Debugging/Testing Non-deterministic MPI Applications

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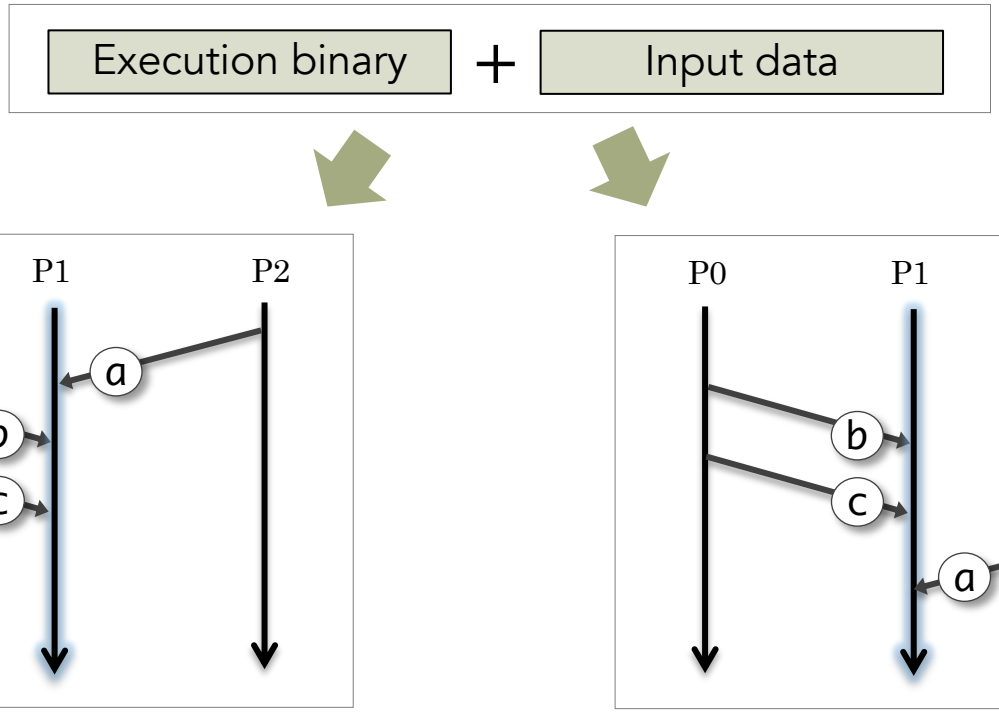
What is non-determinism in MPI applications ?

- Message receive orders change across executions
  - Unpredictable system noise (e.g. network, system daemon & OS jitter)
- Floating point arithmetic orders can also change across executions

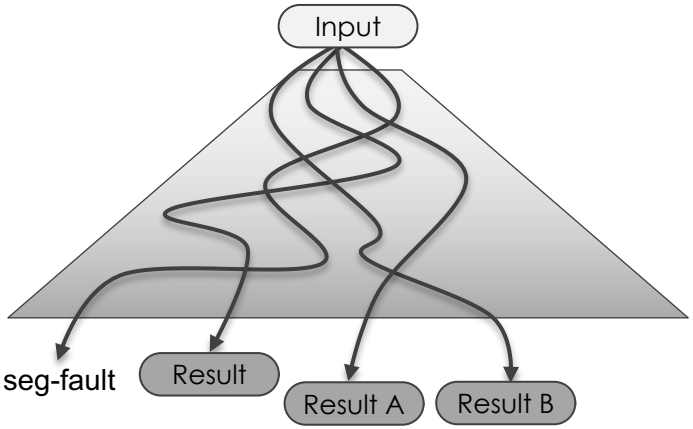


Execution A: (a+b)+c

Execution B: a+(b+c)

Non-determinism increases debugging cost

- Control flows of an application can change across different runs



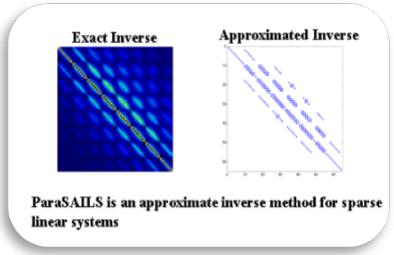
- Non-deterministic control flow
  - Successful run, seg-fault or hang
- Non-deterministic numerical results
  - Floating-point arithmetic is non-associative

$$(a+b)+c \neq a+(b+c)$$

In non-deterministic applications, it's hard to reproduce bugs and incorrect results. It costs excessive amounts of time for "reproducing" target behaviors

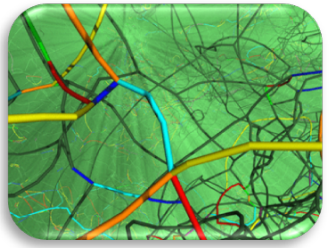
Non-deterministic bugs cost substantial amounts of time and efforts in MPI applications

Diablo/Hypre 2.10.1



- The bug manifested in particular clusters
- 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

ParaDis



- The bug intermittently manifested at 100 to 200 iteration
- The scientists gave up debugging by themselves

and more ...

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

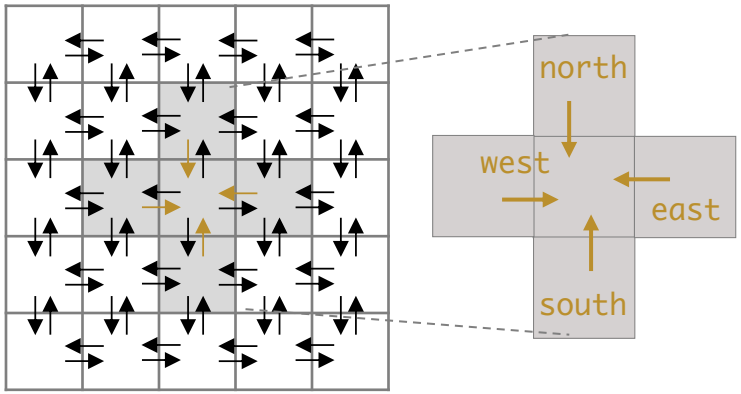
Non-deterministic code w/ MPI_ANY_SOURCE

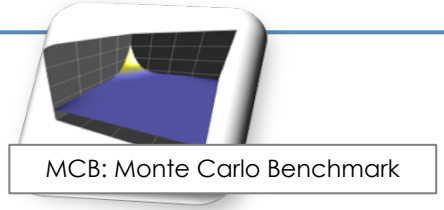
```
MPI_Irecv(…, MPI_ANY_SOURCE, …);
while(1) {
  MPI_Test(flag);
  if (flag) {
    <computation>
    MPI_Irecv(…, MPI_ANY_SOURCE, …);
  }
}
```

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

Example: Communications with neighbors





MCB: Monte Carlo Benchmark

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, …);
    …
  }
}
```

ReMPI deterministically reproduce order of message receives

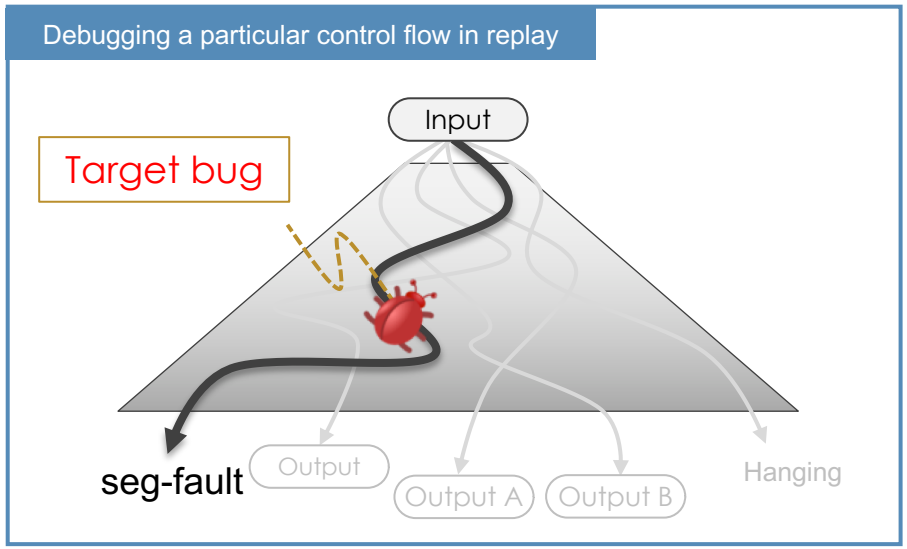
- ReMPI is an MPI record-and-replay tool
  - Record an order of MPI message receives
  - Replay the exactly same order of MPI message receives
- Even if a bug manifests in a particular order of message receives, ReMPI can consistently reproduce the target bug
- ReMPI works with other existing debugging tools
  - STAT
  - Parallel debuggers (e.g., Totalview, DDT)

ReMPI

TOTALVIEW TECHNOLOGIES

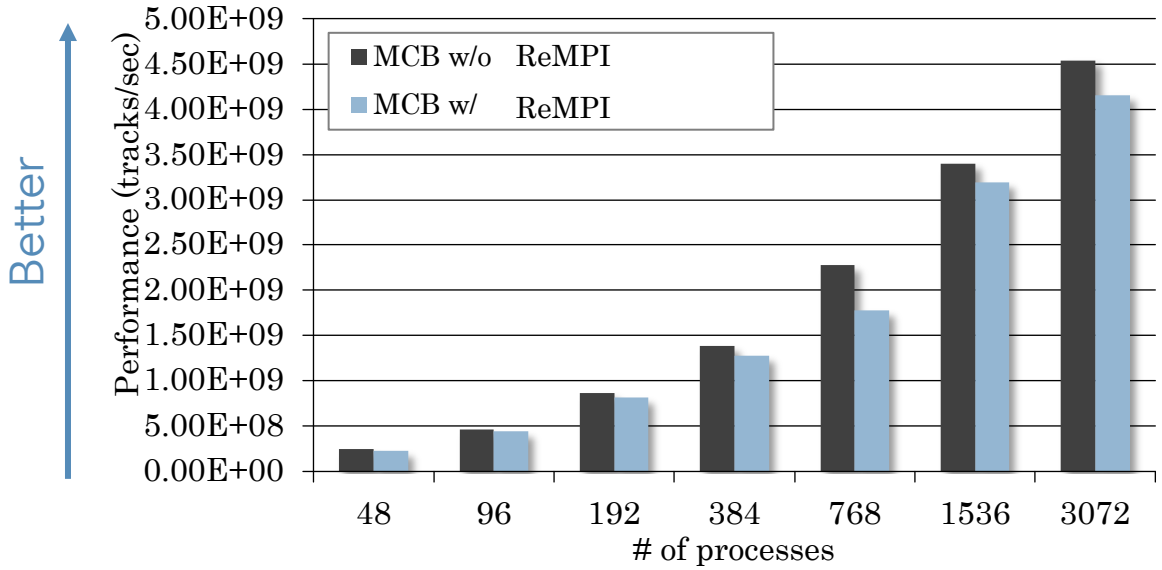
Stack Trace Analysis Tool

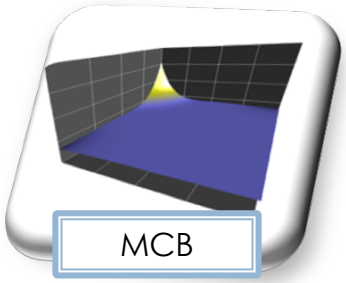
SC15: Kento Sato et al., " Clock delta compression for scalable order-replay of non-deterministic parallel applications"



MCB with/without ReMPI

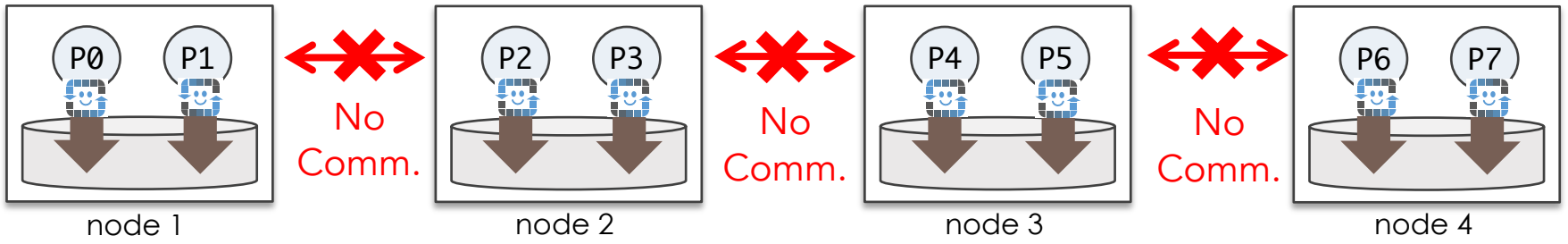
- Performance metric: How many particles are tracked per second





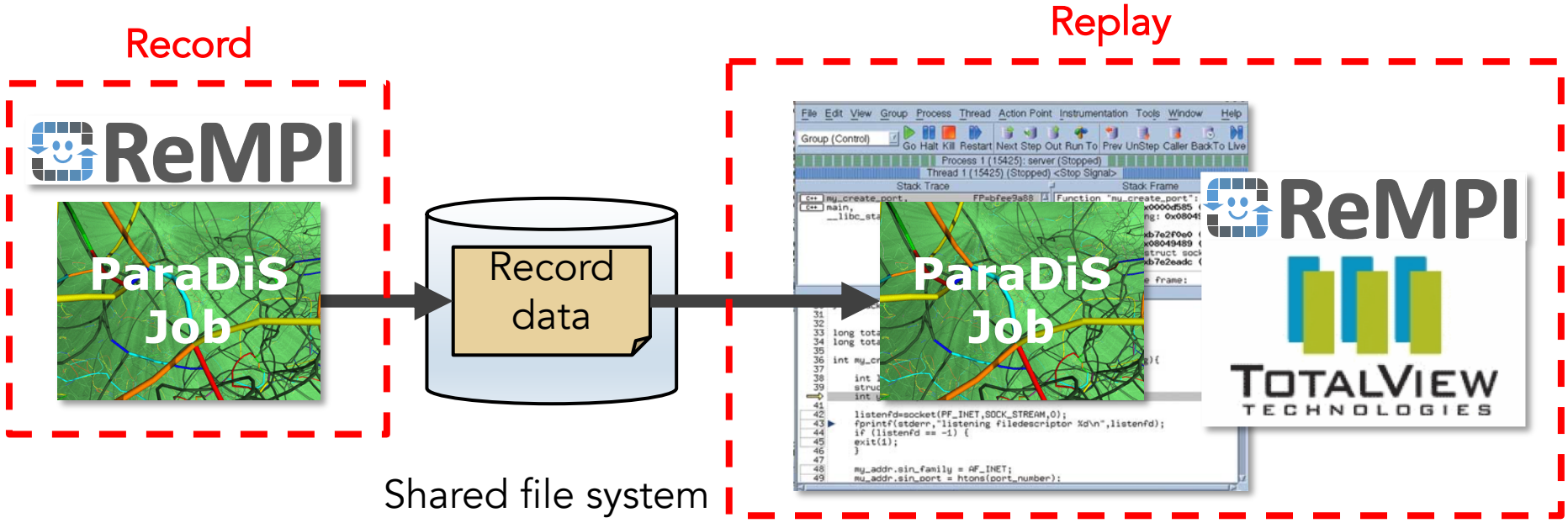
Recording location: Local SSDe

- ReMPI becomes scalable by recording to local memory/storage
  - Each rank independently writes record → No communication across MPI ranks



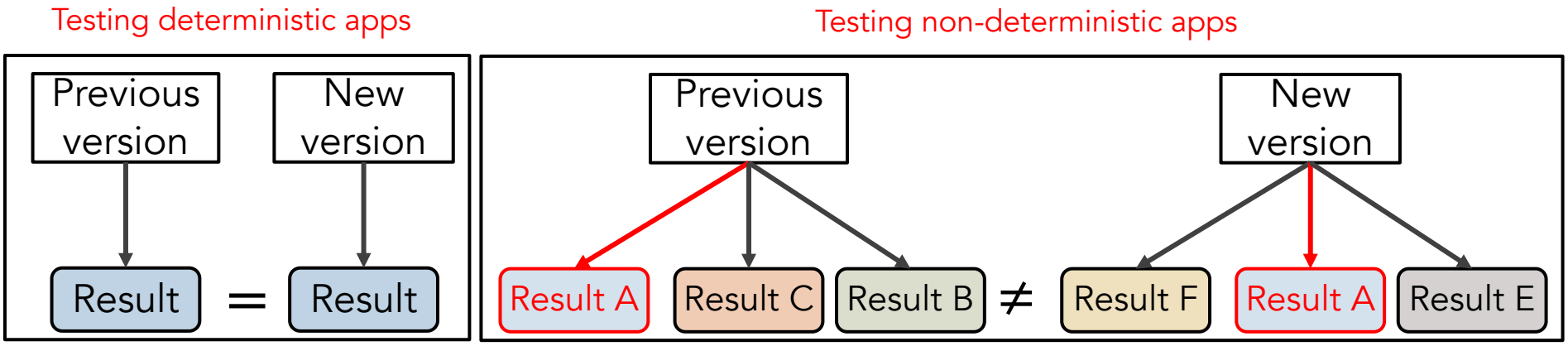
ReMPI case study: ParaDiS

- 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



MPI is not only source of non-determinism

- Applications have been going towards hybrid programming model
  - E.g.) MPI + OpenMP
- OpenMP code adds another level of non-determinism
  - Reduction, critical section or data racy access
  - OpenMP non-determinism affects MPI function call behaviors
  - Need to record both MPI and OpenMP events

CORAL benchmarks

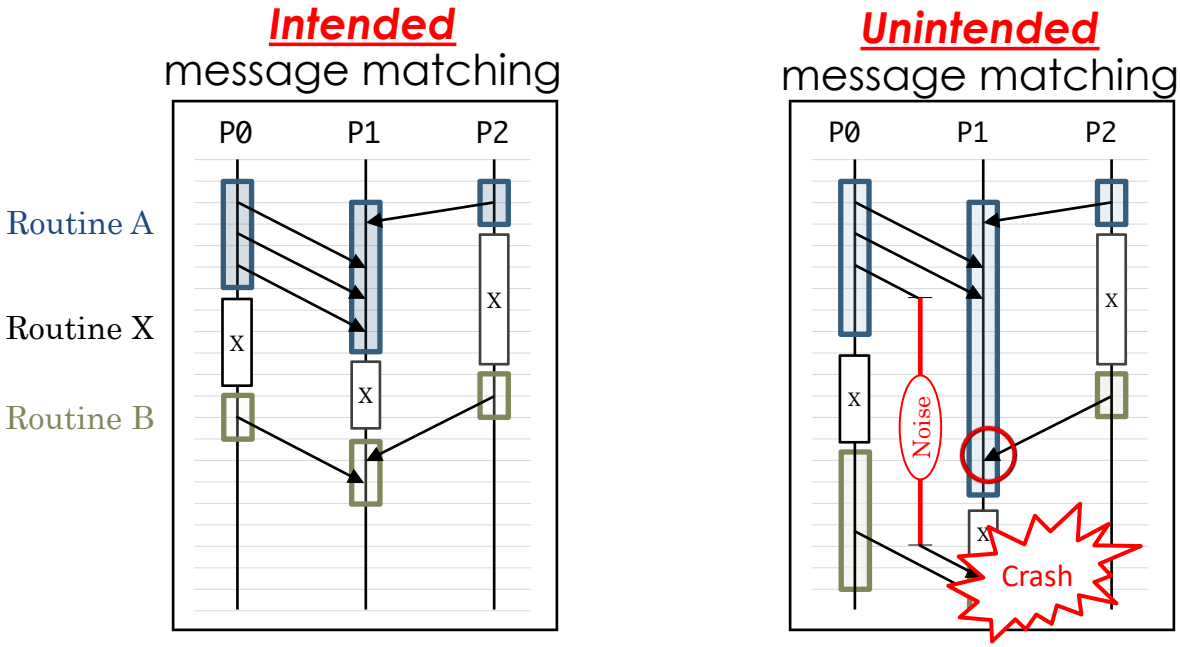
Scalable Science Benchmarks	Priority Level	Lines of Code	Parallelism	
			MPI	OpenMP/ Pthreads
LSMS	TR-1	200,000	X	X
QBOX	TR-1	47,000	X	X
HACC	TR-1	35,000	X	X
Nekbone	TR-1	48,000	X	
Throughput Benchmarks	**Priority Level**	**Lines of Code**	**Parallelism**	
			MPI	OpenMP/ Pthreads
CAM-SE	TR-1	150,000	X	X
UMT2013	TR-1	51,000	X	X
AMG2013	TR-1	75,000	X	X
MCB	TR-1	13,000	X	X
QMCPACK	TR-2	200.000	X	X
NAMD	TR-2	180,000	X	X
LULESH	TR-2	5,000	X	X
SNAP	TR-2	3,000	X	X
miniFE	TR-2	50,000	X	X

MPI+OpenMP

Providing record-and-replay
for MPI+OpenMP application is our future work

Unintended message races in MPI

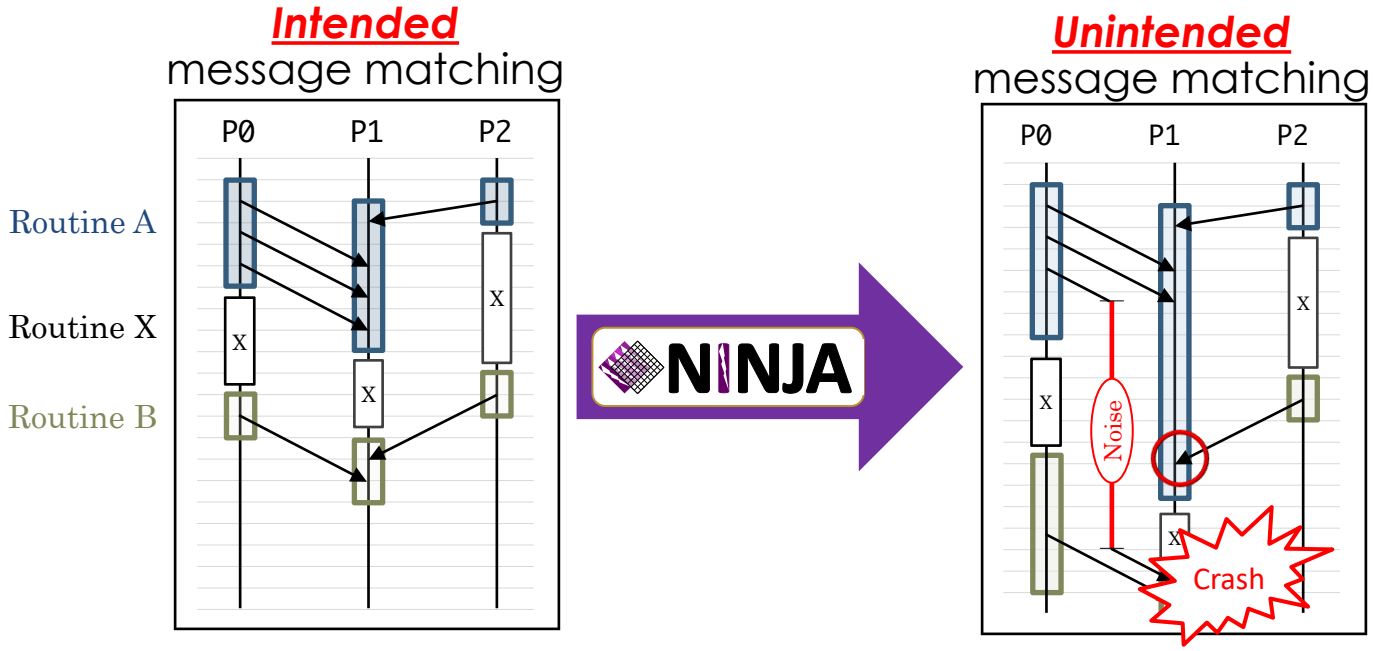
- Many applications are written as a series of communication and computation routines executed by all processes (i.e., data parallel, SPMD)
- Developers must make sure all communication routines are “isolated”
- Example (Routine A and Routine B)
  - Different MPI_TAG or synchronization (e.g. MPI_Barrier)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

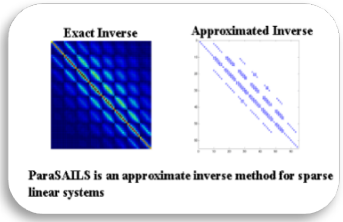


- NINJA detects suspicious communication routines
  - Communication routine using the same MPI_TAG without synchronization
- NINJA injects a delay to MPI messages in order to enforce message races
- NINJA can test if the application has unintended message races

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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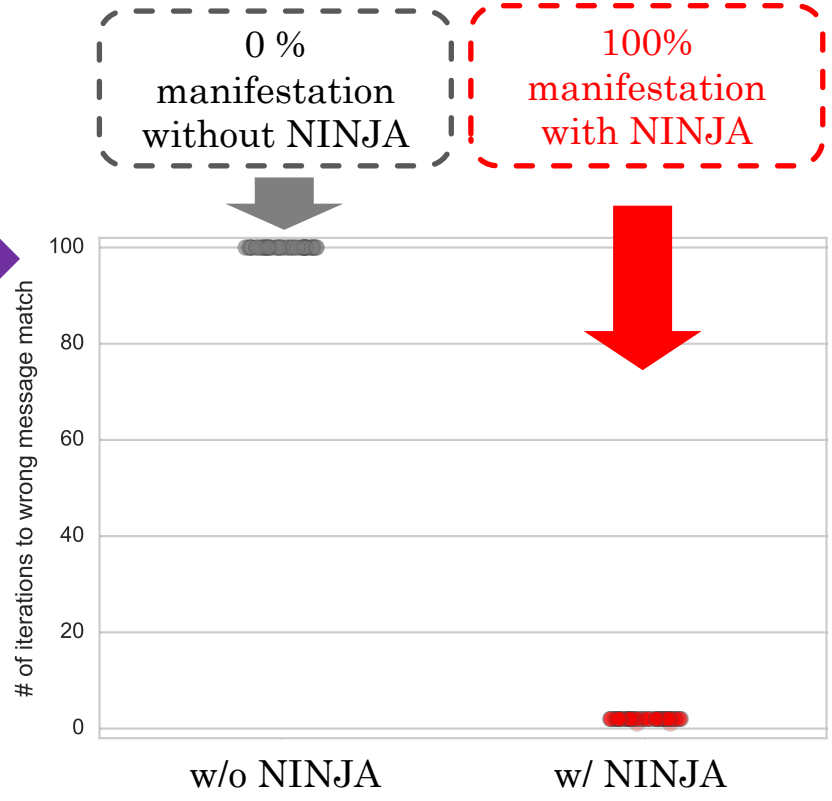
NINJA



Summary

- Non-determinism in MPI applications costs significant time for debugging and testing
- ReMPI and NINJA facilitate debugging/testing non-deterministic MPI applications
  - ReMPI is MPI record-and-replay for reproducing paticular errors
  - NINJA is an noise injection tool for exposing message-race bugs
- We will extend our tools for supporting MPI+OpenMP applications in future

ReMPI

PRUNERS ReMPI  OR https://github.com/PRUNERS/ReMPI

NINJA

PRUNERS NINJA  OR https://github.com/PRUNERS/NINJA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