Debugging Multi-Threaded Applications using Pin-Augmented GDB (PGDB)

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Abstract— *In contrast to single threaded applications, debugging multi-threaded applications is complex because of the non-deterministic nature of concurrent programs. Multiple threads in concurrent programs introduce bugs like datarace, deadlock and livelock. Popular debuggers like GNU Debugger (GDB), Intel Debugger (IDB) and Microsoft Visual Studio Debugger (MVSD) typically use static or compile-time instrumentation and provide many features to debug single threaded programs. However the features dealing with debugging concurrency is limited. In this paper we explore dynamic instrumentation using JIT (Just-In-Time) compilation techniques for run-time behaviour using dynamic instrumentation framework from Intel PIN [1]. Using PIN we augment GDB with support for datarace and deadlock detection with automated breakpoint to GDB. We call it PGDB or PIN-augmented GDB - a multi-threaded debugging platform. We present here a prototype of PGDB for detecting datarace and deadlock during the execution of multi-threaded programs with the support of new commands in PGDB.*

Keywords: Multi-threaded debugging, datarace, deadlock,PGDB or PIN-augmented GDB

1. Introduction

Debugging multi-threaded applications is complex because of the non-deterministic nature of concurrent programs leading to concurrency issues like race conditions and deadlocks. *Datarace* occurs when two or more threads in a program access the same memory location concurrently without using any exclusive locks to serialize their accesses and with atleast one access for write. *Deadlock* is a condition in which two or more threads wait for each other to release a shared resource before resuming their execution.

The classical approach to debugging single threaded applications (sequential programs) involves repeatedly stopping the program, examining the state, and then either continuing or re-executing to stop at an earlier point in execution. Such debugging cycles help developers trace the sequential execution paths well but unfortunately do not identify the concurrency issues in multi-threaded programs.

Most popular debuggers like GNU Debugger (GDB) [4], Intel Debugger (IDB) [5] and Microsoft Visual Studio Debugger (MVSD) [6] provide many features to debug single-threaded programs. However the features dealing with debugging concurrency is limited (Table 1). Earlier Shi et al [7] used PIN to extract different threaded behaviours of applications by displaying the access / change history of a shared variable, tracking locks held by threads and displaying information at the breakpoints but datarace or deadlock was not detected. Also the method incurs huge overhead for instrumentation. In this background our objective is to augment the capabilities of existing debuggers with more multi-threaded support to help debug concurrency issues.

A debugger typically uses static[1] or compile-time instrumentation. However, we choose dynamic[2] or runtime instrumentation so that we can attach / detach debugging support on-the-fly without changing compiled code.For dynamic instrumentation we use the PIN [3] framework from Intel. Using PIN we augment GDB with support for datarace and deadlock detection with automated breakpoint to GDB. We call it PGDB or PIN-augmented GDB. Besides new GDB commands for datarace and deadlock, we also support an option to selectively enable/disable the detection mechanism to reduce the overhead of dynamic instrumentation during program execution.We have tested efficiency and accuracy of PGDB by developing benchmark test cases.

Though the design of PGDB is agnostic to the platform, the programming language or the multi-threading model, our implementation here is based on GDB on Linux with C/C++ language and pthreads [8] library for multi-threading support.

This paper is organized as follows. In Section 2 we outline the architecture of PGDB based on GDB, PIN and their interconnection. The instrumentation mechanisms to empower GDB detect concurrency issues like race condition and deadlock are presented in Section 3 and the implementation aspects covering new GDB commands for concurrency

[1]In *Static Instrumentation* the source code is instrumented during compilation and is used to identify the static program information.

[2]In *Dynamic Instrumentation* the binary (executable) code is instrumented using JIT (Just-In-Time) compilation to collect run-time information.

Table 1: Comparison of PGDB with Existing Debuggers

Feature/Debugger	PGDB	GDB [4]	IDB [5]	MVSD [6]
Examining state of existing threads	✓	✓	✓	✓
Thread specific breakpoints	✓	✓	✓	✓
Thread synchronizing breakpoints	✓	✓	✓	✓
Thread data sharing events	☑	×	✓	✓
Automatic notification of new threads	✓	✓	✓	✓
Logging Feature	☑	×	×	×
Replay Feature	×	×	×	×
Datarace detection	☑	×	×	×
Deadlock detection	☑	×	×	×
Livelock detection	×	×	×	×

☑ - Additional Feature ✓- Feature Present × -Feature Absent

support and enhancement of GDB GUI for user feedback are discussed in Section 4. We present a sample debugging session with PGDB in Section 5. The results debugging and detection for a set of benchmark codes, designed specifically to cover the corner cases of correctness of PGDB, are discussed in Section 6. We conclude in Section 7 with directions for future work.

2. Architecture of PGDB

To augment GDB with the intended multi-threaded debugging features we need the following primitives:

- *Control over memory accesses used by program* to identify memory instructions.
- *Identification of read and write accesses* to know the purpose (reading or writing) of memory access by an instruction.
- *Control over thread granularity* to find the thread ID executing a given instruction and to notify when a particular thread gets created or destroyed.
- *Control over routine granularity* to notify the start and completion of a routine[3].
- *Control over lock* to notify when the locks of a shared-exclusive memory are acquired or released.
- *Control over memory barrier* to identify the user defined synchronization using memory barrier.

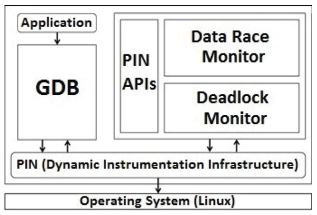
We use the dynamic instrumentation framework of PIN[4] to create pintools that extract the above primitives during the execution of an application under the control of GDB. Since we use pthreads the events of acquiring and releasing the locks are captured from the invocations of `pthread_mutex_lock()` and `pthread_mutex_unlock()` functions respectively. The resulting architecture of PGDB is shown in Figure 1 A. To use PGDB a developer needs to compile the source code in debug mode to create a GDB-compatible binary. The binary then executes in remote mode with PIN having custom instrumentations (as pintools). Finally, GDB is started and connects to PIN through remote port to debug and detect concurrency issues. The developer controls the debugging by issuing our new concurrency detection commands from GDB.

[3]A function is referred to as *routine* by PIN.

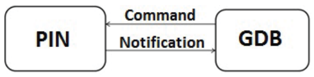
[4]PIN [1] is a binary instrumentation framework on Linux or Windows. A wide variety of program analysis tools, called Pintools [3], can be built using PIN. PIN is a JIT compiler that can inject instrumentation routines in instruction, basic block, routine or image level units. An instrumentation routine is attached as a callback either before or after an instrumentation unit. The design of these callbacks decide the behaviour of the pintool.

2.1 Interconnection of GDB with Pin

GDB supports a *remote* mode where it can communicate to the remote *stub* that understands GDB protocol via a Serial or TCP/IP connection. In PGDB PIN connects to GDB via its remote debugging protocol. The communication with the debugger is two-way as shown in Figure 1 B. GDB sends commands to PIN and PIN sends notifications back whenever the program stops on intended breakpoints or terminates. Note that every program instruction that is executed under the control of the debugger is still instrumented with the PIN.



(a)



(b)

Fig. 1: (A) The Basic Architecture of PGDB (B) Interconnection of GDB with Pin via Remote Debugging Protocol

2.2 Breakpoint Propagation to GDB

PIN provides an API to generate breakpoint in GDB to stop during program execution. When the Data Race Monitor pintool identifies a potential Datarace or the Deadlock Detection pintool finds a deadlock event, a suitable breakpoint is generated from within the respective pintool and is passed on to the GDB console to stop the program execution. This carries the thread ID and message for GDB console.

3. Design of PGDB

In PGDB we augment GDB with features to detect the race condition and deadlock. These features may be turned on or off dynamically during the execution of an application under debug. We instrument `RecordLockBefore()` and `RecordLockAfter()` before and after the calls to `pthread_mutex_lock()` respectively. Further we instrument `RecordUnLockAfter()` after calls to `pthread_mutex_unlock()`. Following instrumentations implement these features:

3.1 Data Race (Detection) Monitor

PIN provides APIs to identify memory accesses and to detect if the thread holds a lock on it or not during the access. Thus, to detect datarace we first identify the shared-exclusive memory locations and then monitor these locations for accesses with or without lock by a thread.

Instrumentation Policy

To identify whether or not a memory location is shared among multiple threads, we maintain a hash table `MemTracker` where the key-field is a (32- or 64-bit) memory address and the value-field is a memory region structure containing the Thread ID and the Access type (READ/WRITE). We perform image instrumentation to get the address range of the main executable image as loaded into memory and shared library images to filter out memory accesses for the main executable only as thread-local and read-only memory accesses do not induce dataraces.We instrument every instruction belonging to the main executable image and shared library images. Identifying memory locations is performed in two analysis routines namely `RecordMemRead()` and`RecordMemWrite()` before Load and Store instructions respectively. We use thread IDs assigned by PIN for thread identification within analysis routine

- **`RecordMemRead` Routine** is called before the execution of a *Load* instruction to analyse read accesses from memory. The memory address, thread ID and context are passed to this routine. When a memory address is accessed for the first time a memory region structure is populated with READ and is added to the `MemTracker`. For subsequent accesses for a memory location for which a memory region structure already exists in `MemTracker` we have the following situations:
  - **Existing Access type is READ**: This is a case of READ-after-READ and there is no datarace.
  - **Existing Access type is WRITE**: This is a case of READ-after-WRITE. There is no action (and no race) if the thread IDs are same. If the thread IDs are different, this memory location should be marked as a shared-exclusive memory.
- **`RecordMemWrite` Routine** is called before the execution of a *Store* instruction to analyse write accesses to memory. The memory address, thread ID and context are passed to this routine. When a memory address is accessed for the first time a memory region structure is populated with WRITE and is added to the `MemTracker`. For subsequent accesses for a memory location for which a memory region structure already exists in `MemTracker` we have the following situation:
  - **Existing Access type is READ or WRITE**: This is a case of WRITE-after-READ or WRITE-after-WRITE. Hence this memory location should be marked as a shared-exclusive memory if the thread IDs are different.

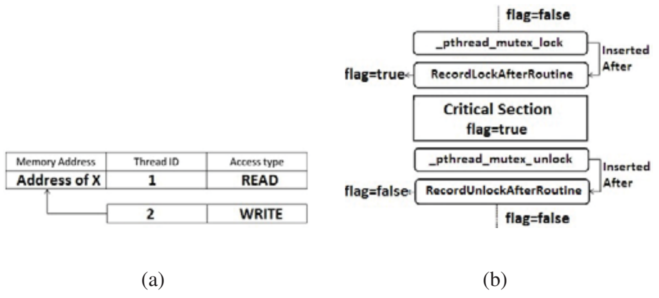


Fig. 2: (A) Race Detection (B) Identification of Safe / Unsafe Access

We maintain a boolean variable `flag` (initialized to false) for each thread for race detection (Figure 2 B). When `RecordLockAfter()` is called, say, by Thread 1, we enter the critical section and set `flag` for Thread 1 as true. Later when `RecordUnlockAfter()` is called, we know that the thread has left the critical section and we reset the `flag` for Thread 1. Hence any access to a shared-exclusive memory location is a safe access while `flag` is true. Otherwise it is unsafe.A memory location if marked as shared-exclusive and has an unsafe access is a potential for datarace invoking the breakpoint.

The above characterization of safety, however, changes when users employ barriers for explicit synchronization. We enumerate different cases of safety with and without barriers in Table 2 and use them to formulate the following analysis strategy for exploring datarace in the presence of barriers.

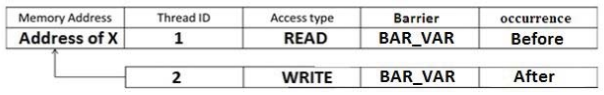
- **`BarrierDetect` Routine** is called before every call of `pthread_barrier_wait()` to track the memory barriers. The `MemTracker` is now extended with additional fields to store the barrier variable associated with a thread and the order of the occurrence (Before / After) of variables relative to the barrier. And if there is no barrier at all then these fields will be `NULL`.
  - **When we encounter a variable X in a thread before crossing a barrier**, we insert a new row in `Memtracker` as `{<Mem_Addr>, <Thread_ID>, <Access_type>, <No>, <NULL>}`. Now we have two possibilities either we cross a barrier after this variable or the barrier is not at all available.
    - **if variable occurs before a barrier** then during crossing the barrier named, say

BAR_VAR, the pthread_barrier_wait() callback will update the above row in Memtracker as {<Mem_Addr>, <Thread_ID>, <Access_type>, <BAR_VAR>, <Before>}.

  * **if there is no barrier at all** then the row in Memtracker will remain unchanged.

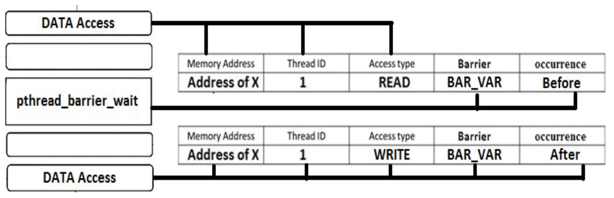
- **If we have already crossed a barrier**, say BAR_VAR, before accessing the variable then we insert {<Mem_Addr>, <Thread_ID>, <Access_type>, <BAR_VAR>, <After>} in Memtracker.

Here BAR_VAR will be the barrier variable name to deal with multiple barriers. If the memory access in two



Memory Address	Thread ID	Access type	Barrier	occurrence
Address of X	1	READ	BAR_VAR	Before
	2	WRITE	BAR_VAR	After

(a)



(b)

Fig. 3: (A) No Race Due to Barrier (B) Updating Memtracker

threads appear before and after the barrier respectively (or vice-versa) like in Figure 3 A we can exclude this condition from potential data-race factors. Then we can formulate the additional logic for any variable X appearing in threads T1 and T2 before or after a barrier as cases 3, 4 and 5 of the Table 2.

```
If (((Occurrence of X in T1 is before barrier)
     AND
     (Occurrence of X in T2 is after barrier))
   OR
    ((Occurrence of X in T2 is before barrier)
     AND
     (Occurrence of X in T1 is after barrier)))
then NO DATA RACE.
```

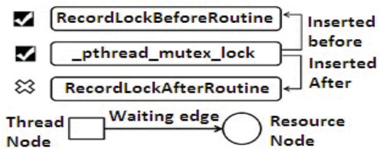
3.2 Deadlock (Detection) Monitor

To detect deadlock we use a *Resource Allocation Graph* (RAG). An RAG is a directed bipartite graph with two types of nodes and two types of edges. A RAG represents a thread by a *Thread Node* and a resource by a *Resource Node*. If a thread t owns (holds a lock on) a resource r, we draw an *Acquired Edge*(Figure 4 B) from r to t. If a thread t is blocked on a resource r, we draw a *Waiting Edge*(Figure 4 A) from t to r. Clearly, there is deadlock if and only if there is a cycle in the RAG. Thus, we can detect deadlock by building the RAG (Figure 4 C).

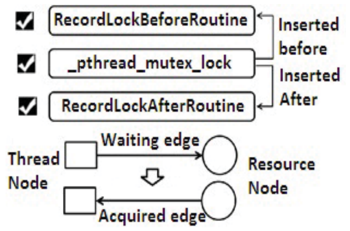
Instrumentation Policy

To construct a RAG we identify the waiting and acquired edges as follows:

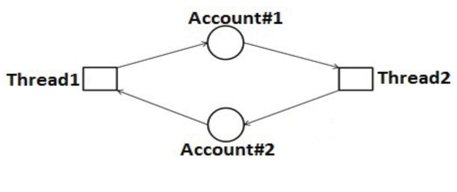
- A waiting edge from thread t to resource (mutex) r is added to the RAG when t is blocked in pthread_mutex_lock(&r) routine because some other thread holds the lock on the mutex r. This is done in RecordLockBefore().
- An acquired edge from thread t to resource (mutex) r is added to the RAG when t acquires the lock on the mutex r by completing pthread_mutex_lock(&r). While an acquired edge is added the existing waiting edge is removed. This is done in RecordLockAfter().
- An acquired edge is removed from the RAG when thread t releases mutex r by completing pthread_mutex_unlock(&r). This is done in RecordUnLockAfter().



(a)



(b)



(c)

Fig. 4: (A) Waiting edge in RAG (B) Acquired edge in RAG (C) Deadlock detection by RAG

Once the RAG is constructed we detect deadlocks by finding cycles in it and the deadlock breakpoint is invoked.

4. Implementation of PGDB

We have implemented the above design over GDB to create PGDB. For this we have added a set of new commands to GDB (Section 4.1). The users can use these command as input to PGDB to control the debugging of concurrency. Further we have enhanced the GUI mode of GDB (Section 4.2) to output debugging information back to the user.

4.1 PGDB Commands

To use the detection monitors from PGDB, we have designed the following simple commands that the developer can issue to PIN through PGDB:

- **monitor help**: Display all customized commands to debug concurrency issues.
- **datarace detection on**: Start the detection of shared-exclusive memory access (datarace).
- **datarace detection off**: Stop the detection of shared-exclusive memory access (datarace).
- **datarace detection status**: Shows whether the detection of datarace is ON or OFF.
- **deadlock detection on**: Start the detection of deadlock.
- **deadlock detection off**: Stop the detection of deadlock.
- **deadlock detection status**: Shows whether the detection of deadlock is ON or OFF.

4.2 Enhancement of GUI Mode of GDB

We have enhanced the support of graphical framework of GDB and built the infrastructure to generate breakpoints by our profilers. Among all existing graphical gdb in the market, we have chosen DDD for this purpose which is a well-known graphical gdb with clean and simple interface. Once DDD layer comes on top of our PGDB, whenever a breakpoint is generated by our profiler, it needs to be propagated to the GUI layer from GDB so as to highlight the cause of the detection by profiler in the source code of the application. This is done very interactively using a cursor pointing the exact line causing the detection of deadlock, datarace.

To integrate our new features with GDB, we designed a shell script to automatically establish the connection between PIN and GDB, and instantiate DDD irrespective of the system architecture on which it is running.Higher level steps are given below:

- Instantiate PIN with the designed Pintool or Profiler
- Start DDD interface which will run the GDB engine in the background
- Establish remote connection between GDB and PIN, as the application to be debugged will be running in PIN which is outside GDB
- Open a separate source window of DDD displaying the source code of test application
- Open a separate data window where variable values will be shown while debugging
- Open the GDB command window to input the custom commands and run the program

5. Sample Debugging Session in PGDB

We present example debugging in PGDB implementation.

5.1 Data Race Breakpoint Feature

Consider the following code being executed by Thread 1. Suppose Thread 2 increments shared variable `x` without a lock. Hence the value of `y` is not deterministic due to race.

```
if (x == 5) // The "Check"
{ y = x * 2;  // If another thread changed x
    // in between "if (x == 5)" and "y = x * 2";
    // y will not be equal to 10.}
```

PGDB identifies the race and halts the program with a breakpoint. When Thread 1 reads the value of `x`, it is registered as a READ operation in `MemTracker` and when Thread 2 increments its value, the race condition is detected (Figure 2 A).

5.2 Deadlock Detection Breakpoint Feature

An example of deadlock is shown below where two threads, Thread 1 and Thread 2, invoke `transfer()` as shown:

```
    void transfer(Account from_account,
        Account to_account, double amount) {
        pthread_mutex_lock(&from_account);
        pthread_mutex_lock(&to_account);

        from_account.withdraw(amount);
        to_account.deposit(amount);

        pthread_mutex_unlock(&to_account);
        pthread_mutex_unlock(&from_account);
    }
Thread 1: transfer(account#1, account#2, 1000);
Thread 2: transfer(account#2, account#1, 500);
```

As Thread 1 starts executing `transfer()` it holds lock on `account#1` and is suspended as it waits for lock on `account#2`. Meanwhile Thread 2 acquires lock on `account#2` and waits indefinitely for Thread 1 to release `account#1`. Deadlock results. A cycle in this RAG (Figure 4 C) implies deadlock.

6. Test Result

The benchmark test suite for test datarace and deadlock are demonstrated in Sections 6.1 and 6.2 respectively. The behaviour and performance on the benchmarks have been presented in Sections 6.3 and 6.4.

6.1 Correctness for Datarace

The following scenarios are needed to test the correctness.

- *Benign Datarace* can occur when:
  - *One shared variable-two threads:* 2 threads T1 and T2 share a variable x with 2 different modes Read(R) or Write(W).

```
T1:                        | T2:
  A1 x = x +1;             |   B1 x = x +1;
  A2 printf("x=%d\n",x);   |   B2 printf("x=%d\n",x);
```

    Datarace is detected in T2 at line B1 and in T1 at line B1 for the execution sequence A1, B1, A2, B2 and B1, A1, A2, B2 respectively.
  - *Two shared variables-two threads:* 2 threads T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                        | T2:
  A1 x = y +1;             |   B1 y = x +1;
  A2 printf("x=%d\n",x);   |   B2 printf("y=%d\n",y);
```

Datarace is detected in T2 at line B1 and in T1 at line B1 for the execution sequence A1, B1, A2, B2 and B1, A1, A2, B2 respectively.

– *Datarace in only one thread:* T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                          | T2:
  A1 pthread_mutex_lock      |   B1 pthread_mutex_lock
       (&mutex);             |        (&mutex);
  A2 x = y +1;               |   B2 y = x +1;
  A3 pthread_mutex_unlock    |   B3 pthread_mutex_unlock
       (&mutex);             |        (&mutex);
  A4 x++;                    |
```

Datarace is detected in T1 at line A4 for the execution sequence A1, A2, A3, B1, B2, A4, B3.

– *Datarace in two threads:* 2 threads T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                         | T2:
  A1 x = y +1;              |   B1 y = x +1;
  A2 y = x;                 |   B2 x = y;
  A3 printf("x=%d\n",x);    |   B3 printf("y=%d\n",y);
```

Datarace is detected in T2 at line B1 and in T1 at line A2 for the execution sequence A1, B1, A2, A3, B2, B3. Another is detected in T1 at line A1 and in T2 at line B3 for the execution sequence B1, B2, A1, A2, B3, A3.

- *Fatal Datarace* can occur when:

– *Case 1:* 2 threads T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                                | T2:
  A1 x=(int*)                      |   B1 x[1]=1;
        malloc(2*sizeof(int));     |   B2 free(x);
  A2 x[0] = 1;                     |
```

Datarace is detected in T1 at line A2 for the execution sequence A1, B1, A2, B2. Also segmentation fault at A2.

– *Case 2:* 2 threads T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                     | T2:
  A1 x++;               |   B1 x++;
  A2 if(x == 0){        |   B2 if(x == 0){
  A3 free(obj);         |   B3 free(obj);
  A4 }                  |   B4 }
  A5 x--;               |   B5 x--;
```

Datarace is detected in T2 at line B1 and in T1 at line A2 for the execution sequence A1:1, B1, A1:2, A2, A3, B2, B3, B4, A4, A5, B5 and Crash will happen at B3. Here A1:1 is "compute x+1" and A1:2 is "assign to x".

– *Case 3:* 2 threads T1 and T2 share a variable x with in Write (W) mode.

```
T1:                     | T2:
  A1 x = x+4;           |   B1 x=3;
```

Datarace is detected in T2 at line B1 for the execution sequence A1:1, B1, A1:2 where A1:1 is "compute x+1" and A1:2 is "assign to x".

- *Benign/Fatal Datarace* can occur when:

– *Case 1:* 2 threads T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                     | T2:
   A1 if ( x<y ) {      |    B1 x=y-1;
   A2 z = x+4;          |
   A3 y = z;            |
   A4 }                 |
   A5 z++;              |
   A6 printf("x=%d",x); |
```

Datarace is not detected even though there is potential datarace in the program for the execution sequence B1, A1 , A2, A3, A4, A5, A6.

– *Case 2:* 2 threads T1 and T2 share 2 variables x and y with 2 different modes Read (R) or Write (W).

```
T1:                     | T2:
   A1 if ( y<0 ) {      |    B1 x=y-1;
   A2 sleep(10);        |
   A3 y = x+4;          |
   A4 }                 |
   A5 y++;              |
   A6 printf("x=%d",x); |
```

Datarace detected due to execution of sleep(10) by T1 as there is potential datarace in the program for the execution sequence A1, A2, B1, A3, A4, A5, A6.

– *Case 3:* 2 threads T1 and T2 share variable x with 2 different modes Read (R) or Write (W).

```
T1:                                | T2:
  A1 x=(int*)                      |   B1 x[1]=1;
        malloc(2*sizeof(int));     |   B2 sleep(10);
  A2 x[0] = 1;                     |   B3 free(x);
```

There exists a Fatal Datarace but it is not detected due to execution of sleep (10) by T2 for the execution sequence B1, B2, A1, A2, B3.

6.2 Correctness for Deadlock

Since PGDB works on dynamic analysis, there are cases of deadlock which get overlooked:

- *Deadlock* detected for the following case:
  T1 and T2 share 2 variables x, y with 2 different modes Read(R) or Write(W) with locking variables mutex1, mutex2.

```
T1:
  A1 pthread_mutex_lock(&mutex1);
  A2 pthread_mutex_lock(&mutex2);
  A3 x = y+1;
  A4 pthread_mutex_unlock(&mutex2);
  A5 pthread_mutex_unlock(&mutex1);
T2:
  B1 pthread_mutex_lock(&mutex2);
  B2 pthread_mutex_lock(&mutex1);
  B3 y = x+1;
  B4 pthread_mutex_unlock(&mutex1);
  B5 pthread_mutex_unlock(&mutex2);
```

Deadlock is detected in T2 at line B2 and datarace is also detected in T1 at line A2 for the execution sequence A1, B1, A2, B2, B3, B4, A3, A4, A5, A5 and for sequence A1, B1, B2, A2, A3, A4, A5, B3, B4, B5 respectively. Though potential deadlock exists in the application, no deadlock occurred and hence not detected by PGDB for execution sequence A1, A2, B1, A3, A4, A5, B2, B3, B4, B5.

6.3 Benchmark Testing

To test the behaviour, accuracy and efficiency of PGDB, we have used (with modification) a set of benchmarks of popular dataraces detected by Google's Thread-Sanitizer Tool[5].

- **Case 1:** *No Datarace condition with one thread.* Benchmark has only one thread and does not have datarace. The result will be negative.
- **Case 2:** *No Datarace condition with synchronization.* Benchmark has two threads accessing one global shared variable which is synchronized with proper locking mechanism to prevent datarace. Thus the result will be negative.
- **Case 3:** *Datarace condition with synchronized and non-synchronized shared variables.* Benchmark has two threads with two global shared variables. One global is accessed using locks while the other is accessed without locks. So access to one of them will lead to datarace. One datarace is reported.
- **Case 4:** *Datarace leading to crash due to write to freed memory or double freeing.* Benchmark has two threads accessing a dynamically allocated memory location which is freed based on a reference count and a non-synchronized access to this reference count will lead to being freed more than once hence leading to program crash. Reported in real time applications like Chrome, SQLite etc.
- **Case 5:** *Datarace on Boolean flag used for thread synchronization.* Benchmark has two threads and the synchronization between these two threads is done using a boolean variable which is shared between the threads and due to out of order execution in latest architectures leads to unexpected results. Datarace will be reported on the shared Boolean flag.
- **Case 6:** *No Datarace condition by adding memory barriers for in-order instruction execution.* This benchmark consists of two threads with two shared variables using memory barriers which enforces ordering of memory access for shared data synchronization to solve unexpected results caused due to out of order instruction execution. Result of PGDB should be negative.
- **Case 7:** *Datarace condition due to improper usage of memory barrier instruction.* This benchmark consists of two threads with two shared variables. The access to these shared data is not synchronized due to usage of memory barrier instructions at improper places leading to datarace. Reported by PGDB.
- **Case 8:** *Datarace condition due to Initializing objects without synchronization.* Benchmark has two threads trying to initialize an object by dynamically allocating memory. Since the allocation is done without any synchronization, it might lead to memory leaks. Should be detected by our PGDB.
- **Case 9:** *Datarace on free.* This benchmark has two threads where one thread dynamically allocates memory in the heap whereas the other thread frees this

[5]https://code.google.com/p/thread-sanitizer/wiki/PopularDataRaces

Table 2: Different Scenarios of Barrier

#	Thread 1	Thread 2	Thread 3	Potential of Datarace between
1	`void* func1() { x = 1; pthread_barrier_wait(&bar);}`	`void* func2() { x++; pthread_barrier_wait(&bar); }`	NA	(T1 & T2)
2	`void* func1() { x = 1; pthread_barrier_wait(&bar);}`	`void* func2() { x++; pthread_barrier_wait(&bar);}`	`void* func3() { x = 2; }`	(T1 & T2) or (T2 & T3) or (T1 & T3)
3	`void* func1() { x = 1; pthread_barrier_wait(&bar);}`	`void* func2() { pthread_barrier_wait(&bar); y=x;}`	NA	None
4	`void* func1() { pthread_barrier_wait(&bar); x = 1; }`	`void* func2() { y = x; pthread_barrier_wait(&bar);}`	NA	None
5	`void* func1() { x = 1; pthread_barrier_wait(&bar);}`	`void* func2() { pthread_barrier_wait(&bar); y = x; }`	`void* func3() { x = 2; }`	(T1 & T3) or (T2 & T3)
6	`void* func1() { x = 1; pthread_barrier_wait(&bar); }`	`void* func2() { y = x; pthread_barrier_wait(&bar); }`	NA	(T1 & T2)
7	`void* function1() { pthread_barrier_wait(&bar); x = 1; }`	`void* func2() { pthread_barrier_wait(&bar); y = x; }`	`void* func3() { x = 2; }`	(T1 & T2) or (T2 & T3) or (T1 & T3)

area causing a crash due to datarace. So, the result of PGDB should be positive with reporting of datarace.

- **Case 10:** *Datarace on exit.* This benchmark has two threads created by the main program which are accessing a shared global object where before both the threads end, the main program exits thereby making the shared object unavailable to both of them. Should be detected and reported by PGDB.
- **Case 11:** *Datarace on mutex.* consists of two threads that are synchronized by locking or unlocking a shared mutex and any change in mutex value or its destruction by one thread will affect the other thread still in execution leading to datarace of the mutex. This datarace should be reported by PGDB.
- **Case 12:** *Datarace on file descriptor.* consists of two threads that are accessing the same file descriptor for read/write purpose without any synchronisation leading to data being written on a wrong file or socket causing leaking of sensitive data into an untrusted network connection in real time. Reported by PGDB.

Table 3: PGDB Output for Datarace

Benchmark Case	Expected Output	PGDB Output
Case 1	No Datarace	×
Case 2	No Datarace	×
Case 3	Datarace Exists	✓
Case 4	Datarace Exists	✓
Case 5	Datarace Exists	✓
Case 6	Datarace Exists	✓
Case 7	Datarace Exists	✓
Case 8	Datarace Exists	✓
Case 9	Datarace Exists	✓
Case 10	No Datarace	×
Case 11	Datarace Exists	✓
Case 12	Datarace Exists	✓

✓- Data Race detected × -Data Race not detected

6.4 Performance Testing

The user can selectively turn on or off the instrumentation to increase performance. While instrumentation adds considerable overhead on the execution time, we find that with PGDB's selective instrumentation it can be significantly reduced.

7. Conclusion and Future Work

We have presented strategies to dynamically instrument multi-threaded programs (written in C/C++ using pthreads library) using PIN and to integrate the same with GDB (on Linux) to debug for dataraces and deadlocks, if any. The support has been implemented with new commands in PGDB (Table 1). Going forward we would like to support livelock detection in PGDB, extend the augmentations for Microsoft Visual Studio Debugger [6] on Windows, and support other thread libraries / models like Windows threads [11], Intel TBB [9] and Boost [10]. We would also like to improve the performance of the pintools to make PGDB more effective.

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