

Formatting Submissions for a USENIX Conference: An (Incomplete) Example

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Abstract

Multithreaded programs suffer from nondeterministic behavior ranging from data races to uninitialized variables. GPU (graphic processing unit) programs are especially vulnerable to bugs related to nondeterministic behavior due to their high level of parallelization. These bugs can be especially difficult to catch, as merely running the program again with the same inputs does not guarantee that the bug will rear its head again. Frameworks like PinPlay and Instant Replay allow a user to record and deterministically replay a program, but no tool yet exists with the same functionality for GPU programs.

Our goal is to create a tool that allows a user to capture the execution of their GPU program and replay the execution. The source of nondeterminism we're focusing on is data races. We want to be able to replay a GPU program such that not only do threads interacting with memory run in the same order, but also the state of memory throughout the program is identical to when it was recorded. We used NVBit (NVidia Binary Instrumentation Tool) to instrument instructions that operate on memory (loads and stores). On record, we record all loads and stores. On replay, we use locks to replay the loads and stores for each memory address in order. This paper will describe the design of our tool, as well as discuss its usage on racey GPU programs. We hope our tool will serve as a proof of concept for further endeavors into GPU record and replay tools.

1 Introduction - 1 page

"Define and motivate the problem with examples, briefly talk about challenges. Explain your core high-level idea. Give an overview of your solution and summarize key results" Discuss other solutions (none exist). Talk about other kinds of nondeterminism like multiple kernels, uninitialized memory. Describe the core concept, which is to get all values when recording and replay them in order.

Nondeterminism is the root of many complex bugs. The move to increasingly parallel programs

When a GPU program starts running on the CPU, the CPU uses the GPU for parallel computing by launching kernels onto it. Each of these kernels consists of threads, which are organized into uniformly-sized blocks. All threads in the kernel run the exact same kernel function, though their control flows may differ. Threads can access different kinds of memory. Every thread has its own register and local memory, which are only able to be accessed by that thread and only live for the lifetime of the thread. Shared memory is shared among threads in a block, which allow threads to communicate with each other. Finally, global memory is shared among all the threads in the application.

We decided to focus on data races specifically related to shared and global memory. Let's motivate this with an example program:

```
#include <stdio.h>

__global__ void saxpy(int n, float a, float *x, float *y)
    int i = blockIdx.x*blockDim.x + threadIdx.x;
    if (i < n) y[i] = a*x[i] + y[i];
}

int main(void) {
    int N = 1<<20;
    float *x, *y, *d_x, *d_y;
    x = (float*)malloc(N*sizeof(float));
    y = (float*)malloc(N*sizeof(float));

    cudaMalloc(&d_x, N*sizeof(float));
    cudaMalloc(&d_y, N*sizeof(float));

    for (int i = 0; i < N; i++) {
        x[i] = 1.0f;
        y[i] = 2.0f;
    }

    cudaMemcpy(d_x, x, N*sizeof(float), cudaMemcpyHostToDevice);
    cudaMemcpy(d_y, y, N*sizeof(float), cudaMemcpyHostToDevice);
```

```

// Perform SAXPY on 1M elements
saxpy<<<(N+255)/256, 256>>>(N, 2.0f, d_x, d_y);

cudaMemcpy(y, d_y, N*sizeof(float), cudaMemcpyDeviceToHost);
float maxError = 0.0f;
for (int i = 0; i < N; i++)
    maxError = max(maxError, abs(y[i]-4.0f));
printf("Max error: %f\n", maxError);

cudaFree(d_x);
cudaFree(d_y);
free(x);
free(y);
}

```

2 Design - 3 pages

GPlayU is composed of three stages: record, processing, and replay.

2.1 Record

2.2 Processing

The result of the record stage was a file for each kernel. In the record stage, every interaction with memory was recorded (load or store) alongside its associated values (address, thread number, counter, and value that was loaded or stored). This data needs to be processed before feeding it to the replay stage. This is accomplished by a simple program written in C++14. Let's look at a short example output file from the record stage:

```

5 0x0c 1 S G 0xff
3 0x0c 2 S G 0x01
8 0x0c 5 L G 0x00
9 0x0c 5 L G 0xff

```

Each line is has values in the order count, address, `thread_id`, store/load, global/shared, and value. As this data is not going to be in order, the processing stage could simply order by count and print the data back out. The the replay stage would force load and store instructions to run in the exact same order on replay. However, this would incur a lot of unnecessary overhead.

In the example, thread 1 is loading from address 0x04 at count 1, then thread 2 is storing to address 0x0c at count 3. Since these two threads operate on different locations in memory, enforcing the ordering of the two is not necessary. Potential data races can be examined and controlled in a more fine-grained manner by looking first at addresses, then the accesses to those addresses. The processing stage does not

actually detect data races, but identifies addresses that may have write/write or write/read dependencies, and outputs the order of memory accesses to those addresses.

Therefore data must be organized first by address, and then by `thread_id`. The result of the processing stage is again a file for each kernel, organized by address. This stage must also account for the double loads output by the recording stage: when encountering the data for two loads by the same thread at the same address, the first datum contains the correct count, while the second contains the correct value.

The first line of processing output is how many addresses there are with potential data races. Then each line is composed of the addresses, the number of memory operations on that address, followed by a tuple of `thread_id`, store/load, and value. Here is the output from the sample:

```

1
0x0c 3 2 S 0x01 1 S 0xff 5 L 0xff

```

There are also a couple simple optimizations in this stage that make a big difference in output file size, especially when run on larger programs. To reiterate, GPlayU is designed to preserve the state of memory after the replay of a program by controlling for data races, so all optimizations were made within these constraints. Here is some sample record output to show the optimizations:

```

1 0x10 1 L G 0x00
2 0x10 1 L G 0x00
3 0x10 2 L G 0x00
4 0x10 2 L G 0x00
5 0x0c 1 S G 0xff
6 0x0c 1 S G 0x00
7 0x04 2 S G 0xff
8 0x04 3 S G 0xff
9 0x1c 3 S G 0xff

```

There are four different optimizations at each of the memory addresses in the sample output that altogether result in the processing stage reporting no potential data races.

- ONLY LOADS** The only memory operations on the address 0x10 are loads. Since there are no stores actually changing the value at this memory address, it is unnecessary to output these loads.

- SAME THREAD** At address 0x0c, there are two stores executed by the same thread. Within threads, instructions are executed sequentially, so these two stores will always be in the same order. Therefore, if all the memory operations at a certain address are executed by the same thread, there are no data races.

- SAME VALUE** At address 0x04, there are two stores executed by different threads. However, the threads are storing the same values, so it doesn't matter which thread executes the store first.

- ONE OPERATION** At address 0x1c, there is only one memory operation. There is only one possible ordering with one operation, so this is not a data race.

2.3 Replay

Similar to the record stage, the replay stage also necessitates instrumenting all loads and stores. Additionally, the replay stage needs to take the output of processing, read it in on the host, and distribute it to the device, where thread ordering will be enforced. Data is read into a two-dimensional array on the host and then copied to the device for use in replaying.

At each load or store, the relevant memory address is checked to see if there are any dependencies associated with it. If so, the thread checks if it is the next to be run. This information is stored in device array, and the lock is not needed to read it. When the thread is next to be run, it grabs the lock, which is global to all threads. While in possession of the lock, the thread does the following: it first executes the load or store with the value saved in the device array by manually moving the value into memory or a register. Then it updates the value of the next thread to be run.

The instrumentation functions for load and store instructions are called before the instruction executes. The execution order of these instructions must be controlled, so they replay stage cannot simply let go of the lock after asserting that it is that thread's turn to execute and leave the thread to run the subsequent load or store. The actual instruction must be deleted and manually executed while holding the lock.

Using NVBit and Cuda. What was instrumented and recorded? What challenges did we face? (ASLR, had to use a count to keep track of order when recording, had to implement our own locks, needed to manually replay loads and stores to make sure order is maintained) What other design decisions have we considered (replaying just by inserting data values, but not maintaining ordering. This gives us the same output from a program, but does not replay memory as well.)

3 Implementation - 0.5 page

"Explain subtle implementation details" -Explain how we implemented a lock?

4 Evaluation

"Convince the reader that your system works and explain when it fails" 8-9 benchmarks discuss overhead (maybe look at overhead with only loads/only stores)

5 Related Work - 0.5-1 page

Pin-Play How is our work the same? How is it the same? What ideas were adopted from other works?

Our work, however, is certainly not the first to be done on GPUs and determinism. In 2013, GPUDet was released as the first massively parallel and strongly deterministic architecture. It guarantees determinism by only allowing threads to communicate at fixed, deterministic intervals.

6 Discussion - 0.5 page

"Discuss your limitations and possible workarounds"

7 Conclusion - 2-3 paragraphs

"Summarize your paper and briefly point out the future work"

Future work - actually doing something different with shared vs global.

8 Footnotes, Verbatim, and Citations

Footnotes should be placed after punctuation characters, without any spaces between said characters and footnotes, like so.¹ And some embedded literal code may look as follows.

```
int main(int argc, char *argv[])
{
    return 0;
}
```

Now we're going to cite somebody. Watch for the cite tag. Here it comes. Arpachi-Dusseau and Arpachi-Dusseau co-authored an excellent OS book, which is also really funny [?], and Waldspurger got into the SIGOPS hall-of-fame due to his seminal paper about resource management in the ESX hypervisor [?].

The tilde character (~) in the tex source means a non-breaking space. This way, your reference will always be attached to the word that preceded it, instead of going to the next line.

And the 'cite' package sorts your citations by their numerical order of the corresponding references at the end of the paper, ridding you from the need to notice that, e.g, "Waldspurger" appears after "Arpachi-Dusseau" when sorting references alphabetically [?, ?].

It'd be nice and thoughtful of you to include a suitable link in each and every bibtex entry that you use in your submission, to allow reviewers (and other readers) to easily get to the cited work, as is done in all entries found in the References section of this document.

Now we're going to take a look at Section 9, but not before observing that refs to sections and citations and such are colored and clickable in the PDF because of the packages we've included.

¹Remember that USENIX format stopped using endnotes and is now using regular footnotes.

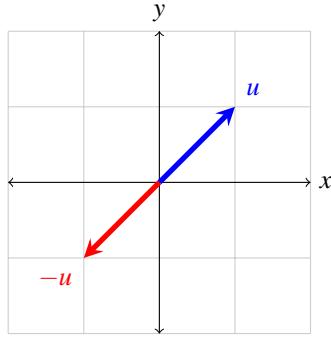


Figure 1: Text size inside figure should be as big as caption's text. Text size inside figure should be as big as caption's text. Text size inside figure should be as big as caption's text. Text size inside figure should be as big as caption's text. Text size inside figure should be as big as caption's text.

9 Floating Figures and Lists

Here's a typical reference to a floating figure: Figure 1. Floats should usually be placed where latex wants them. Figure 1 is centered, and has a caption that instructs you to make sure that the size of the text within the figures that you use is as big as (or bigger than) the size of the text in the caption of the figures. Please do. Really.

In our case, we've explicitly drawn the figure inlined in latex, to allow this tex file to cleanly compile. But usually, your figures will reside in some file.pdf, and you'd include them in your document with, say, \includegraphics.

Lists are sometimes quite handy. If you want to itemize things, feel free:

fread a function that reads from a stream into the array `ptr` at most `nobj` objects of size `size`, returning `returns` the number of objects read.

Fred a person's name, e.g., there once was a dude named Fred who separated usenix.sty from this file to allow for easy inclusion.

The `noindent` at the start of this paragraph in its tex version makes it clear that it's a continuation of the preceding paragraph, as opposed to a new paragraph in its own right.

9.1 LaTeX-ing Your TeX File

People often use `pdflatex` these days for creating pdf-s from tex files via the shell. And `bibtex`, of course. Works for us.

Acknowledgments

The USENIX latex style is old and very tired, which is why there's no `\acks` command for you to use when acknowledging.

Sorry.

Availability

USENIX program committees give extra points to submissions that are backed by artifacts that are publicly available. If you made your code or data available, it's worth mentioning this fact in a dedicated section.