PRUNERS

Providing Reproducibility for Uncovering Non-Deterministic Errors in Runs on Supercomputers

Computational Reproducibility at Exascale (CRE2017)
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Debugging/Testing large-scale applications is challenging

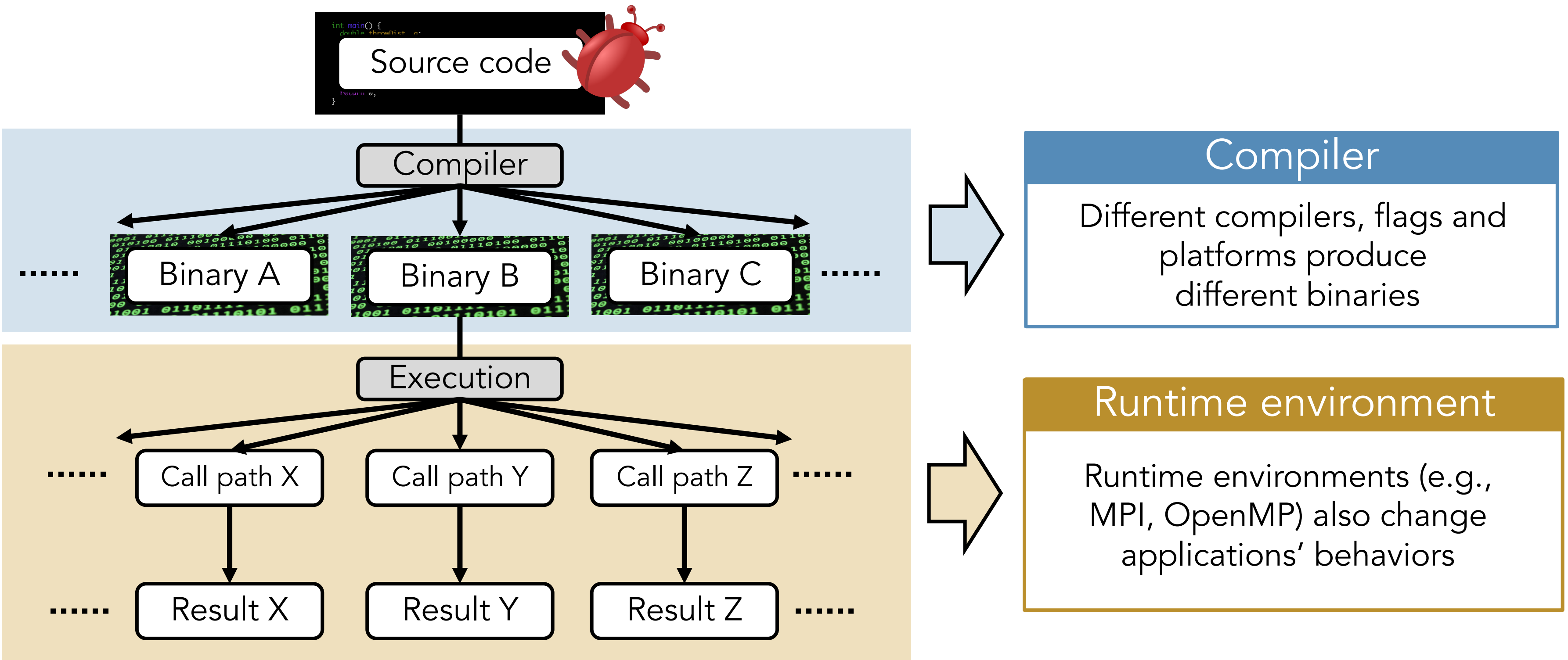
"On average, software developers spend
50% of their programming time finding and fixing bugs." [1]

Debugging/Testing are inevitable software development processes.
Tools facilitating Debugging/Testing are indispensable

[1] Source: http://www.prweb.com/releases/2013/1/prweb10298185.htm, CAMBRIDGE, UK (PRWEB) JANUARY 08, 2013

Bugs are not created equal !

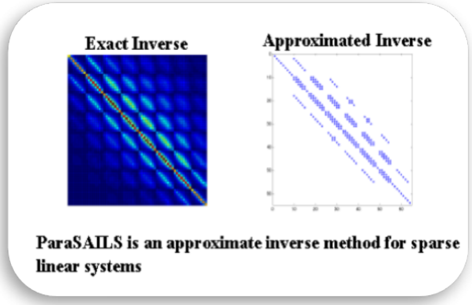
- When debugging/testing, reproducibility is very important



- Examples
  – Bugs that manifest themselves when using –O3, but do not with –O0
  – Bugs that do not manifests themselves

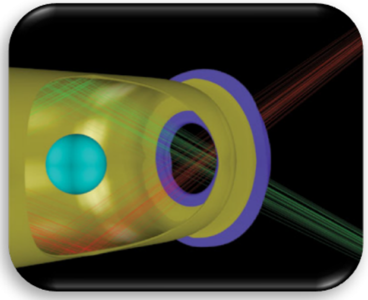
Non-deterministic bugs cost substantial amounts of time and efforts

Diablo/Hypre 2.10.1



- The bug manifested in particular machines
- It hung only once every 30 runs after a few hours
- The scientists spent 2 months in the period of 18 months, and then gave up on debugging it

HYDRA (porting on Sequoia)

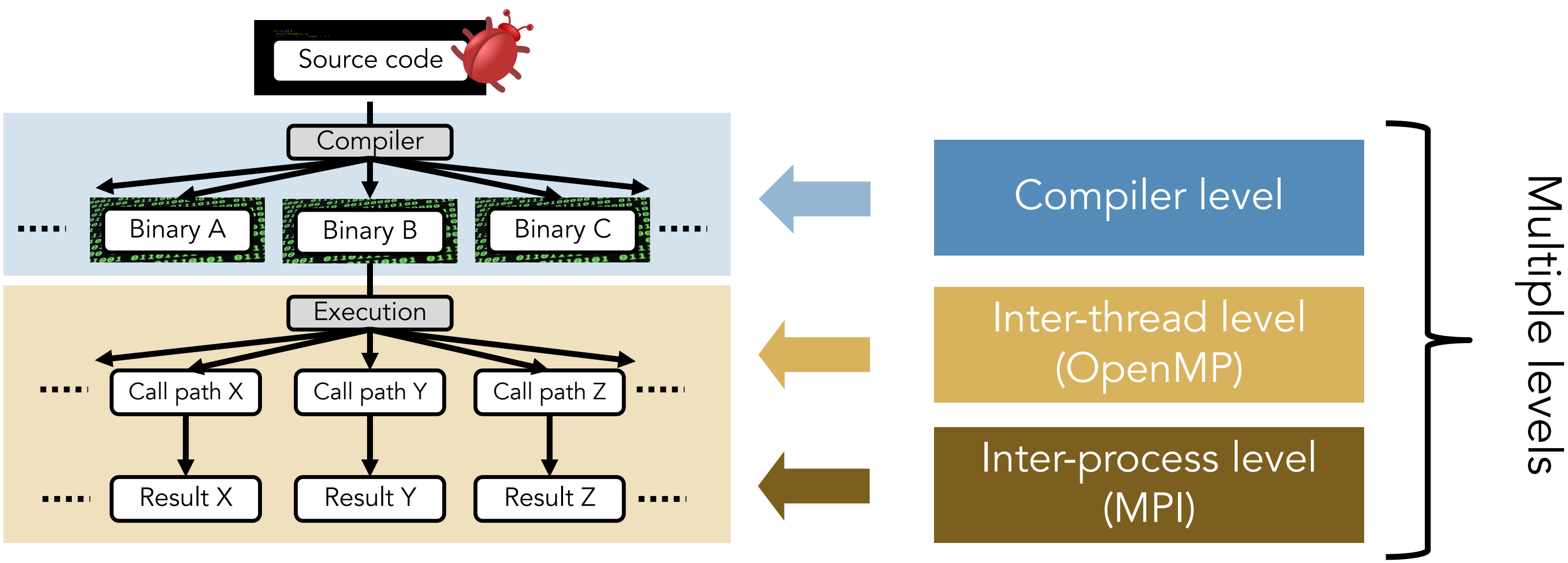


- MPI/OpenMP application non-deterministically crashed in an OpenMP region when compiling with optimization levels
- Manifested intermittently at or above 8K MPI processes
- The scientists spent months, and then ended up disabling OpenMP

and more ...

Non-deterministic bugs are introduced at multiple levels

- Introduced at the compiler level or at different runtime levels
- A monolithic tool won’t work for all cases
- Debugging/testing toolset
  - Individual tool works effectively
  - Interoperable and composable each other
  - Make debugging/testing easier even under other existing debuggers



PRUNERS Multi-level debugging/testing capabilities

The PRUNERS Toolset comprises four individual tools that can co-operate

FLiT	Compiler-induced floating-point computation variability tester	Compiler level
archer	Data race detector for OpenMP programs	OpenMP
ReMPI	MPI record-and-replay tool for reproducing non-deterministic MPI bugs	MPI
NINJA	Noise injection tool for exposing message race bugs	MPI

Multiple levels

Different compilers, compiler flags and platforms produce different numerical results

- No guarantee that floating-point computation on one platform is the same on another platform
  - E.g.) Apply associativity rules of real arithmetic

```
gcc-4.9.3  -O0
gcc-4.9.3  -O3
icc-16.0.3 -O0
```

Shewchuk/Kahan summation

```
float val = x + y;
float err = y - (val - x);
```

```
icc-16.0.3 -O3
```

```
float val = x + y;
float err = y - (val - x);
```

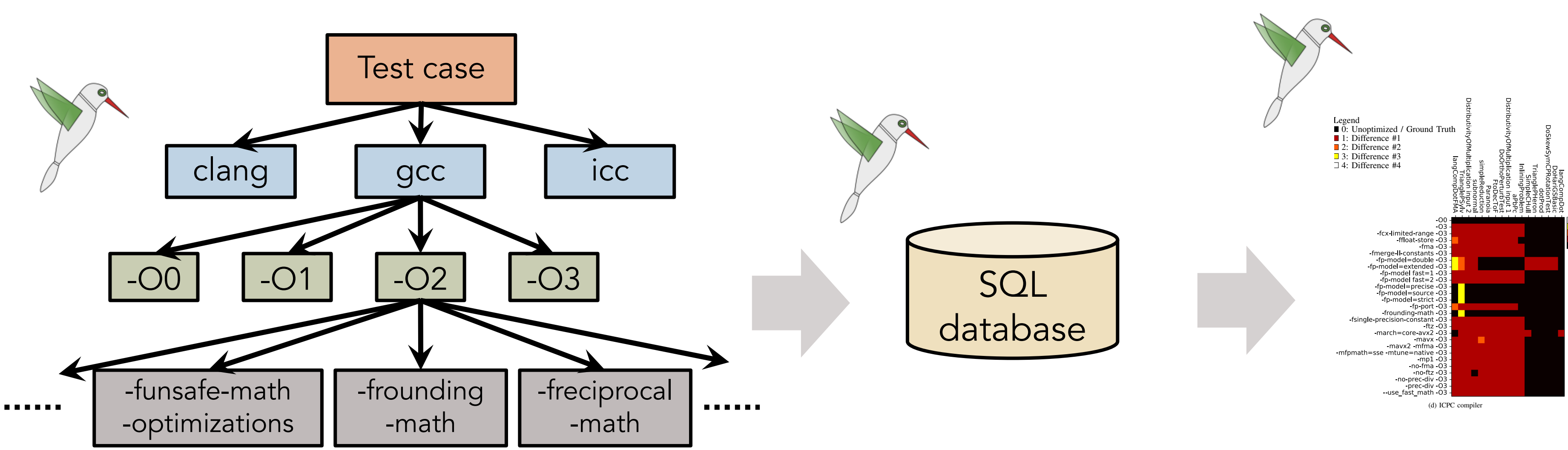
```
float val = x + y;
float err = y - y;
```

0

Understanding how sensitive your algorithm is w.r.t. to different round-off errors introduced by different compilers and flags are important for code verification and validation

FLiT (Floating-point Litmus Tester)

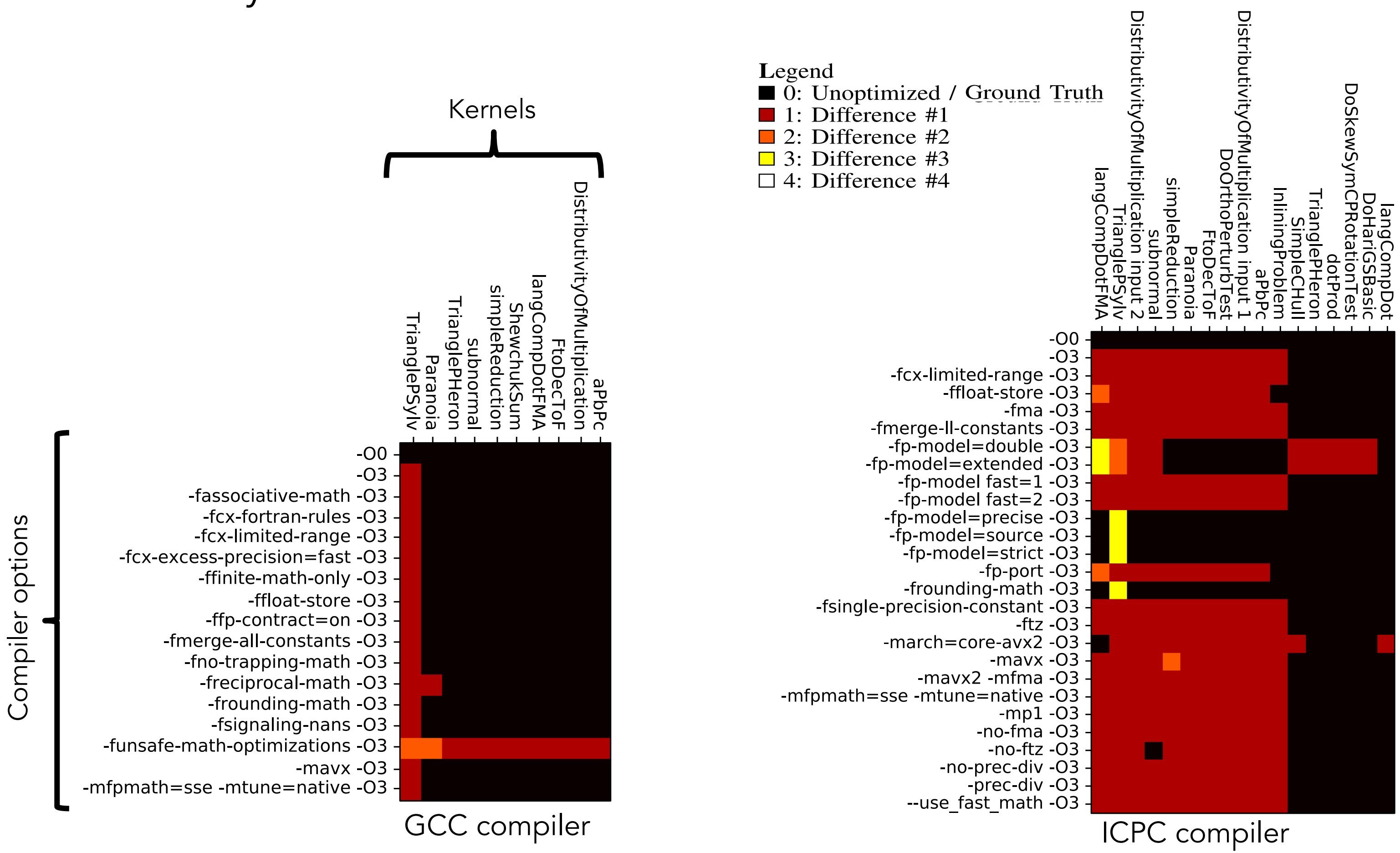
- FLiT is a reproducibility test framework
  – Test floating-point arithmetic variability in any user-given collection of programs
- FLiT tests the variability through hundreds of combinations
  – Different compilers, compiler flags, and also different hosts
- Results are stored in SQL database and used for visualization and for further analysis



Visualization

FLiT case study

- We tested several kernels which have compiler-induced FP variability
  - Difference in numerical results across different compilers, flags and kernels
- Example
  - When you want to find a compiler option that makes your applications faster while reproducing the exactly same results as non-optimized code, FLiT becomes very useful tool

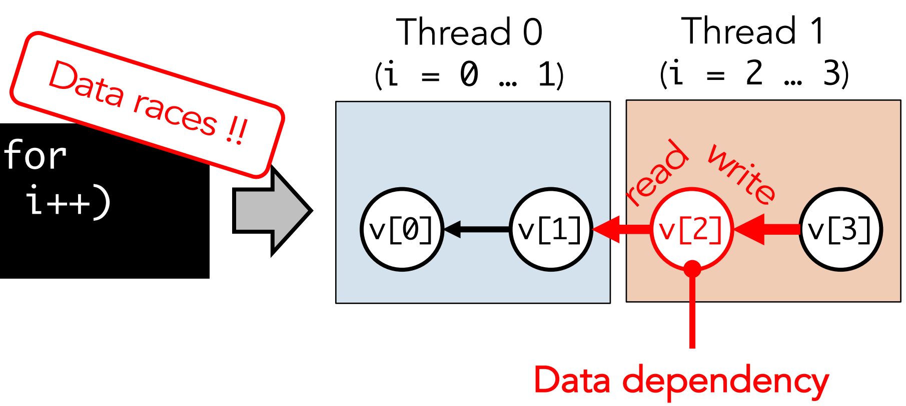


OpenMP easily creates non-deterministic bugs

- Data races in OpenMP are the most malignant non-deterministic bugs
- Depending on orders of read and write, numerical results change
- Orders of read and write are non-deterministic, it introduces non-deterministic bugs

Example

```
#pragma omp parallel for
for(int i = 0; i < 4; i++)
  v[i] = v[i+1] + 1;
```



In large-scale applications,
it is difficult to identify data races manually

Archer

- Archer is a data race detector combining static and dynamic analysis

OpenMP Source code → **Static Analysis** (OpenMP C/C++ Clang/LLVM Compiler) → **Dynamic Analysis** (Tsan and OpenMP RT) → **Report**

- Static analysis
  - Exclude regions that can be statically detected to be race-free for dynamic analysis (Blacklisting)

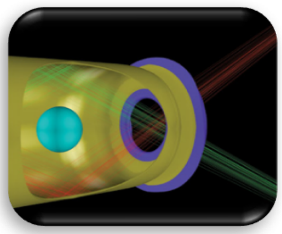
- Dynamic analysis
  - Detect data races based on LLVM/Clang ThreadSanitizer combined with OMPT-based annotation

Archer significantly reduce runtime overhead while providing high precision and accuracy

Archer case study: HYDRA

- Archer easily detected data races !

HYDRA (porting on Sequoia)



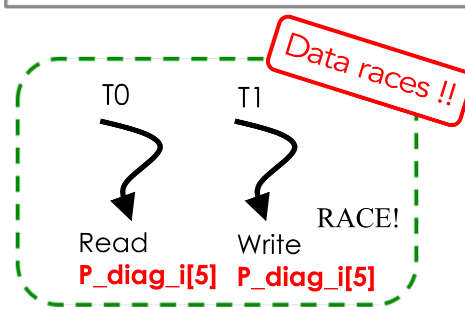
- MPI/OpenMP application non-deterministically crashed in an OpenMP region when compiling with optimization levels
- Manifested intermittently at or above 8K MPI processes
- The scientists spent months, and then ended up disabling OpenMP

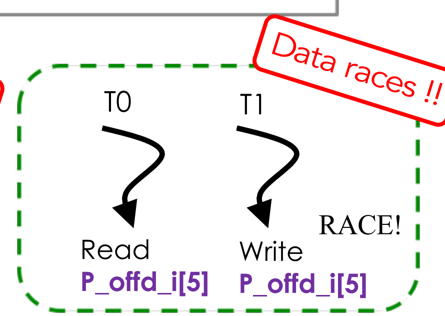
Archer

```
1002: hypre_BoomerAMGInterpTruncation(…) {
…
1007:   int *P_diag_i = hypre_CSRMatrixI(P_diag);
1014:   int *P_offd_i = hypre_CSRMatrixI(P_offd);
…
1062: #pragma omp parallel private(...)
1064:   {
…
1172:    if(max_elmst>0) {
…
1179:      for(i=start; i<stop; i++) {
…
1183:        last_index = P_diag_i[i+1];
1184:        last_index_offd = P_offd_i[i+1];

1248:          P_diag_i[i] = cnt_diag;
1249:          P_offd_i[i] = cnt_offd;
…
1484:   } /* end parallel region */
1491:   return ieer;
1492: }
```

About 50 variables
423 lines





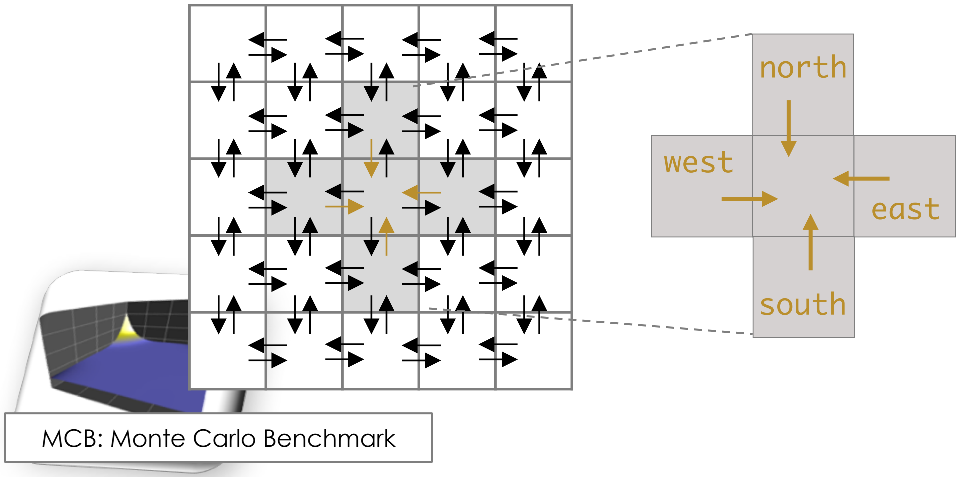
MPI can also introduce non-determinism

- It's typically due to communication with MPI_ANY_SOURCE
- In non-deterministic applications, each MPI rank doesn't know which other MPI rank will send message and when
- Example
  - If processes communication with neighbors, messages can arrive in any order from neighbors

MPI_ANY_SOURCE communication

```
MPI_Irecv(…, MPI_ANY_SOURCE, …);
while(1) {
  MPI_Test(flag);
  if (flag) {
    <computation>
    MPI_Irecv(…, MPI_ANY_SOURCE, …);
  }
}
```

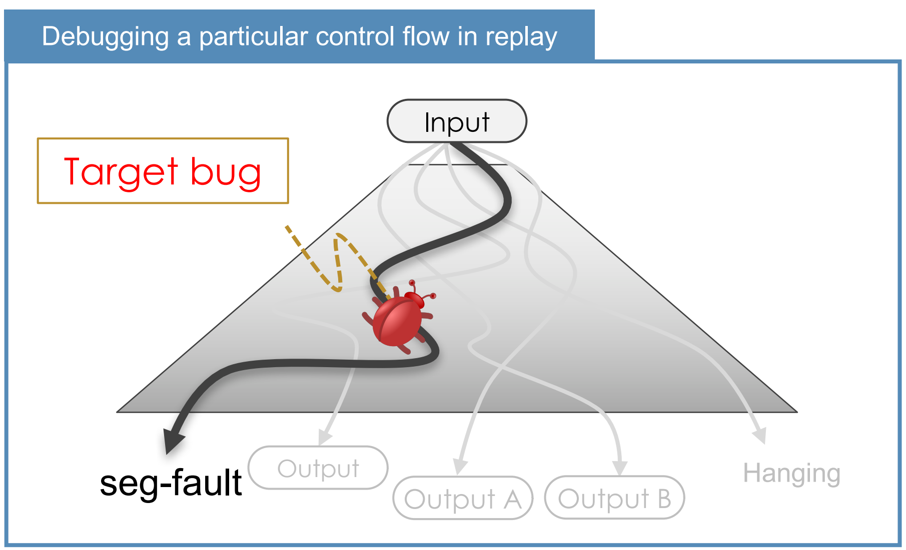
Example: Communications with neighbors



If a bug manifests through a particular message receive order,
It's hard to reproduce the bug, thereby, hard to debug it

ReMPI deterministically reproduces order of message receives

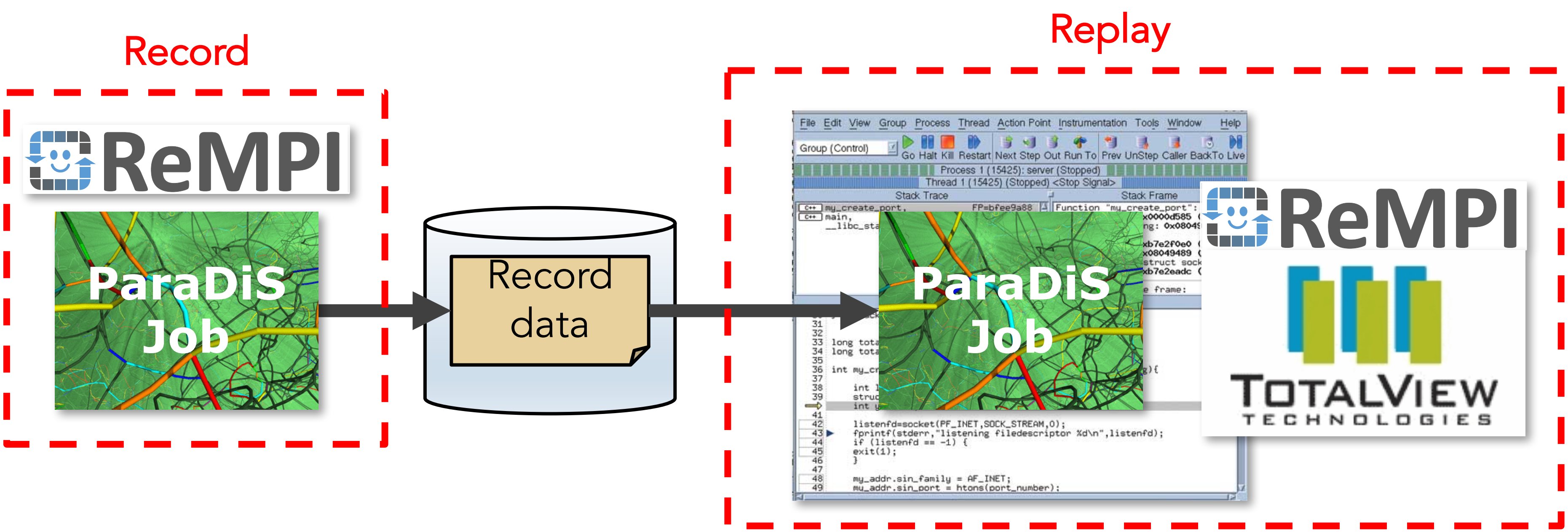
- ReMPI is an MPI record-and-replay tool
  - Record an order of MPI message receives
  - Replay the exactly same order of MPI message receives
- Even if a bug manifests in a particular order of message receives, ReMPI can consistently reproduce the target bug



ReMPI

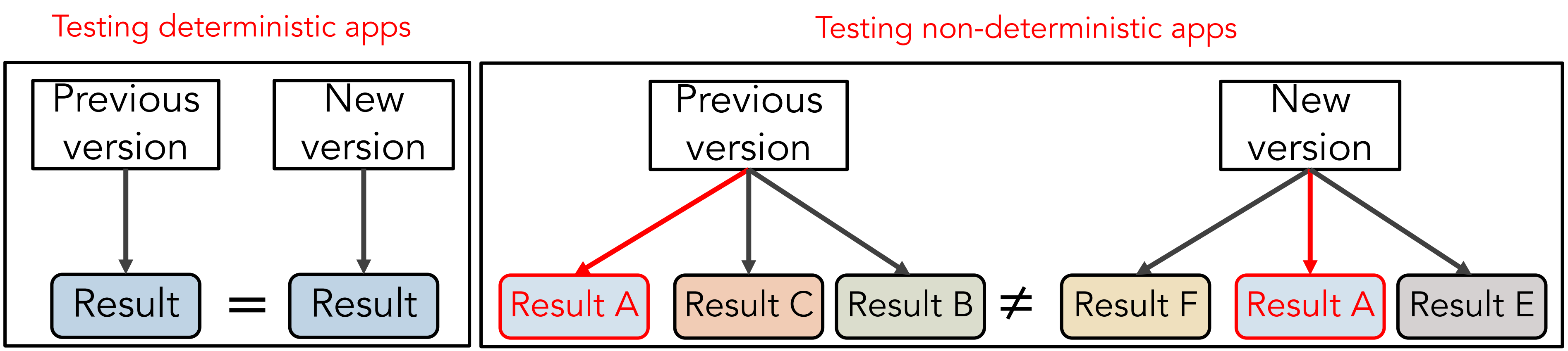
ReMPI case study: ParaDiS

- ParaDis
  - non-deterministically crashed after 100 to 200 iterations
- ReMPI reproduced the bug at the exactly same iteration
- ReMPI is interoperable with parallel debuggers and makes debugging non-deterministic bug easier
  - We recorded a buggy behavior in record mode
  - We diagnosed with TotalView under replay mode



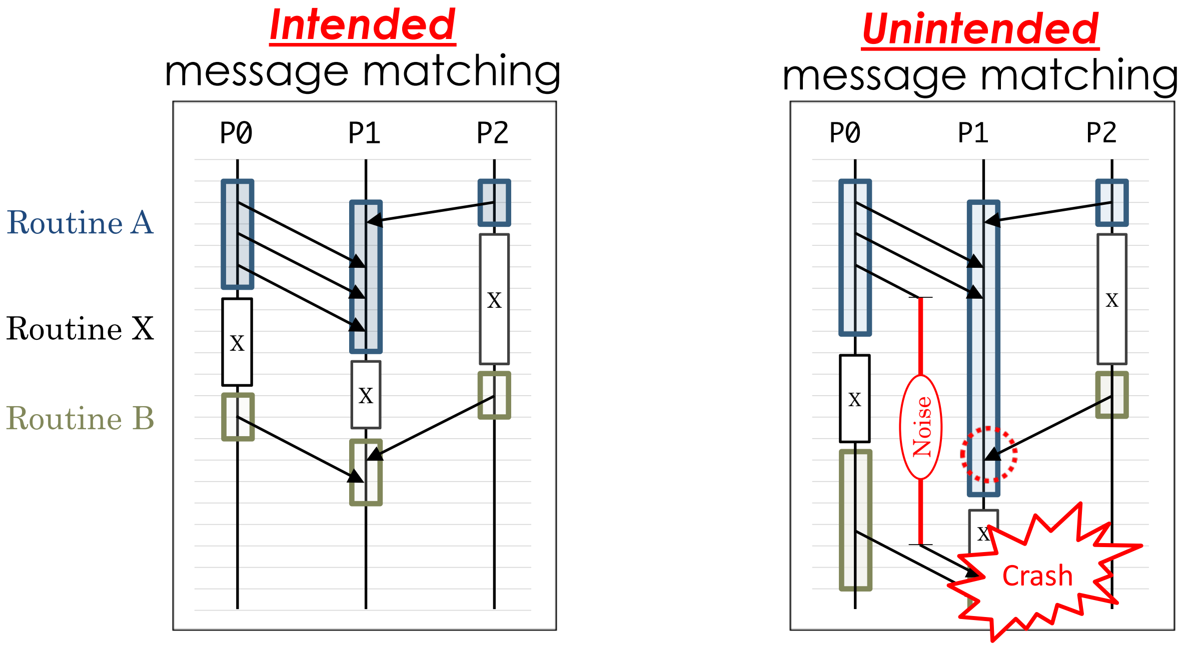
ReMPI is also useful for "Testing"

- "Testing" is also important for maintaining software quality
- MPI non-deterministic applications present significant challenges to testing
  - The non-determinism can produce different results from run to run by nature
- Using ReMPI, computational scientists can easily reproduce MPI behaviors, which facilitate testing



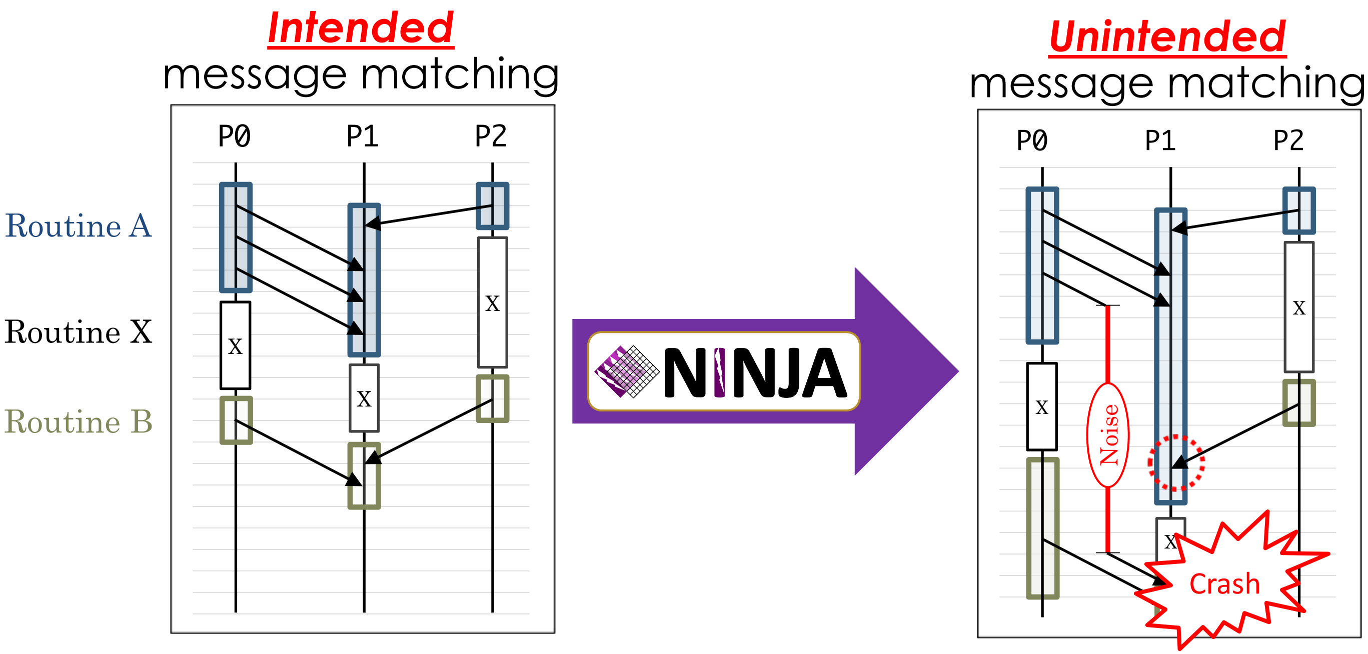
Unintended message races in MPI

- Many applications are written as a series of communication and computation routines (i.e., data parallel, SPMD)
- Developers must make sure all communication routines are "isolated"
- Example (Routine A and Routine B)
  - Different MPI_TAG or synchronization (e.g. MPI_Barrier) between the two routines
- If not isolated, message race bugs potentially occur
  - E.g.) A message sent in Routine B is received in Routine A
- Unintended message races are non-deterministic and infrequently occur



NINJA: Noise Injection Agent Tool

- NINJA exposes message race bugs by injecting noise

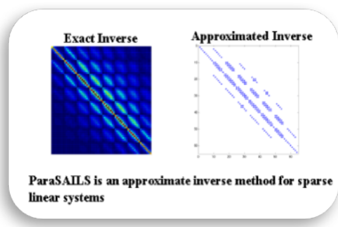


- NINJA detects suspicious communication routines
  - Communication routine using the same MPI_TAG without synchronization
- NINJA injects a delay to MPI messages in order to enforce message races
- NINJA can test if the application has unintended message races

NINJA cast study: Diablo/Hypre-2.10.1(in ParaSail module)

- Unintended message races in Hypre
- Prior to NINJA, the bug does not manifest itself in Hypre test code
- NINJA consistently exposed message races in the test code

Diablo/Hypre 2.10.1



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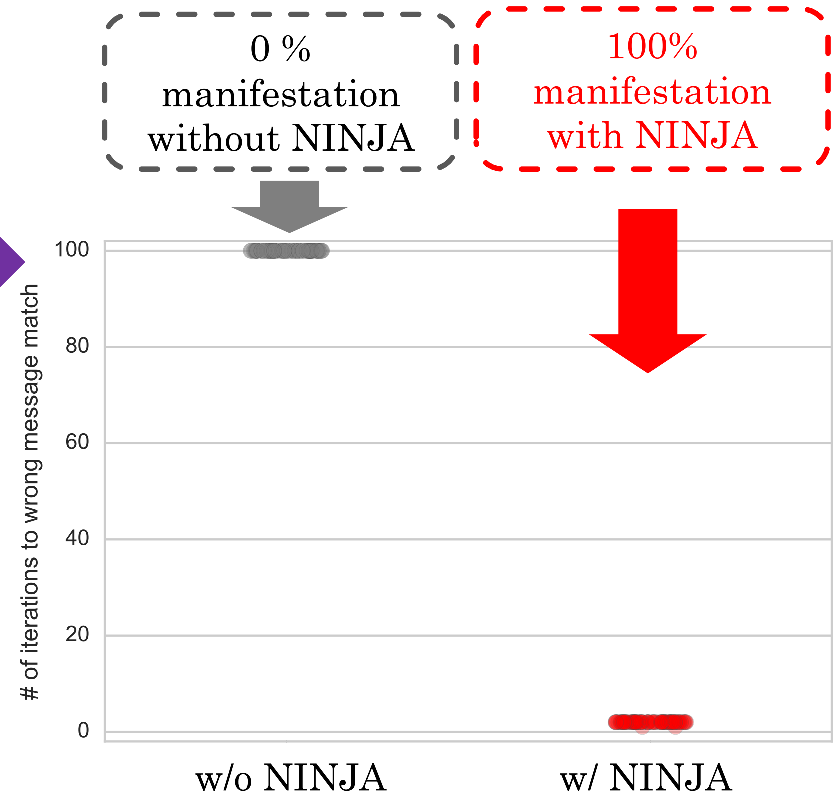
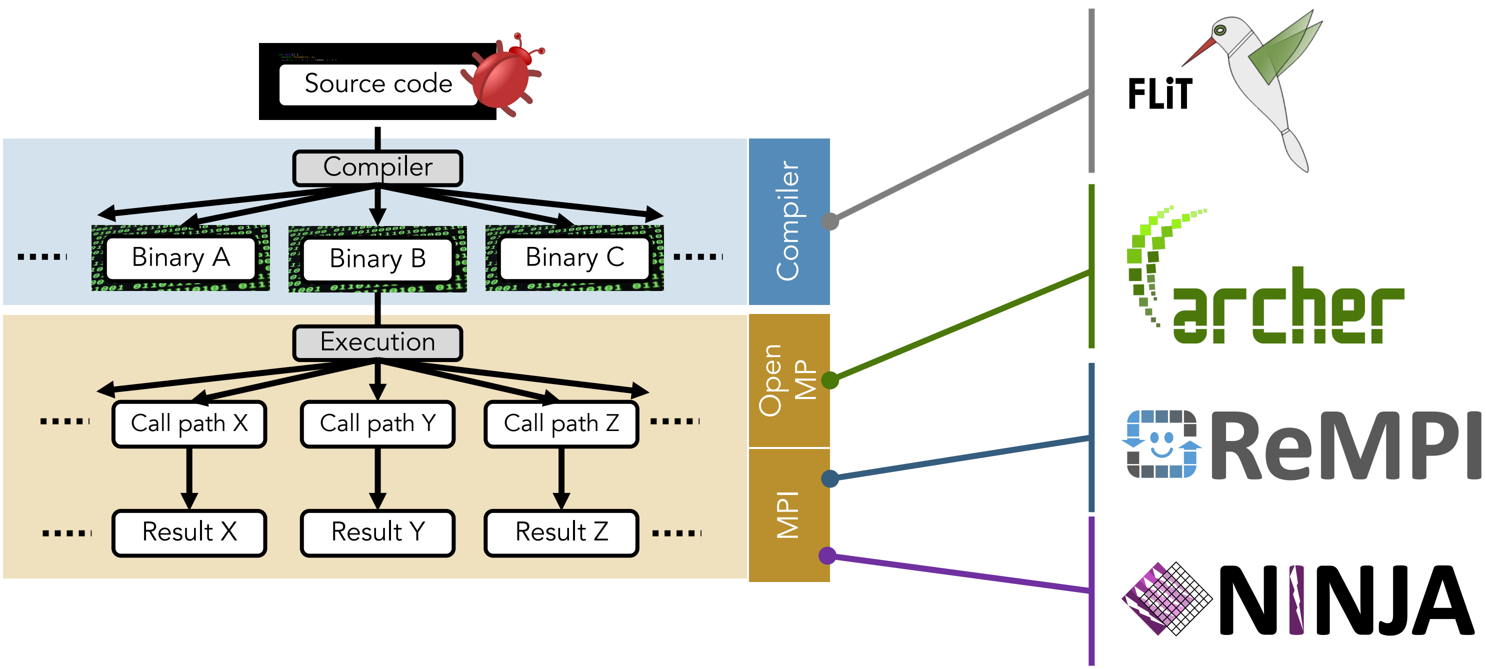
NINJA



Summary

- Debugging and testing large-scale HPC applications are becoming more challenging
- The PRUNERS toolset facilitates debugging and testing
- Exscale computing will be the culmination of non-deterministic execution for unprecedentedly high performance, and PRUNERS leads the way to solve its debugging and testing challenges.

PRUNERS



PRUNERS

https://pruners.github.io/

PRUNERS toolset

FLiT

archer

ReMPI

NINJA

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