

# DiffTrace: Efficient Whole-Program Trace Analysis and Diffing

Saeed Taheri

*School of Computing*

*University of Utah*

Salt Lake City, Utah, USA

staheri@cs.utah.edu

Ian Briggs

*School of Computing*

*University of Utah*

Salt Lake City, Utah, USA

ian.briggs@gmail.com

Ganesh Gopalakrishnan

*School of Computing*

*University of Utah*

Salt Lake City, Utah, USA

ganesh@cs.utah.edu

Martin Burtscher

*Department of Computer Science*

*Texas State University*

San Marcos, Texas, USA

burtscher@cs.txstate.edu

**Abstract—** Abstract to be written

**Index Terms—** diffing, tracing, debugging

## I. INTRODUCTION

### BEGIN Ganesh

Debugging high performance computing code remains a challenge at all levels of scale. Conventional HPC debuggers [?], [?], [?] excel at many tasks such as examining the execution state of a complex simulation at a detailed level and allowing the developer to re-execute the program close to the point of failure. However, they do not provide a good understanding of why a program version that worked earlier failed upon upgrade or feature addition. Innovative solutions are needed to highlight the salient differences between two executions in a manner that makes debugging easier as well as more systematic. A recent study conducted under the auspices of the DOE [?] provides a comprehensive survey of existing debugging tools. It classifies them under *four* software organizations (serial, multithreaded, multi-process, and hybrid), *six* method types (formal methods, static analysis, dynamic analysis, nondeterminism control, anomaly detection, and parallel debugging), and lists a total of 30 specific tools. Despite this abundance of tools and approaches, many significant problems remain to be solved before debugging *can be approached by the HPC community as a collaborative activity* so that HPC developers can share their solutions and extend a common framework

In this paper, we provide our fundamentally fresh look at debugging. We point out three significant problems that we have addressed in our work, and provide our preliminary solutions backed up by case studies. While our work has not (yet) addressed the situations in which millions of threads and thousands of processes run for days and produce an error, we strongly believe that we can get there only through a series of *rigorous* approaches that overcome key limitations found in conventional debugging approaches in a step-by-step manner, accompanied by careful measurements of the merits of the new approach. The main contribution of this paper is the first such critical measurements of our proposed approach.

a) *Problem-1: Need to Generalize Approaches for Outlier Detection.*: Almost all debugging approaches seek to find outliers (“unexpected executions”) amongst thousands of

running processes and threads. The approach taken by most existing tools is to look for symptoms in a specific bug-class that they cover. Unfortunately, this approach calls for a programmer having a good guess of what the underlying problem might be, and to then pick the right set of tools to deploy. If the guess is wrong, the programmer has no choice but to refine their guess and look for bugs in another class, re-executing the application and hoping for better luck with another tool. This iterative loop of re-execution followed by applying a best-guess tool for the suspected bug class can potentially consume large amounts of execution cycles and also waste an expert developer’s time.

*Solution to Problem-1: Whole Program Tracing for Debugging:* In this setting, our first contribution is a debugging approach in which the application is not merely run with a single symptom-specific tool attached as described earlier. Instead, we collect *whole program traces* of function calls and returns, using a PIN-based function call tracing facility called ParLoT that we have developed and previously reported [?]. We store these traces for potential examination by multiple tools and approaches. The advantage of whole program binary tracing supported in ParLoT is that we can collect function calls at *any desired level of abstraction*. For instance, if the programmer wants to cover activities at the MPI level, the OpenMP level and perhaps even lower levels (e.g., the MPI library or the OpenMP runtime), they can do so using ParLoT.

Clearly, the more APIs at which function calls are recorded, the more burdensome trace collection becomes. However, the advantage is that correspondingly more tools can then be applied to the collected traces. There is always a sweet-spot in this trade-off space, depending on the particular debugging situation. However, our fundamental insight is that *given the inevitability of heterogeneous programming* (the use of multiple concurrency models), it is important to be collecting traces from a few related APIs at a time, so that one can study bugs in one of the concurrency models or a bug resulting from a bad cross-model interaction from a *single run of the program*.

In our research, we have thus far demonstrated the advantage of ParLoT with respect to collecting both MPI and OpenMP traces from a *single run of a hybrid MPI/OpenMP program*. We demonstrate that from this single type of traces, it is possible to pick out MPI-level bugs or OpenMP-level bugs.

While we have not covered all these combinations in our work so far, the main contribution claimed is the ability to cover multiple APIs while debugging, and without re-executions or guess-work.

While this approach to whole-program tracing may sound extremely computation intensive, we employ novel on-the-fly compression techniques within ParLoT. In our previous study [?], we report compression efficiencies exceeding 16,000. This allows us to bring out the function call traces without significantly burdening the memory subsystem or I/O networks in the HPC cluster.

*b) Problem-2: Need to Generalize Approaches for Outlier Detection::* Given that outlier detection is central to debugging, it is important to be employing efficient representations of the traces collected from threads and processes so that one can compute *distances* between these traces more systematically, without involving human reasoning in the loop. The representation must also be versatile enough to be able to “Diff” the traces<sup>1</sup> with respect to *an extensible number of vantage points*. These vantage points could be diffing with respect to process level activities, diffing with respect to thread-level activities, a combination thereof, or even finite sequences of process/thread calls (say, to locate *changes* in caller/callee relationships).

*Solution to Problem-2: Use of Concept Lattices in Debugging:* In DiffTrace, we employ *concept lattices* to amalgamate the collected traces. Concept lattices have previously been employed in HPC to perform structural clustering of process behaviors [?] to present performance data more meaningfully to users. The authors of that paper employ the notion of *Jaccard distances* to cluster performance results that are closely related to process structures (determined based on caller/callee relationships).

In DiffTrace, we employ incremental algorithms for building and maintaining concept lattices from the ParLoT-collected traces. In addition to Jaccard distances, in our work we also perform hierarchical clustering of traces and provide a tunable threshold for outlier detection. We believe that these uses of concept lattices and more refinement approaches for outlier detection are new in HPC debugging.

*c) Problem-3: Loop Detection::* Most programs spend most of their time in loops. Therefore it is important to employ state-of-the-art algorithms for loop extraction from execution traces. It is also important to be able to diff two executions with respect to changes in their looping behaviors.

*Solution to Problem-3: Rigorous Approaches to Loop Analysis:* In DiffTrace, we employ the notion of NLRs (what does it stand for?) for extracting loops. Each repetitive loop structure is given an identifier, and nested loops are expressed as repetitions of this identifier exponentiated (as with regular expressions). This approach to summarizing loops can help manifest bugs where the program does not hang or crash, but nevertheless run differently in a manner that informs the developer engaged in debugging.

<sup>1</sup>Hence the name of our tool, **DiffTrace**.

To summarize, the key contributions of this paper are the following [[fix the section numbers later]]:

- A method to organize function call traces collected from processes and threads into concept lattices, and a method to detect loops from dynamic traces (Section ??).
- Details of the algorithms employed in DiffTrace (Section ??).
- Experimental studies on a heterogeneous program called Iterated Local Champion Search (ILCS, Section ??).
- Strengths and limitations of DiffTrace, plans for future work (Section ??).

## END Ganesh

[[Ganesh and Saeed have written some text before for the intro which is available in v0/intro.tex (also available but commented in current file). Current version is based on our discussion on May 8th]]

- Importance of whole program diffing : understand changes, debug (DOE REPORT [1])
- Efficient tracing supports selective monitoring at multiple levels
  - Bugs not there at a predictable API level
  - Prior work (ParLoT) supports whole program tr.
- Dissimilarity is important to know: bugs, changes during porting,...
- Key enablers of meaningful diffing:
  - Formal concepts (novel contrib to debugging)
  - Loop detection (loop diffing can help)
- Importance, given the growing heterogeneity

**\*\* TODO: Highlights of results obtained as a result of the above thinking should be here. This typically comes before ROADMAP of paper.**

In summary, this paper makes the following main contributions:

- A tunable tracing and trace-analysis tool-chain for HPC application program understanding and debugging
- A variation of the NLR algorithm to compress traces in lossless fashion for easier analysis and detecting (broken) loop structures
- An FCA-based clustering approach to efficiently classify traces with similar behavior
- A tunable ranking mechanism to highlight suspicious trace instances for deeper study
- A visualization framework that reflects the points of differences or divergence in a pair of sequences.

The rest of the paper is as follows:

- Sec 2: Background
- Sec 3: Components
- Sec 4: Case Study: ILCS
- Sec 5: Related Work
- Sec 6: Concluding Remarks

## II. BACKGROUND

The general idea is to utilize ParLoT [2] traces for studying HPC application behaviors towards fault detection and

localization. ParLOT collects whole-program function calls and returns at different levels via dynamic binary instrumentation [3], and incrementally compresses them on-the-fly. Upon termination of the application, ParLOT flushes out per-thread trace files containing compressed sequence of executed function IDs. The compression mechanism of ParLOT significantly reduces the time, memory and disk overhead, leaves the majority of the system bandwidth for the application. With the mindset of “*pay a little upfront to dramatically reduce the number of overall debug iterations*”, ParLOT well overcomes the challenge of whole-program *trace collection* and leaves the *trace analysis* for offline post-mortem analysis, saving HPC resources.

In this paper, we introduce DiffTrace, a tool-chain that provides an infrastructure for iterative and configurable search space reduction of the HPC whole-program function-call traces, to ease the process of detection of the most impacted trace(s) and/or region of trace(s). Considering a “successful” termination of the application as *normal behavior*, DiffTrace takes steps towards *abnormal behavior* detection when an application crashes, time outs or produces a corrupted answer. Each abnormal behavior is a potential fault cause or a manifestation of the fault. However, faults in HPC applications may occur or influence the program behavior at different locations and granularities, due to high and hybrid level of parallelism. Also typical HPC applications spend most of their execution time in a main loop until a convergence or over timesteps, and a fault may get triggered or causing problems after some iteration. DiffTrace gives the HPC developers the capability of going through the pipeline of trace processing multiple times, each time putting a flash-light on various aspects of the applications’ dynamic behavior, gradually collecting evidence about what has happened during execution.

- **Initial Step:** Pre-processing (decompression and filter) - removing uninteresting trace entries
- **Detecting loops:** Loops in source codes reflect themselves as a sequence of *repetitive patterns*, resulting in often-long but redundant traces. A “nested loop recognition” mechanism then mines loops from traces as “*a measure of progress*” per thread, and also a loss-less abstraction to ease the rest of trace analysis.
- **FCA:** The control flow of events in parallel architectures often follow a *regular pattern* such as SPMD, odd-even and master/slave. This characteristic often makes all traces of a single execution tend to fall into just a few “conceptually/behaviorally equivalent classes”. Adopted from the work by Webber et al [39], we have applied *formal concept analysis* (FCA)[7] techniques to reduce the trace search space into a few classes of traces, and also using the *concept lattice* (CL) data structure as the *model* of execution for further analysis.
- **Diffing/Ranking Suspicious Traces/Outlier detection** Measuring Buggy vs. bugFree clustering under various combination of parameters - find out which traces changed the most and rank parameters based on B-score.

Figure 1. Simplified MPI implementation of Odd/Even Sort

	Main Function	oddEvenSort()
1	int main(){	oddEvenSort(rank, cp){
2	int rank,cp;	...
3	MPI_Init()	for (int i=0; i < cp; i++)
4	MPI_Comm_rank(..., &rank);	{
5	MPI_Comm_size(..., &cp);	int ptr = findPtr(i, rank);
6	// initialize data to sort	...
7	int *data[data_size];	if (rank % 2 == 0) {
8	...	MPI_Send(..., ptr, ...);
9	oddEvenSort(rank, cp);	MPI_Recv(..., ptr, ...);
10	...	} else {
11	MPI_Finalize();	MPI_Recv(..., ptr, ...);
12	}	MPI_Send(..., ptr, ...);
13		}
14		...
15		}
16		}

Table I  
PRE-DEFINED FILTERS

Category	Sub-Category	Description
Primary	Returns	Filter out all returns
	PLT	Filter out the “plt” function calls for external functions/procedures that their address needs to be resolved dynamically from Procedure Linkage Table (PLT)
MPI	MPI All	Only keep functions that start with “MPI_”
	MPI Collectives	Only keep MPI collective calls (MPI_Barrier, MPI_Allreduce, etc)
	MPI Send/Recv	Only keep MPI_Send, MPI_Isend, MPI_Recv, MPI_Irecv and MPI_Wait
	MPI Internal Library	Keep all inner MPI library calls
OMP	OMP All	Only keep OMP calls (starting with GOMP_)
	OMP Critical	Only keep OMP_CRITICAL_START and OMP_CRITICAL_END
	OMP Mutex	Only keep OMP_Mutex calls
System	Memory	Keep any memory related functions (memcpy, memchk, alloc, malloc, etc)
	Network	Keep any network related functions (network, tcp, sched, etc)
	Poll	Keep any poll related functions (poll, yield, sched, etc)
	String	Keep any string related functions (strlen, strcpy, etc)
Advanced	Custom	Any regular expression can be captured
	Everything	Does not filter anything

- **gdiff:** holds the actual points of differences in the outlier trace w.r.t. its corresponding normal trace - What has changed after a *bug* is encountered

Odd/Even sort is a variant of the bubble-sort operates in two alternate phases: *Phase-even* where even processes exchange (compare and swap) values with right neighbors and *Phase-odd* where odd processes exchange values with right neighbors. Figure 1 shows the simplified MPI implementation of the odd/even sort algorithm. We are using this example to explain our ideas and methodologies through out this section.

#### A. Pre-processing

- Decompressing traces and throw away function IDs that their function name does not match the regex of filters
- **filters:** There are some pre-defined filters but based on the application semantics, one can apply any filter with regex format.
- table I shows pre-defined filters.

#### B. Nested Loop Representation

- Summarizing repetitive patterns of traces in form of NLR (Nested Loop Representation).
- Adopting NLR algorithm from Philip Clauss paper (explaining the algorithm)
- Example on odd/even traces.

Figure 2. DiffTrace Overview

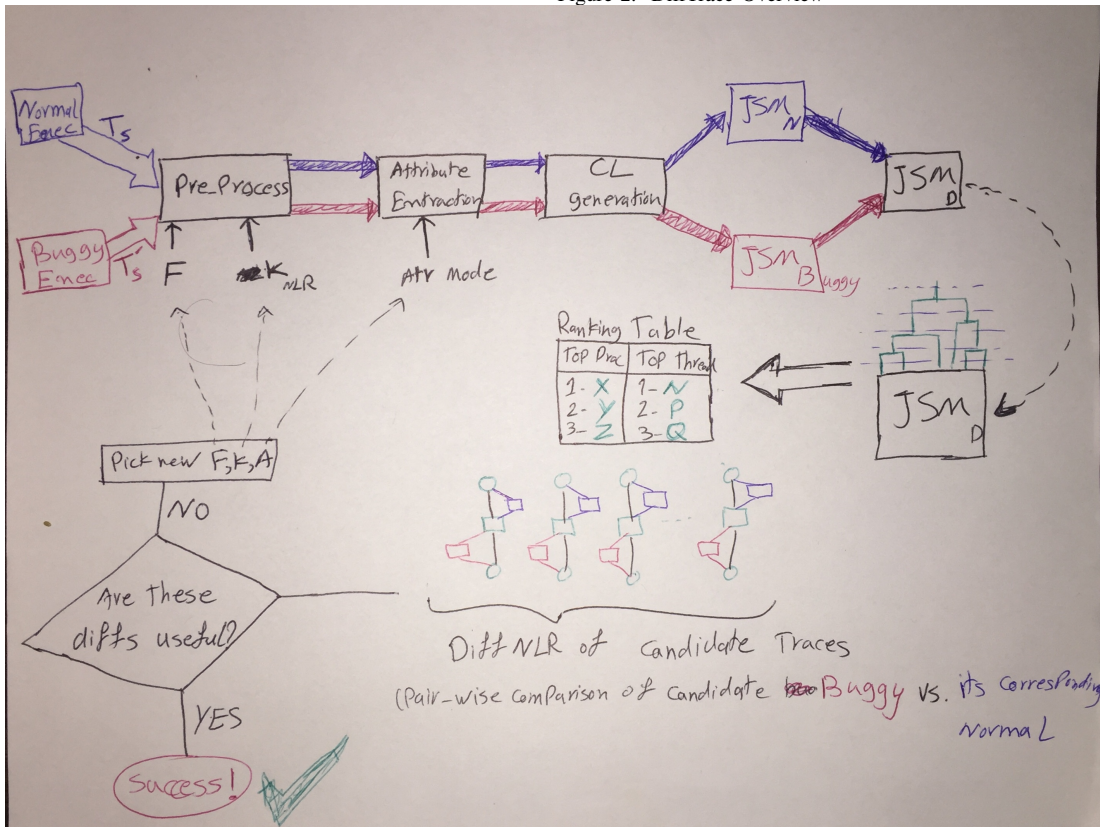


Table II  
THE GENERATED TRACES FOR ODD/EVEN EXECUTION WITH FOUR PROCESSES

$T_0$	$T_1$	$T_2$	$T_3$
...	...	...	...
main	main	main	main
MPI_Init	MPI_Init	MPI_Init	MPI_Init
MPI_Comm_Rank	MPI_Comm_Rank	MPI_Comm_Rank	MPI_Comm_Rank
MPI_Comm_Size	MPI_Comm_Size	MPI_Comm_Size	MPI_Comm_Size
...	...	...	...
oddEvenSort	oddEvenSort	oddEvenSort	oddEvenSort
...	...	...	...
findPtr	findPtr	findPtr	findPtr
MPI_Send	MPI_Recv	MPI_Send	MPI_Recv
MPI_Recv	MPI_Send	MPI_Recv	MPI_Send
...	...	...	...
findPtr	findPtr	findPtr	findPtr
MPI_Send	MPI_Recv	MPI_Send	MPI_Recv
MPI_Recv	MPI_Send	MPI_Recv	MPI_Send
...	...	...	...
MPI_Finalize	MPI_Finalize	MPI_Finalize	MPI_Finalize

### C. Hierarchical Clustering via FCA

- Introducing FCA with some backgrounds
- CL incremental construction
- Context sample from odd/even example
- Actual CL from odd/even example
- Obtaining JSM from reduced CL via LCA
- JSM sample from odd/even example
- Hierarchical Clustering based on the obtained JSM provides insight about general behavior of the execution

Table III  
CONTEXT

	MPI_Init()	MPI_Comm_Size()	MPI_Comm_Rank()	MPI_Send()	MPI_Recv()	MPI_Finalize()
Rank 0	x	x	x		x	x
Rank 1	x	x	x	x		x
Rank 2	x	x	x	x		x
Rank 3	x	x	x	x		x

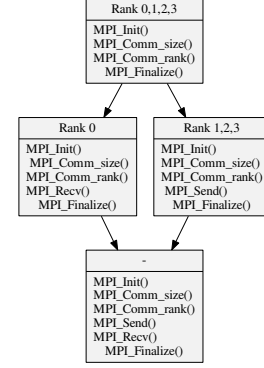


Figure 3. Sample Concept Lattice from Obj-Atr Context in table II-C

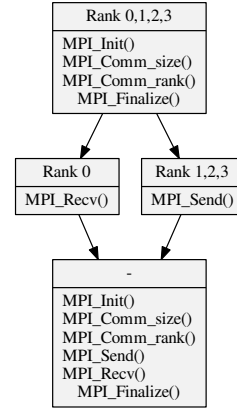


Figure 4. Concept Lattice with reduced labels

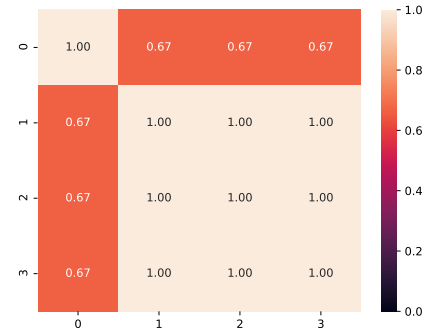


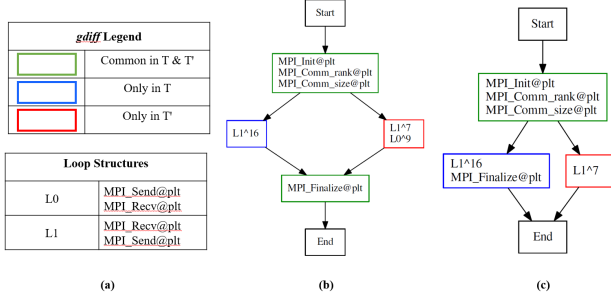
Figure 5. Pair-wise Jaccard Similarity Matrix (JSM) of MPI processes in Sample code



Figure 6. A line change in oddEvenSort (left) that might cause a deadlock in oddEvenSort\_DL (right)

	oddEvenSort()	oddEvenSort_DL()
1	<b>oddEvenSort</b> (rank, cp){	<b>oddEvenSort_DL</b> (rank, cp){
2	...	...
3	for (int i=0; i < cp; i++)	for (int i=0; i < cp; i++)
4	{	{
5	int ptr = findPtr(i, rank);	int ptr = findPtr(i, rank);
6	...	...
7	if (rank % 2 == 0) {	if (rank % 2 == 0) {
8	MPI_Send(..., ptr, ...);	MPI_Send(..., ptr, ...);
9	MPI_Recv(..., ptr, ...);	MPI_Recv(..., ptr, ...);
10	} else {	} else {
11	MPI_Recv(..., ptr, ...);	MPI_Send(..., ptr, ...);
12	MPI_Send(..., ptr, ...);	MPI_Recv(..., ptr, ...);
13	} ...	} ...
14	...	...
15	}	}
16	}	}

Figure 7. (a) The legend of *gdiff* and the list of loop structures (b) *gdiff*(5) of *swapBug* (c) *gdiff*(5) of *dlBug*



#### D. Diffing

- Comparison of JSMs (i.e., hierarchical clusterings) would give insight about how a change (bug, library update, porting to new system) has changed the behavior of the program.
- Outlier detection via Diffing JSMs
  - the method by Fowlkes to measure the similarity score of two clusterings
  - detecting outlier(s) by detecting if an object (trace) falls into a different cluster
  - an illustration of the idea on odd/even - explaining a potential deadlock.

- introducing *gdiff*: holds the actual points of differences in the outlier trace w.r.t. its corresponding normal trace
- sample *gdiff*s from odd/even example

##### 1) Ranking Suspicious Traces:

- Select a set of parameters and let DiffTrace generate JSMs based on the parameters (from both buggy and bug-free).
- Calculate B-score and outliers for all possible combinations of parameters
- sort outliers (i.e., suggestions as suspicious traces that suffer the most from the change) based on their B-score, lower scores shows bigger change in JSMs, higher chance of showing the actual outlier.

“Diff” algorithm by Meyers [12] takes two sequences  $S_A$  and  $S_B$  and computes the minimal *edit* to convert  $S_A$  to  $S_B$ . This algorithm has been used in GNU *diff* to compare two

text files and in git for efficiently keeping track of file changes. Since ParLOT preserves the order of function calls in the binary, each per thread trace  $T_i$  is totally ordered, thus *diff* can reflect the differences of a pair of  $T$ s. *gdiff* is the graphical visualization of *diff*, aligning common and different blocks of a pair of sequences horizontally and vertically, making it easier for analyst to see the differences of a pair of sequences in a glance. For simplicity, our implementation of *gdiff* only takes one argument  $x$  as the suspicious trace

$$gdiff(x) \equiv gdiff(T_x, T'_x)$$

where  $T_x$  is the trace of thread/process  $x$  of a normal/successful execution and  $T'_x$  is the corresponding trace of faulty execution.

The for loop in line 4 of *oddEvenSort()* iterates over phases of the algorithm and based on the phase, the appropriate partner for each rank is getting discovered by the function *findPtr()* (line 6). The odd/even ranks then exchange their chunks of data (lines 9-13) and a set of sort, merge and copy operations would be performed on received data by each rank (which are replaced by ... in line 15 for simplicity).

Execution of odd/even sort application with four processes (`mpirun -np 4`) while ParLOT trace collection is enabled on top of the application, would result in  $T_0, T_1, T_2$  and  $T_3$  (table II). This execution terminates successfully with expected results and the set of generated traces clearly reflects the expected behavior (control flow) of odd and even processes.

According to MPI Standard [cite MPI-forum or openMPI url], *MPI\_Send* is a *blocking send* used the *standard* communication mode. In this mode, MPI may buffer outgoing messages and the send call may complete before a matching receive is invoked. On the other hand, buffer space may be unavailable, or MPI may choose not to buffer outgoing messages, for performance reasons. In this case, the send call will not complete until a matching receive has been posted, and the data has been moved to the receiver. This shows that, based on the MPI implementation, the *oddEvenSort\_DL()* (figure 6) might end up causing a deadlock, because of the order swap of *MPI\_Recv* and *MPI\_Send* in lines 11-12.

We have planted two artificial bugs (*swapBug* and *dlBug*) in the code in figure 1 and launched the code with 16 processes. *swapBug* swaps the order of *MPI\_Send* and *MPI\_Recv* in rank 5 after 7th iteration (of the loop in line 3 of *oddEvenSort*) simulating a potential deadlock and *dlBug* simulates an actual deadlock (e.g., infinite loop) in the same location (rank 5 after 7th iteration). Upon collection of ParLOT traces from execution above buggy versions, DiffTrace first decompresses traces and filters out all non-MPI functions. Then two major loops are detected, **L0** and **L1** (figure 7-(a)) that are supposed to occur 16 times in even and odd ranks, respectively. After analysis of CL models of execution,  $x = 5$  has been suggested as the most affected trace by the artificial bugs. Figure 7-(b) shows the *gdiff*(5) of *swapBug* where  $T_5$  iterates over the loop [MPI\_Recv - MPI\_Send] for 16 times (L1^16) after the MPI initialization while the order swap has well reflected in  $T'_x$

(L1<sup>7</sup> - L0<sup>9</sup>). Both processes seem to be terminated fine by executing MPI\_Finalize(). However, *gdiff*(5) of *dlBug* (figure 7-(c)) shows that while  $T_5$  have executed MPI\_Finalize and terminated well,  $T'_5$  got stuck after executing L1 seven times and have never reached MPI\_Finalize.

This example shows that our approach can locate the impacted part of each execution by a fault. Having a pre-understanding of *how the application should behave normally* would reduce the number of iterations by picking the right set of parameters on each pass.

### III. CASE STUDY: ILCS

#### A. Experimental Methodology

So far, we are able to collect whole-program execution traces, preprocess them (decompress, filter, detect loops, extract attributes) and inject each *PT* to concept lattice data structure. Concept lattices help us having a single model for the execution of HPC application with thousands of processes/threads. Concept lattices also classify *PTs* based on their Jaccard distance. Full pair-wise Jaccard distance matrix can be extracted from the concept lattice in linear time and reduces the search space from thousands of *PTs* to just a few equivalent classes of *PTs*. Studying JSM by itself helps the user to understand the program behavior as a whole, and how each process/thread behaving. However, comparing the JSM of the bug-free version of the application versus the buggy version would reveal insights about how the bug impacted the behavior of the application. In particular, we are interested to see how the bug changes the formation of equivalent classes of *PTs*. Inspired by a method for comparing two different clustering [13], we count the number of objects (*PTs*) in each cluster and see which *PT(s)* fall into different clusters once the bug is introduced. A set of candidate *PTs* then would be reported to the user for more in-depth study. Here is where we take advantage of diffNLR to see how does the bug changes the control flow of a candidate *PT* comparing to its corresponding *PT* of native run.

Table 8 shows different parameters that we can pre-process *PTs* with. Each combination of these parameters would result in a different concept lattice, thus different JSM and different clusterings. A table similar to V is created for each injected bug. Each row of the table is showing the set of parameters used to create JSMs. Then by calculating  $|JSM(buggy) - JSM(bugfree)|$  we are interested to see which *PT* changes the most after the bug injected and falls into a single cluster. The object(s) in the cluster with the fewest members (below a threshold) are potential candidates of *threads that are manifesting the bug* and the diff(buggy,bug-free) is in our interest to see how does the bug changes its control flow.

#### B. Case Study: ILCS-TSP

Here is the ILCS framework pseudo-code. User needs to write `CPU_Init()`, `CPU_Exec()` and `CPU_Output()`.

```
int main(argc, argv){
    MPI_Init();
    MPI_Comm_size()
    MPI_Comm_rank(my_rank)
    //Figuring local number of CPUs
    MPI_Reduce() // Figuring global number of CPUs
    CPU_Init();
    //For storing local champion results
    champ[CPUs] = malloc();
    MPI_Barrier();
    #pragma omp parallel num_threads(CPU+1)
```

```
{
    rank = omp_get_thread_num()
    if (rank == 0){ //communication thread
        do{
            //Find and report the thread with
            //local champion, global champion
            MPI_AllReduce();
            //Find and report the process with
            //global champion
            MPI_AllReduce();
            //The process with the global champion
            //copy its results to bcast_buffer
            if (my_rank == global_champion){
                #pragma omp cirtical
                memcpy(bcast_buffer, local_champ)
            }
            //Broadcast the champion
            MPI_Bcast(bcast_buffer)
        } while (no_change_threshold);
        cont=0 // signal worker threads to stop
    } else{ // worker threads
        while(cont){
            //Calculate Seed
            local_result = CPU_Exec()
            if (local_result < champ[rank]){
                #pragma omp cirtical
                memcpy(champ[rank], local_result)
            }
        }
    }
    //Find and report the thread with
    //local champion, global champion
    MPI_AllReduce();
    //Find and report the process with
    //global champion
    MPI_AllReduce();
    // The process with the global champion
    // copy its results to bcast_buffer
    if (my_rank == global_champion){
        #pragma omp cirtical
        memcpy(bcast_buffer, local_champ)
    }
    //Broadcast the champion
    MPI_Bcast(bcast_buffer)
    if (my_rank==0){
        CPU_Output(champ)
    }
    MPI_Finalize()
}
/* User code for TSP problem */
CPU_Init(){
    // Read In data from cities
    // Calculate distances
```



Filters										CL Attributes	Clustering	
Prime		General		MPI		OMP		Other				
Filter	Description	Filter	Description	Filter	Description	Filter	Description	Filter	Description			
ret	Filter Returns	@plt	...@plt	mpi	MPI_...	ompcrit	OMP critical	Custom	Defining specific regex to filter	Objects: Traces Attributes: set of <atr:freq>		single
.plt	Filter .plt	mem	Memory related malloc memcpy etc	mpiall	..MPI... MPID... PMPI...	ompmu tex	OMP mutex	incEveryth ing	Include whatever is not in the Filters	Single: set of single trace entries atr: sing	No Frequency: only presence of attribute entries matters freq:-	complete
		net	Network related	mpicol	MPI collectives	omppall	OMP all functions			Double: set of 2-consecutive entries atr: doub	Log10: log(freq) of each entry matters (for large frequency numbers freq: log10(#atr)	average
		poll	Poll Related poll, yield	mpisr	MPI send/recv						Actual: actual frequency of each entry matters freq: #atr	weighted
		str	String related strcpy strcmp etc									centroid
												median
												ward

Figure 8. Filters, Attributes and other Parameters used to pre-process ParLOT Traces (PTs)

```

// Return data structure to store champion
}

CPU_Exec(){
// Find local champions (TSP tours)
}

CPU_Output(){
// Output champion
}

```

Table ?? describes the bug that I injected to ILCS-TSP

Table IV  
INJECTED BUGS TO ILCS-TSP

ID	Level	Bugs	Description
1	MPI	allRed1wrgOp-1-all-x	Different operation (MPI_MAX) in only one process (buggyProc = 2) for MPI_ALLREDUCE() in Line 21
2		allRed1wrgSize-1-all-x	Wrong size in only one process (buggyProc = 2) for MPI_ALLREDUCE() in Line 21
3		allRed1wrgSize-all-all-x	Wrong Size in all processes for MPI_ALLREDUCE() in Line 21
4		allRed2wrgOp-1-all-x	Different operation (MPI_MAX) in only one (buggyProc) for first MPI_ALLREDUCE() – L277:ilcsTSP.c
5		allRed2wrgSize-1-all-x	Wrong size in only one (buggyProc) for first MPI_ALLREDUCE() – L277:ilcsTSP.c
6		allRed2wrgSize-all-all-x	Wrong Size in all processes for second MPI_ALLREDUCE() – L277:ilcsTSP.c
7		bcastWrgSize-1-all-x	Wrong Size in only one (buggyProc) of MPI_Bcast() – L290:ilcsTSP.c
8		bcastWrgSize-all-all-x	Wrong Size n all processes for MPI_Bcast() – L240:ilcsTSP.c
9	OMP	misCrit-1-1-x	Missing Critical Section in buggyProc and buggyThread – L170:ilcsTSP.c
10		misCrit-all-1-x	Missing Critical Section in buggyThread and all procoesses – L170:ilcsTSP.c
11		misCrit-1-all-x	Missing Critical Section in buggyProc and all threads – L170:ilcsTSP.c
12		misCrit-all-all-x	Missing Critical Section in all procs and threads – L170:ilcsTSP.c
13		misCrit2-1-1-x	Missing Critical Section in buggyProc and buggyThread – L230:ilcsTSP.c
14		misCrit2-all-1-x	Missing Critical Section in buggyThread – L230:ilcsTSP.c
15		misCrit2-1-all-x	Missing Critical Section in buggyProc and all threads – L230:ilcsTSP.c
16		misCrit2-all-all-x	Missing Critical Section in all procs and threads – L230:ilcsTSP.c
17		misCrit3-1-all-x	Missing Critical Section in buggyProc and all threads – L280:ilcsTSP.c
18		misCrit3-all-all-x	Missing Critical Section in all procs and threads – L280:ilcsTSP.c
19	General	infLoop-1-1-1	Injected an infinite loop after CPU_EXEC() in buggyProc,buggyThread & buggyIter L164:ilcsTSP.c



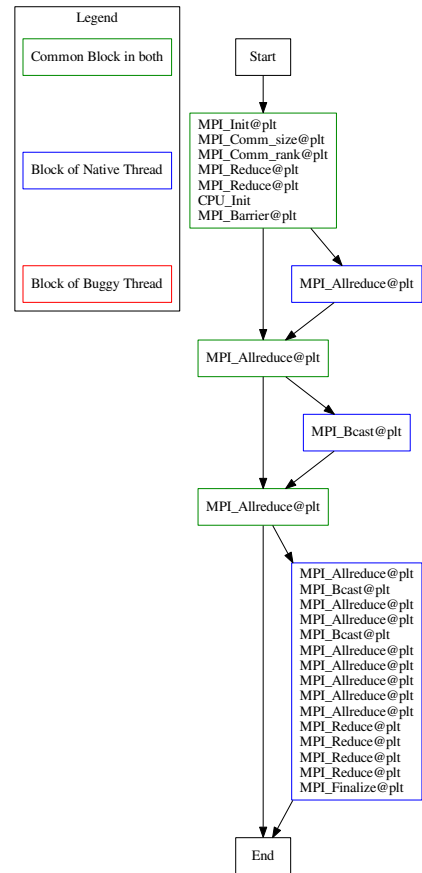
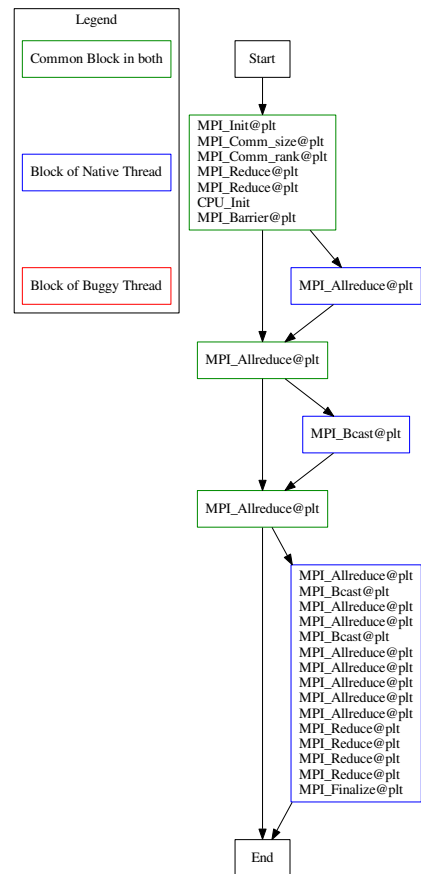


Figure 11. Bug2: diffNLR  $PT_{1,0}$  - buggy vs. native

Similar to table V, the same ranking system tells us to check  $PT_{1,0}$  and  $PT_{3,0}$ . Note that the bug injected to only one process ( $P_3$ ) to have the wrong size.)

**::EXPLANATIONS OF OBSERVATIONS::**



3) *Bug3: Wrong Size in MPI AllReduce() (all processes)*: We have injected a bug (row 3 table IV) where `MPI_Allreduce()` had been invoked with a wrong size.

**::MORE EXPLANATIONS ABOUT WHAT THE BUG IS::**

Similar to table V, the same ranking system tells us to check  $PT_{1,0}$  and  $PT_{3,0}$ . Note that the bug injected to only one process ( $P_3$ ) to have the wrong size.)

## EXPLANATIONS OF OBSERVATIONS:

4) *Bug4: Wrong Op in MPI AllReduce(): no effect!, program terminates fine:* maybe all images show some reflection

5) *Bug5: Wrong Size in next MPI AllReduce()(one process)::no effect, program terminates fine:* maybe all images show some reflection

6) *Bug6: Wrong Size in next MPI AllReduce()(all processes)::no effect, program terminates fine:* maybe all images show some reflection

7) *Bug7: Wrong Size in MPI Bcast()(one process):::* maybe all images show some reflection

8) *Bug8: Wrong Size in next MPI Bcast()(all processes)::no effect, program terminates fine:* maybe all images show some reflection

9) *3: Missing Critical Section one thread in on process:* I planted the bug (missing critical section) in process 2

#### IV. RELATED WORK

##### A. Program Understanding

- Score-P [14]
- TAU [15]
- ScalaTrace: Scalable compression and replay of communication traces for HPC [16]
- Barrier Matching for Programs with Textually unaligned barriers [17]
- Pivot Tracing: Dynamic causal monitoring for distributed systems - Johnathan mace [18]
- Automated Charecterization of parallel application communication patterns [19]
- Problem Diagnosis in Large Scale Computing environments [20]
- Probablistic diagnosis of performance faults in large-scale parallel applications [21]
- detecting patterns in MPI communication traces - robert preissl [22]
- D4: Fast concurrency debugging with parallel differntial analysis - bozhen liu [23]
- Marmot: An MPI analysis and checking tool - bettina krammer [24]
- MPI-checker - Static Analysis for MPI - Alexandrer droste [25]
- STAT: stack trace analysis for large scale debugging - Dorian Arnold [26]
- DMTracker: Finding bugs in large-scale parallel programs by detecting anomaly in data movements [27]
- SyncChecker: Detecting synchronization errors between MPI applications and libraries - [28]
- Model Based fault localization in large-scale computing systems - Naoya Maruyama [29]
- Synoptic: Studying logged behavior with inferred models - ivan beschastnikh [30]
- Mining temporal invariants from partially ordered logs - ivan beschastnikh [31]
- Scalable Temporal Order Analysis for Large Scale Debugging - Dong Ahn [32]
- Inferring and asserting distributed system invariants - ivan beschastnikh - stewart grant [33]

- PRODOMETER: Accurate application progress analysis for large-scale parallel debugging - subatra mitra [34]
- Automaded : Automata-based debugging for dissimilar parallel tasks - greg [35]
- Automaded : large scale debugging of parallel tasks with Automaded - ignacio [36]
- Inferring models of concurrent systems from logs of their behavior with CSight - ivan [37]

##### B. Trace Analysis

- Trace File Comparison with a hierarchical Sequence Alignment algorithm [38]
- structural clustering : matthias weber [39]
- building a better backtrace: techniques for postmortem program analysis - ben liblit [40]
- automatically charecterizing large scale program behavior - timothy sherwood [41]

##### C. Visualizations

- Combing the communication hairball: Visualizing large-scale parallel execution traces using logical time - katherine isaacs [42]
- recovering logical structure from charm++ event traces [43]
- ShiViz - Debugging distributed systems - [44]

##### D. Concept Lattice and LCA

- Vijay Garg - Applications of lattice theory in distributed systems
- Dimitry Ignatov [?] - Concept Lattice Applications in Information Retrieval
- [7] [11] [45] [8] [12]

##### E. Repetitive Patterns

- [46] [47] [48] [49] [50]

##### F. STAT

Parallel debugger STAT[26]

- STAT gathers stack traces from all processes
- Merge them into prefix tree
- Groups processes that exhibit similar behavior into equivalent classes
- A single representative of each equivalence can then be examined with a full-featured debugger like TotalView or DDT

What STAT does not have?

- FP debugging
- Portability (too many dependencies)
- Domain-specific
- Loop structures and detection



45	(7)11.mem.ompcrit.cust.0K10	sing.actual	1:(3_0,4_0):0.75	1:(2_1,3_1):0.00	1:(3_2,6_2):0.57	1:(1_3,2_3):0.89
			2:(2_0,3_0):0.75	2:(0_1,4_1):0.00	2:(3_2,5_2):0.57	2:(0_3,7_3):0.89
			3:(1_0,6_0):0.75	3:(0_1,5_1):0.00	3:(2_2,4_2):0.50	3:(4_3,6_3):0.50
46	(7)11.mem.ompcrit.cust.0K10	sing.log10	1:(3_0,4_0):0.75	1:(2_1,3_1):0.00	1:(0_2,2_2):0.33	1:(1_3,2_3):0.33
			2:(2_0,3_0):0.75	2:(0_1,4_1):0.00	2:(3_2,7_2):0.33	2:(6_3,7_3):0.33
			3:(1_0,6_0):0.75	3:(0_1,5_1):0.00	3:(3_2,6_2):0.33	3:(1_3,4_3):0.20
47	(7)11.mem.ompcrit.cust.0K10	sing.orig	1:(3_0,4_0):0.75	1:(2_1,3_1):0.00	1:(0_2,2_2):0.33	1:(1_3,2_3):0.33
			2:(2_0,3_0):0.75	2:(0_1,4_1):0.00	2:(3_2,7_2):0.33	2:(6_3,7_3):0.33
			3:(1_0,6_0):0.75	3:(0_1,5_1):0.00	3:(3_2,6_2):0.33	3:(1_3,4_3):0.20

Figure 13. Part of ranking table for MisCrit 1-1

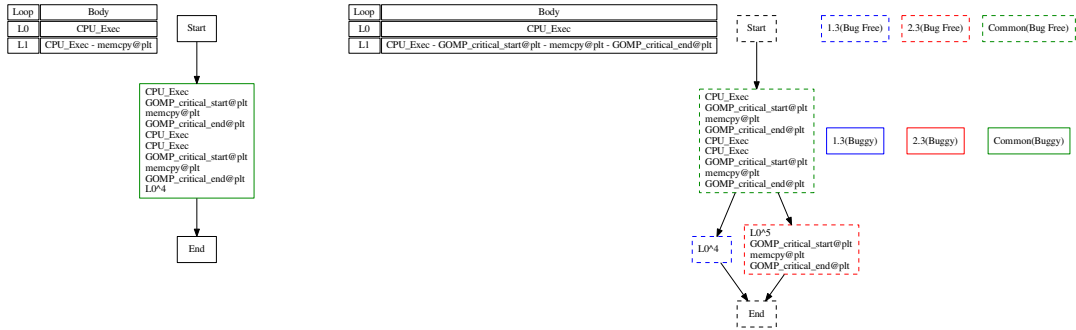


Figure 14. diffNLR of process 1 thread 3 and process 2 thread 3 buggy(missing critical section) vs. bug-free

## V. CONCLUDING REMARKS

## REFERENCES

- [1] G. Gopalakrishnan, P. D. Hovland, C. Iancu, S. Krishnamoorthy, I. Laguna, R. A. Lethin, K. Sen, S. F. Siegel, and A. Solar-Lezama, "Report of the HPC correctness summit, jan 25-26, 2017, washington, DC," *CoRR*, vol. abs/1705.07478, 2017. [Online]. Available: <http://arxiv.org/abs/1705.07478>
- [2] S. Taheri, S. Devala, G. Gopalakrishnan, and M. Burtcher, "Parlot: Efficient whole-program call tracing for HPC applications," in *Programming and Performance Visualization Tools - International Workshops, ESPT 2017 and VPA 2017, Denver, CO, USA, November 12 and 17, 2017, and ESPT 2018 and VPA 2018, Dallas, TX, USA, November 16 and 11, 2018, Revised Selected Papers*, 2018, pp. 162–184. [Online]. Available: [https://doi.org/10.1007/978-3-030-17872-7\\_10](https://doi.org/10.1007/978-3-030-17872-7_10)
- [3] C.-K. Luk, R. Cohn, R. Muth, H. Patil, A. Klauser, G. Lowney, S. Wallace, V. J. Reddi, and K. Hazelwood, "Pin: Building customized program analysis tools with dynamic instrumentation," in *Proceedings of the 2005 ACM SIGPLAN Conference on Programming Language Design and Implementation*, ser. PLDI '05. New York, NY, USA: ACM, 2005, pp. 190–200.
- [4] J.-D. Choi and A. Zeller, "Isolating failure-inducing thread schedules," in *Proceedings of the 2002 ACM SIGSOFT International Symposium on Software Testing and Analysis*, ser. ISSTA '02. New York, NY, USA: ACM, 2002, pp. 210–220. [Online]. Available: <http://doi.acm.org/10.1145/566172.566211>
- [5] "Dynamic characteristics of loops," *IEEE Transactions on Computers*, vol. C-33, no. 2, pp. 125–132, Feb 1984.
- [6] A. Ketterlin and P. Clauss, "Prediction and trace compression of data access addresses through nested loop recognition," in *Proceedings of the 6th Annual IEEE/ACM International Symposium on Code Generation and Optimization*, ser. CGO '08. New York, NY, USA: ACM, 2008, pp. 94–103. [Online]. Available: <http://doi.acm.org/10.1145/1356058.1356071>
- [7] B. Ganter and R. Wille, *Formal Concept Analysis: Mathematical Foundations*, 1st ed. Secaucus, NJ, USA: Springer-Verlag New York, Inc., 1997.
- [8] V. K. Garg, "Maximal antichain lattice algorithms for distributed computations," in *Distributed Computing and Networking*, D. Frey, M. Raynal, S. Sarkar, R. K. Shyamasundar, and P. Sinha, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 240–254.
- [9] D. I. Ignatov, "Introduction to formal concept analysis and its applications in information retrieval and related fields," *CoRR*, vol. abs/1703.02819, 2017. [Online]. Available: <http://arxiv.org/abs/1703.02819>
- [10] F. Alqadah and R. Bhatnagar, "Similarity measures in formal concept analysis," *Annals of Mathematics and Artificial Intelligence*, vol. 61, no. 3, pp. 245–256, Mar 2011. [Online]. Available: <https://doi.org/10.1007/s10472-011-9257-7>
- [11] R. Godin, R. Missaoui, and H. Alaoui, "Incremental concept formation algorithms based on galois (concept) lattices," *Computational Intelligence*, vol. 11, no. 2, pp. 246–267.
- [12] E. W. Myers, "An O(ND) difference algorithm and its variations," *Algorithmica*, vol. 1, no. 2, pp. 251–266, 1986. [Online]. Available: <https://doi.org/10.1007/BF01840446>
- [13] E. B. Fowlkes and C. L. Mallows, "A method for comparing two hierarchical clusterings," *Journal of the American Statistical Association*, vol. 78, no. 383, pp. 553–569, 1983. [Online]. Available: <https://amstat.tandfonline.com/doi/abs/10.1080/01621459.1983.10478008>
- [14] A. Knüpfer, C. Rössel, D. an Mey, S. Biersdorff, K. Diethelm, D. Eschweiler, M. Geimer, M. Gerndt, D. Lorenz, A. D. Malony, W. E. Nagel, Y. Oleynik, P. Philippen, P. Saviankou, D. Schmidt, S. Shende, R. Tschüter, M. Wagner, B. Wesarg, and F. Wolf, "Score-p: A joint performance measurement run-time infrastructure for periscope, scalasca, tau, and vampir," in *Tools for High Performance Computing 2011 - Proceedings of the 5th International Workshop on Parallel Tools for High Performance Computing, ZIH, Dresden, September 2011*, 2011, pp. 79–91.
- [15] S. S. Shende and A. D. Malony, "The Tau parallel performance system," *International Journal on High Performance Computer Applications*, vol. 20, pp. 287–311, May 2006. [Online]. Available: <http://portal.acm.org/citation.cfm?id=1125980.1125982>
- [16] M. Noeth, P. Ratn, F. Mueller, M. Schulz, and B. R. de Supinski, "Scalatrace: Scalable compression and replay of communication traces for high-performance computing," *Journal of Parallel and Distributed Computing*, vol. 69, no. 8, pp. 696 – 710, 2009, best Paper Awards: 21st International Parallel and Distributed Processing Symposium (IPDPS 2007).
- [17] Y. Zhang and E. Duesterwald, "Barrier matching for programs with textually unaligned barriers," in *Proceedings of the 12th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming*, ser. PPoPP '07. New York, NY, USA: ACM, 2007, pp. 194–204. [Online]. Available: <http://doi.acm.org/10.1145/1229428.1229472>
- [18] J. Mace, R. Roelke, and R. Fonseca, "Pivot tracing: Dynamic causal monitoring for distributed systems," *ACM Trans. Comput. Syst.*, vol. 35, no. 4, pp. 11:1–11:28, Dec. 2018. [Online]. Available: <http://doi.acm.org/10.1145/3208104>
- [19] P. C. Roth, J. S. Meredith, and J. S. Vetter, "Automated characterization of parallel application communication patterns," in *Proceedings of the 24th International Symposium on High-Performance Parallel and Distributed Computing*, ser. HPDC '15. New York, NY, USA: ACM, 2015, pp. 73–84. [Online]. Available: <http://doi.acm.org/10.1145/2749246.2749278>
- [20] A. V. Mirgorodskiy, N. Maruyama, and B. P. Miller, "Problem diagnosis in large-scale computing environments," in *SC '06: Proceedings of the 2006 ACM/IEEE Conference on Supercomputing*, Nov 2006, pp. 11–11.
- [21] I. Laguna, D. H. Ahn, B. R. de Supinski, S. Bagchi, and T. Gamblin, "Probabilistic diagnosis of performance faults in large-scale parallel applications," in *Proceedings of the 21st International Conference on Parallel Architectures and Compilation Techniques*, ser. PACT '12. New York, NY, USA: ACM, 2012, pp. 213–222. [Online]. Available: <http://doi.acm.org/10.1145/2370816.2370848>
- [22] R. Preissl, T. Köckerbauer, M. Schulz, D. Kranzlmüller, B. R. de Supinski, and D. J. Quinlan, "Detecting patterns in mpi communication traces," *2008 37th International Conference on Parallel Processing*, pp. 230–237, 2008.
- [23] B. Liu and J. Huang, "D4: Fast concurrency debugging with parallel differential analysis," in *Proceedings of the 39th ACM SIGPLAN Conference on Programming Language Design and Implementation*, ser. PLDI 2018. New York, NY, USA: ACM, 2018, pp. 359–373. [Online]. Available: <http://doi.acm.org/10.1145/3192366.3192390>
- [24] B. Krammer, M. Mäkelä, and M. Resch, "Mpi application development using the analysis tool marmot," vol. 3038, 12 2004, pp. 464–471.
- [25] A. Droste, M. Kuhn, and T. Ludwig, "Mpi-checker: Static analysis for mpi," in *Proceedings of the Second Workshop on the LLVM Compiler Infrastructure in HPC*, ser. LLVM '15. New York, NY, USA: ACM, 2015, pp. 3:1–3:10. [Online]. Available: <http://doi.acm.org/10.1145/2833157.2833159>
- [26] D. H. Ahn, B. R. de Supinski, I. Laguna, G. L. Lee, B. Liblit, B. P. Miller, and M. Schulz, "Scalable temporal order analysis for large scale debugging," in *Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis*, Nov 2009, pp. 1–11.
- [27] Q. Gao, F. Qin, and D. K. Panda, "Dmtracker: finding bugs in large-scale parallel programs by detecting anomaly in data movements," in *SC '07: Proceedings of the 2007 ACM/IEEE Conference on Supercomputing*, Nov 2007, pp. 1–12.
- [28] Z. Chen, X. Li, J. Chen, H. Zhong, and F. Qin, "Syncchecker: Detecting synchronization errors between mpi applications and libraries," in *2012 IEEE 26th International Parallel and Distributed Processing Symposium*, May 2012, pp. 342–353.
- [29] N. Maruyama and S. Matsuoka, "Model-based fault localization in large-scale computing systems," in *2008 IEEE International Symposium on Parallel and Distributed Processing*, April 2008, pp. 1–12.
- [30] I. Beschastnikh, J. Abrahamson, Y. Brun, and M. D. Ernst, "Synoptic: Studying logged behavior with inferred models," in *Proceedings of the 19th ACM SIGSOFT Symposium and the 13th European Conference on Foundations of Software Engineering*, ser. ESEC/FSE '11. New York, NY, USA: ACM, 2011, pp. 448–451. [Online]. Available: <http://doi.acm.org/10.1145/2025113.2025188>
- [31] I. Beschastnikh, Y. Brun, M. D. Ernst, A. Krishnamurthy, and T. E. Anderson, "Mining temporal invariants from partially ordered logs," in *Managing Large-scale Systems via the Analysis of System Logs and the Application of Machine Learning Techniques*, ser. SLAML '11. New York, NY, USA: ACM, 2011, pp. 3:1–3:10. [Online]. Available: <http://doi.acm.org/10.1145/2038633.2038636>
- [32] D. H. Ahn, B. R. de Supinski, I. Laguna, G. L. Lee, B. Liblit, B. P. Miller, and M. Schulz, "Scalable temporal order analysis for large scale debugging," in *Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis*, ser. SC

- '09. New York, NY, USA: ACM, 2009, pp. 44:1–44:11. [Online]. Available: <http://doi.acm.org/10.1145/1654059.1654104>
- [33] S. Grant, H. Cech, and I. Beschastnikh, “Inferring and asserting distributed system invariants,” in *Proceedings of the 40th International Conference on Software Engineering*, ser. ICSE '18. New York, NY, USA: ACM, 2018, pp. 1149–1159. [Online]. Available: <http://doi.acm.org/10.1145/3180155.3180199>
- [34] S. Mitra, I. Laguna, D. H. Ahn, S. Bagchi, M. Schulz, and T. Gamblin, “Accurate application progress analysis for large-scale parallel debugging,” in *Proceedings of the 35th ACM SIGPLAN Conference on Programming Language Design and Implementation*, ser. PLDI '14. New York, NY, USA: ACM, 2014, pp. 193–203. [Online]. Available: <http://doi.acm.org/10.1145/2594291.2594336>
- [35] G. Bronevetsky, I. Laguna, S. Bagchi, B. R. de Supinski, D. H. Ahn, and M. Schulz, “Automated: Automata-based debugging for dissimilar parallel tasks,” in *2010 IEEE/IFIP International Conference on Dependable Systems Networks (DSN)*, June 2010, pp. 231–240.
- [36] I. Laguna, T. Gamblin, B. R. de Supinski, S. Bagchi, G. Bronevetsky, D. H. Ahn, M. Schulz, and B. Rountree, “Large scale debugging of parallel tasks with automated,” in *Proceedings of 2011 International Conference for High Performance Computing, Networking, Storage and Analysis*, ser. SC '11. New York, NY, USA: ACM, 2011, pp. 50:1–50:10. [Online]. Available: <http://doi.acm.org/10.1145/2063384.2063451>
- [37] I. Beschastnikh, Y. Brun, M. D. Ernst, and A. Krishnamurthy, “Inferring models of concurrent systems from logs of their behavior with csight,” in *Proceedings of the 36th International Conference on Software Engineering*, ser. ICSE 2014. New York, NY, USA: ACM, 2014, pp. 468–479. [Online]. Available: <http://doi.acm.org/10.1145/2568225.2568246>
- [38] M. Weber, R. Brendel, and H. Brunst, “Trace file comparison with a hierarchical sequence alignment algorithm,” in *2012 IEEE 10th International Symposium on Parallel and Distributed Processing with Applications*, July 2012, pp. 247–254.
- [39] M. Weber, R. Brendel, T. Hilbrich, K. Mohror, M. Schulz, and H. Brunst, “Structural Clustering: A New Approach to Support Performance Analysis at Scale.” IEEE, May 2016, pp. 484–493. [Online]. Available: <http://ieeexplore.ieee.org/document/7516045/>
- [40] B. Liblit and A. Aiken, “Building a better backtrace: Techniques for postmortem program analysis,” Berkeley, CA, USA, Tech. Rep., 2002.
- [41] T. Sherwood, E. Perelman, G. Hamerly, and B. Calder, “Automatically characterizing large scale program behavior,” in *Proceedings of the 10th International Conference on Architectural Support for Programming Languages and Operating Systems*, ser. ASPLOS X. New York, NY, USA: ACM, 2002, pp. 45–57. [Online]. Available: <http://doi.acm.org/10.1145/605397.605403>
- [42] K. E. Isaacs, P.-T. Bremer, I. Jusufi, T. Gamblin, A. Bhatele, M. Schulz, and B. Hamann, “Combing the communication hairball: Visualizing parallel execution traces using logical time,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, pp. 2349–2358, 2014.
- [43] K. E. Isaacs, A. Bhatele, J. Lifflander, D. Böhme, T. Gamblin, M. Schulz, B. Hamann, and P. Bremer, “Recovering logical structure from charm++ event traces,” in *SC '15: Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*, Nov 2015, pp. 1–12.
- [44] I. Beschastnikh, P. Wang, Y. Brun, and M. D. Ernst, “Debugging distributed systems,” *Commun. ACM*, vol. 59, no. 8, pp. 32–37, Jul. 2016. [Online]. Available: <http://doi.acm.org/10.1145/2909480>
- [45] M. A. Bender, M. Farach-Colton, G. Pemmasani, S. Skiena, and P. Sumazin, “Lowest common ancestors in trees and directed acyclic graphs,” *Journal of Algorithms*, vol. 57, no. 2, pp. 75 – 94, 2005. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0196677405000854>
- [46] M. Crochemore and W. Rytter, “Usefulness of the karp-miller-rosenberg algorithm in parallel computations on strings and arrays,” *Theoretical Computer Science*, vol. 88, no. 1, pp. 59 – 82, 1991. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/030439759190073B>
- [47] R. M. Karp, R. E. Miller, and A. L. Rosenberg, “Rapid identification of repeated patterns in strings, trees and arrays,” in *Proceedings of the Fourth Annual ACM Symposium on Theory of Computing*, ser. STOC '72. New York, NY, USA: ACM, 1972, pp. 125–136. [Online]. Available: <http://doi.acm.org/10.1145/800152.804905>
- [48] A. Nakamura, T. Saito, I. Takigawa, M. Kudo, and H. Mamitsuka, “Fast algorithms for finding a minimum repetition representation of strings and trees,” *Discrete Applied Mathematics*, vol. 161, no. 10, pp. 1556 – 1575, 2013. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0166218X13000024>
- [49] M. Crochemore and W. Rytter, *Jewels of Stringology*. World Scientific, 2002. [Online]. Available: <https://books.google.com/books?id=ipuPQgAACAAJ>
- [50] —, *Text Algorithms*. New York, NY, USA: Oxford University Press, Inc., 1994.

## APPENDIX