PRUNERS

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

PMCD/JOWOG February 14th, 2018

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LLNL-PRES-741293

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

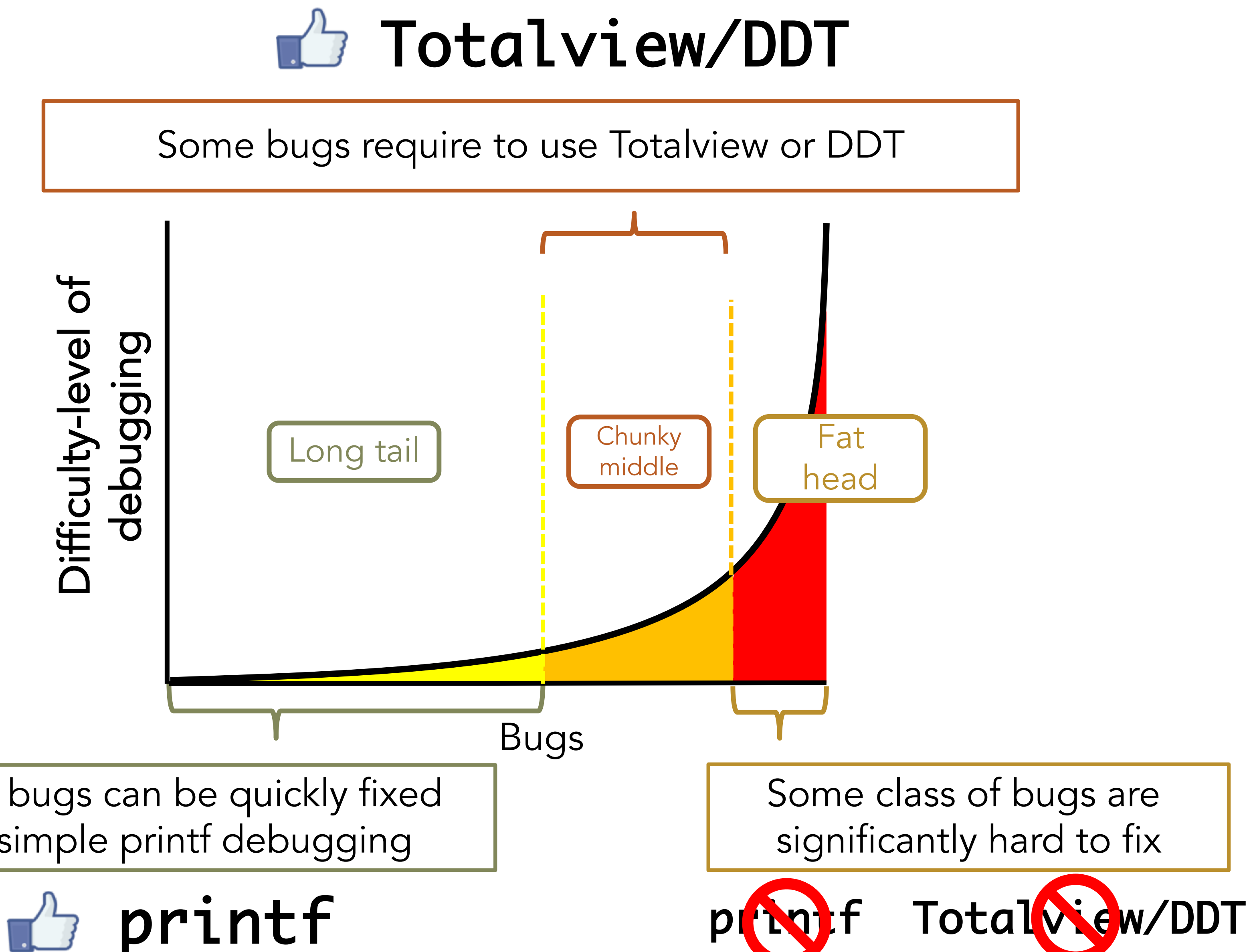
Debugging/Testing large-scale applications is challenging

"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

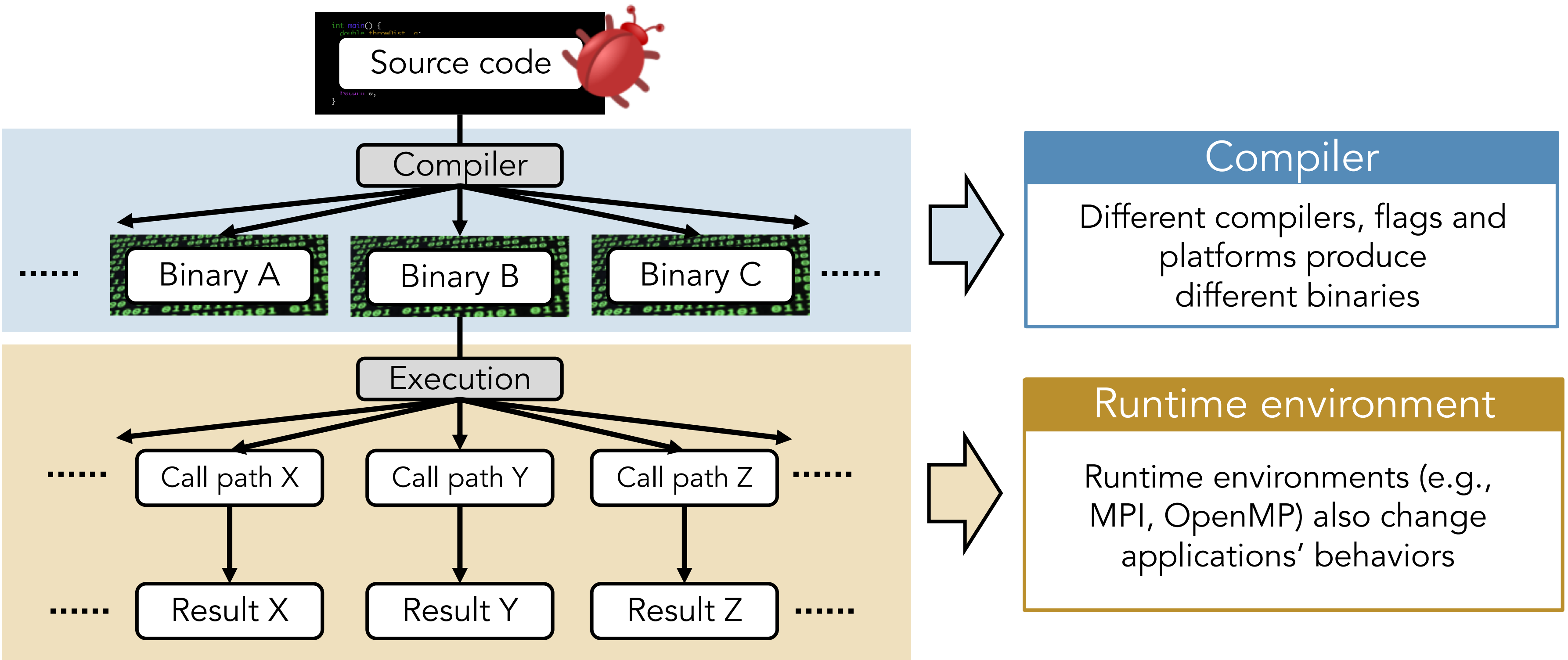
[1] Source: http://www.prweb.com/releases/2013/1/prweb10298185.htm, CAMBRIDGE, UK (PRWEB) JANUARY 08, 2013

Easy-to-fix bugs VS. Difficult-to-fix bugs



Bugs are not created equal !

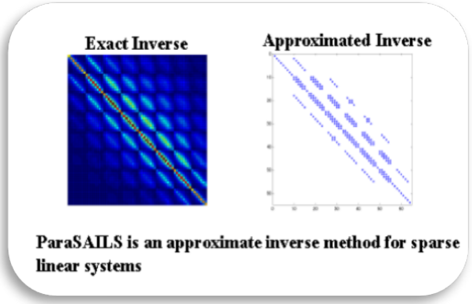
- When debugging/testing, reproducibility is very important



- Examples
  - Bugs that manifest themselves when using –O3, but do not with –O0
  - Bugs that manifests in a run and do not in the next run

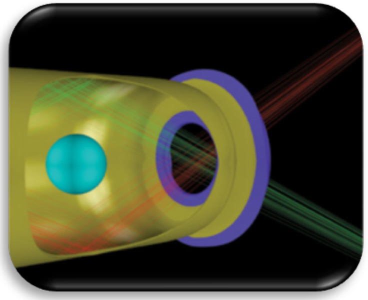
Non-deterministic bugs cost substantial amounts of time and efforts

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)

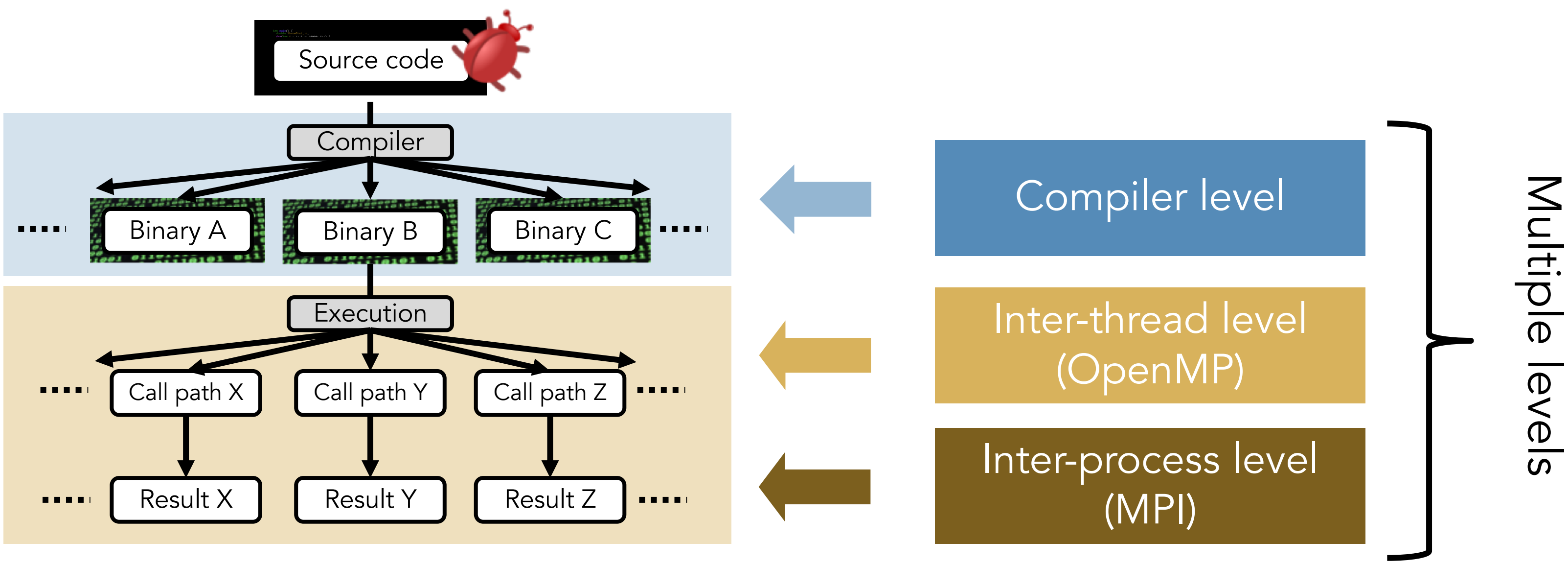


- MPI/OpenMP application non-deterministically crashed in an OpenMP region when compiling with optimization levels
- Manifested intermittently at or above 8K MPI processes
- The scientists spent months, and then ended up disabling OpenMP

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

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);
```

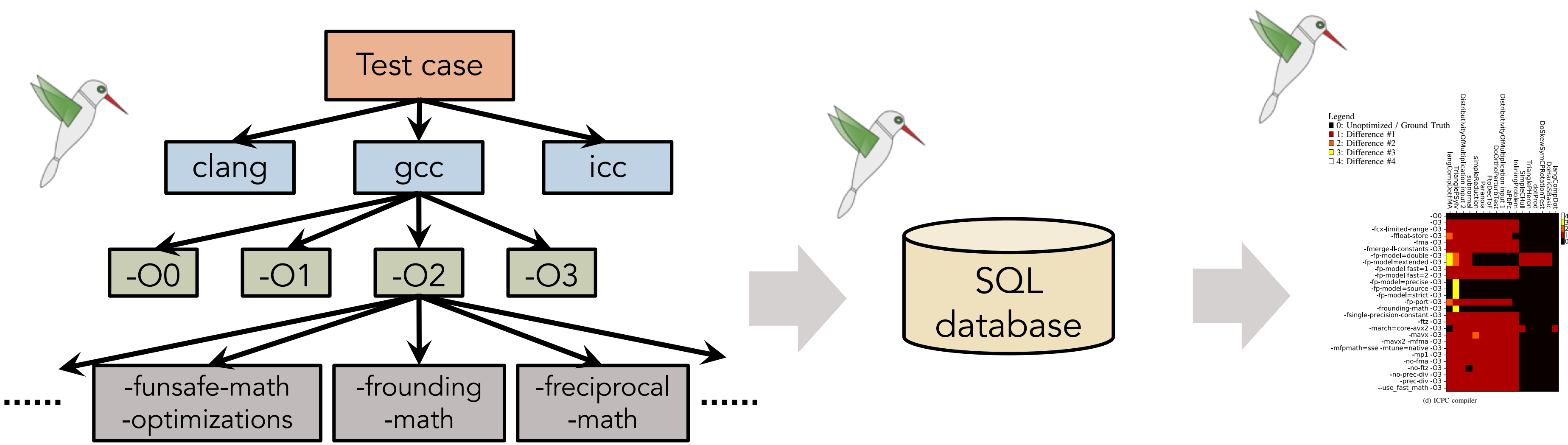
```
float val = x + y;
float err = y − y;
```

→ 0

It's important to understanding how sensitive your numerical algorithm is w.r.t. round-off errors introduced by different compilers for code verification and validation

FLiT (Floating-point Litmus Tester)

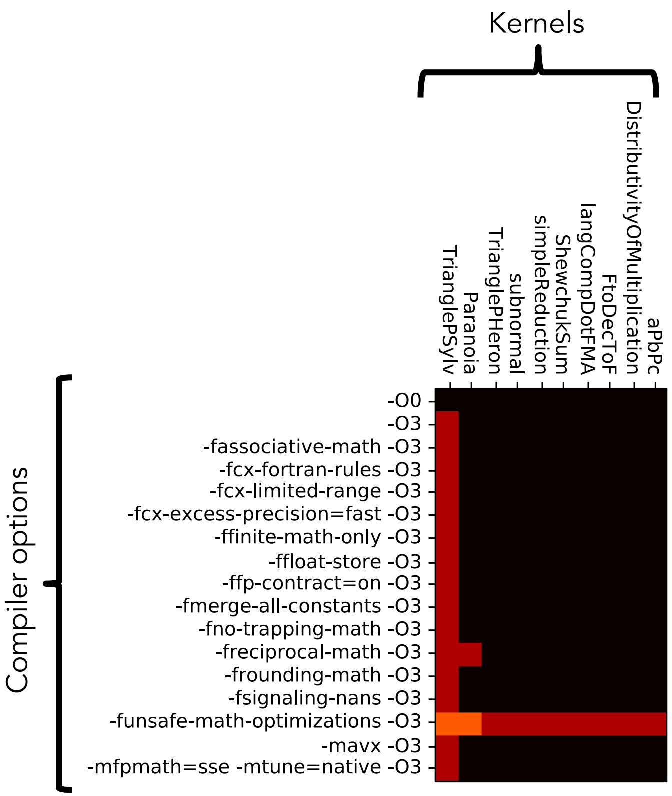
- FLiT is a reproducibility test framework
  - Test floating-point arithmetic variability in any user-given collection of programs
- FLiT tests the variability through hundreds of combinations
  - Different compilers, compiler flags, and also different hosts
- Results are stored in SQL database and used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



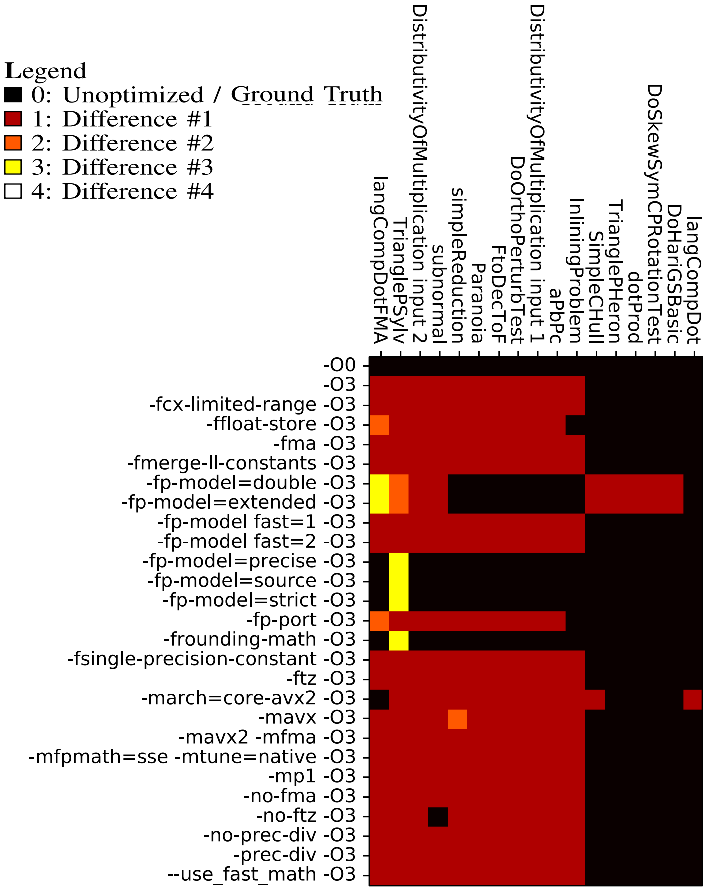
Visualization

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



GCC compiler



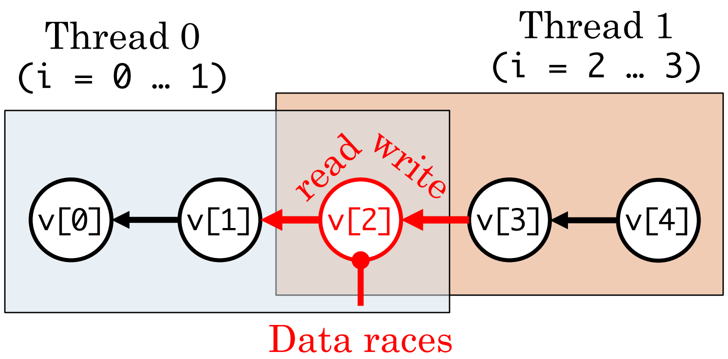
ICPC compiler

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

Data racy code

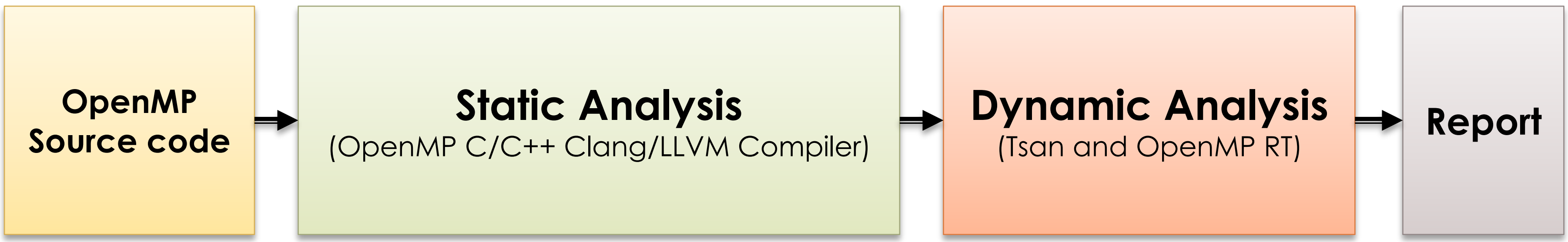
```
#pragma omp parallel for
for(int i = 0; i < 4; i++)
  v[i] = v[i+1] + 1;
```



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

Archer

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



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

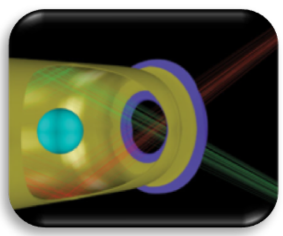
- Dynamic analysis
  – Detect data races based on LLVM/Clang ThreadSanitizer combined with OMPT-based annotation

Archer significantly reduce runtime overhead while providing high precision and accuracy

Archer case study: HYDRA

- Archer easily detected data races !

HYDRA (porting on Sequoia)



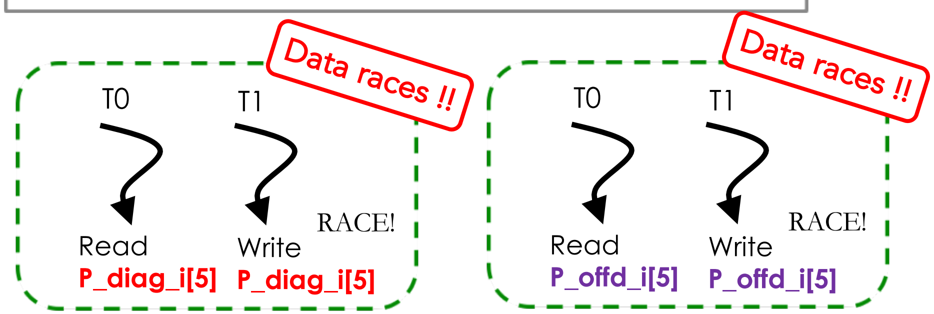
- MPI/OpenMP application non-deterministically crashed in an OpenMP region when compiling with optimization levels
- Manifested intermittently at or above 8K MPI processes
- The scientists spent months, and then ended up disabling OpenMP

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: }
```

423 lines
About 50 variables



How MPI introduces 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 ranks will send message and when

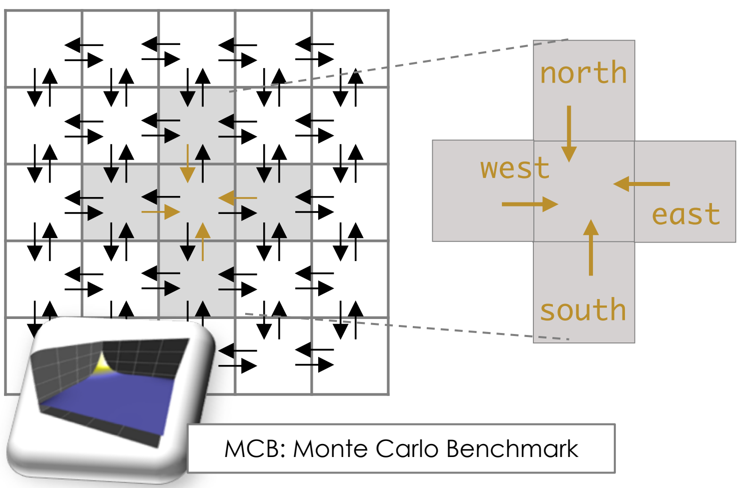
Non-deterministic code w/ MPI_ANY_SOURCE

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

CORAL benchmark: MCB (Monte carlo benchmark)

- Use of MPI_ANY_SOURCE is not only source of non-determinism
  - MPI_Waitany/Waitsome/Testany/Testsome also introduce non-determinism
- MCB produces different numerical results from run to run

Example: Communications with neighbors



Non-deterministic code w/o MPI_ANY_SOURCE

```
MPI_Irecv(…, north_rank, …, reqs[0]);
MPI_Irecv(…, south_rank, …, reqs[1]);
MPI_Irecv(…, west_rank , …, reqs[2]);
MPI_Irecv(…, east_rank , …, reqs[3]);
while(1) {
  MPI_Testsome(…, reqs, …, flag, status);
  if (flag) {
    …
    <computation>
    for (…) MPI_Irecv(…, status.MPI_SOURCE, …);
    …
  }
}
```

**In non-deterministic applications,
if a bug manifests through a particular message receive order,
it's hard to reproduce the bug, thereby, hard to debug it**

ReMPI deterministically reproduce 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

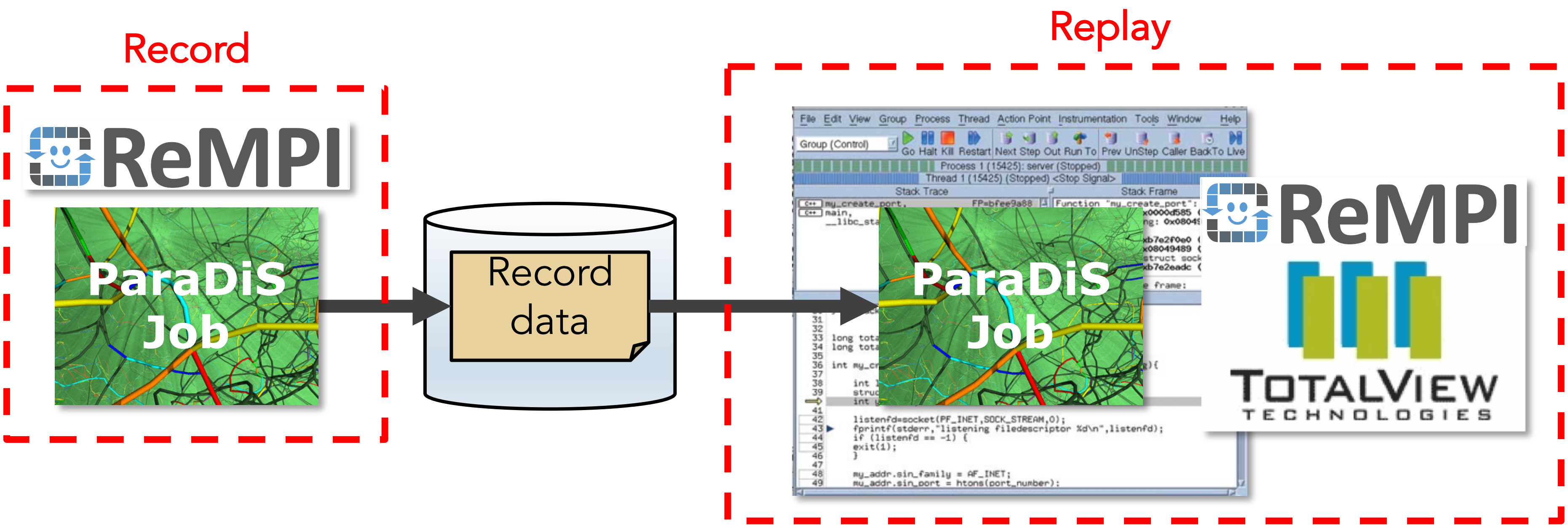
- Even if a bug manifests in a particular order of message receives, ReMPI can consistently reproduce the target bug

ReMPI

SC15: Kento Sato et al., " Clock delta compression for scalable order-replay of non-deterministic parallel applications”

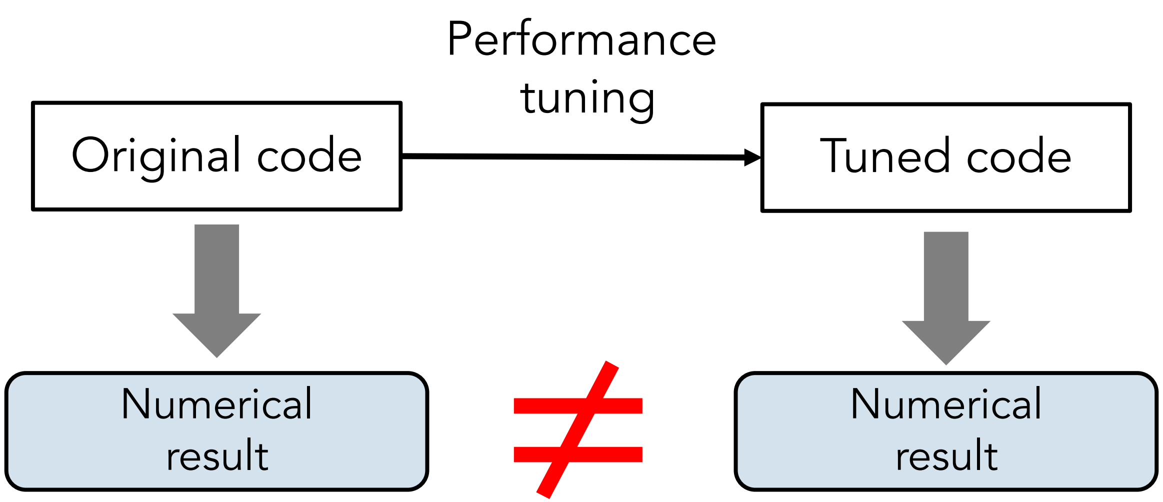
ReMPI case study: ParaDiS

- 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



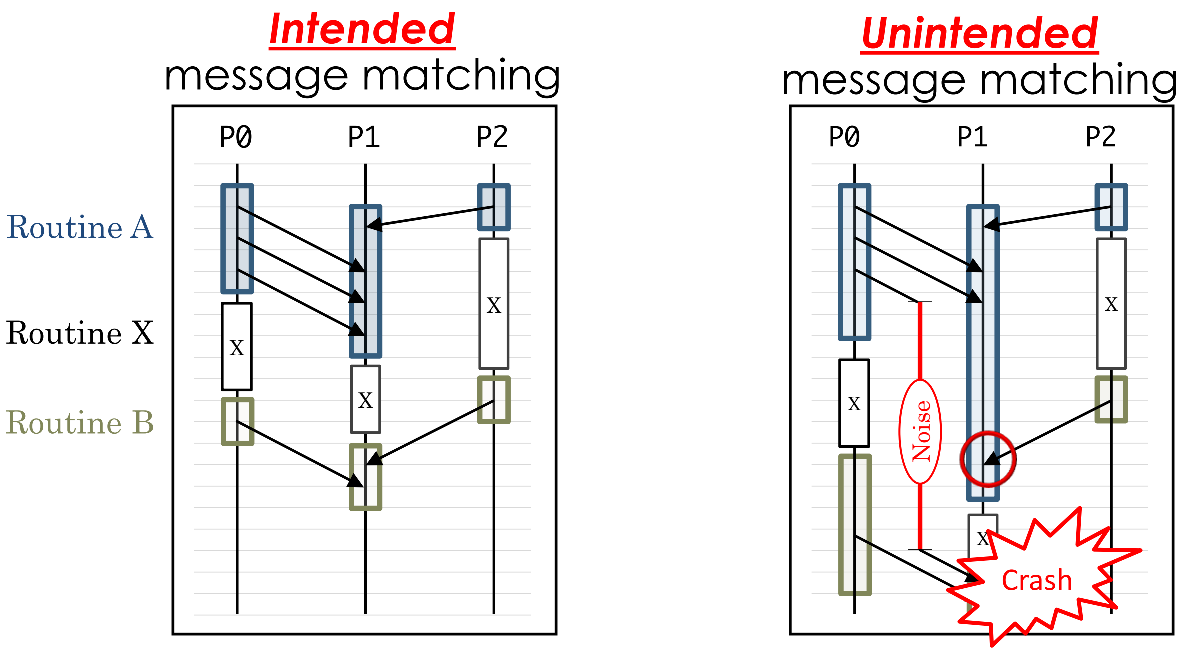
ReMPI is also useful for "Testing"

- "Testing" is also important for maintaining software quality
- However, non-deterministic MPI applications present significant challenges to testing
  - The non-determinism can produce different results from run to run by nature
  - It's difficult to reason the different numerical results are due to MPI non-determinism or software bug
- Using ReMPI, computational scientists can easily reproduce MPI behaviors, which facilitate testing



Unintended message races in MPI

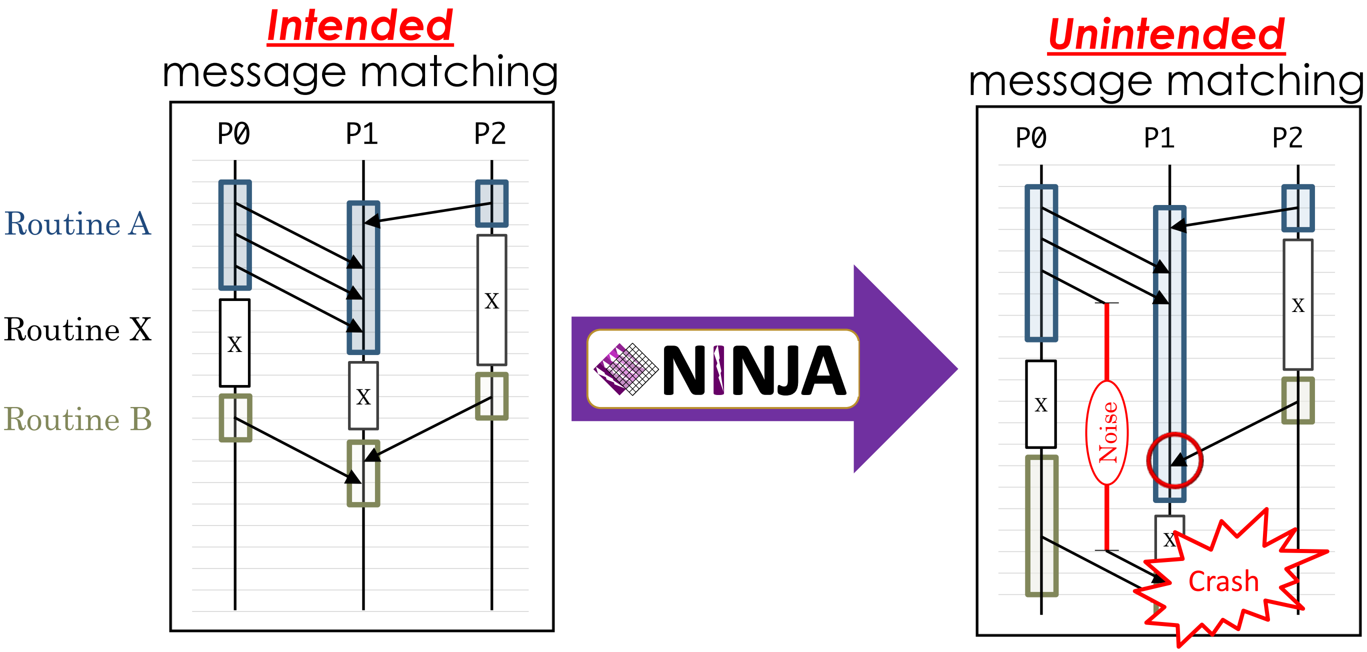
- Many applications are written as a series of communication and computation routines executed by all processes (i.e., data parallel, SPMD)
- Developers must make sure all communication routines are "isolated"
- Example (Routine A and Routine B)
  - Different MPI_TAG or synchronization (e.g. MPI_Barrier) 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

PPoPP2017: Kento Sato et al., Noise Injection Techniques for Reproducing Subtle and Unintended Message Races”

- NINJA (Noise Injection Agent Tool) exposes message race bugs by injecting noise

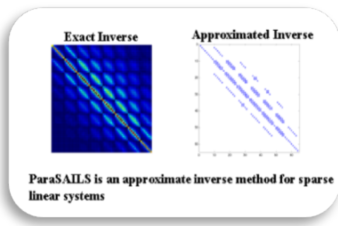


- NINJA detects suspicious communication routines
  - Communication routine using the same MPI_TAG without synchronization
- NINJA injects a delay to MPI messages in order to enforce message races
- NINJA can test if the application has unintended message races

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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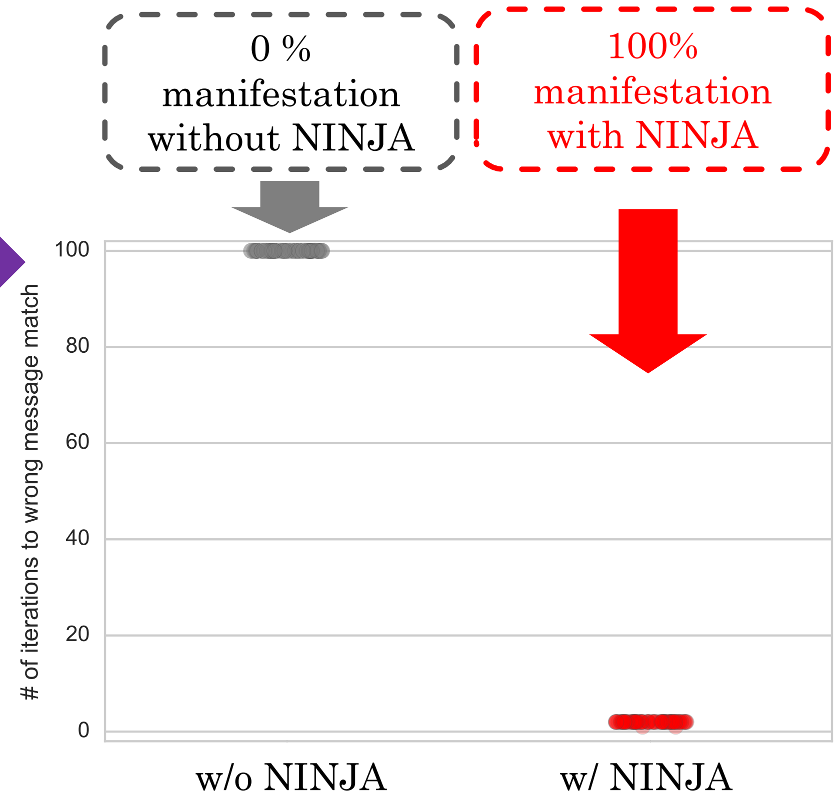
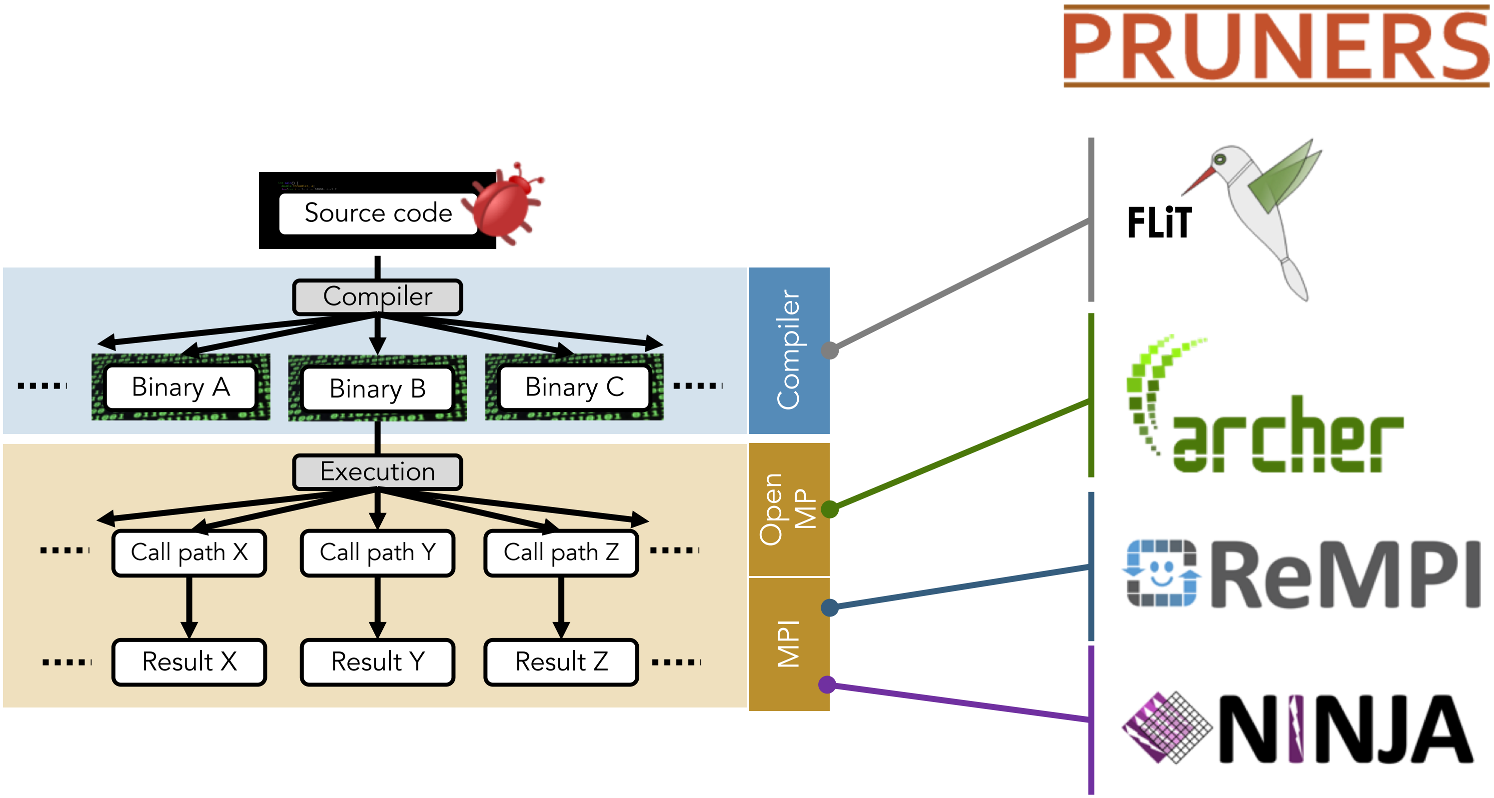
NINJA



Summary

- Debugging and testing are becoming more challenging due to non-determinism in HPC applications
- The PRUNERS toolset facilitates debugging and testing for non-deterministic applications



PRUNERS

https://pruners.github.io/

PRUNERS toolset

FLiT | archer | ReMPI | NINJA

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