CONCURRENCY AND COMPUTATION: PRACTICE AND EXPERIENCE
Concurrency Computat.: Pract. Exper. 2010; **22**:45–67
Published online 13 August 2009 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/cpe.1469

Visualizing massively multithreaded applications with ThreadScope

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SUMMARY

As highly parallel multicore machines become commonplace, programs must exhibit more concurrency to exploit the available hardware. Many multithreaded programming models already encourage programmers to create hundreds or thousands of short-lived threads that interact in complex ways. Programmers need to be able to analyze, tune, and troubleshoot these large-scale multithreaded programs. To address this problem, we present ThreadScope: a tool for tracing, visualizing, and analyzing massively multithreaded programs. ThreadScope extracts the machine-independent program structure from execution trace data from a variety of tracing tools and displays it as a graph of dependent execution blocks and memory objects, enabling identification of synchronization and structural problems, even if they did not occur in the traced run. It also uses graph-based analysis to identify potential problems. We demonstrate the use of ThreadScope to view program structure, memory access patterns, and synchronization problems in three programming environments and seven applications. Copyright © 2009 John Wiley & Sons, Ltd.

Received 5 January 2009; Revised 1 May 2009; Accepted 7 June 2009

KEY WORDS: visualization; multithreading; structure

INTRODUCTION

Today, personal computers commonly have two to four CPU cores, and shared-memory supercomputers have hundreds to thousands of cores. In the near future, we may expect personal computers

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Contract/grant sponsor: Sandia National Laboratories; contract/grant number: DE-AC04-94AL85000

to have hundreds, and shared-memory supercomputers to have tens of thousands of cores. As a result, more and more programs must become multithreaded in order to exploit the available hardware. A number of programming models and libraries such as OpenMP [1], Cilk [2], Intel's Threading Building Blocks [3], and qthreads [4] are emerging to simplify the construction of such programs.

Because of its inherent non-determinism, threaded programming has always been a challenging task. Programmers must avoid errors specific to parallel execution such as race conditions and deadlocks. Synchronization bugs can hide in programs for years, undetected until a specific machine configuration or scheduling order is used. Programmers must also deal with new performance issues like data structure contention and variable levels of available parallelism in addition to standard performance tuning issues. Parallelism problems become more complex and hard to analyze or predict as the scale of parallel execution increases.

We have designed ThreadScope to visualize the structure of parallel applications, which assists the programmer with troubleshooting and debugging massively multithreaded programs. ThreadScope uses existing tracing tools to instrument multithreaded applications and uses those traces to visualize the logical structure. The logical structure of multithreaded programs does not rely on a specific order of execution other than that specified by synchronization methods. This approach removes the need to replicate a threading problem in order to identify it.

The high-level structure of a program reveals the program's parallel and sequential components, as well as potential bottlenecks. This structure is independent of the underlying machine, though may be dependent on the input. Graphs of the structure can be dense and detail-heavy. The challenge in any dense visualization is deciding where to expand and condense details. To clarify and simplify the visual depiction of the program structure, we employ a static single assignment (SSA) form to remove programming idioms and coalesce memory cells into logical memory objects. These simplification techniques demonstrate how application-specific data structures can be handled. By analyzing the graph structure, we may also identify race conditions and deadlocks. Unlike some correctness checkers [5], this approach does not require the software to be described in a new special-purpose language, but can address existing applications without modification. A few key operations—reading and writing to memory, synchronization operations, and spawning or joining threads—are the basic structural elements of any multithreaded application. Thus, this analysis technique can be a part of the debugging process, rather than the design process.

Because this approach relies on specific building blocks of multithreaded applications, it is not specific to a particular threading library or model. This paper demonstrates ThreadScope's visualization capabilities and analysis features on several programs using a variety of parallel programming models, and discusses the use of this visualization for structural identification of problems. The programming models used include the Cilk threading library [2], the qthread threading library [4], and the standard pthread library. These models were chosen for their variety of synchronization mechanisms; however, the ThreadScope technique may be adapted for use with additional environments.

The key advance of this work is the graph-based structural approach to error identification, which can identify race conditions and deadlocks as well as predict potential bottlenecks and the underlying programming model. Identification of livelocks and analysis of message-passing parallel applications are venues for future work.

DOI: 10.1002/cpe

METHODOLOGY

The graphs presented in this paper are the result of a two-stage data collection and analysis process. In the first stage, a program, such as the example Cilk program in Figure 1, is traced by an existing tracing tool. This trace is translated into an ‘event description’ language. Tracing the program in Figure 1 produces the event description in Figure 2. ThreadScope includes several tools for generating these event descriptions from several tracing tools, including Dtrace [6], Apple’s libamber [7], and the SST simulator [8]. Other tracing tools could be used to produce similar event descriptions; the basic requirement is the ability to detect thread and synchronization operations. In the second stage, ThreadScope uses the event description to generate dot-attributed graph language, which is rendered by the GraphViz [9] graphics package into a graph similar to Figure 3.

A ThreadScope graph G is a pair (V, E) where V is a set of vertices and E is a set of directed edges between the vertices where $E \subseteq \{(u, v)|u, v \in V \wedge u \neq v\}$. There are two types of vertices and three categories of edges. The vertices represent either serial execution blocks or memory objects. Execution blocks are graphically represented by round vertices, and memory objects are represented by rectangular vertices, scaled to represent their size. Each execution block is given a unique identifying number, as are objects. When the graph is drawn, the first execution block is colored gray to identify it. The edge categories are thread operations (spawns, joins, and continuations), memory operations (reads, writes, and atomic read/writes), and memory object identity transitions. Read and write edges come in a further two varieties, to distinguish atomic or synchronous operations from potentially unsafe operations. A thread, as ThreadScope defines it, is a sequence of execution

```
#include <cilk-lib.cilkh>
#include <stdlib.h>
cilk int genrand() {
    return random();
}
cilk int main() {
    int obj1 = spawn genrand();
    int obj2 = spawn genrand();
    sync;
    return obj1 + obj2;
}
```

Figure 1. Trivial Cilk program.

DOI: 10.1002/cpe

```
MALLOC now=3 addr=0x100 size=40
MALLOC now=5 addr=0x200 size=40
INIT now=10 tid=1 frame=0x100 threadid=0x0.0
INIT now=11 tid=1 frame=0x200 threadid=0x0.0
SPAWNED now=12 tid=2 frame=0x100 entry=1
SPAWNED now=13 tid=3 frame=0x200 entry=1
MWRITE now=22 tid=2 addr=0x104 size=4
MWRITE now=23 tid=3 addr=0x204 size=4
ENDED now=24 tid=2 frame=0x100 entry=1 next=2
ENDED now=25 tid=3 frame=0x200 entry=1 next=2
SYNC now=30 tid=1 threadid=0x0.0
MREAD now=32 tid=1 addr=0x104 size=4
MREAD now=34 tid=1 addr=0x204 size=4
FREE now=36 tid=1 addr=0x100
FREE now=36 tid=1 addr=0x200
```

Figure 2. ThreadScope event description log of program in Figure 1.

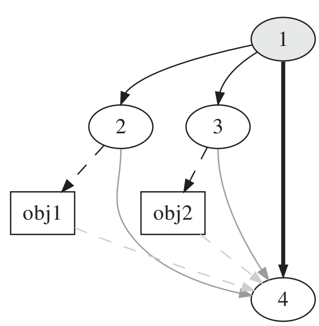


Figure 3. Graph generated from event log in Figure 2.

blocks that are connected by thread continuations. Thread continuations are implicitly inserted whenever an execution block executes a potentially blocking operation that necessarily establishes a ‘happens-before’ dependency [10] on everything that follows it.

In this paper, the graphs are monochromatic, which can make distinctions between edge-types difficult to see. In practice, edges are presented in color. Here, thread operations are represented by solid edges. Thread continuations are represented by thick black edges, spawns by thin black edges, and joins by thin gray edges. Memory operations are represented by dotted or dashed edges, for safe and unsafe operations, respectively. Reads are black and writes are gray. Atomic read/write operations are dotted with arrows at both ends. Memory object transitions are thick, dashed, light gray lines.

For example, in Figure 3, round nodes 1 and 4 correspond to the `main()` function from Figure 1; node 1 represents lines 6–8 and node 4 represents lines 9–11. The `sync` operation in line 9 divides the thread into two execution blocks because it is a potentially blocking operation. Nodes 2 and 3 are both instances of the `genrand()` function, spawned in lines 7 and 8, respectively. They each write to a memory object (`obj1` and `obj2`) and exit. The spawn operations in lines 7 and 8 are indicated by the thin black edges of the graph, and the sync operation is indicated by the thin gray edges.

The graph is a progression through the logic of the program where parallelism is the x axis and the y axis represents logical ordering. The number of potentially concurrent actions at any point in the threaded program is equal to the number of solid lines or nodes at the y coordinate corresponding to the logical progression through the program. The maximum number of solid edges crossed by a horizontal line at that y coordinate is the maximum theoretical parallelism at that point.

Tracing

Event descriptions can be generated from a variety of tracing tools, from instrumented threading libraries, to runtime function call interceptors [11], to full instruction logs. ThreadScope's current set of event-collection tools are based on one of three data collection methods: instrumenting the threading library, system-level runtime tracing, and full instruction traces. In particular, there are implementations for the qthread library [4], Dtrace [6], Apple's libamber [7], and Sandia's SST simulator [8]. Because ThreadScope presents trace-based parallel application structure, it works best when that structure does not depend on the input. The parallelism presented in ThreadScope graphs is entirely dependent upon the parallelism requested during the instrumented application run. In an explicitly parallel environment like Cilk or pthreads, all programmatic parallelism—the parallelism expressed by the programmer—is expressed at runtime and can be captured and expressed in a ThreadScope graph by a runtime tracing tool. Implicitly parallel environments, such as OpenMP [1] or UPC [12], usually adapt the programmatic parallelism to the available parallelism in ways that are not detectable at runtime without language-level instrumentation. Graphing the programmatic parallelism of an implicitly parallel environment would require generating the event description log at the level where the programmatic parallelism is visible, such as in the compiler.

Each tracing method has its own benefits and drawbacks. For example, an instrumented threading library can provide event tracing with relatively low overhead and can faithfully record all thread and synchronization operations. However, an instrumented threading library usually traces the entire execution of the program, which may not be desired. This can be addressed by adding functions to control tracing behavior that can be called by the program, though this would require modifying and recompiling the program in question.

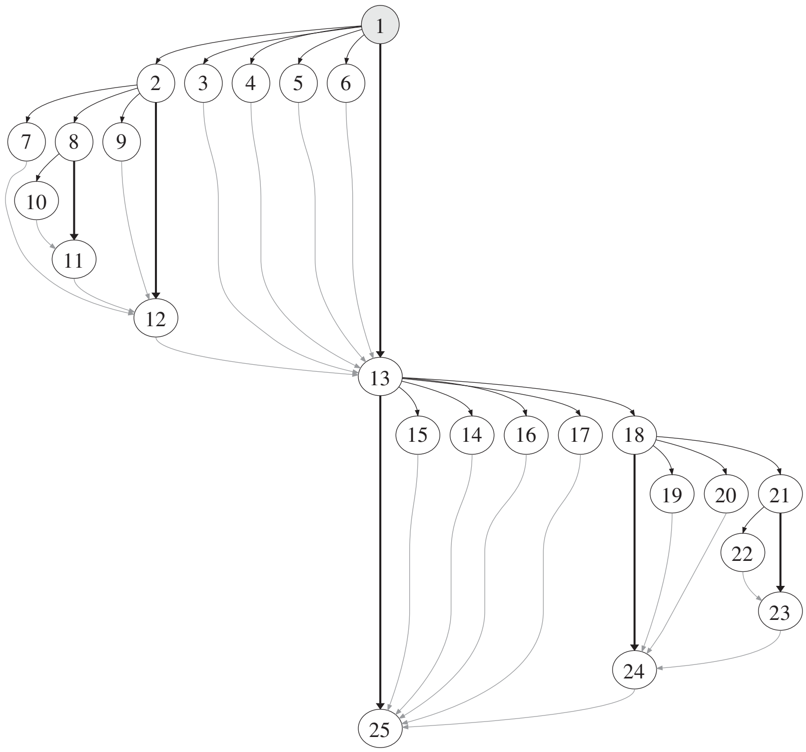


Figure 4. Structure of a Cilk application with a bottleneck.

System-level runtime tracing, such as with valgrind [11] or Dtrace [6], provides the ability to track function calls or even track specific instructions. The overhead of this type of tracing depends on how intrusive it is. For example, a Dtrace script can detect basic thread operations with relatively low overhead, and can be limited to tracing only a portion of an application's runtime. However, the utility of Dtrace event logs is limited because Dtrace cannot detect individual memory accesses. Examples of graphs based on Dtrace output are Figures 4–6.

Full instruction tracers, such as Apple's libamber [7] trace generator or Sandia's cycle-accurate Structural Simulation Toolkit [8], record every instruction, and thus can track every memory operation. This thorough data collection has a relatively high cost. Cycle-accurate simulation has the highest overhead, but avoids perturbing instruction ordering and thus can observe application behavior without affecting it. The event description in Figure 2 was translated from the verbose output of the SST simulator.

Each tracing technique has overhead associated with it. In many cases, as illustrated in Table I, a great deal of overhead. The numbers in that table compare the execution time of each program run uninstrumented to the execution time with instrumentation. In most cases there is some additional post-processing time necessary to generate the event log from the trace outputs. The overhead of the tracing technique is primarily of importance when considering how long it will take to debug

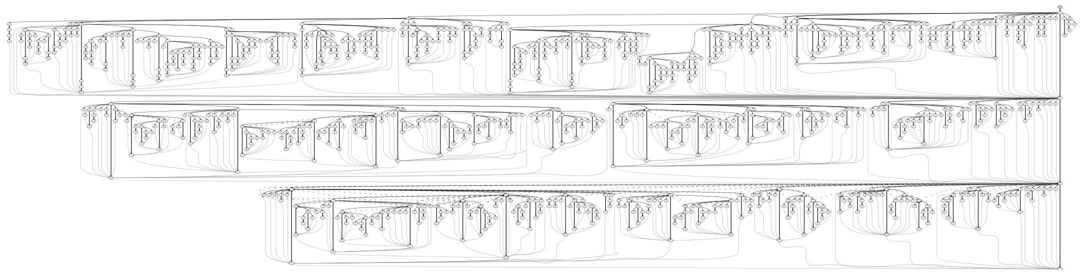


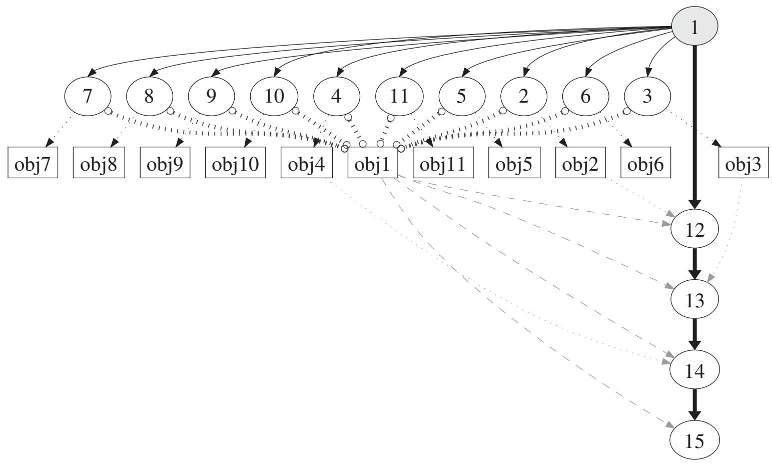
Figure 5. Structure of Cilk bucketsort (*overview without details*).

the program; it does not affect correctness unless the application being traced has strict timing requirements. This is especially true for cycle-accurate simulation, because the application being simulated is not aware of real wall-clock time, and the overhead of recording each instruction has no impact on execution order.

The event description

Each event in ThreadScope's event language consists of a type and several attributes in key = value form. The basic thread lifetime events are `INIT`, `SPAWNED`, and `ENDED`, corresponding to when threads are allocated, run, and complete. Synchronization events include `LOCK`, `UNLOCK`, `SYNC`, `WAIT`, `INCR` and several others representing full-empty bit operations. Memory accesses are described by `MWRITE` and `MREAD` events. Unknown event types are ignored by the graph generator, thus allowing the event language to be expanded for additional analysis. For example, malloc-related events' (`MALLOC`, `FREE`, and `REALLOC`) operations were added late in the development process to enhance memory object tracking. The event descriptions do not generally include data from within the threading libraries or system libraries. The event logs omit this information purposefully, to focus on thread-level application behavior.

Every event has a timestamp (a monotonically increasing integer) and a tid (a CPU identifier or worker-thread identifier). Other attributes depend on the event. Threads are uniquely identified by a 'frame' identifier and the time that they began executing, since frame identifiers may be reused. For example, the `INIT` event indicates that a thread has been allocated. It has a 'frame' attribute that specifies the identity of the thread being initialized—typically the address of the thread's bookkeeping structure or stack. The `INIT` event specifies the identity of the thread generating the event with the 'threadid' attribute; the default value for threads that are not spawned is '0×0.0'. The `SPAWNED` event indicates that a previously allocated thread has begun executing. This event defines a thread's identity (for future use in a 'threadid' attribute), and so has three required fields: a timestamp (labeled 'now'), a parallelism identifier (labeled 'tid'), and the relatively unique 'frame' attribute. It has one optional field, 'entry', used for threading environments that allow for continuations. The `ENDED` event indicates that a thread has stopped executing. It requires the 'now' and 'tid' fields, as well as a 'frame' field and an indication whether the thread is expected to continue. This indication is an optional 'next' field that specifies what 'entry' number the frame




```
size_t iterend = start;
size_t each = len / NUM_SHEPHERDS;
int donecount = 0;
for (i=0;i<NUM_SHEPHERDS;i++) {
    array[i].startat = iterend;
    array[i].stopat = iterend += each;
    array[i].donecount = &donecount;
    array[i].arg = arg;
    if (extra > 0)
        { array[i].stopat++; extra--; }
    qthread_fork_to(qloop_wrapper, &(qwa[i]),
                    &(rets[i]), i);
}
for (i=0;donecount<NUM_SHEPHERDS;i++)
    qthread_readFF(me, NULL, &(rets[i]));
```

```
long qt_loop_wrapper(qthread_t *me,
    const struct wrapper_args *arg)
{
    arg->func(me, arg->startat,
              arg->stopat, arg->arg);
    qthread_incr(arg->donecount, 1);
    return 0;
}
```

Figure 6. Structure of `qt_loop_balance()` spawning ten threads with C source code.

will next use. Subsequent SPAWNED events are considered to be continuations of previous threads if their ‘frame’ and ‘entry’ values match the ‘frame’ and ‘next’ values of an ENDED thread.

Memory is tracked by its address, and so synchronization events and memory accesses require an ‘addr’ attribute. However, memory is typically treated as a collection of logical storage ‘objects’ rather than as a large set of sequentially addressed one-byte storage units. Thus, ThreadScope tracks

Table I. Tracing overheads compared with uninstrumented execution.

Benchmark	Instrumented thread library	System-level tracing	Instruction tracing
HPCCG	1.01x	22.39x	19 698.79x
Pagerank	3.49x	58.19x	8692.25x
Piping	1.09x	72.85x	108.76x

the threads and memory objects used in an application as objects with relationships to each other to simplify application structure. Memory addresses can be grouped into objects, for example as the result of `MALLOC` events.

Visual representation

The first component of visualizing the structure of an application is to represent the relationships between its threads. Very simple relationships were illustrated in Figure 3.

A graph of this nature, for a given execution of a parallel application, can be generated for any threading mechanism that has uniquely identifiable threads. It demonstrates the logical connections between threads, and can be useful for identifying potential bottlenecks in the application. Regions where there is no available parallelism are bottlenecks that can be visually identified using this graphing technique. For example, Figure 4 demonstrates a simple threaded application with an obvious bottleneck.

The graph in Figure 4 does not indicate the severity of the bottleneck; it may be the synchronization and respawning of more threads or something more computationally intensive. The graph only reveals that there is a section of the program (node 13) that cannot execute in parallel. That information is often a fact worth investigating when attempting to improve application performance. Figure 4 is a small excerpt from a Cilk application performing a parallel bucket sort. The full graph of this application is presented in Figure 5. Even without reading the source of the application, it is clear that it has two bottlenecks of the sort illustrated in Figure 4. These bottlenecks segment the computation into three parallelized segments and four purely serial segments.

MEMORY ACCESS PATTERNS

Once the structure of an application has been analyzed, the next step in performance and correctness analysis is to examine the program's memory access patterns. Even small programs generate a large volume of memory references. Including them all in a graph would make it dense and difficult to analyze. Making sense of the graph requires displaying only the memory references that are meaningful, and including them in the graph in ways that are helpful to the problem that is being analyzed. Exactly which memory references are meaningful depends on the application and the situation, but there are some general simplifications that are frequently helpful in presenting a clearer picture of application behavior.

DOI: 10.1002/cpe

Improving visualization clarity

One way to present a clearer picture is to eliminate from the graph all memory locations that are not written. This is useful for clearly presenting race conditions, programming errors, and synchronization bottlenecks. For example, Figure 6 illustrates the `qt_loop_balance()` function from the qthread library. The `qt_loop_balance()` function spawns a number of threads. Each thread, just before exiting, increments a shared counter with the atomic `qthread_incr()` function. The parent thread will wait for each thread to finish in turn. Each time a thread finishes, the shared counter's value is checked against the number of threads the parent spawned. If the counter's value is equal to the number of threads originally spawned, the parent can avoid waiting for the remaining threads individually.

In Figure 6, the dotted edges beginning and ending in gray circles are the atomic increment operations (`qthread_incr()`), the dotted black edges are synchronized memory writes (in this case, writing the return code of the function), and the gray edges (both dotted and dashed) are the relevant memory reads. In this case, a memory read is considered 'relevant' if the read was either a blocking operation (`qthread_readFF()`; the dotted gray edges) or operated on an object that had previously been written to. The graph illustrates a `qt_loop_balance()` loop that spawned 10 threads. Each thread wrote to both the shared counter and the thread's return-value location. The parent thread waited on three of the threads via a blocking operation (`qthread_readFF()`), each time checking the shared counter before waiting on the next thread. It waited on only three threads to finish (2, 3, and 4) before observing that the shared counter was the correct value.

Figure 6 is a small snippet of a graph generated by the HPCCG [13] benchmark. A larger snippet, representing about 3% of its total runtime, is presented in Figure 8(a). This benchmark relies heavily on `qt_loop_balance()`. Since this function is used sequentially, and frequently, its serial components have the potential to become a bottleneck. Note that the structure of the program can be observed in the memory and thread behavior, without requiring *a priori* knowledge of memory layout, data structures, or programmer's intent.

Considering only memory locations that are accessed by multiple threads is another useful simplification. For example, in a simple threaded matrix multiplication implementation, each memory location should only be written to by a single thread. If multiple threads write to the same memory location, that is probably a bug. Threads also typically use thread-specific scratch memory, often in the stack, that has no direct bearing on the logical structure or correctness of the application. The previous `qt_loop_balance()` structure simplifies slightly with this technique and makes the flow of information clearer, as illustrated in Figure 7. The HPCCG benchmark's graph is simplified this way in Figure 8(b).

Object condensing

Programmers typically treat memory as a collection of logical objects rather than as a collection of sequentially addressed bytes. As such, displaying the logical objects rather than the addressed bytes simplifies the visual representation of memory operations. However, objects are hard to define, much less identify from a raw memory address stream. For example, an object may intuitively include an array; but it may be more useful to treat each element of the array as a separate object. Complex data structures only add to the problem. With limited *a priori* knowledge, the best approach is a

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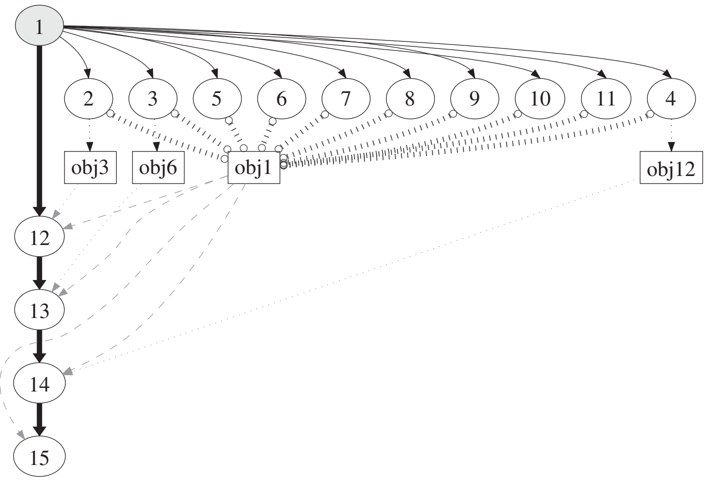


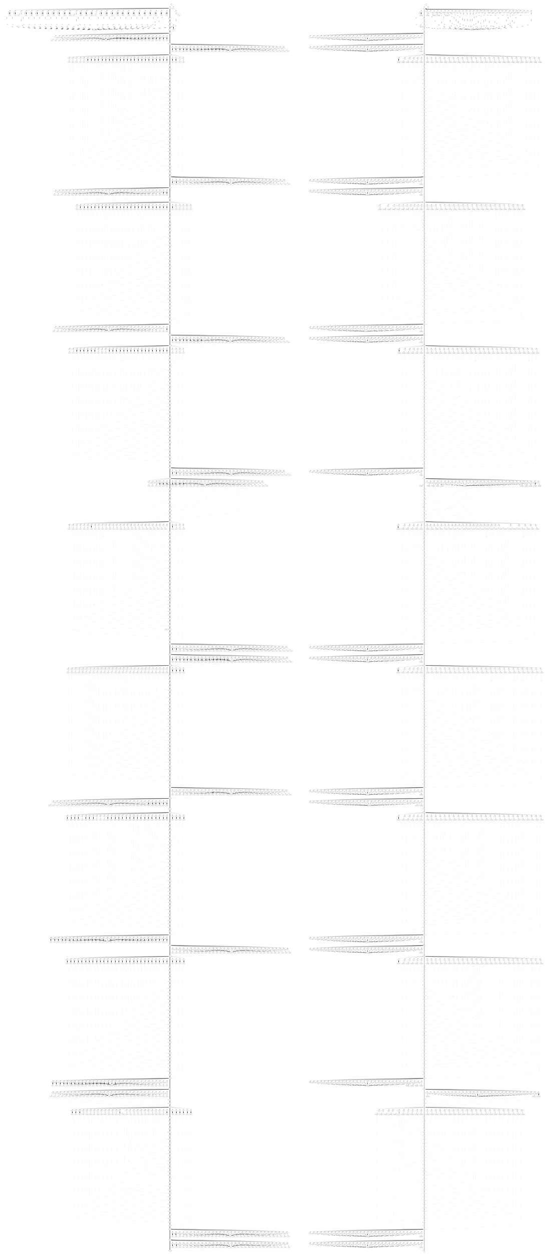
Figure 7. `qt_loop_balance()` spawning ten threads, memory limited to multiple-accesses.

winnowing process, consisting of successive identifications of important memory references from the set of unidentified references.

In many cases, shared data structures are protected by synchronization operations of some kind, such as mutual exclusion locks, semaphores, or full/empty bits. In a very real sense, shared objects are defined by the locks that protect them, and obtaining the lock indicates that lock's associated memory object is about to be accessed. Because of this behavior pattern, objects that are associated with specific locks can be extracted from a stream of memory address references by tracking the state of the synchronization operations during memory access. In the case of mutex locks, whenever a thread accesses a memory location, that location is associated with whatever locks are currently held by the accessing thread. If an address is ever accessed without those locks, then it is not protected by them and cannot be considered part of the memory object associated with that lock. By the end of the sequence of memory references, each lock is associated with a set of memory addresses that it protects. That set of memory addresses comprises a single logical memory object. This object may not be contiguous and may not be entirely what the programmer expected or intended, but it is a de-facto memory object. Addresses that are accessed by multiple threads without a lock may indicate programming errors, and deserve closer attention.

Memory addresses that are not protected by synchronization operations can be clustered into objects in other ways. References to stack variables and global data can be identified not only by considering the memory region, but also with the aid of debugging information in the application binary.

Memory references into the 'heap' region of the address space can be associated with the allocated region to which they belong, however that is often insufficiently specific. Memory pools, arena allocation, and structured `mmap()`ed files are all situations where usefully identifying discrete memory objects can be especially difficult if they are not associated with synchronization operations. It is possible to take a probabilistic approach, estimating discrete memory objects with the help of



(a) (b)

Figure 8. Structure graphs of 3% of the HPCCG benchmark (*overview without details*): (a) including only written addresses and (b) including only shared addresses.

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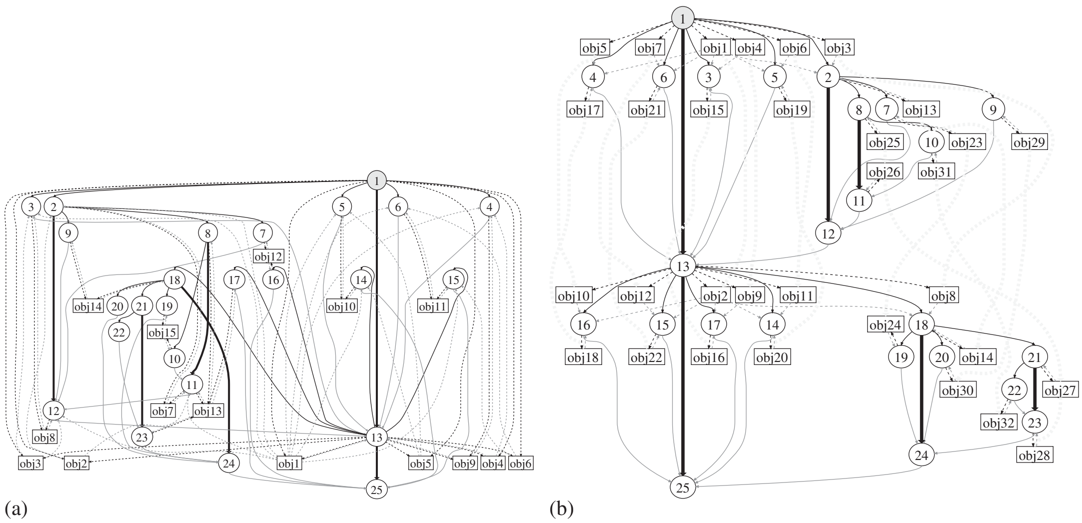

Figure 9. Structural impact of memory access and identity tracking: (a) naïve and (b) SSA-like identity tracking.

proximity and temporal access patterns, but without *a priori* knowledge of the application, grouping memory references into objects is, at best, a guessing game. The only option that guarantees relative correctness is to assume that each unprotected memory location is an independent memory object.

Address re-use

Memory re-use impacts the observed structure of the application. Allocated memory and stack addresses are often re-used, even though the object they represent has changed. It is considered good practice to re-use memory as much as possible, to take advantage of processor caches, and so tight algorithms typically re-use memory for unrelated computations. If the logical status of a memory object is not considered, structure can be difficult to extract; the threads will all appear to be operating on the same memory. For example, Figure 9(a) is the same program that was illustrated in Figure 4, but with memory references added. The logical structure so easily seen in the original graph has become hard to discern.

The most direct way of determining the logical identity of a memory object is to keep track of when it is allocated and deallocated: when it is deallocated, the memory is logically reset and if that memory is re-allocated, it clearly represents an entirely new logical object. Unfortunately, allocation and deallocation only apply to heap-type memory regions, and even then are not always easy to recognize—for example, in applications that implement memory pools or that simply re-use variables. Allocation and deallocation tracking is an incomplete and thus unreliable approach.

We can also track the logical identity of memory by assuming that its identity changes when it is written. This approach is commonly known in the compiler community as SSA [14]. This divides a memory block's existence into separate identities much in the same way that threads are separated into connected execution blocks. If we use strict SSA to establish memory identity transitions,

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each memory block may eventually obtain a large number of identities. Most of these identities are irrelevant to the overall flow of the application and can be merged together. We can focus on important memory references by applying the previously discussed simplification heuristics, such as eliminating memory object identities that are not accessed by more than one thread. The operations upon and previous identities of a memory object impact whether an object must be considered to be shared by multiple threads. For instance, if a memory object is re-used by non-concurrent threads, the two instances are distinct only if the second thread writes to the object before reading from it. If the first action on the object is a read, the object must be treated as shared with the threads that had previously used it. Figures 9(a) and (b) represent the same program, but Figure 9(b) has a clearer structure because of this type of identity tracking.

Condensing structure with *a priori* knowledge

Not all memory references are equally important to analysis and debugging. For example, a shared data structure—such as a hash table or a kernel-supplied file descriptor—may occupy a large discontiguous portion of memory. If that data structure and its accessor functions are assumed to be correct or at least outside the scope of analysis, it can be beneficial to represent that data structure in the graph as a single object, rather than as a large set of independent memory locations.

ThreadScope's memory tracking can be modified by adding new events to the event description, thereby providing *a priori* information about the application's behavior. For example, `malloc()`-tracking uses `MALLOC`, `FREE`, and `REALLOC` events to define memory objects.

Figure 10 illustrates the potential risks and benefits of redefining memory objects. Figure 10(a) is an example of a program with three threads that each insert an entry into a shared hash table and then get it back out again. In this case, the hash table is a simplistic one that allocates a separate object for each key/value pair with `malloc()`. Figure 10(b) presents the result of using `malloc` to define memory objects. The structure is relatively clear. Another way of condensing is to isolate objects by their operand functions. Figure 10(c) reduces the hash table to a single logical object that is accessed by multiple threads. Note that, like Figure 9(a), the logical structure of the graph is obscured by reducing the memory objects too far. Unfortunately, determining the existence of a hash table and isolating key and value pairs are difficult to do automatically from a raw address stream. Events representing hash table operations need to be added to the event log to mask the hash implementation's specific behavior.

ISOLATING POTENTIAL PROBLEMS

Identifying problems in parallel applications when there are few parallel threads of execution is not particularly difficult: the graphs have few components and the patterns of possible errors are easy to recognize visually. However, as the number of threads and the scale of the application increases so does the complexity and size of the thread structure graphs. Merely rendering the entire graph can be a challenge when analyzing an application that uses thousands of threads. One powerful option for handling large graphs is the ZGRViewer tool [15]. Without such a tool, useful analysis requires that the volume of data presented in a single graph be limited to areas of interest, such as problem areas. There are two primary components to isolating potential problems in a thread

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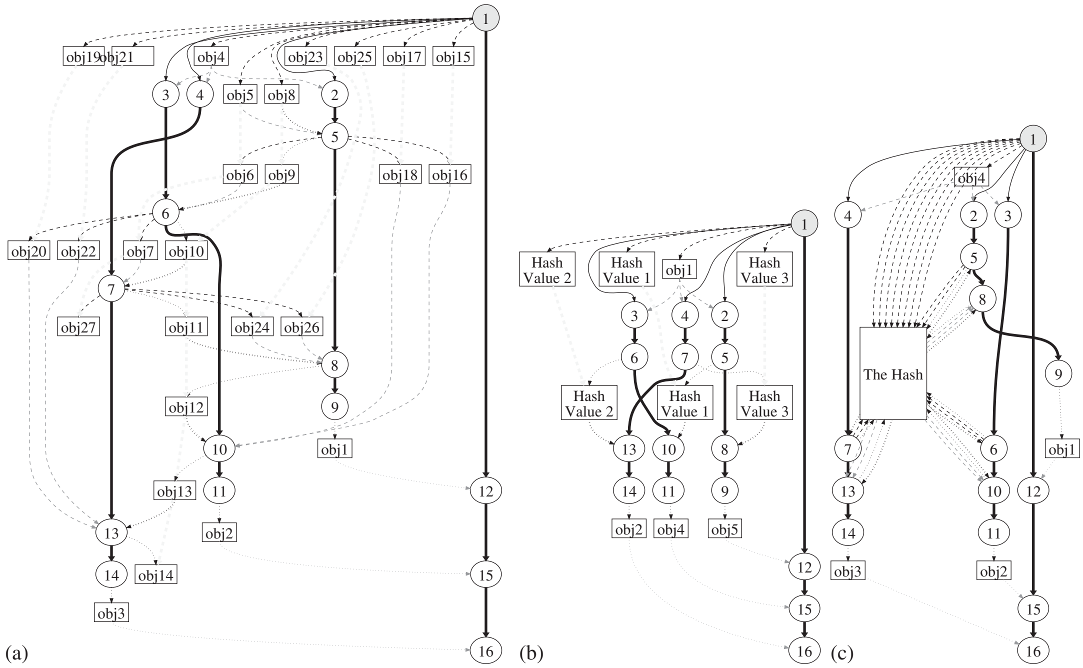

Figure 10. Simple hash table application, with memory object condensing options: (a) individual memory references; (b) condensing malloc-defined blocks; and (c) condensing class-defined blocks.

structure graph: identification of areas of interest in the graph and selective display of only the portions of the graph relevant to that interest.

Structural threading problems

Some of the most basic problems that afflict threaded programs are structural problems that can be revealed and identified graphically. Problems such as race conditions and deadlocks are common problems that can often be discovered using structural analysis.

Deadlocks

Tracking a deadlock down using a basic debugger can be an especially difficult exercise when there are a large number of locks involved. Deadlock is defined by the four Coffman conditions [16]:

1. Mutual exclusion.
2. Hold and wait.
3. No preemption.
4. Circular wait.

DOI: 10.1002/cpe

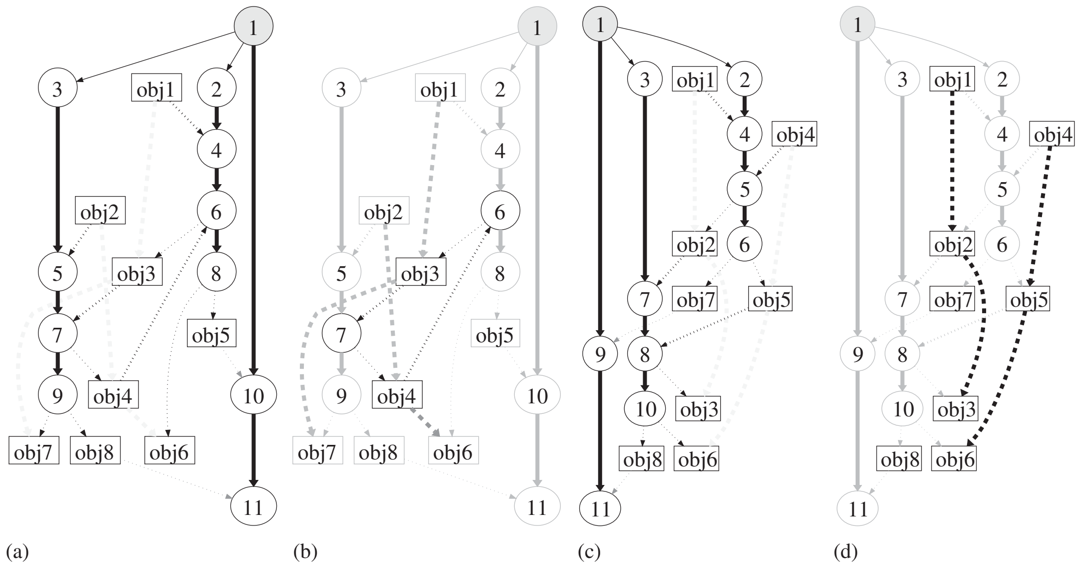

Figure 11. Identification of potential deadlock via structure: (a) circular wait; (b) highlighted circuit; (c) no circular wait; and (d) highlighted dependencies.

In most multithreading programming models, the first three conditions for deadlock are assumed. The fourth, circular wait, is a structural description that becomes apparent from the thread structure graph of a deadlocked program, even if the program does not deadlock during execution. Figure 11(a) presents a program that does not necessarily deadlock, but has the potential. In this program, two threads lock two locks. One thread (starting with node 2) locks the first lock (obj1/3/7), unlocks it, then locks and unlocks the second lock (obj2/5/6). The other thread (starting with node 3) locks the second lock (obj2), locks the first lock (obj3), then unlocks them in the same order. Because of the inconsistent ordering, this is a potential deadlock that may not occur at runtime. This can be detected with dependency tracking [17]. We can interpret the structure graph as a resource-allocation graph that will have a circuit if deadlock can occur. Figure 11(b) highlights the circular dependency. Note that this program can (and did, during graph generation) run to completion, despite the potential deadlock, depending on how the threads are scheduled. Potential deadlock, however, can be identified with a depth-first traversal of the graph. When the previous program is rewritten to ensure that the locks are only obtained in a specific order, as illustrated in Figure 11(c), the circular wait is eliminated. The memory state transitions are highlighted to illustrate the lack of a cycle in Figure 11(d).

Race conditions

There are many different kinds of race conditions, but not all of them can be easily recognized by even the most advanced automatic analysis system. We can relatively easily identify basic race conditions, such as when multiple threads manipulate the same memory object without

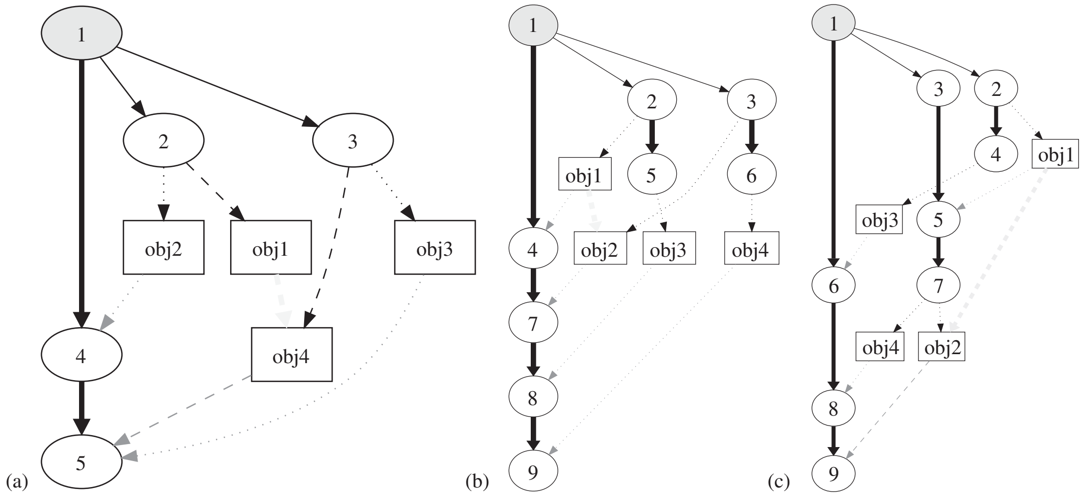

Figure 12. Identifying race conditions via structure: (a) unprotected race; (b) protected race; and (c) ordered access.

synchronization. When the race is to see which piece of data will be placed in a thread-safe memory object, identifying the race condition can become fairly difficult. However, visualizing all of the relevant accesses to a given memory object can reveal the potential for race conditions. If multiple threads access the same memory object, there is a potential race condition and source of concern. Figure 12 illustrates three different kinds of shared-memory access. In Figure 12(a), two threads (2 and 3) attempt to write into the same memory object that thread 5 later reads. However, there is no required ordering to these writes, and thread 5's read could return either value written or even some combination of the two. Figure 12(b) illustrates the common situation of a shared-memory object protected by mutexes. This protection eliminates the potentially corrupt data read, but does not establish a required ordering for the writes. The writes do not depend on one another, so they can be executed in any order. This non-determinism may not be an error, depending on the application. Finally, Figure 12(c) illustrates shared access to a protected memory object that does not have a race condition. Because the writes are logically ordered through dependence relations, the contents of the memory object are deterministic. Thus, the final read is both safe and deterministic despite being unsynchronized. Because these graphs represent the logical structure of the program, a dangerous potential race condition (12(a)) can be identified even if no error is apparent at runtime.

It is worth emphasizing that not all race conditions, defined as timing-dependent logic, are errors. For example, the correctness of the `qt_loop_balance()` implementation from Figure 6 does not rely upon a specific ordering of thread completions.

Graph-based problem identification

The useful portions of the graph can be isolated by presenting only a subgraph of the structure. For example, the graph can be reduced to the subgraph of only the nodes that are connected

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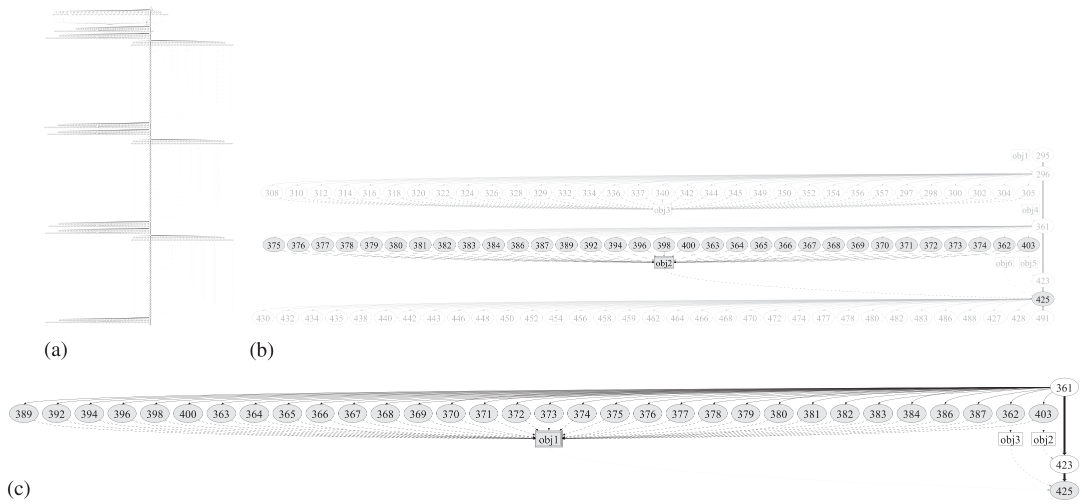

Figure 13. Race condition isolation: presentation options. (a) full graph; (b) distance of four; and (c) nearest common ancestor.

to a given thread or memory object of interest. Because the graphs are directed graphs, it is possible to find the nearest common ancestor of two or more nodes of interest, and present only the subgraph of the paths from those nodes to their common ancestor. Figure 13 illustrates such graphs. Figure 13(a) is a graph of a short application with an intentional race condition in it. Figure 13(b) narrows the graph of the application to only the nodes that have a distance of four or less from the memory object with the race condition—the nodes that are directly connected to the memory object are highlighted. Figure 13(c) presents the graph of the threads that touch the memory object of interest and the ancestral tree up through the nearest common ancestor of those threads. Both of these presentation modes are useful for visually locating potential structural problems.

The other aspect of debugging is identifying the problems in a large graph algorithmically so that they can be isolated and displayed. This is where heuristics are useful, similar to standard compiler warnings. One common structurally detectable race condition is where a write occurs to an object that has not necessarily been read yet. A race condition also occurs when there are two writes to a memory location that do not depend on each other, which can be identified algorithmically. When a deadlock occurs, of course, the affected threads and memory operations can be identified, isolated, and displayed. Identifying potential deadlocks is also possible to do algorithmically.

THREAD MODELS

One of the particularly interesting aspects of this kind of multiprocessing analysis is that the programming scheme employed by the parallel algorithm being studied can be observed and

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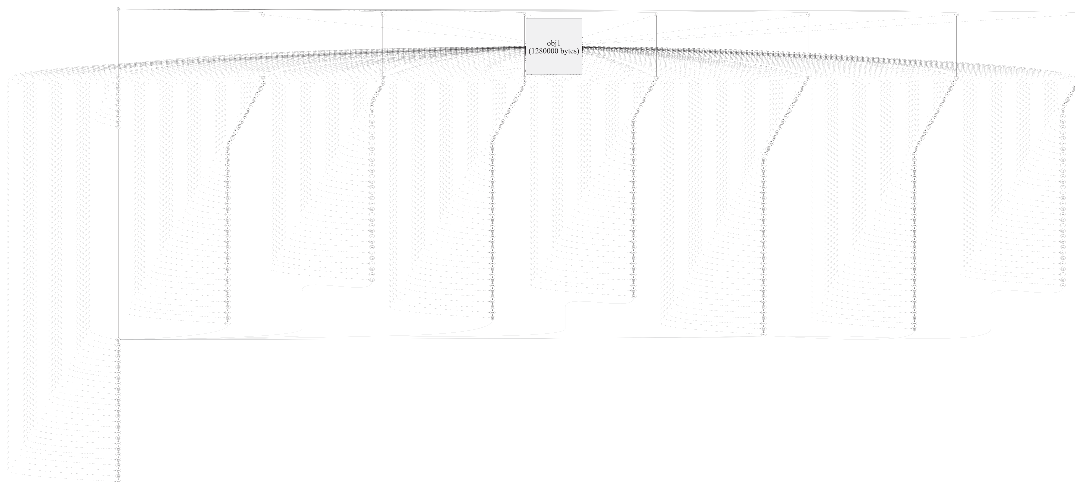

Figure 14. Structure of 10% of Cilk bucketsort, including memory references.

understood without in-depth knowledge of the program itself. The computation model and communication patterns used by the application impact the performance characteristics of the application, and provide an indication of likely performance trends. The computation model is closely associated with the communication pattern and provides insight into potential optimizations and problems that can assist in debugging and maintenance.

For example, graphs in Figure 8 were generated from the HPCCG application, which uses qthreads. HPCCG uses a distinctly phase-oriented programming model that is comparable to the Bulk Synchronous Parallel [18] and PRAM [19] computation models. In each parallelized segment of the application, threads are created, executed, and then results are communicated, largely in the form of synchronization operations. These computational segments can be viewed more closely in Figure 6, which illustrates a single iteration of the underlying qthread-based parallel construction of HPCCG.

The bucketsort implementation, graphed in Figure 5, is an example of a distinctly different parallel computation model. While the program is obviously composed of three distinct phases, without memory references, the memory model cannot be determined. The graph in Figure 5 is produced with a Dtrace-based event description, which could not detect memory references. Figure 14 is a graph of 10% of the same bucketsort program, but traced with SST in order to include memory references. Predictably, it is centered around the large array that it is sorting, depicted as the large box near the top of the graph. This behavior makes it similar in some ways to a Linda-based application [20]. The same would be true for most parallel applications centered around a single data structure, though some data structures can be graphed more usefully, such as a hash table, as illustrated in Figure 10.

Flow-based applications [21] have another distinct structure. This structure is illustrated in Figure 15, which is a graph of a simple parallel stream processor. This program spawns four threads. The first thread generates random numbers and puts them into a circular buffer. The second thread

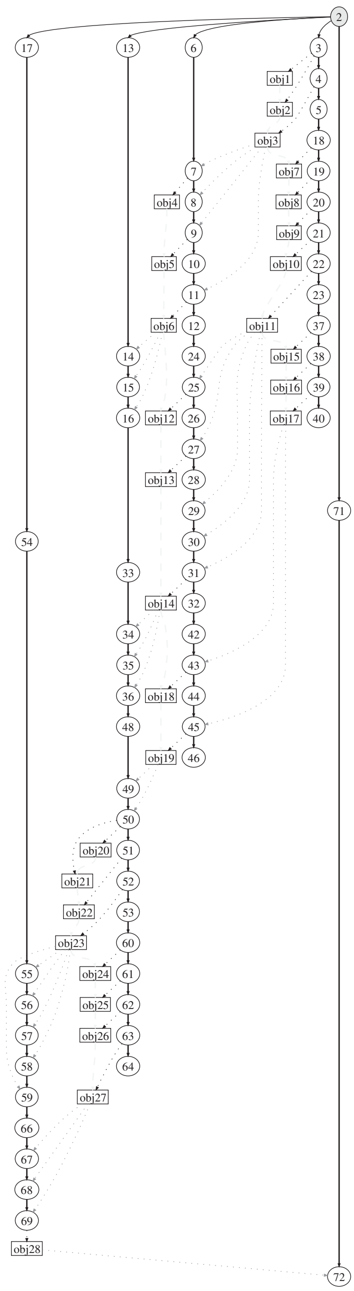

Figure 15. Structure of a flow-based application.

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fetches numbers from that circular buffer and feeds only the odd numbers into a second circular buffer. The third thread fetches numbers from the second circular buffer, sorts them, and then puts them into a third circular buffer. The fourth thread fetches numbers out of the third circular buffer and prints the unique ones. All three circular buffers have a capacity of three. Note that, rather than relying on a large set of shared objects that multiple threads can access, each shared-memory object is only accessed by two threads. This leads to a distinctive visual pattern. The resulting thread structure graph has some distinct similarities with respect to the corresponding FBP diagram.

RELATED WORK

ThreadScope is a hybrid approach to parallel program analysis. It is primarily a visualizer, to make program structure clear and to make structural analysis easy. The graph framework used to generate this visualization, however, leads to opportunities for detecting basic structural problems algorithmically.

Multithreaded applications have a history of being difficult to visualize, because there are few strict rules about their behavior. Some of the oldest parallel visualizers, such as Pablo [22] and Tapestry [23], are essentially monitoring programs that keep track of statistics like communication bandwidth and latencies. More recent variations, such as Bedy's [24] thread monitoring system and the Gthread [25] visualization package from the PARADE [26] project give somewhat more detailed information about locks and thread status. Getting more detail has typically meant tailoring the visualizer to a particular environment. For example, the Gthread system works only on KSR machines, Eden [27] is specific to Haskel programs, and Pajè [28] is a visualization system specifically for data-flow programs such as those written in the Athapascan [29] environment. Pajè monitors long-lived parallel threads, diagrams blocked states, and illustrates message transfer and latency. Assuming that threads are relatively few and long-lived is typical of many parallel visualizers. In many cases, such as with ParaGraph [30], PARvis [31], and Moviola [32], the visualization assumes one thread per node, and then focuses on the communication and blocked status of those 'threads'. They provide time-process communication graphs that make it easy to identify basic communication problems. Explicit communication is typical of the MPI programming model, and MPI visualization tools like Vampir [33] provide similar information in similar-looking graphs. ThreadScope graphs use communication behavior to help define structure, rather than presenting a structure based on the hardware layout.

As multithreaded applications have become more popular, automated correctness checkers have received a great deal of interest. In some cases these tools stem from serial application correctness checkers. This is especially true for memory checkers such as IBM's Rational Purify [34] and Valgrind [11]. Valgrind is particularly interesting because it has developed a validation component, Helgrind [35], to perform validation of common threading operations and watch for potential race conditions. Another similar tool is Intel's Thread Checker [36]. These tools are all dynamic program analysis tools, similar to the tracing tools that generate the event description logs that ThreadScope uses. The ThreadScope approach is more akin to shape analysis, such as done by Sagiv *et al.* [37], because of the way it renames memory objects based on access behavior, though ThreadScope relies primarily on thread behavior.

CONCLUSION

Analyzing parallel applications continues to be an area of great interest as parallel runtime environments become more powerful, complex, and unpredictable. The work presented in this paper provides a powerful method of understanding the behavior of lightweight-threaded applications in several common lightweight-threaded environments. This allows application structure to be compared across multiple threading environments and assists in quickly identifying hard-to-reproduce logical problems. Most importantly, this work allows the memory use patterns and thread structure to be combined in a single visualization tool, enabling not only correctness analysis but also providing the information necessary to plan thread/data partitioning schemes.

ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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