

# FlipTracker: Understanding Natural Error Resilience in HPC Applications

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**Abstract**—As high-performance computing systems scale in size and computational power, the danger of silent errors, i.e., errors that can bypass hardware detection mechanisms and impact application state, grows dramatically. Consequently, applications running on HPC systems need to exhibit resilience to such errors. Previous work has found that, for certain codes, this resilience can come for free, i.e., some applications are naturally resilient, but few studies have shown the code patterns—combinations or sequences of computations—that make an application naturally resilient. In this paper, we present FlipTracker, a framework designed to extract these patterns using fine-grained tracking of error propagation and resilience properties, and we use it to present a set of computation patterns that are responsible for making representative HPC applications naturally resilient to errors. This not only enables a deeper understanding of resilience properties of these codes, but also can guide future application designs towards patterns with natural resilience.

**Index Terms**—Fault tolerance, Natural Resilience, High-Performance Computing, Resilience computation patterns

## I. INTRODUCTION

Ensuring execution correctness and result integrity in High-Performance Computing (HPC) simulations is an urgent need in extreme-scale systems. As systems scale and the number of system components grow, the chances of experiencing errors increases as well [1]. Although most soft errors—transient faults that are induced by electrical noise or external high-energy particle strikes—can be detected and corrected by hardware- and system-level mechanisms, some errors can escape these mechanisms and propagate to the application. These *silent errors* can then generate Silent Data Corruption (SDC), impacting scientific results without users realizing it.

As the probability of SDC grows, it becomes increasingly necessary to develop applications that can transparently tolerate, or *mask*, these errors before they affect the application’s numerical output. Previous work on fault tolerance, which typically focused on individual applications, demonstrates that a number of applications have this property and can mask errors as they appear. Examples of such applications are algebraic multi-grid solvers (AMG) [2], Conjugate Gradient (CG) solvers [3], GMRES iterative solvers [4], Monte Carlo simulations [5], and machine learning algorithms, such as clustering [6] and deep-learning neural networks [7], [8].

While previous work attributes this natural resilience at a high-level to either the probabilistic or iterative nature of the application, the community still lacks the fundamental understanding on the program constructs that result in such natural

error resilience. Fundamentally, we do not have clear answers to questions, such as: Are there any common computation patterns (i.e., combinations or sequences of computations) that lead to natural error resilience? If so, how can these patterns be found? How can future application design benefit from patterns exhibiting natural resilience? Finding answers to these questions is critical for error detection and recovery to avoid overprotecting regions of code that are naturally resilient.

In this paper, we characterize application natural resilience using common HPC programs and identify six common resilience computation patterns. Examples of such patterns are *dead corrupted variables*, where sets of corrupted temporal variables are not used afterwards, and *repeated additions*, a pattern that amortizes the effect of incorrect data values.

To capture and extract these patterns, however, a new method is required. While some methods exist to inject faults and statistically quantify their manifestation, such as *random fault injection* [2], [9], [10], [11], [12], and to use *program analysis* [13], [14], [15], [16], [17] to track errors on individual instructions, these methods miss the fine-grained information on error propagation as well as the context needed to explain, at a fine granularity, how errors propagate and consequently how natural resilient computations occur. In other words, these approaches do not provide the needed reasoning about how multiple computations work together to make an error disappear or to diminish its impact.

To address the above problems, we design FlipTracker, a framework to analytically track error propagation and to provide fine-grained understanding of the propagation and tolerance of errors in HPC applications, and then apply it to a series of representative HPC applications to extract the patterns that provide natural resilience.

Our framework has three key features. *First*, we introduce an application model that partitions the application into code regions. Such a model allows us to build a high-level picture on how an error propagates across code regions, or is tolerated with the combination of multiple code regions. *Second*, using data dependency analysis, we identify the input and output variables of each code region, which allows us to perform isolated fault injections at the entry of code regions to study their resilience in an isolated fashion. Further, it allows us to quickly track how the corrupted values change across code regions as caused by their resilience computation patterns. *Third*, we track how the number of live, yet corrupted locations

change within code regions, an approach that reveals resilience patterns that cannot be easily found by traditional high-level fault propagation approaches.

We present two use cases to demonstrate how resilience computation patterns can be used to (1) improve application resilience during programming and (2) predict the degree of application resilience.

In summary, the contributions of this paper are

- 1) An abstract code structure model that enables us to reason about the natural resilience properties of code segments;
- 2) The design of a framework that enables fine-grained and comprehensive analysis of error propagation to capture application natural resilience;
- 3) An implementation of the framework, `FlipTracker`, using the LLVM compiler and a study of a set of representative HPC programs on which `FlipTracker` is demonstrated;
- 4) An analysis and formal definition of six resilience computation patterns that we discover in these programs;
- 5) Two use cases that demonstrate the usage of resilience computation patterns.

## II. BACKGROUND

In this section, we define our fault manifestation model, as well as the concept of resilience computation patterns.

### A. Fault Model

We consider soft errors, also known as transient faults, that propagate to state visible to the application; by *state* we mean mainly machine registers and memory. We do not consider errors that are detected, and possibly corrected in hardware, e.g., by hardware-level mechanisms such as memory scrubbing, ECC, or other techniques. Furthermore, as most other studies in this area [18], [19], [20], [13], [14], [21], we only consider single bit flip errors since it is generally accepted that multi-bit errors are much less likely to occur, even in larger HPC systems [22].

1) *Fault Manifestation Model*: We use fault injection to mimic the effect of real soft errors in the application (Section IV-C describes our fault injection scheme). We define two classes of executions: *fault-free* runs, on which no fault is injected, and *faulty* runs on which a fault is injected. When a fault is injected, we define three possible fault manifestations:

- **Verification Success**: in this case, any of two possible scenarios occur: (a) the program outcome in a faulty-run is exactly the same as the outcome in a fault-free run; or (b) the program outcome in a faulty-run is slightly different from the outcome in a fault-free run, but the program successfully passes the test in its verification phase, i.e., the application output is considered correct to the user.
- **Verification Failed**: the program terminates, but the outcome does not pass the test in the verification phase. This is a strong indication of SDC that was not tolerated.
- **Crashed**: the injected fault generates a crash or a hang.

2) *Success Rate*: Success rate is a metric that quantifies application resilience. In a fault injection campaign, where  $M$  fault injection tests are performed (see Section IV-C for details), the success rate is defined as

$$suc\_rate = \frac{\#Verification\ Success}{M}, \quad (1)$$

where  $\#Verification\ Success$  is the number of Verification Success cases of the campaign. In this paper, we use the success rate as a metric to quantify application resilience.

### B. Resilience Computation Patterns

When a fault propagates to application state, it initially corrupts one (or a few) data locations, i.e., registers and memory locations. As time passes, instructions that are influenced by those corrupted locations can also become corrupted, causing the total number of corrupted locations in the application to increase over time. Some applications, or code regions of an application, however, which can tolerate faults, could make the total number of corrupted locations decrease. The above phenomena are depicted in Figure 7 in our evaluation section. If the decrease is sufficient, the fault manifests as Verification Success. Although some applications, or code regions, that can tolerate faults do not have such decrease of number of corrupted locations, they are characterized with a decrease of error magnitude—the relative error of a faulty value with respect to its correct value. We say that the above fault tolerant applications or code regions are *naturally resilient*.

We define a *resilience computation pattern* as a series or a combination of series of computations (or instructions) that are responsible for contributing to a decrease of the total number of corrupted data locations or a decrease of error magnitude in corrupted data values, and for ultimately helping the program tolerate a fault. In this paper, we are interested in characterizing the properties of such patterns to answer the following questions: (a) Why does such a decrease in the number of corrupted locations or error magnitude occur, and (b) What are the patterns that cause this effect?

## III. DESIGN OF FLIPTRACKER

In this section, we introduce our method to identify resilience computation patterns.

`FlipTracker` takes as input an HPC program, creates a dynamic execution trace generated using LLVM instrumentation, and then uses our novel analysis techniques to provide a fine-grained representation of error propagation and error tolerance. This analysis allows us to easily identify the resilience computation patterns that may exist in the program, possibly in different code regions of the program.

Our method is based on a top-level characterization of HPC applications, which we then use to track error propagation and tolerance at a low level. In particular, we model an application as a chain of code regions, which work together to produce the final result of the application. Each of these code regions can have *input*, *output*, and *internal* variables. Errors can propagate at any point in time to any of these variables.

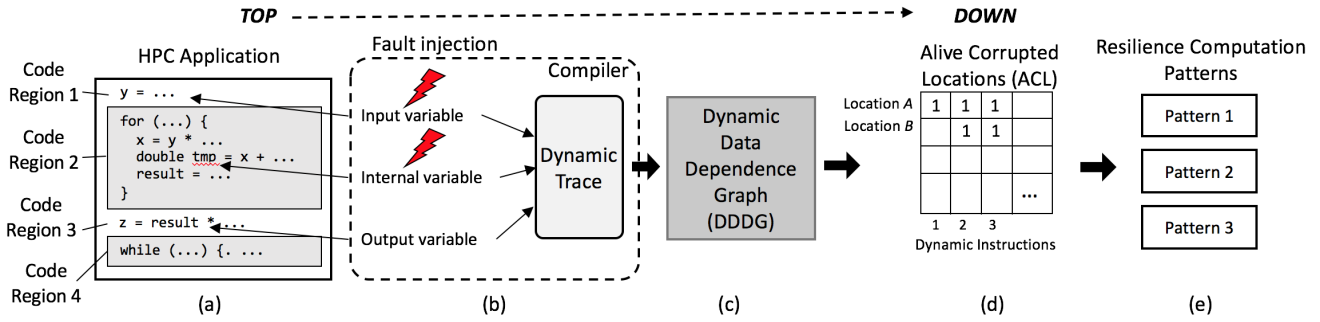


Fig. 1. An overview of FlipTracker.

```

1 static void conj_grad() { //called from the main loop
2   ...
3   for () { //a first-level inner loop
4     for () { //a second-level inner loop
5       for () { ... } //a third-level inner loop
6     }
7   }
8   for () { ... } //a first-level inner loop
9 }

```

Fig. 2. An example HPC application (CG) with iterative structures.

Based on the above application model, we build a dynamic data dependency graph (DDDG) from an instruction trace collected at runtime that allows us to check the value variation of corrupted variables across code region instances (i.e., the top level). Using the DDDG, we then build a table, which we call the *alive corrupted locations* (ACL) table, that keeps track of the corrupted locations for each dynamic instruction. This table allows us to examine the variation of the number of alive, corrupted variables to identify fault tolerance at the instruction level (i.e., the bottom level). In the next sections we give more details of each of these steps (see Figure 1).

#### A. Application Code Region Model

We characterize HPC applications as sets of iterative structures or loops. In an HPC application, a main computation loop usually dominates the application execution time. Within this main loop, there are a number of inner loops that are typically used to update large data objects (e.g., a mesh structure in computational fluid dynamics), and iterative computations are performed to compute properties of these objects, such as energy of particles. Figure 2 shows an example of such loop program abstractions corresponding to CG [23].

**Code Regions.** Since HPC applications are typically composed of combinations of loops, we model an application as a chain of *code regions* delineated by loop structures (Step (a) in Figure 1). A code region can be either a loop or any block of code between two neighboring loops. An application can have multi-level nested loops. We allow the user to decide at which loop level, code regions are defined. Note that code regions defined at different loop levels *only affect* the analysis time (not the analysis correctness) to identify resilient code regions

and patterns. Code regions defined at the level of innermost loop tend to be small and easy for fine-grained instruction level analysis. However, we can have many of such small code regions, which increases our exploration space. On the other hand, code regions defined at the level of outermost loop tend to be large and we have a smaller exploration space of code regions, but it would be time-consuming for fine-grained instruction level analysis. In our work, we define each of the first-level inner loops as a code region.

**Code Region Variables.** Given a code region, we classify the variables within the code region as *input* variables, *output* variables, and *internal* variables. Input variables are those that are declared outside of the code region and referenced in the code region. Output variables are those that are written in the code region and read after the code region. Other variables that the code region writes to or reads from are internal variables. A code region can have many dynamic instances, each of which corresponds to one invocation of the code region at runtime. The values of input, output, and internal variables can vary across multiple instances of a code region.

**Rationale Behind the Model.** Our loop-based model follows the natural way in which HPC programs are coded and analyzed; HPC programs are composed of a handful of high-level loops where the program spends most of its time. Our loop-based model also enables a divide-and-conquer approach, where we can identify application subcomponents that may or may not have resilience patterns. For example, in the error propagation analysis, if the input variables of a code region are not corrupted, one can infer that the region is not impacted by an error and we can skip propagation analysis on it.

#### B. Tracing Code Region Data

The DDDG allows us to identify input, output, and internal variables of a code region. We construct a DDDG for each code region from a dynamic instruction trace of the application using an algorithm inspired by the construction of a program dependence graph [24], except that our graph is dynamic rather than static: vertices are the values of variables obtained from registers or memory; edges are operations transforming input values into output values of variables. Using the DDDG as a code region representation, we identify the input and output variables of the code region: root nodes represent inputs and leaf nodes represent outputs. Other nodes are internals.

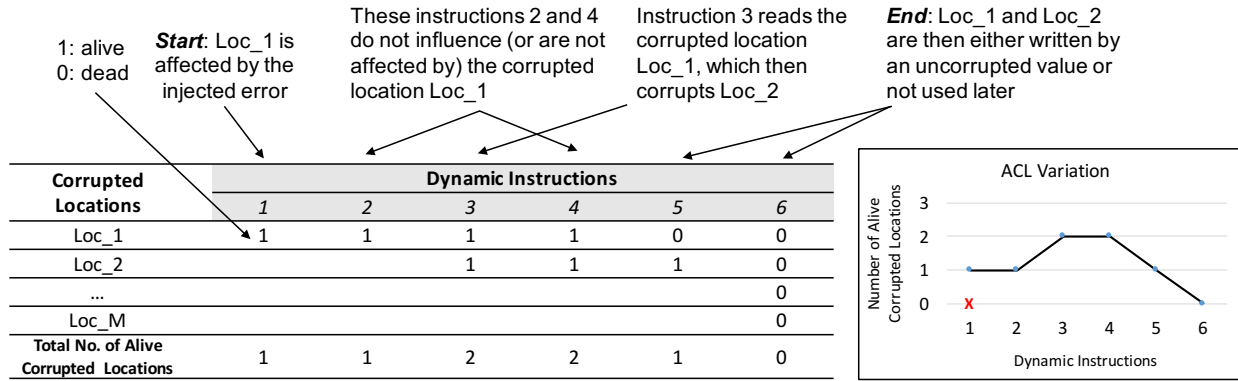


Fig. 3. An example of the ACL table.

Within the corresponding DDDG of each code region, we inject an error into either the input, output, or internal variables (Steps (b)–(c) in Figure 1). A DDDG allows us to compare data propagations in regions with and without fault occurrence, which allows us to detect control flow divergence by comparing operations. Further, the values of variables are embedded in the DDDG, which helps us to track how specific variables change their values across operations; such value change reveals whether, how, and where fault tolerance occurs.

### C. Analyzing Corrupted Variables

We identify variables that, once corrupted, return to their non-corrupted state and in which dynamic instruction. This is key in identifying resilience computation patterns since we need to identify the point in time where the error is tolerated and its location in the code region (Step (d) in Figure 1).

Using the DDDG, our analysis of corrupted variables gives us a low-level representation in terms of *instructions* of how data propagates in the code region. Since program abstractions, such as variables, are not explicitly represented at this level, we need a different way of tracking variable values. We introduce a method that tracks *alive corrupted locations*, discussed as follows. In the following discussion, since a variable value can be either in a register location or in a memory location, we use the term *location* to cover both options.

**Alive Corrupted Locations.** Traversing through the collected instruction trace, we use the DDDG to build and dynamically update a table of the *alive corrupted locations*, or ACL. Generally speaking, the ACL table stores the number of alive, corrupted locations after each dynamic instruction. We call a location “alive” if the value in that location will be referenced again in the remainder of the computation.

Each row of the table shows whether a specific location is alive or not after each dynamic instruction, as instructions are encountered in the trace. Each column of the table shows, for a specific corrupted location, whether it is alive or not *after* a dynamic instruction. Based on the column information, we can determine the total number of alive, corrupted locations after each traced instruction.

Figure 3 gives an example of the ACL table. Each table element has a value of 1 or 0, which indicates whether a corrupted location after a specific dynamic instruction is alive or not. We use the first row as an example to explain the table. The location *Loc\_1* is corrupted by a fault after instruction 1. *Loc\_1* then becomes an alive, corrupted location. Next, *Loc\_1* remains alive until instruction 5 where the location is updated and the fault in the location is overwritten by a clean value. The number of alive, corrupted locations are counted after each dynamic instruction, shown in the last row of the table.

### D. Identifying Resilience Patterns from Code Regions

As we traverse the instruction trace, the DDDG and ACL table contain the necessary information to detect resilient code regions. Resilience patterns are extracted from them.

When the DDDG is used to identify resilient code regions, we compare the values of input and output locations in a DDDG between faulty and fault-free runs. An input location can be corrupted *directly*—an error was directly injected into the location—or *indirectly*—an error was injected in a previous code region, but the error propagates to the input location of the code region in question. Given a code region, there are two possible cases when fault tolerance occurs:

- **Case 1:** the value of any input location in the code region’s DDDG in a faulty run is incorrect (with respect to the DDDG from a matching fault-free run), i.e., there is at least one corrupted input location; however, the values of all output locations are correct.
- **Case 2:** at least one of the input locations and one of the output locations in a faulty run are incorrect (with respect to the DDDG from a matching fault-free run), but the error magnitude in at least one corrupted input or output location becomes smaller after the code region instance. The error magnitude is defined as

$$error\_magnitude = \frac{|value_{correct} - value_{incorrect}|}{|value_{correct}|} \quad (2)$$

In Case 1, it is reasonable to infer that the code region in question has natural fault tolerance—the corruption of the

input location is directly masked within the code region, and does not impact the output correctness.

In Case 2, the error still exists, i.e., there is some amount of error in the code region locations; however, the impact of the error, measured by its magnitude in the input or output locations, becomes smaller, as a function of the code region. This means that the target code region may result in an application outcome that is numerically different from that of the fault-free executions. However, when such a different outcome passes the application verification and is acceptable as a valid result, we say that Case 2 has fault tolerance.

When the ACL is used to identify resilient code regions, the algorithm to detect resilience patterns given an ACL is as follows. We identify first if in any column, an alive corrupted location becomes dead for a given instruction  $i$ , where  $i < N$  and  $N$  is the last instruction before the application outputs its result. If this occurs, we mark  $i$  as a potential member of resilience computation patterns. In Figure 3, the instruction 5 consuming the location `Loc_1` is a potential member of resilience computation patterns. Once all of such instructions are found, we identify their source code locations (file and line of code) and provide them to the user for further analysis.

#### IV. IMPLEMENTATION

We implement `FlipTracker` as a two-step process: first we use a parallel tracer built on top of LLVM to extract the instruction traces, and then use these traces to dynamically generate and update the DDDGs and the matching ACL tables. We do this for both fault-free runs as well as faulty runs.

##### A. Parallel Tracing

`FlipTracker` uses an LLVM instrumentation tool, LLVM-Tracer [25], to generate a dynamic instruction trace. In this trace we store metadata for each instruction, such as the instruction type, names of registers, and operand values. In our case, *instructions* refer to LLVM instructions, which are generated at the intermediate representation (IR) of the program and instrumented by LLVM-Tracer. This approach does not support MPI programs out-of-the-box, which we need to support our HPC workloads. Thus we extend LLVM-Tracer to instrument Message Passing Interface (MPI) programs, so that traces are saved into a file for each MPI process.

Since trace generation is a per-process task, no synchronization is required to generate and save per-process traces into different files. Note also that, in our study, LLVM-Tracer only instruments program instructions—instructions from the MPI runtime are not instrumented as we expect that most errors arise from application computations. This however, is not a limitation per se—our approach can easily be directed to also instrument instructions in any parallel runtime. Furthermore, our current implementation can identify errors that propagate through MPI communications and then happen in computation, even though we do not instrument MPI runtime.

**Trace Splitting.** Traces for an HPC program can be quite large for processing. Although there is a number of approaches

that handle the problem of large traces (e.g., trace compression [26], [27]), we take a simple approach that splits a trace into smaller pieces. Each of small pieces corresponds to an instance of a code region, which reduces the scope for each analysis and further allows us to parallelize the analysis.

##### B. DDDG Generation and Usage

Once the trace is generated, `FlipTracker` takes the dynamic trace as input, and generates a DDDG by examining the data dependency of the operands in each operation. Our technique is based on the work of Holewinski et al. [28], who proposed a methodology to generate DDDG from a dynamic trace. The generated DDDG is then used to identify the input, internal, and output locations for the code region instance using Graphviz [29]. The DDDG is also used to determine corrupted locations by dynamically building the ACL table.

**ACL Table Generation.** The algorithm to generate an ACL table is motivated by dynamic taint analysis in the security research [30], [31], [32], which focuses on computations affected by contaminated sources. The difference between taint analysis and our approach is that we exclude tainted locations that are never used as well as those that are overwritten by an uncorrupted value from the untainted location set. In other words, we only consider alive corrupted locations in application execution. We use a DDDG to acquire the dynamic data dependence to track the error propagation, and, simultaneously, we count the number of alive corrupted locations after each dynamic instruction in the input trace.

##### C. Fault Injection and Statistical Significance

We implement a fault injection framework based on `FlipIt` [9], which allows us to inject a bit flip in the user-specified population of instructions and operands. Injections are performed randomly into input and internal locations of code region instances. Our fault injection uses a uniformly distributed fault model, similar to [33], [34]. Given an input or output location for a code region instance, we calculate the number of fault injection sites by analyzing the dynamic LLVM instruction trace. Then, we follow the statistical approach in [34] to calculate the number of fault injection tests for a target at 95% confidence level and 3% margin of error.

#### V. EVALUATION

We apply `FlipTracker` to representative HPC programs to study their resilience properties and ultimately to extract naturally resilient patterns that other programs can use.

##### A. Experimental Setup

We use ten representative HPC programs in our experiments, including eight HPC benchmarks (CG, MG, IS, LU, BT, SP, DC, and FT from the NAS Parallel Benchmarks in C [23], [35] with input Class S), an HPC proxy application (LULESH [36] with input “-s 3”), and a benchmark from the machine learning domain (KMEANS from the Rodinia benchmark suite [37] with input “100.txt”).

**Trace Partitioning and Code Region Selection.** HPC programs can have several static loop structures, and depending on

TABLE I  
RESILIENCE COMPUTATION PATTERNS IN CODE REGIONS OF THE HPC PROGRAMS. DCL, RA, DO REPRESENT DEAD CORRUPTED LOCATIONS, REPEATED ADDITIONS AND DATA OVERWRITING, RESPECTIVELY.

Program	Code region	Line No.	#instr in an iteration	Pattern Found?	DCL	RA	CS	Shifting	Trunc	DO
CG	cg_a	434-439	21017	NO						
	cg_b	440-453	14002	YES		✓				✓
	cg_c	454-460	31755757	YES			✓			✓
	cg_d	461-574	1196022	NO						
	cg_e	575-584	18202	NO						
MG	mg_a	425-429	606145	YES			✓			✓
	mg_b	430-437	719	YES	✓	✓				
	mg_c	438-456	1019509	YES	✓					✓
	mg_d	457-462	3313305	YES	✓		✓			✓
KMEANS	k_a	131-142	1647	NO						
	k_b	144-153	62	NO						
	k_c	156-187	2185944	YES			✓			✓
	k_d	190-194	36	YES	✓					✓
IS	is_a	435-472	792630	NO						
	is_b	473-478	983040	YES				✓	✓	
	is_c	500-638	741367	YES	✓					✓
LULESH	l_a	2652-2693	297376	YES	✓				✓	✓

program input, each static loop can generate several dynamic instances. To keep the number of loop instances manageable for analysis, we focus on high-level loop structures. Particularly, we define a code region as a section of the program that is either (a) a first-level inner loop (if there is any inner loop), or (b) a code block between two neighbor inner loops.

We list the code regions that we analyzed and their corresponding line numbers and the number of instructions within one iteration of the main loop in Table I.

### B. Parallel Tracing Overhead

We measure the overhead of trace gathering for MPI programs to study the feasibility of our approach. Figure 4 shows that our approach incurs modest overhead: 45% on average when using 64 processes on 8 nodes, comparing to an uninstrumented baseline. It is therefore feasible to gather traces at small/medium scales. For large scales, one can selectively collect traces for individual functions or use techniques such as [38]. We leave the challenge of efficiently gathering traces at very large scale for future work.

Since the resilience computation patterns that we are interested in occur in the computation code regions of the program (not in the communication part), we focus on the single process where the fault is injected.

**Nondeterminism.** MPI nondeterminism can bring difficulty to match code regions between faulty and fault-free runs. While in many MPI programs, nondeterminism can be controlled by eliminating application sources of nondeterminism, such as calls to `rand()` and/or `time()`, in other programs this is difficult because of nondeterminism introduced by MPI point-to-point communication patterns. To address these applications, we rely on record-and-replay tools [39], [40], on which a fault-free run is recorded and it is then replayed in all subsequent faulty executions.

### C. Code Region Fault Injection Results

We inject faults in input or internal locations of code regions and measure success rate. We perform experiments in two dimensions: (a) across code regions in a given iteration (See

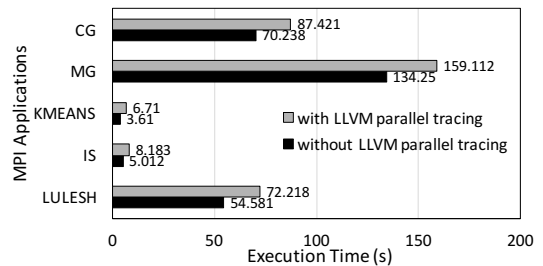


Fig. 4. LLVM parallel tracing performance (64 processes on 8 nodes)

“per-code-region” results); (b) in a given code region across all iterations (See “per-iteration” results).

**Per-Code-Region Results.** Since different code regions could have different numbers of instances, to be consistent, we perform the analysis on the first instance of each code region, i.e., in the iteration 0 of the main loop (see Figure 5).

In KMEANS we find that, for faults on internal locations the code region `k_d` is more resilient than others because many memory *free* operations free temporal corrupted locations, while for faults on input locations, many segmentation faults cause almost zero success rate. We find a relatively high success rate in MG—we find cases of repeated addition and dead corrupted location patterns that account for the fault tolerance (Section VI explains these patterns in details). In IS we find that a bit-shift operation that occurs on input locations masks faults in the `is_b` code region, which increases its success rate. In CG, we find two code regions (`b` and `c`) that have higher success rates than others because the error magnitudes in variables (particularly `p[]`) become smaller due to a computation pattern that repeatedly adds values. In LULESH, there is only one code region—faults frequently cause application crashes, which explains the low success rate.

**Per-Iteration Results.** We focus on a single code region and examine its fault tolerance on several loop iterations. In particular, we treat the main loop of each program as a single code region and each iteration of the main loop as one instance of the code region. Figure 6 shows the results. We find that the success rates of different iterations can be similar. MG

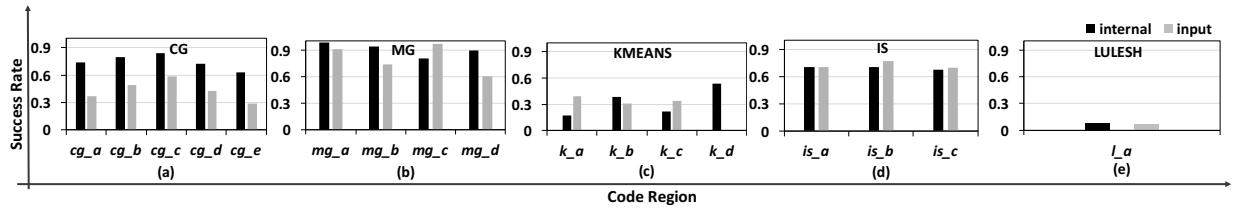


Fig. 5. Fault injection results for code region instances at iteration 0.

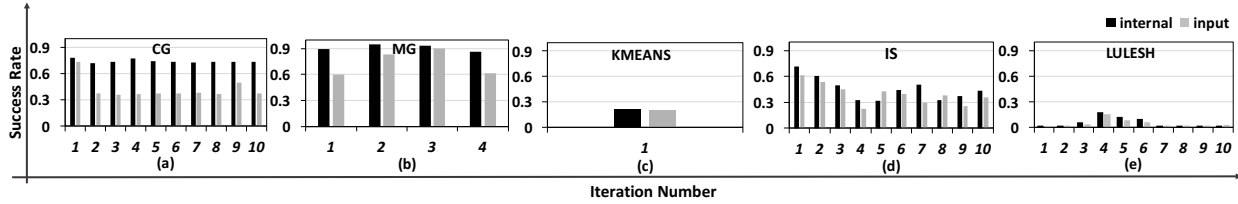


Fig. 6. Fault injection results for individual iterations of the main loop.

(internal locations) and CG exemplify this conclusion. The success rates over multiple iterations can also be very different, e.g., in IS and LULESH. After examining the DDDGs, we find that control flow differences between the iterations of the main loop are the main reason accounting for this difference.

## VI. RESILIENCE COMPUTATION PATTERNS

We present a formal description of the resilience computation patterns. Table I summarizes them in applications.

### Pattern 1: Dead Corrupted Locations (DCL)

In this pattern, the values of several corrupted input locations are *aggregated* into fewer output locations, with aggregations being a combination of multiple operations (e.g., additions and multiplications). While the errors in the corrupted input locations can propagate to one (or a few) locations, many of these corrupted input locations are not used anymore (they become dead locations) and the total number of corrupted locations decreases.

We frequently find Pattern 1 in LULESH. Figure 8 shows the code excerpt extracted from LULESH that accounts for the decrease of the number of alive corrupted locations within the routine *LagrangeNodal* (see ① and ② in Figure 7). The array *hourgram*[][] is a temporal corrupted location that is dead after the sample code snippet. The error has propagated to its elements before the example code. Although the error propagates from *hourgram* to temporal variables *hxx*[], which are then aggregated into *hgfz*[], the number of alive, corrupted variables decreases since the corrupted elements of *hourgram*[][] become dead after this code. We also find this pattern in the MG code.

### Pattern 2: Repeated Additions

In this pattern, the value of a corrupted location is repeatedly added by other correct values. Those correct values amortize the effect of the incorrect value. This pattern does not necessarily cause a decrease of alive, corrupted locations (as in Pattern 1), but over time the corrupted value approaches the correct value such that the application execution can be successful.

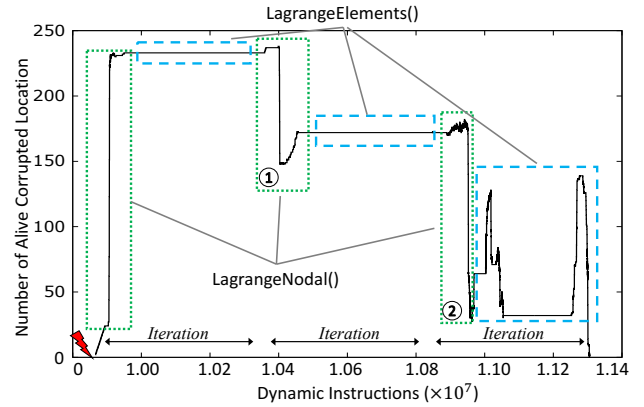


Fig. 7. A real case of ACL table. It shows the number of ACL-s in LULESH after a fault is injected into the last third iteration of the main loop.

```

1 for(Index_t i = 0; i < 4; i++){
2   hxx[i] = hourgam[0][i]*xd[0]+hourgam[1][i]*xd[1]+
3   hourgam[2][i]*xd[2]+hourgam[3][i]*xd[3]+
4   hourgam[4][i]*xd[4]+hourgam[5][i]*xd[5]+
5   hourgam[6][i]*xd[6]+hourgam[7][i]*xd[7];
6 }
7 ...
8 for(Index_t i = 0; i < 8; i++) {
9   hgfz[i] = coefficient*
10    (hourgam[i][0]*hxx[0]+hourgam[i][1]*
11    hxx[1] +
12    hourgam[i][2]*hxx[2]+hourgam[i][3]*
13    hxx[3]);

```

Fig. 8. Example of the Dead Corrupted Locations in LULESH

We observe Pattern 2 in the iterative solvers MG and CG. Figure 9 shows a code excerpt covering this pattern in MG. Here, we inject a fault in an element of the array *u* and then the array element *u*[*i3*][*i2*][*i1*] is added with new data values (Lines 6-9). This code is repeatedly executed in the main computation routine (*mg3P*). As a result, the array element *u*[*i3*][*i2*][*i1*] is repeatedly added along with new data values.



```

1 for (i3 = 1; i3 < n3-1; i3++) {
2   for (i2 = 1; i2 < n2-1; i2++) {
3     ...
4     for (i1 = 1; i1 < n1-1; i1++) {
5       u[i3][i2][i1] = u[i3][i2][i1]
6         +c[0]*r[i3][i2][i1]
7         +c[1]*(r[i3][i2][i1-1]+r[i3][i2][i1+1]
8           +r1[i1])
9         +c[2]*(r2[i1]+r1[i1-1]+r1[i1+1]);
10    } } }

```

Fig. 9. Example of the Repeated Additions pattern in MG

TABLE II  
THE REPEATED ADDITIONS PATTERN TAKES EFFECT IN MG

	original value	corrupted value	error magnitude
$itr_1$	0	0.00000059604645	$\infty$
$itr_2$	-0.004373951680278	-0.004373951059397	6.20880999391282E-10
$itr_3$	-0.004816104396391	-0.004816104262613	1.33777999962448E-10
$itr_4$	-0.004664456032917	-0.004664455968072	6.48450000292899E-11

We examine the value of the array element ( $u[10][10][10]$ ) where a single bit-flip happens on the 40th bit in the first invocation of the function  $mg3P$ . This function is iteratively called four times. We examine error magnitude (as defined in Equation 2, recalling that error magnitude is the relative error of a faulty value). Table II shows that the error magnitude becomes increasingly smaller as  $mg3P$  is repeatedly called, reducing the effect of data corruption. Note that although the error magnitude at the second invocation of  $mg3P$  is very small, it is still not acceptable for the verification phase of MG. However, as the corrupted value is closer to the correct value at the fourth invocation of  $mg3P$ , the corrupted value is acceptable by MG and regarded as a correct solution.

```

1 /* find cluster center id with min dist to pt */
2 for (i=0; i<npts; i++) {
3   float dist;
4   dist = euclid_dist_2(pt, pts[i], nfeatures);
5   if (dist < min_dist) {
6     min_dist = dist;
7     index = i;
8   }
9 }

```

Fig. 10. Example of the Conditional Statement pattern in KMEANS

#### Pattern 3: Conditional Statements

In this pattern, a conditional statement such as an *if* condition, which tolerates a fault as long as the result of the statement in a faulty case remains the same (true/false) as in a fault-free case, consequently avoiding a control-flow divergence that otherwise could have occurred. The conditional statement can cause a decrease in the number of alive corrupted locations.

Although Pattern 3 is simple, it can become a major reason for fault tolerance in applications. KMEANS exemplifies this case: Figure 10 shows a code segment where a condition statement (Line 5) plays a major role to tolerate faults in the array *feature*. In essence, the code tries to find the minimum distance between a target data point and the center data point

```

1 /* Determine the number of keys in each bucket */
2 for ( i=0; i<NUM_KEYS; i++ )
3   bucket_size[key_array[i] >> shift]++;

```

Fig. 11. Example of the shifting pattern in IS.

of each cluster based on the feature values of data points. This conditional statement tolerates errors that happen in the array *feature*, which takes most of the memory footprint of KMEANS. As long as the code segment can find the correct cluster with the minimum distance to the target point, the application outcome remains correct.

Besides the above example, we often find Pattern 3 in the program verification phases of MG and CG, where the final computation result is compared with a threshold to determine the result validity and/or to terminate execution.

#### Pattern 4: Shifting

In this pattern, bits are lost due to bit shifting operations. If the lost bits are corrupted, fault tolerance occurs and we say that the pattern completely masks (or eliminates) the faulty bit.

We find Pattern 4 in IS—we show an example in Figure 11. IS is a benchmark that implements bucket sorting for input integers (called “keys” in the benchmark). The input integers are placed into multiple buckets based on their significant bits. To decide into which bucket a key will be placed, IS applies a shift operation on the key (Line 3 in Figure 11). If the data is corrupted in the least significant bits of the key, the shift operations can still correctly place the key into the corresponding bucket, hence tolerating faults in the key.

#### Pattern 5: Data Truncation

In this pattern, corrupted data is not presented to the user when used as a final result, or corrupted data is truncated.

We find Pattern 5 in LULESH, where in its last execution phase the computation results of a *double* data type are reported in “%12.6e” format (using the `printf` C function). In this format, the mantissa of the computation result is partially cut-off and not fully presented to the user; thus if the cut-off mantissa is corrupted by a fault, the erroneous value will not be seen by the user.

#### Pattern 6: Data Overwriting

In this pattern, corrupted data is overwritten by a correct value, and the data corruption is consequently eliminated.

We find Pattern 6 in all benchmarks, as it is commonly found in the output of many instructions. This occurs in particular when the value of a corrupted location is overwritten by an instruction that generates a clean uncorrupted value.

**Discussion.** The effectiveness of some patterns (repeated additions, conditional statement, shifting, and data truncation) depends on the program input. For example, the effectiveness of the shifting pattern is dependent on the number of shifted bits—the more bits are shifted, the more random bit-flip errors



can be tolerated. This is different from software design patterns that are general and independent of program input.

## VII. CASE STUDIES

Resilience computation patterns have many potential uses. We give two use cases. Here, whenever we use fault injection, we use 99% confidence level and 1% margin of error to decide the number of fault injection tests based on [34].

TABLE III  
RESULTS AFTER APPLYING RESILIENCE PATTERNS TO CG.

Resi. Pattern Applied	App. Resi.	Exe time (s)/Average (s)
None	0.59	158.659-159.468 / 159.010
DCL and overwrt.	0.78	158.859-159.457 / 159.167
Truncation	0.614	158.605-159.338 / 158.835
All together	0.782	158.574-159.457 / 158.859

### A. Use Case 1: Resilience-Aware Application Design

We apply resilience patterns to the CG benchmark, aiming to improve its resilience. We successfully apply three patterns: **dead corrupted location (DCL)**, **data overwriting**, and **truncation**. The results are shown in Table III, where the first column shows the resilience pattern(s) applied; the second column is the application resilience—the success rate measured by doing fault injection; the third column is the execution time for one run with or without applying resilience pattern(s). We report the average execution time for 20 runs in Table III. Figures 12 and 13 in Appendix A show the code where we apply the three patterns.

To apply DCL and data overwriting, we introduce two temporal arrays at the beginning of `sprnvc()` to replace two global arrays `v[]` and `iv[]` referenced in `sprnvc()` (see Figure 12). Furthermore, to ensure the program correctness, the updated values of the two temporal arrays are copied back to `v[]` and `iv[]` at the end of `sprnvc()`. Because of the copy-back, errors occurring in `v[]` and `iv[]` during the execution of `sprnvc()` can be overwritten. Moreover, errors that might occur in the two temporal arrays become dead (not accumulated as in the global arrays), after the copy-back. Overall, we improve application resilience by 32.2% with less than 0.1% performance loss (caused by a small amount of data movement).

To apply the truncation pattern, we select 10 iterations (340-350th iterations) of a loop within the function `conj_grad()`, which is used to calculate  $p \cdot q$  (see Figure 13). We replace 64-bit floating-point multiplications with 32-bit integer multiplications (particularly lines 508-510 in the source code). After applying the pattern, the precision loss (64 bit vs. 32 bit) does not affect the correctness of the final output. The reason is as follows. As an iterative solver, CG gradually averages out the precision loss across iterations. Furthermore, CG uses a conditional statement that compares the CG output with a threshold to verify the output correctness. Such conditional statement can further tolerate the precision loss. Table III shows that we improve application resilience by 4.1% with no performance loss. We apply the three patterns together and improve the application resilience by a total of **32.5%** with less than 0.1% performance loss.

### B. Use Case 2: Predicting Application Resilience

The current common practice to quantify the resilience of an application is to use random fault injection. However, random fault injection misses the application context that can explain how errors propagate and consequently are tolerated. In this case study, we are exploring a way alternative to random fault injection to quantify application resilience. Since resilience computation patterns explain application resilience, we may estimate the resilience of an application by counting the number of instances of such patterns in the application. This approach can quantify the contribution of each resilience pattern to application resilience, which demonstrates the effectiveness of resilience patterns.

**Model Construction.** We build a Bayesian multivariate linear regression model [41] to predict the resilience (i.e., success rate) of an application. The model uses the number of pattern instances for each resilience computation pattern as input, and outputs a single value  $P_{suc\_rate}$ , the predicted success rate. We model the above idea as follows:

$$P_{suc\_rate} = \sum_{i=1}^{\#patterns} \beta_i x_i + \epsilon. \quad (3)$$

In Equation 3,  $x_i$  is the number of pattern instances for a specific pattern  $i$  normalized by total number of instructions within the application. We name  $x_i$  the pattern rate (e.g., condition rate, shift rate, and truncation rate). We normalize the number of pattern instances to enable a fair comparison between applications with different number of instructions. In total, there are  $\#patterns$  patterns ( $\#patterns$  is six in our modeling).  $\beta_i$  is the model coefficients and  $\epsilon$  is the intercept.

**Experiments and Model Validation.** We perform two experiments. In the *first* experiment, we build the model using all the patterns from the ten benchmark programs (Section V-A) to show that the data fits the model well. This experiment requires running the ten benchmarks, collecting the number of pattern instances for each pattern, and performing random fault injection to obtain success rates for each benchmark.

In the *second* experiment, we train the model using data from different combinations of nine of the ten benchmarks, and make a prediction for success rate for the one remaining benchmark. We then validate the model prediction by measuring its accuracy (i.e., relative error) with respect to the success rate that is obtained by doing fault injection. This experiment is to see how accurate the model is in predicting the success rate of an unseen program.

**Experimental Results.** For the first experiment, we calculate the “ $R$ -square” value of the model.  $R$ -square is used for measuring the fitness of a statistic model. The  $R$ -square value in our experiment is 96.4%, which is close to 1. A value close to 1 indicates that the model explains the variability of the prediction result around its mean. The model therefore fits and explains the data very well.

For the second experiment, the prediction results are shown as the prediction error rate in Table IV. The average prediction error excluding the prediction error on DC is 14.3%. The

TABLE IV  
THE QUANTIFICATION OF RESILIENCE PATTERNS AND THE PREDICTION ACCURACY. SR=SUCCESS RATE

Benchmark	Condition Rate	Shift Rate	Truncation Rate	Dead Location Rate	Repeat Addition Rate	Overwrite Rate	Measured SR	Predicted SR	Prediction Err. Rate
CG	0.088	2.45E-08	2.185	0.298	2.61E-07	0.999	0.739	0.652	11.8%
MG	0.037	2.74E-03	1.145	0.314	0.000	0.999	0.879	0.810	7.8%
LU	0.022	8.11E-06	0.188	0.319	0.000	0.999	0.575	0.642	11.7%
BT	0.015	0.000	0.074	0.334	0.000	0.999	0.656	0.573	12.7%
IS	0.040	2.86E-02	0.001	0.311	0.000	0.985	0.653	0.712	9.0%
DC	0.139	0.174	0.078	0.302	9.22E-07	0.994	0.578	0.204	64.6%
SP	0.042	0.000	0.428	0.389	4.15E-08	0.999	0.385	0.466	21.0%
FT	0.038	1.99E-03	1.591	0.338	0.000	0.999	0.876	1.000	14.2%
KMEANS	0.079	7.18E-07	2.484	0.375	7.87E-05	0.979	0.843	1.000	18.6%
LULESH	0.048	2.60E-03	0.550	0.378	6.88E-06	0.937	0.926	0.725	21.7%

prediction error on DC is large (64.6%), because the model does not distinguish error tolerance capabilities of different instances of repeated additions and conditional statement (see the limitation discussed below), thus predictions for DC are affected by this limitation.

**Importance of Resilience Patterns: Feature Analysis.** We use standardized regression coefficient [42], an indicator that presents the importance of predictors, to understand which resilience patterns are the most important. We compute the standardized regression coefficients for the model trained in the second experiment.

On average, the *averaged standardized regression coefficients* of Shifting, Truncation, Dead Location, Repeated Addition, Overwriting, and Conditional Statement are 1.48, 1.73, 0.38, 0.25, 0.92, and 1.69, respectively. *We conclude that Truncation (1.73), Shifting (1.48), and Conditional Statement (1.69), that have the largest coefficients, contribute the most to resilience. On the other hand, patterns such as Repeated Addition and Dead Location have less impact.*

**Limitation and Future Work.** Different instances of a pattern can have different weight into application resilience. For example, considering different cases of shifting where the value is shifted to right/left  $x$  times. Depending on the value of  $x$ , the error may or may not be masked. While simply counting the number of pattern instances limits the prediction accuracy (one should also take into account the value of locations), this demonstrates a simple but practical use case of the patterns.

## VIII. RELATED WORK

**Resilience Computation Patterns.** A limited number of previous studies reveal the existence of resilience patterns [11], [43]; these efforts, however, lack a systematic method to identify these patterns. In [11], Li et al. identify conditional statement and truncation for error masking in GPU programs. In [43], Cook and Zilles identify shift, conditional statement and truncation. Those research efforts manually examine fault tolerance cases, while our work is different in several aspects. First, we introduce a novel *framework and methodology to systematically* identify patterns. For complex applications, manual identification of those patterns is unfeasible. Second, we identify more complex patterns (e.g., DCL and repeated additions). Those new patterns require multiple instructions to take effect. Finding those patterns must be based on a complete picture on error propagation. The existing work identifies pat-

terns based on the analysis of individual instructions without sufficient considerations of interactions between instructions, hence lacking a complete picture to identify patterns.

**Error Detector Placement.** Existing research uses compiler static and/or dynamic instruction analysis to enable application-level fault tolerance by detecting code vulnerabilities. For example, Pattabiraman et al. use static analysis [15] and a data-dependence analysis [16] to determine the placement of error detectors in applications. Their work determines the critical variables that are likely to propagate errors based on metrics, such as highest dynamic fan-out. Different from us, their work cannot locate resilience patterns.

**Visualization.** Recently, techniques that allow visualization of corrupted application data across loop iterations and MPI processes have been developed. For example, Calhoun et al. [17] replicate instructions to track and visualize how errors propagate within the application. However, their approach can be expensive when analyzing complex applications. Our approach, based on the abstract code structure model, can accelerate tracking error propagation.

## IX. CONCLUSIONS

Understanding natural error resilience in HPC applications is important in creating applications that can naturally tolerate errors. However, our knowledge on natural error resilience has been quite limited, mainly because of a lack of systematic methods to identify resilience computation patterns. Our framework, FlipTracker, exposes these patterns by enabling fine-grained tracking of error propagation and fault tolerance to enable users to pinpoint resilience computations in HPC programs. By tracking data flows and value variations based on a code region model, we identify and summarize six common resilience patterns, which increase our understanding of how natural resilience occurs. We also present two case studies of practical applications of these resilience patterns.

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## REFERENCES

- [1] M. Snir, R. W. Wisniewski, J. A. Abraham, S. V. Adve, S. Bagchi, P. Balaji, J. Belak, P. Bose, F. Cappello, B. Carlson *et al.*, "Addressing failures in exascale computing," *The International Journal of High Performance Computing Applications*, vol. 28, no. 2, pp. 129–173, 2014.
- [2] M. Casas, B. R. de Supinski, G. Bronevetsky, and M. Schulz, "Fault resilience of the algebraic multi-grid solver," in *Proceedings of the 26th ACM International Conference on Supercomputing (ICS)*, 2012.
- [3] P. Sao and R. Vuduc, "Self-stabilizing iterative solvers," in *Proceedings of the Workshop on Latest Advances in Scalable Algorithms for Large-Scale Systems*, ser. ScalA, 2013.
- [4] J. Elliott, M. Hoemmen, and F. Mueller, "Evaluating the impact of SDC on the GMRES iterative solver," in *IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, 2014, pp. 1193–1202.
- [5] R. A. Ashraf, R. Gioiosa, G. Kestor, R. F. DeMara, C.-Y. Cher, and P. Bose, "Understanding the propagation of transient errors in HPC applications," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2015.
- [6] L. Leem, H. Cho, J. Bau, Q. A. Jacobson, and S. Mitra, "ERSA: Error resilient system architecture for probabilistic applications," in *Design, Automation & Test in Europe Conference & Exhibition (DATE)*, 2010.
- [7] C. Alippi, V. Piuri, and M. Sami, "Sensitivity to errors in artificial neural networks: A behavioral approach," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 42, no. 6, pp. 358–361, 1995.
- [8] V. Piuri, "Analysis of fault tolerance in artificial neural networks," *Journal of Parallel and Distributed Computing*, vol. 61, no. 1, pp. 18–48, 2001.
- [9] J. Calhoun, L. Olson, and M. Snir, "Flipit: An LLVM based fault injector for HPC," in *Workshops in Euro-Par*, 2014.
- [10] D. Li, J. S. Vetter, and W. Yu, "Classifying soft error vulnerabilities in extreme-scale scientific applications using a binary instrumentation tool," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2012.
- [11] G. Li, K. Pattabiraman, C.-Y. Cher, and P. Bose, "Understanding error propagation in GPGPU," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2016.
- [12] V. C. Sharma, A. Haran, Z. Rakamaric, and G. Gopalakrishnan, "Towards formal approaches to system resilience," in *Pacific Rim International Symposium on Dependable Computing*, 2013.
- [13] S. K. S. Hari, S. V. Adve, H. Naeimi, and P. Ramachandran, "Relyzer: Exploiting application-level fault equivalence to analyze application resiliency to transient faults," in *International Conference on Architectural Support for Programming Language and Operating Systems (ASPLOS)*, 2012.
- [14] S. K. Sastry Hari, R. Venkatagiri, S. V. Adve, and H. Naeimi, "GangES: Gang error simulation for hardware resiliency evaluation," in *International Symposium on Computer Arch.*, 2014.
- [15] K. Pattabiraman, Z. Kalbarczyk, and R. K. Iyer, "Automated derivation of application-aware error detectors using static analysis," *IEEE Transactions on Dependable and Secure Computing*, vol. 8, no. 1, 2011.
- [16] K. Pattabiraman, Z. Kalbarczyk, and R. K. Iyer, "Application-based metrics for strategic placement of detectors," in *Pacific Rim International Symposium on Dependable Computing*, 2005.
- [17] J. Calhoun, M. Snir, L. N. Olson, and W. D. Gropp, "Towards a more complete understanding of SDC propagation," in *International Symposium on High-Performance Parallel and Distributed Computing (HPDC)*, 2017.
- [18] V. Sridharan, N. DeBardleben, S. Blanchard, K. B. Ferreira, and S. Gurusurthi, "Memory errors in modern systems: The good, the bad, and the ugly," in *ACM International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, 2015.
- [19] V. Sridharan and *etc.*, "Feng Shui of supercomputer memory: Positional effects in dram and sram faults," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2013.
- [20] M. Wilkening, V. Sridharan, S. Li, F. Previlon, S. Gurusurthi, and D. R. Kaeli, "Calculating arch vulnerability factors for spatial multi-bit transient faults," in *IEEE/ACM International Symposium on Microarchitecture (MICRO)*, 2014.
- [21] R. Venkatagiri, A. Mahmoud, S. K. S. Hari, and S. V. Adve, "Approxlyzer: Towards a systematic framework for instruction-level approximate computing and its application to hardware resiliency," in *International Symposium on Microarchitecture (MICRO)*, 2016.
- [22] H. Schirmeier, C. Borchert, O. Spinczyk, and J. A. Rivers, "Avoiding pitfalls in fault-injection based comparison of program susceptibility to soft errors," in *IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*, 2015.
- [23] D. H. Bailey, L. Dagum, E. Barszcz, and H. D. Simon, "NAS Parallel Benchmark Results," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 1992.
- [24] J. Ferrante, K. J. Ottenstein, and J. D. Warren, "The program dependence graph and its use in optimization," *ACM Transactions on Programming Languages and Systems*, vol. 9, no. 3, pp. 319–349, 1987.
- [25] Y. S. Shao and D. Brooks, "ISA-independent workload characterization and its implications for specialized architectures," in *IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS)*, 2013.
- [26] A. Janapsatya, A. Ignjatovic, S. Parameswaran, and J. Henkel, "Instruction trace compression for rapid instruction cache simulation," in *Proceedings of the Conference on Design, Automation and Test in Europe (DATE)*, 2007.
- [27] 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 Distributed Computing*, vol. 69, no. 8, pp. 696–710, 2009.
- [28] J. Holewinski, R. Ramamurthi, M. Ravishankar, N. Fauzia, L.-N. Pouchet, A. Rountev, and P. Sadayappan, "Dynamic trace-based analysis of vectorization potential of applications," in *ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI)*, 2012.
- [29] E. R. Gansner and S. C. North, "Graphviz: an open graph visualization system and its applications to software engineering," *Software - Practice and Experience*, vol. 30, no. 11, pp. 1203–1233, 2000. [Online]. Available: <http://www.graphviz.org>
- [30] J. Newsome and D. Song, "Dynamic taint analysis for automatic detection, analysis, and signature generation of exploits on commodity software," in *Network and Distributed Systems Security Symposium (NDSS)*, 2005.
- [31] F. Aleen, M. Sharif, and S. Pande, "Input-driven dynamic execution prediction of streaming applications," in *Proceedings of the ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPOPP)*, 2010.
- [32] J. Zeng, Y. Fu, K. A. Miller, Z. Lin, X. Zhang, and D. Xu, "Obfuscation resilient binary code reuse through trace-oriented programming," in *Proceedings of the ACM SIGSAC Conference on Computer & Communications Security (CCS)*, 2013.
- [33] G. Georgakoudis, I. Laguna, D. S. Nikolopoulos, and M. Schulz, "Refine: Realistic fault injection via compiler-based instrumentation for accuracy, portability and speed," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2017.
- [34] R. Leveugle, A. Calvez, P. Maistri, and P. Vanhauwaert, "Statistical fault injection: Quantified error and confidence," in *Conference on Design, Automation and Test in Europe (DATE)*, 2009.
- [35] S. Seo, G. Jo, and J. Lee, "Performance characterization of the NAS parallel benchmarks in opencl," in *Proceedings of the 2011 IEEE International Symposium on Workload Characterization (IISWC)*, 2011.
- [36] I. Karlin, J. Keasler, and R. Neely, "Lulesh 2.0 updates and changes," Tech. Rep. LLNL-TR-641973, August 2013.
- [37] S. Che, M. Boyer, J. Meng, D. Tarjan, J. W. Sheaffer, S.-H. Lee, and K. Skadron, "Rodinia: A benchmark suite for heterogeneous computing," in *IEEE International Symposium on Workload Characterization (IISWC)*, 2009.
- [38] I.-H. Chung, R. E. Walkup, H.-F. Wen, and H. Yu, "Mpi performance analysis tools on Blue Gene/L," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2006.
- [39] K. Sato, D. H. Ahn, I. Laguna, G. L. Lee, and M. Schulz, "Clock delta compression for scalable order-replay of non-deterministic parallel applications," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, 2015.

- [40] R. Xue, X. Liu, M. Wu, Z. Guo, W. Chen, W. Zheng, Z. Zhang, and G. Voelker, "MPIWiz: Subgroup reproducible replay of MPI applications," *ACM Sigplan Notices*, vol. 44, no. 4, pp. 251–260, 2009.
- [41] T. P. Minka, "Bayesian linear regression," Tech. Rep., 2010.
- [42] J. Bring, "How to standardize regression coefficients," *The American Statistician*, vol. 48, no. 3, pp. 209–213, 1994.
- [43] J. J. Cook and C. Zilles, "A characterization of instruction-level error derating and its implications for error detection," in *International Conference on Dependable Systems and Networks (DSN)*, 2008.

## X. APPENDIX

### A. Details of Use Case 1: Resilience-Aware Application Design

Figure 12 and Figure 13 show two code excerpts extracted from CG, where dead corrupted location, data overwriting and truncation are applied, respectively.

For the case of dead corrupted location and data overwriting, the original code is shown in Figure 12(a) and the new code is shown in Figure 12(b) (we include some comments to explain the difference). In particular, we use two temporal arrays  $v\_tmp$  and  $iv\_tmp$  to replace two global arrays  $v$  and  $iv$ . We then copy values in the arrays  $v\_tmp$  and  $iv\_tmp$  back to the arrays  $v$  and  $iv$  after the computation.

Figure 13 shows how we apply the truncation. In particular, we replace 64-bit floating-point multiplications to 32-bit integer multiplications (see Lines 11-12 in Figure 13.b).

```

1 static void sprnvc(int n, int nz, int nn1, double v
2 [], int iv[]){
3     int nzv, ii, i;
4     double vecelt, vecloc;
5
6
7
8
9
10    nzv = 0;
11    while (nzv < nz) {
12        vecelt = randlc(&tran, amult);
13        vecloc = randlc(&tran, amult);
14        i = icnvrt(vecloc, nn1) + 1;
15        if (i > n) continue;
16        logical was_gen = false;
17        for (ii = 0; ii < nzv; ii++) {
18            if (iv[ii] == i) {
19                was_gen = true;
20                break;
21            }
22        }
23        if (was_gen) continue;
24        v[nzv] = vecelt;
25        iv[nzv] = i;
26        nzv = nzv + 1;
27    }
28
29
30
31
32 }

```

(a)

```

1 static void sprnvc(int n, int nz, int nn1, double v[],
2 int iv[]){
3     int nzv, ii, i;
4     double vecelt, vecloc;
5     double v_tmp[NONZER+1]; //define a temp array
6     int iv_tmp[NONZER+1]; //define a temp array
7     for(i=0;i<=NONZER;i++){
8         v_tmp[i] = v[i]; //initialization
9         iv_tmp[i] = iv[i]; //initialization
10    }
11    nzv = 0;
12    while (nzv < nz) {
13        vecelt = randlc(&tran, amult);
14        vecloc = randlc(&tran, amult);
15        i = icnvrt(vecloc, nn1) + 1;
16        if (i > n) continue;
17        logical was_gen = false;
18        for (ii = 0; ii < nzv; ii++) {
19            if (iv_tmp[ii] == i) { //replace iv with iv_tmp
20                was_gen = true;
21                break;
22            }
23        }
24        if (was_gen) continue;
25        v_tmp[nzv] = vecelt; //replace v with v_tmp
26        iv_tmp[nzv] = i; //replace iv with iv_tmp
27        nzv = nzv + 1;
28    }
29    for(i=0;i<=NONZER;i++){
30        v[i] = v_tmp[i]; //copy back
31        iv[i] = iv_tmp[i]; //copy back
32    }

```

(b)

Fig. 12. A code excerpt from the function *sprnvc()* in CG for the Use Case 1. (a) shows the original code excerpt before patterns are applied; (b) shows the code excerpt when dead corrupted location and data overwriting are applied.

```

1 static void conj_grad(int colidx [],
2 ...,
3 double p[],
4 double q[])
5 {
6     ...
7     // Obtain p,q
8     d = 0.0;
9     for (j = 0; j < lastcol - firstcol + 1; j++) {
10
11
12
13
14
15         d = d + p[j]*q[j];
16     }
17     ...
18
19 }

```

(a)

```

1 static void conj_grad(int colidx [],
2 ...,
3 double p[],
4 double q[])
5 {
6     ...
7     // Obtain p,q
8     d = 0.0;
9     for (j = 0; j < lastcol - firstcol + 1; j++) {
10         if (j<=350&&j>=340){
11             int tmp = p[j]; // truncation
12             int tmp1 = q[j]; // truncation
13             d = d + tmp*tmp1;
14         }else{
15             d = d + p[j]*q[j];
16         }
17     }
18     ...
19 }

```

(b)

Fig. 13. A code excerpt from the function *conj\_grad()* in CG for the Use Case 1. (a) shows the original code excerpt before the truncation pattern is applied; (b) shows the code excerpt when the truncation is applied.