#pragma omp parallel
{
#pragma omp for nowait
for (i = 0; i < N; i++) {
    a[i] = 3.0 * i * (i + 1);
}
}
#pragma omp for
for (i = 1; i < N; i++) {
    b[i] = a[i] - a[i - 1];
}
```

c) master and synchronization Constructs: The only synchronization constructs not supported by the operational semantics are those related to tasking: taskwait and taskgroup which, as said previously, will be modeled in future work. When a thread encounters a synchronization directive, a rule logs the synchronization information for the current thread. Every memory access executed by the thread within a synchronization construct is collected in the rw data structure, with the information that the memory access are protected by a synchronization primitive. The data race detection, as shown in rule 12 uses this information to identify a potential non-synchronized access and report the race.

IV. Implementation

The operational semantics is a mathematical model and must clearly be adapted to real-world implementation settings. We have implemented a preliminary version of such a tool called SWORD. The main idea behind this tool is to log all OpenMP events and memory accesses into a file (one such file...
is created per thread). When the program execution terminates, an offline data race detection algorithm analyzes the log files to identify potential data races. The main advantages of this approach are: (1) dramatically reduced memory overheads compared to other tools (including ARCHER), and (2) parallelizable offline analysis.

More specifically, SWORD includes a compiler instrumentation pass for the source program and two checking phases. The compiler instrumentation inserts in the program, for each load and store, a call to a SWORD runtime routine that implements the event collection algorithm. Phase one consists of logging into files every memory access and synchronization operation that each thread executes at runtime. The SWORD runtime intercepts parallel regions begin/end, synchronization operations (e.g. critical sections, barriers, etc.), and other OpenMP events through the OMPT interface. This implementation benefits from our operational semantics directly including events that match OMPT events.

During the execution of the program, the SWORD runtime uses a buffer for each thread to collect the data regarding memory accesses and OpenMP events. When the buffer is full, SWORD compresses it, dumps it in a log file, and makes it available to collect new data. The use of data compression in this manner helps reduce memory overheads. Once the program finishes its execution, the log folder contains a log-file per thread.

The second phase consists of the offline analysis of the logs to identify the data races that manifested during the program execution. The algorithm identifies the pairs of concurrent threads using the offset-span label mechanism described in Section II-C. The data race detection algorithm identifies memory conflicts between two concurrent threads. The algorithm obtains the information about the thread’s memory accesses and synchronization operations from the logs, and looks for data races. Since the analysis requires only to read from the log files, the offline algorithm can be parallelized across multiple cores and a cluster of nodes to speedup the process.

V. CONCLUSIONS

In this paper, we have presented an operational semantics to model the concurrency structure of OpenMP and enabling data race detection for structured parallelism. The operational semantics rules are straightforward and can serve as a valuable reference to everyday programmers. Also, the example II-C shows how our approach can identify data races even in corner cases where other techniques (e.g., those purely based on the happens-before tracking) can fail. In summary, our work provides a formalization to help researchers and tool developers to better understand OpenMP concurrency, and help them reliably and systematically build more precise data race checkers that reduce memory overheads.

As already described, we are working on a possible implementation of the operational semantics to support a new data race checker called SWORD. Details of the engineering of SWORD will be presented in future work.

To the best of our knowledge, our contribution is the first simple operational semantics to model the concurrency structure of OpenMP at a level that tool-builders care about. Our semantics is not yet suitable for those interested in issues such as (1) OpenMP’s weak memory consistency model, (2) OpenMP’s GPU offload features, and (3) OpenMP’s tasking constructs. However, our semantics offers a very appealing starting point for such extensions.

The operational semantics rules mesh with the OMPT events providing a powerful as well as standardized instrumentation approach to represent the concurrency structure of an OpenMP program and enable targeted data race detection. We believe that with this formalization and the ongoing work we can build precise and accurate data race checkers that exploit the structured parallelism of parallel programming models such as OpenMP and its future incarnations.

REFERENCES

[1] S. Savage, M. Burrows, G. Nelson, P. Sobalvarro, and T. Anderson, “Eraser: A dynamic data race detector for multi-threaded programs,” SIGOPS Oper. Syst. Rev., pp. 27–37, Oct. 1997.

[2] C. Flanagan and S. N. Freund, “FastTrack: Efficient and Precise Dynamic Race Detection,” in Proceedings of the 30th ACM SIGPLAN Conference on Programming Language Design and Implementation, ser. PLDI ’09, New York, NY, USA, 2009, pp. 121–133.

[3] P. Chatarasi, J. Shirako, M. Kong, and V. Sarkar, An Extended Polyhedral Model for SPMD Programs and Its Use in Static Data Race Detection, Cham, 2017, pp. 106–120.

[4] H. Ma, S. Diersen, L. Wang, C. Liao, D. J. Quinlan, and Z. Yang, “Symbolic analysis of concurrency errors in OpenMP programs,” in ICPP, 2013, pp. 510–516.

[5] S. Atzeni, G. Gopalakrishnan, Z. Rakamaric, D. H. Ahn, I. Laguna, M. Schulz, G. L. Lee, J. Protze, and M. S. Müller, “ARCHER: Effectively Spotting Data Races in Large OpenMP Applications,” in 2016 IEEE International Parallel and Distributed Processing Symposium (IPDPS), May 2016, pp. 53–62.

[6] Tim Lewis, “OpenMP Specifications.” [Online]. Available: http://www.openmp.org/specifications/

[7] Intel, “Intel Cilk Plus.” [Online]. Available: https://www.cilkplus.org

[8] P. Charles, C. Grothoff, V. Saraswat, C. Donawa, A. Kielsstra, K. Ebcioglu, C. von Praun, and V. Sarkar, “X10: An object-oriented approach to non-uniform cluster computing,” SIGPLAN Not., pp. 519–538, Oct. 2005.

[9] A. E. Eichenberger, J. Mellor-Crummey, M. Schulz, M. Wong, N. Copty, R. Dietrich, X. Liu, E. Loh, and D. Lorenz, “OMPT: An OpenMP tools application programming interface for performance analysis,” in OpenMP in the Era of Low Power Devices and Accelerators, 2013, pp. 171–185.

[10] R. Raman, J. Zhao, V. Sarkar, M. Vechev, and E. Yahav, “Scalable and precise dynamic database detection for structured parallelism,” SIGPLAN Not., pp. 531–542, Jun. 2012.

[11] ———, “Efficient data race detection for async-finish parallelism,” in Proceedings of the First International Conference on Runtime Verification, ser. RV’10, Berlin, Heidelberg, 2010, pp. 368–383.

[12] R. O’Callahan and J.-D. Choi, “Hybrid dynamic data race detection,” SIGPLAN Not., pp. 167–178, Jun. 2003.

[13] L. Lamport, “Time, clocks and the ordering of events in a distributed system,” The Journal of Supercomputing, July 1978.

[14] F. Mattern, “Virtual time and global states of distributed systems,” in Parallel and Distributed Algorithms, 1988, pp. 215–226.

[15] C. J. Fidge, “Timestamps in Message-Passing Systems that Preserve the Partial Ordering,” in 11th Australian Computer Science Conference, University of Queensland, Australia, 1988, pp. 55–66.

[16] J. Mellor-Crummey, “On-the-fly detection of data races for programs with nested fork-join parallelism,” in Proceedings of the 1991 ACM/IEEE Conference on Supercomputing, 1991, pp. 24–33.