DiffTrace: Efficient Whole-Program Trace Analysis and Diffing for Debugging

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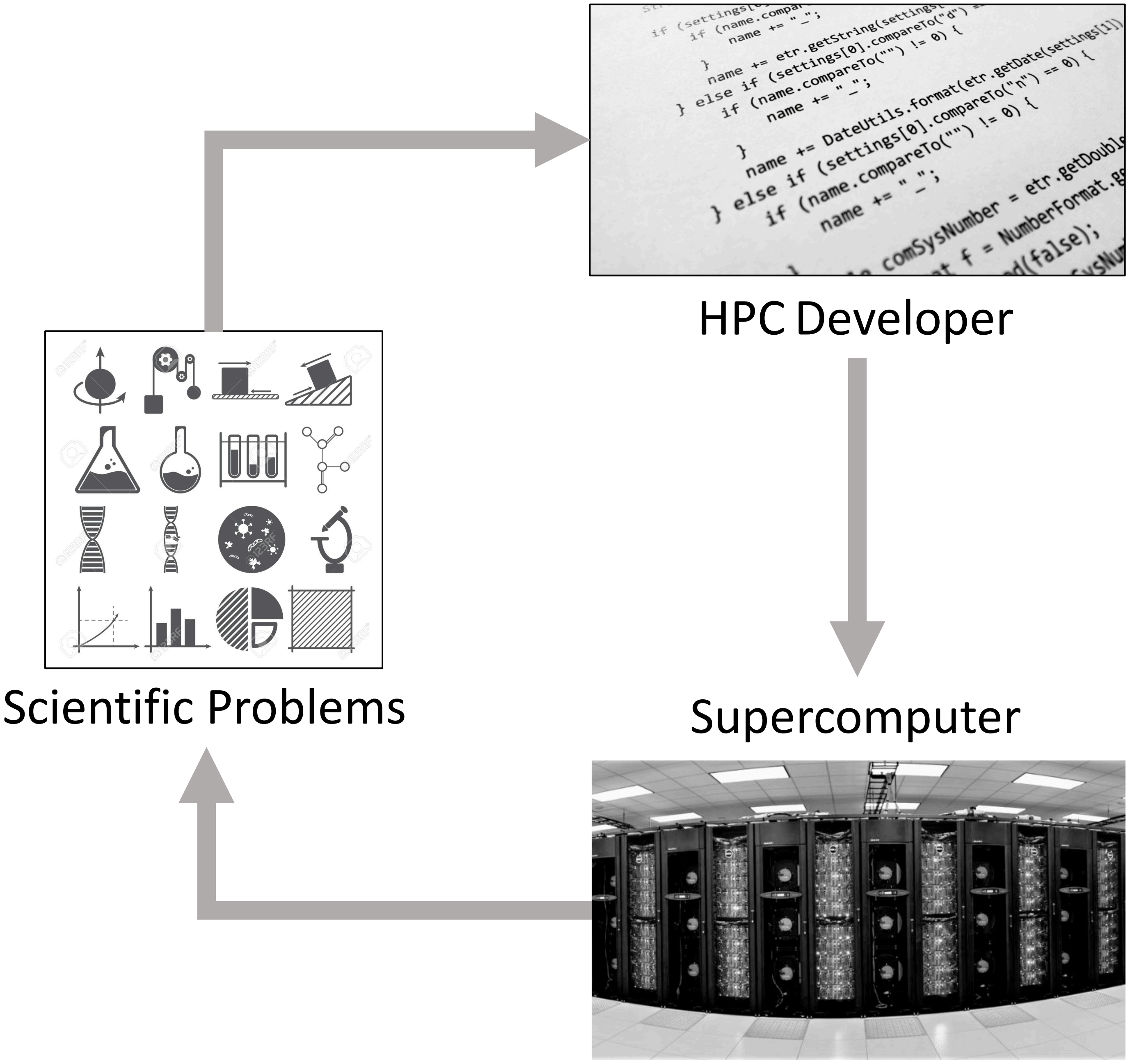
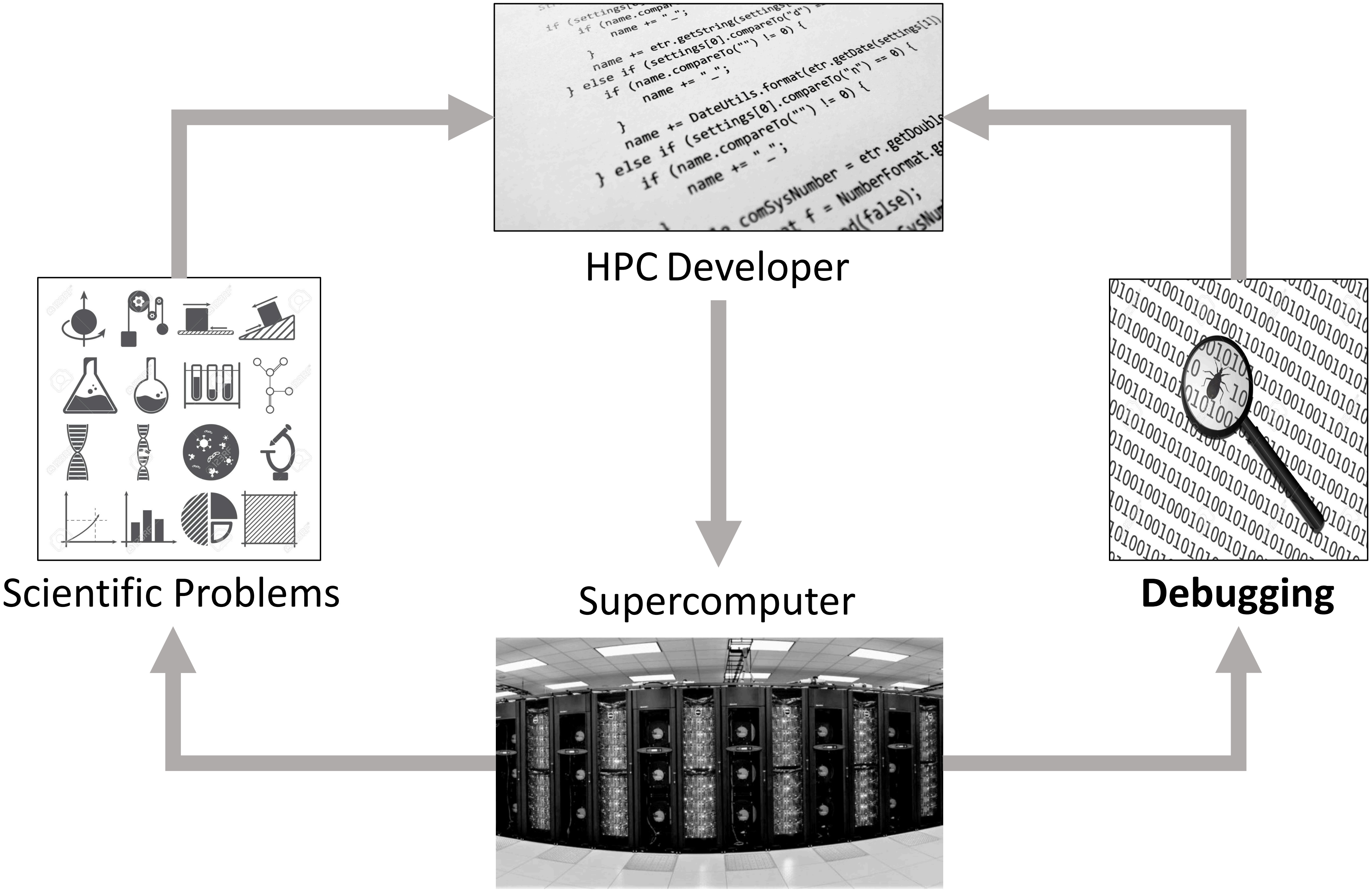

HPC Developer
Supercomputer
Scientific Problems


HPC Developer
Scientific Problems
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Debugging

HPC Debugging is Challenging…

- Hierarchy of parallelism
- Heterogeneity of compilers & libraries
- Complex and large code bases
- Debugging iterations are **expensive**
  - Resources (time, CPU cycles, energy, etc.)
  - Reproducibility limitations

Debugging Approaches

Existing Approaches
Iteratively • Guess the potential bug • Pick the right debugger • Instrumentation / Re-compile • Re-execute • Gather limited data for specific bug • Analyze data

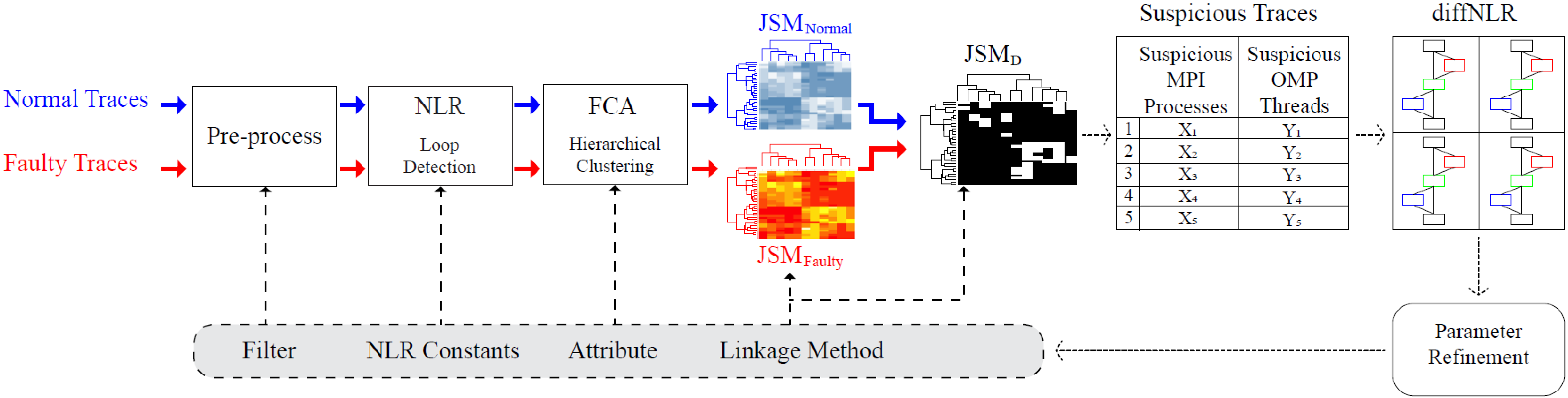
Debugging Approaches

Existing Approaches	**DiffTrace Approach**
Iteratively • Guess the potential bug • Pick the right debugger • Instrumentation / Re-compile • Re-execute • Gather limited data for specific bug • Analyze data	Collect one standard set of data Iteratively (offline): • Intelligently summarize data • **Compare** w/ expected behavior • Detect outliers • Visualize points of **differences**

Parallel/HPC Debuggers

- Relative Debugging [DeRose’15]
- Delta Debugging [Choi’02]
- Structural Clustering [Weber’16]
- STAT [Arnold’07]
- AutomaDeD [Laguna’11]

DiffTrace Overview



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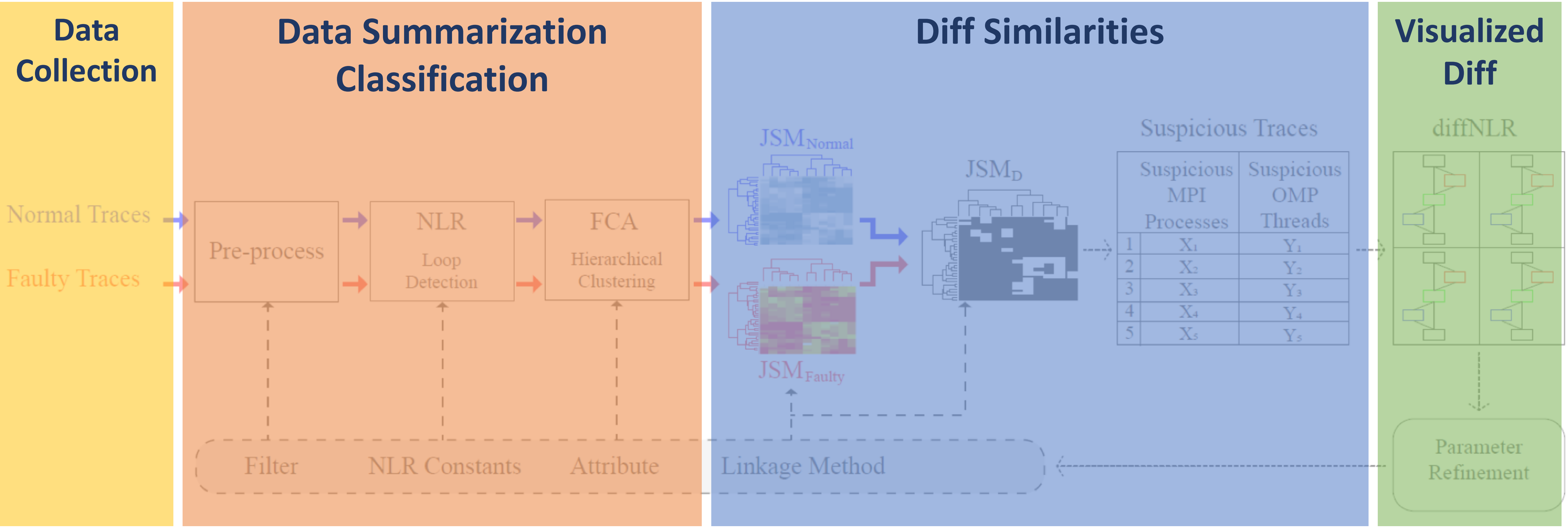

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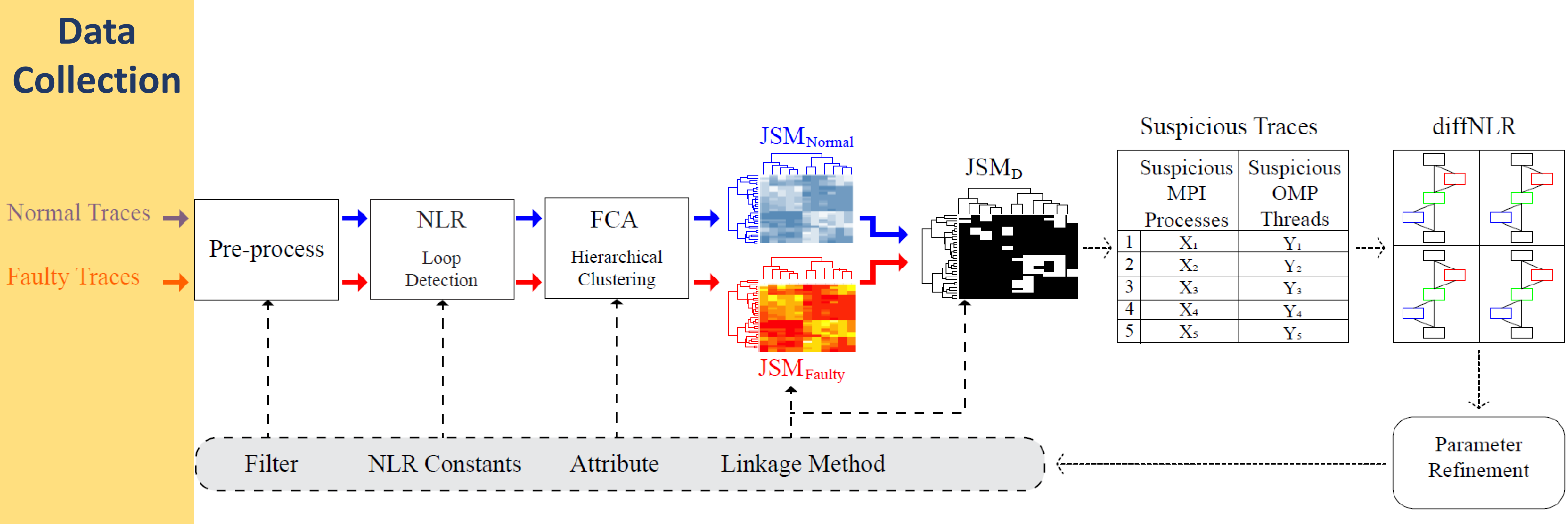
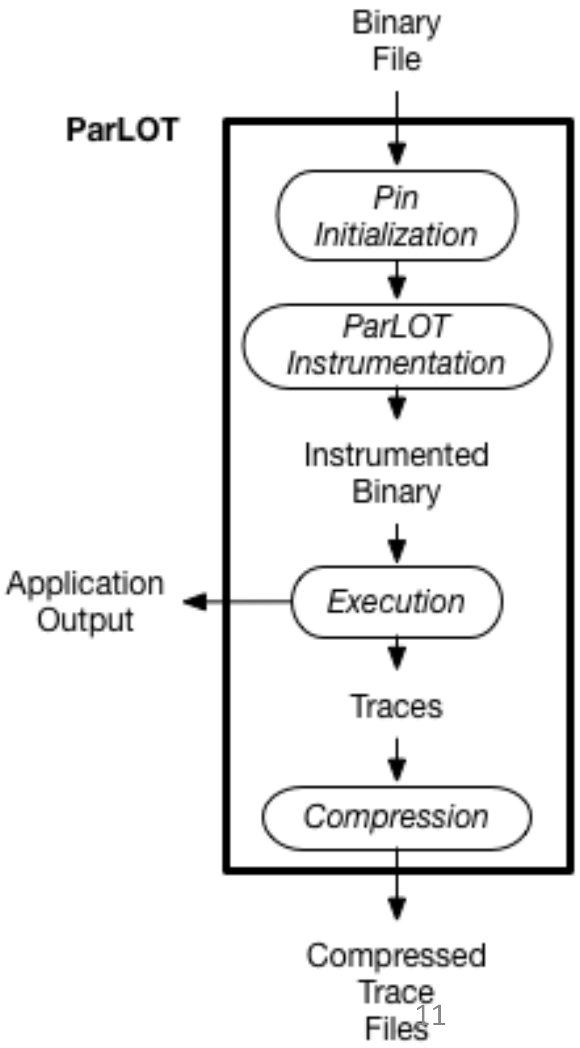


ParLOT [ESPT'18]

- Instruments binary using Intel **PIN** API
- Captures **function calls/returns** (main/all image)
- **Compress** traces incrementally on-the-fly
  - Avg. compression ratio: **1117.1**
  - Avg. required bandwidth: **7.8 KB/S**
  - Avg. overhead on exec. time: **1.94**
- Enables offline analysis of the whole program



A Walk-through Example

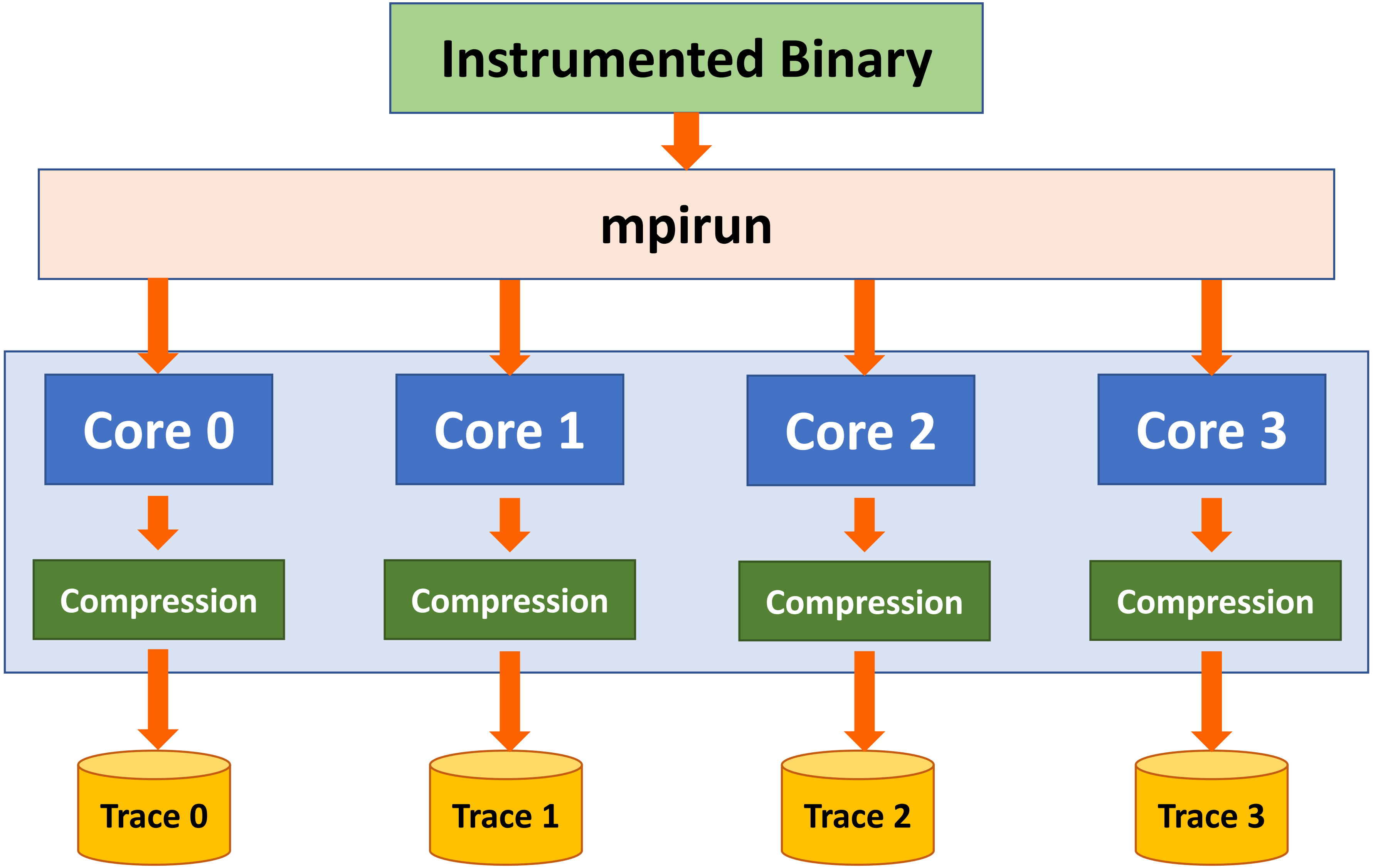
Main Function

```
int main(){
 int rank,cp;
 MPI_Init()
 MPI_Comm_rank(..., &rank);
 MPI_Comm_size(..., &cp);
 // initialize data to sort
 int *data[data_size];
 ...
 oddEvenSort(rank, cp);
 ...
 MPI_Finalize();
}
```

oddEvenSort()

```
oddEvenSort(rank, cp){
 ...
 for (int i=0; i < cp; i++)
 {
  int ptr = findPtr(i, rank);
  ...
  if (rank % 2 == 0) {
   MPI_Send(..., ptr, ...);
   MPI_Recv(..., ptr, ...);
  } else {
   MPI_Recv(..., ptr, ...);
   MPI_Send(..., ptr, ...);
  }
  ...
 }
}
```

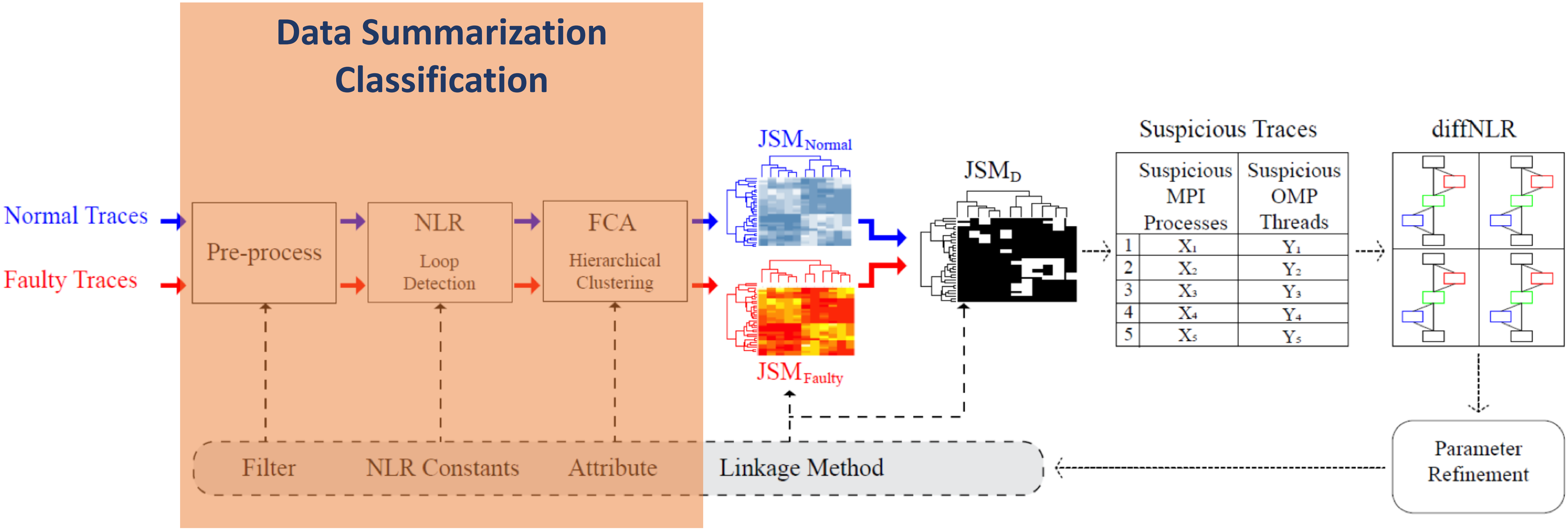
Tracing (mpirun -np 4 pin -t parlot.so -- ./oddeven)



Tracing (mpirun -np 4 pin -t parlot.so -- ./oddeven)

T_0	T_1	T_2	T_3
…	…	…	…
main	main	main	main
MPI_Init	MPI_Init	MPI_Init	MPI_Init
MPI_Comm_rank	MPI_Comm_rank	MPI_Comm_rank	MPI_Comm_rank
MPI_Comm_size	MPI_Comm_size	MPI_Comm_size	MPI_Comm_size
…	…	…	…
oddEvenSort	oddEvenSort	oddEvenSort	oddEvenSort
…	…	…	…
findPtr	findPtr	findPtr	findPtr
MPI_Send	MPI_Recv	MPI_Send	MPI_Recv
MPI_Recv	MPI_Send	MPI_Recv	MPI_Send
…	…	…	…
MPI_Finalize	MPI_Finalize	MPI_Finalize	MPI_Finalize

DiffTrace Overview



Data Pre-processing

Filter Class	Sub-class	Example
Primary	**Returns**	Filter out Returns
	PLT	Procedure Linkage Table
MPI	**MPI ALL**	Functions start with "MPI_"
	MPI Collectives	MPI_Barrier
	MPI Send/Recv	MPI_Send, MPI_Isend
	MPI Library	Inner MPI library
OMP	**OMP ALL**	Functions start with “GOMP_”
	OMP Critical	OMP_Critical_Start
	OMP Mutex	OMP_Mutex
Secondary	Memory	Memcpy
	Network	TCP
	Poll	Poll, yield
	String	strlen
Advanced	Custom	Any source-code function

Loop Summarization

- Programs are (nested) **loops!**
- Loops reflect as sequences of **repetitive** patterns
- Why detecting/summarizing loops?
  - Easy-to-read representation of long traces
  - Reveal unfinished or broken loops due to a fault

Nested Loop Recognition (NLR)

Adapted from NLR algorithm [Ketterlin'14]

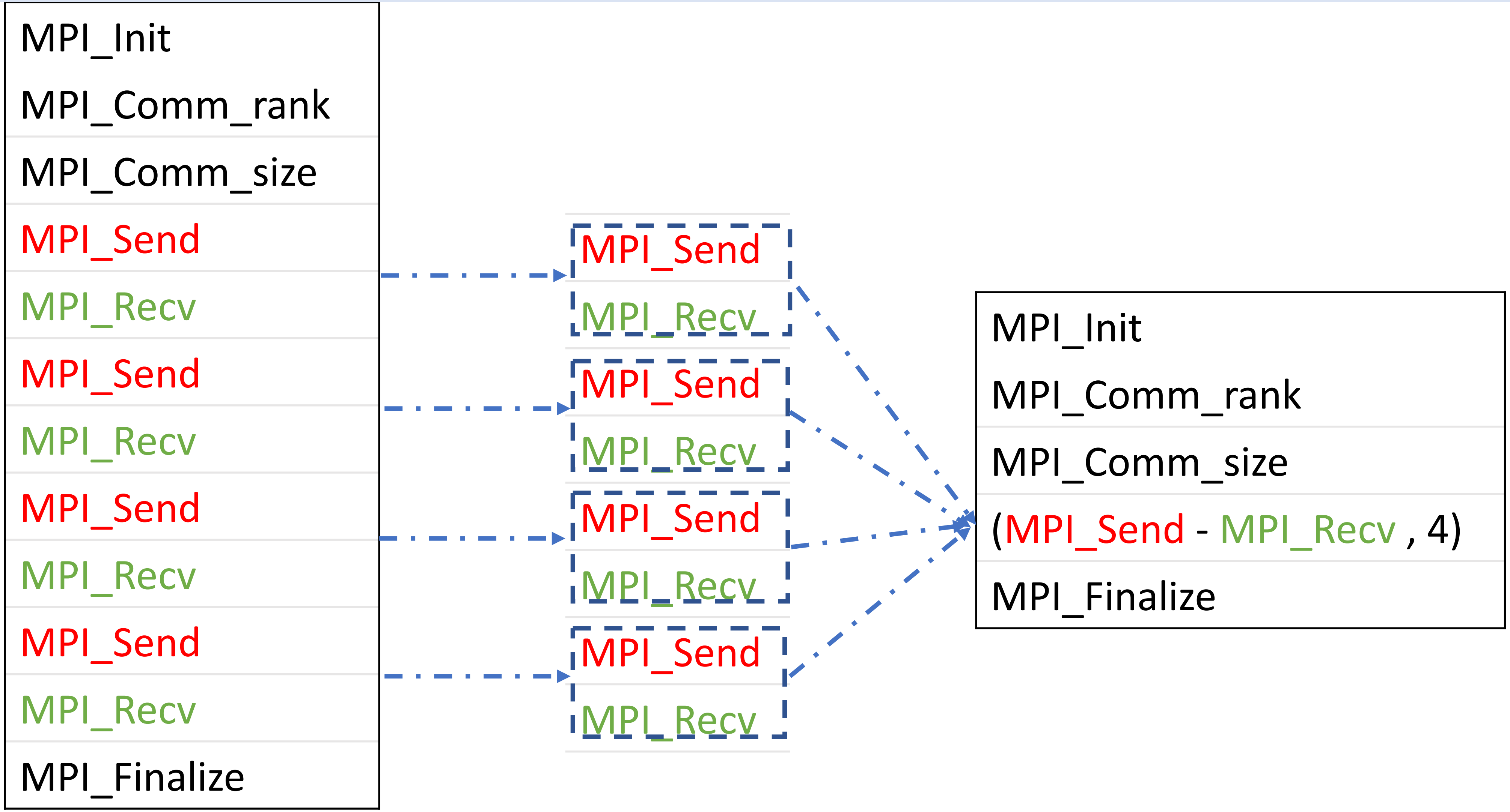
Convert each trace to its equivalent NLR (Nested Loop Representation)

Push **elements** of the trace to a **stack** one by one

On each push:

- Recursively examine the upper elements of the stack to
  - **Form** the loop structure from elements or
  - **Extend** the existing loop structure

Trace to NLR


MPI_Init
MPI_Comm_rank
MPI_Comm_size
MPI_Send
MPI_Recv
MPI_Send
MPI_Recv
MPI_Send
MPI_Recv
MPI_Send
MPI_Recv
MPI_Finalize
MPI_Send
MPI_Recv
MPI_Send
MPI_Recv
MPI_Send
MPI_Recv
MPI_Send
MPI_Recv
MPI_Init
MPI_Comm_rank
MPI_Comm_size
(MPI_Send - MPI_Recv , 4)
MPI_Finalize

Trace to NLR

Loop Table	
L0	MPI_Send - MPI_Recv
L1	MPI_Recv - MPI_Send

T_0	T_1	T_2	T_3
MPI_Init	MPI_Init	MPI_Init	MPI_Init
MPI_Comm_rank	MPI_Comm_rank	MPI_Comm_rank	MPI_Comm_rank
MPI_Comm_size	MPI_Comm_size	MPI_Comm_size	MPI_Comm_size
L0 ^ 2	**L1 ^ 4**	**L0 ^ 4**	**L1 ^ 2**
MPI_Finalize	MPI_Finalize	MPI_Finalize	MPI_Finalize

Hierarchical Clustering via FCA

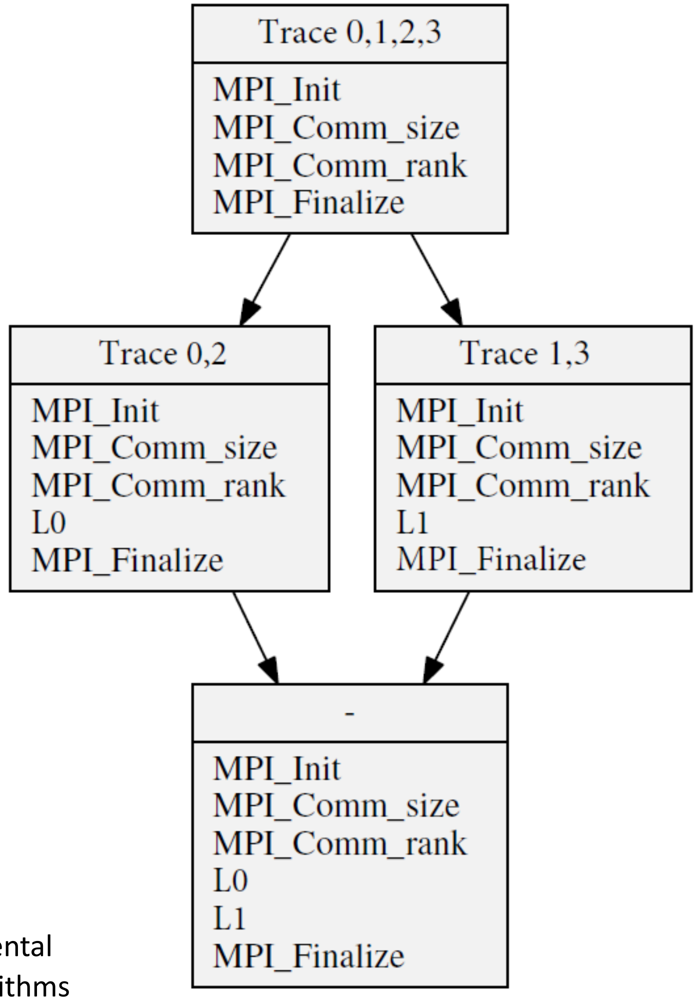
- Few **equivalence classes** of threads/processes in HPC applications
  - Master/worker, Odd/Even, Producer/Consumer
- Clustering based on this property
  - Distinguish between structurally different threads
  - Reduce the search space for bug location
  - Detect mis-behaved traces (i.e., outliers)
- STAT: Prefix trees; AutomaDeD: Markov model
- DiffTrace Approach: **Formal Concept Analysis (FCA)**

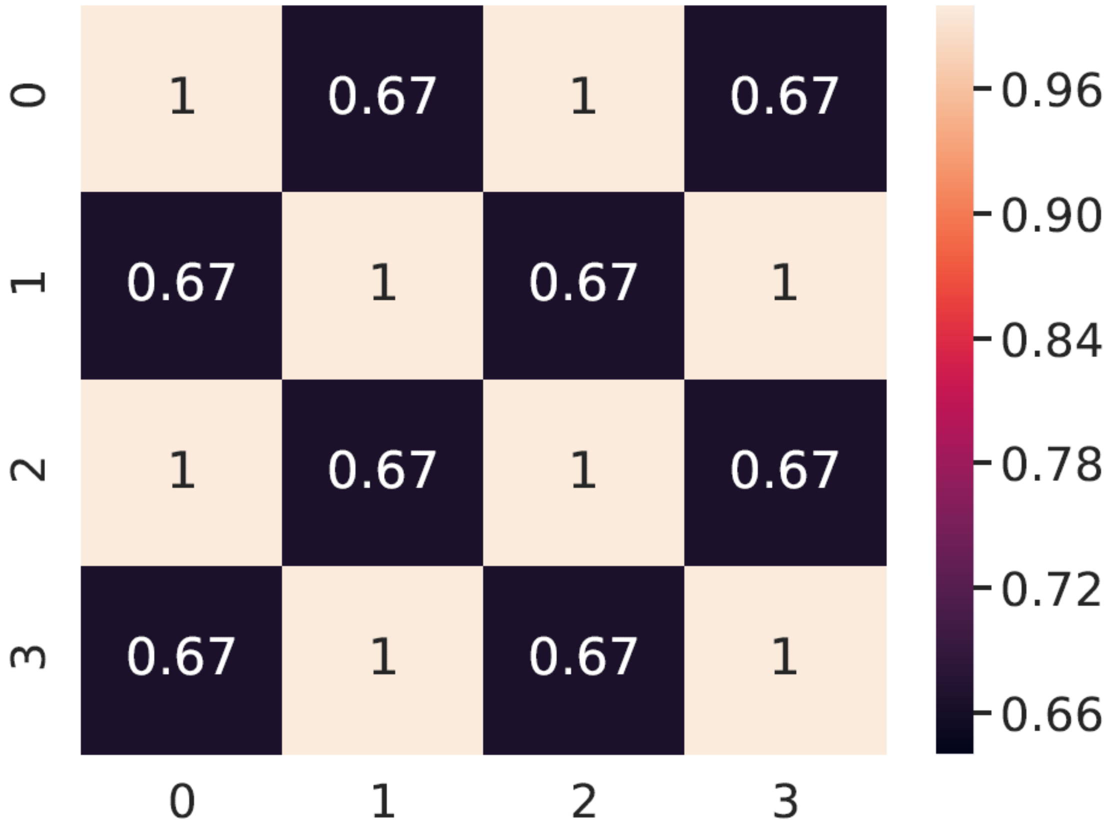
FCA

- *Formal Concept Analysis* (FCA) is a way of deriving a **concept hierarchy** from a collection of **objects** and their **attributes.**

	MPI_Init()	MPI_Comm_Size()	MPI_Comm_Rank()	L0	L1	MPI_Finalize()
Trace 0	×	×	×	×		×
Trace 1	×	×	×		×	×
Trace 2	×	×	×	×		×
Trace 3	×	×	×		×	×

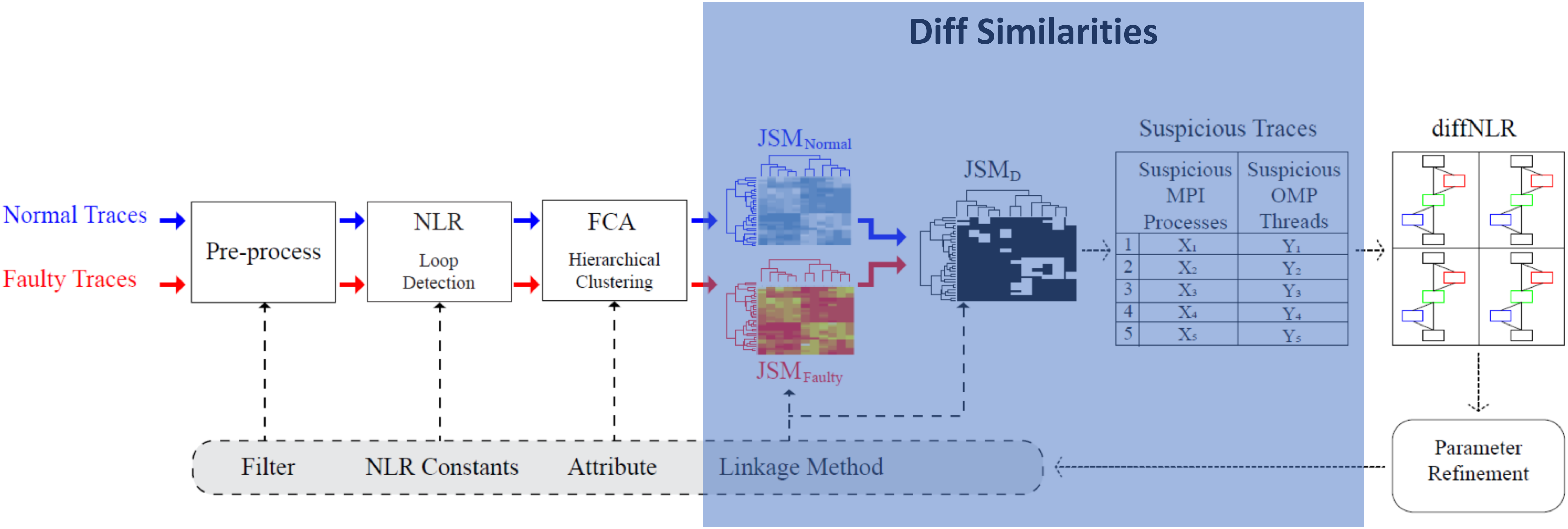
Concept Lattice & JSM (Jaccard Similarity Matrix)





[R. Godin et al, “Incremental concept formation algorithms based on galois (concept) lattices”]

DiffTrace Overview



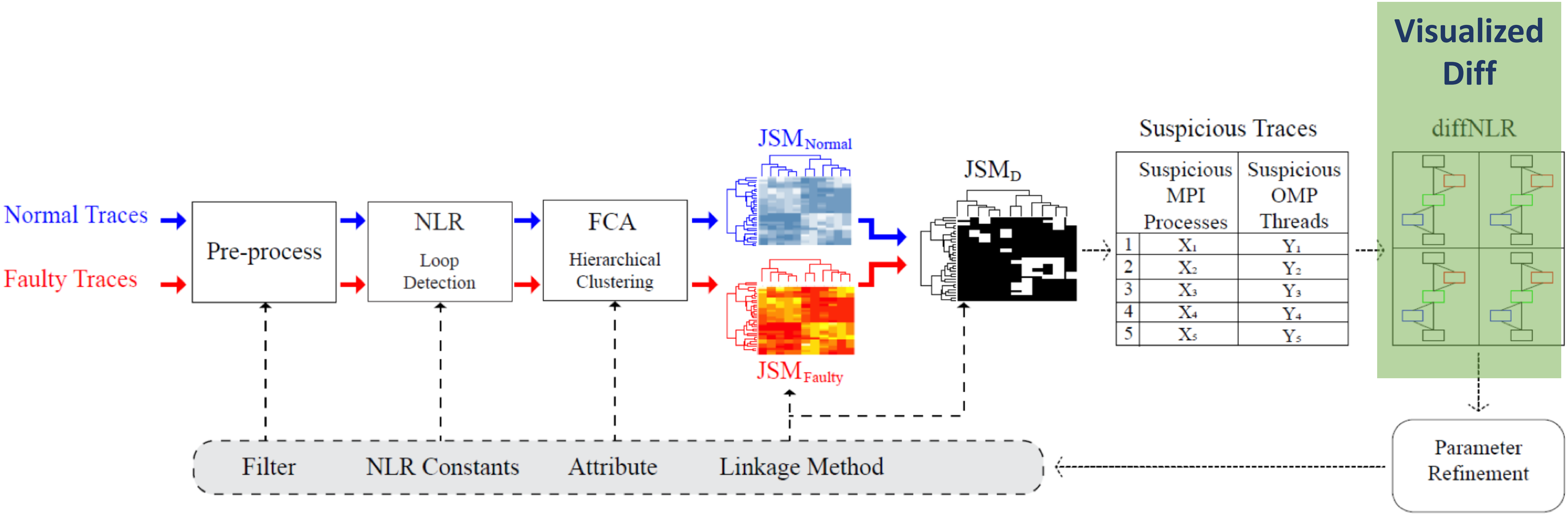
Diff Similarity Matrices

- Compute how **similarity** relations among traces of a normal execution **changes** when faults are introduced.
- $JSM_D = |JSM_{faulty} - JSM_{normal}|$
- Hierarchical clustering based on JSM_D:

Reveals the traces that have changed the most w.r.t their similarity with other traces

- Ranking metric: **B-score –** The distance between two clusterings

DiffTrace Overview



Potential Bug

oddEvenSort()

```
oddEvenSort(rank, cp){
 ...
 for (int i=0; i < cp; i++)
 {
  int ptr = findPtr(i, rank);
  ...
  if (rank % 2 == 0) {
   MPI_Send(..., ptr, ...);
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Planted Bug

Deadlock:

- Only after 7 iterations
- Only in process #5
- Suggested Rank: **#5**
- diffNLR(5_{normal},5_{faulty})

diffNLR

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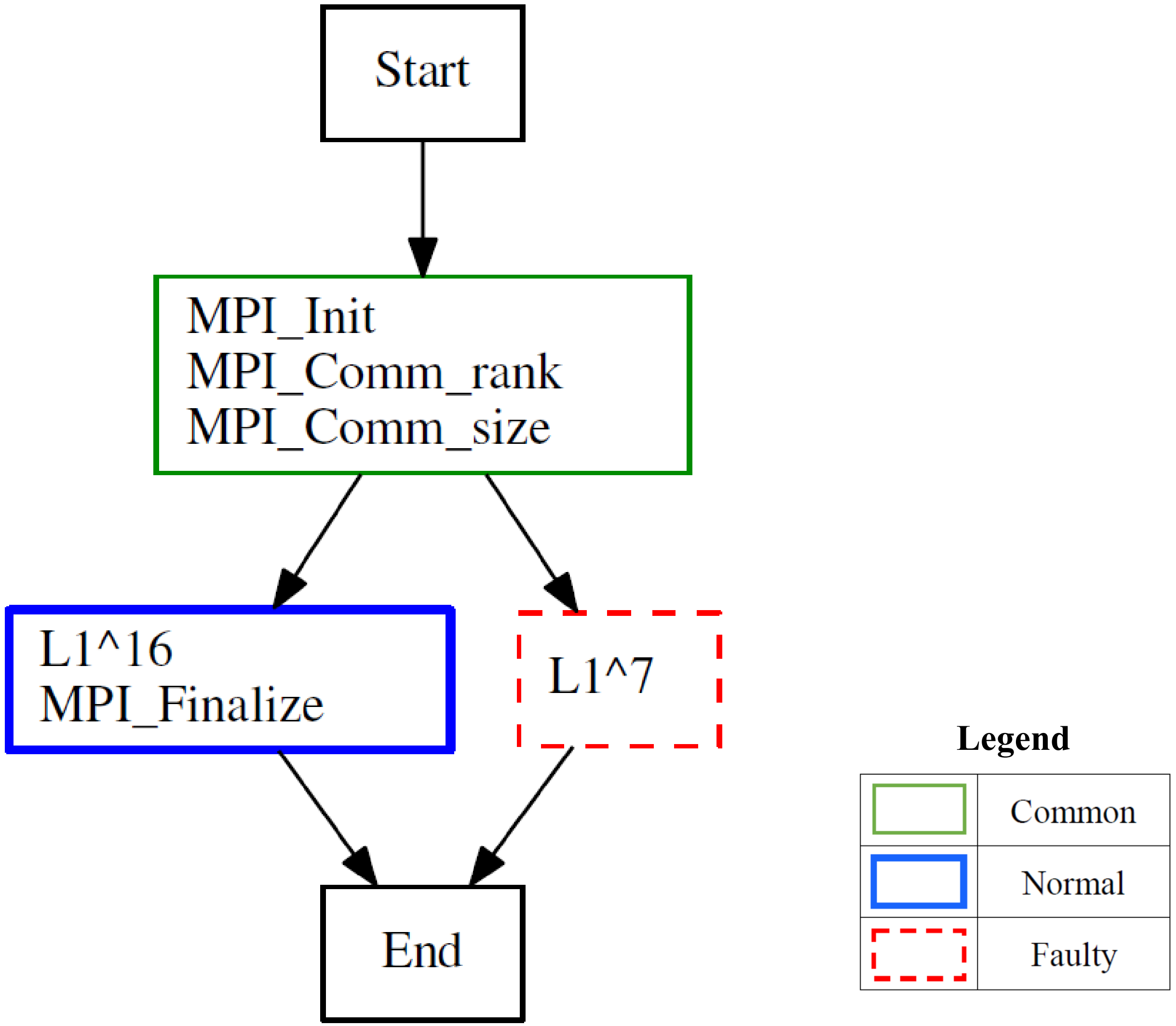

ILCS Case Study

- **ILCS:** A scalable framework for running iterative local searches on HPC platforms. LOC: 276 , Scales up to **32,768** cores

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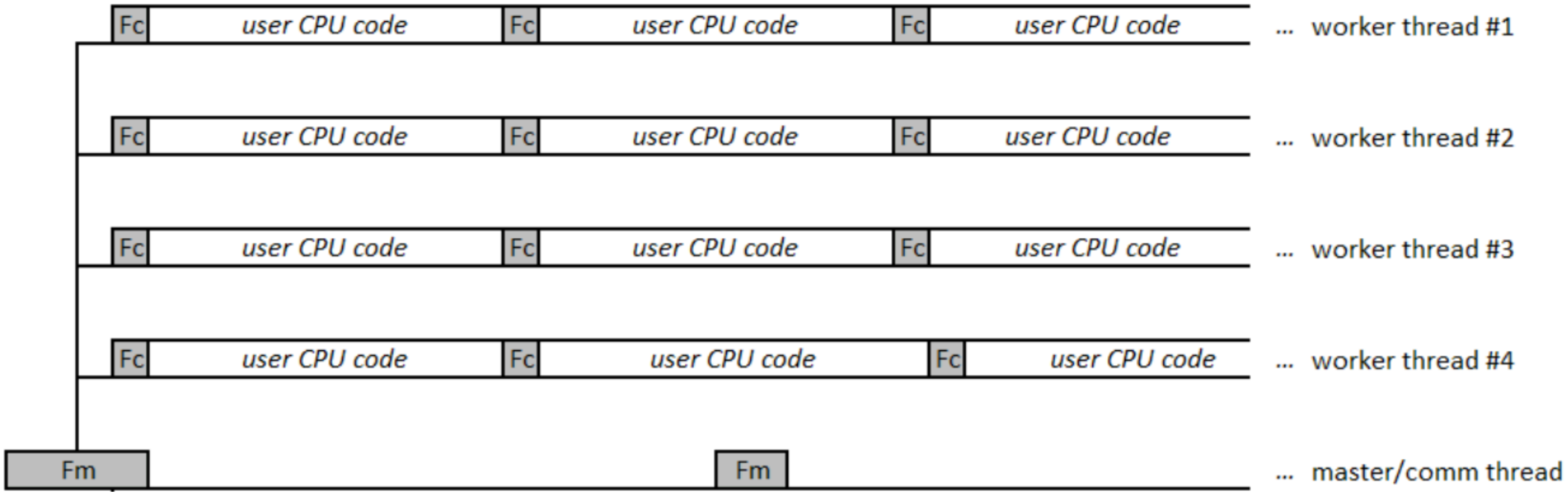
  - Workers: find the local champion
  - Masters: globally reduce local champions



Result #1: Unprotected Memory Access

- Worker thread **#4** of process **#6**
- Omitted the critical section
- Results in data race that might produce corrupted result

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Filter	Attributes	B-score	Top Processes	Top Threads
11.plt.mem.cust.0K10	doub.noFreq	0.244	7, 3, 4	**6.4**, 7.3, 1.4, 3.3, 3.4, 4.2
11.plt.mem.cust.0K10	doub.log10	0.244	7, 3, 4	**6.4**, 7.3, 1.4, 3.3, 3.4, 4.2
01.plt.mem.cust.0K10	doub.noFreq	0.244	7, 3, 4	**6.4**, 7.3, 1.4, 3.3, 3.4, 4.2
01.plt.mem.cust.0K10	doub.log10	0.244	7, 3, 4	**6.4**, 7.3, 1.4, 3.3, 3.4, 4.2
01.mem.ompcrit.cust.0K10	sing.log10	0.262	3	**6.4**, 7.1, 3.3, 4.1, 5.1, 6.1
01.mem.ompcrit.cust.0K10	sing.noFreq	0.262	3	**6.4**, 7.1, 3.3, 4.1, 5.1, 6.1
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11.mem.ompcrit.cust.0K10	sing.noFreq	0.262	3	**6.4**, 7.1, 3.3, 4.1, 5.1, 6.1
11.plt.mem.cust.0K10	doub.actual	0.273	7	**6.4**, 2.4, 3.4, 4.2, 4.4
01.plt.mem.cust.0K10	doub.actual	0.273	7	**6.4**, 2.4, 3.4, 4.2, 4.4

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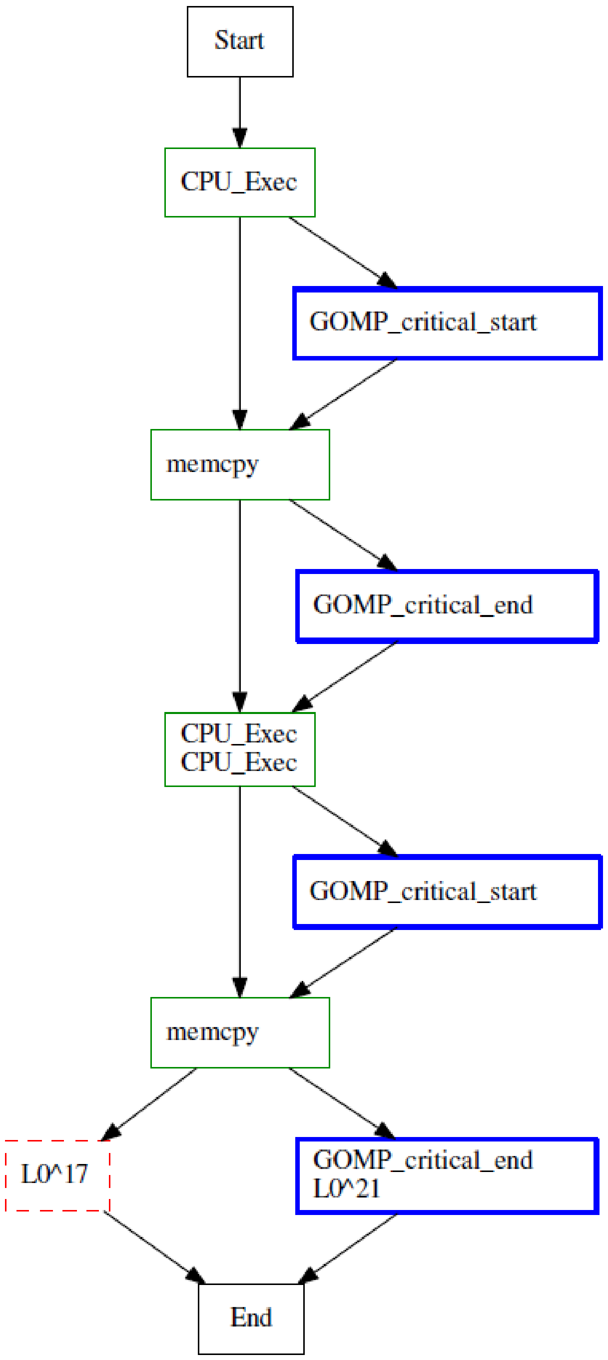

Result #2: Collective with Wrong Size

- MPI_Allreduce with wrong size: DL
- Process #2

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Filter	Attributes	B-score	Top Processes	Top Threads
11.mpicol.cust.0K10	sing.log10	0.439	0, 7, 2, 4, 5, 6	1.1, 1.3, 3.1, 3.2, 3.4
11.mpicol.cust.0K10	sing.noFreq	0.439	0, 7, 2, 4, 5, 6	1.1, 1.3, 3.1, 3.2, 3.4
11.mpi.cust.0K10	doub.noFreq	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpi.cust.0K10	doub.actual	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpiall.cust.0K10	doub.noFreq	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpiall.cust.0K10	doub.actual	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpicol.cust.0K10	doub.noFreq	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpicol.cust.0K10	doub.actual	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpi.cust.0K10	sing.log10	0.465	0, 7, 2, 4, 5, 6	1.1, 1.3, 3.1, 3.2, 3.4
11.mpi.cust.0K10	sing.noFreq	0.465	0, 7, 2, 4, 5, 6	1.1, 1.3, 3.1, 3.2, 3.4
11.mpiall.cust.0K10	sing.log10	0.465	0, 7, 2, 4, 5, 6	1.1, 1.3, 3.1, 3.2, 3.4
11.mpiall.cust.0K10	sing.noFreq	0.465	0, 7, 2, 4, 5, 6	1.1, 1.3, 3.1, 3.2, 3.4
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11.mpi.cust.0K10	doub.noFreq	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpi.cust.0K10	doub.actual	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpiall.cust.0K10	doub.noFreq	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
11.mpiall.cust.0K10	doub.actual	0.457	0, 7, 2, 4, 5, 6	1.4, 3.3, 3.4
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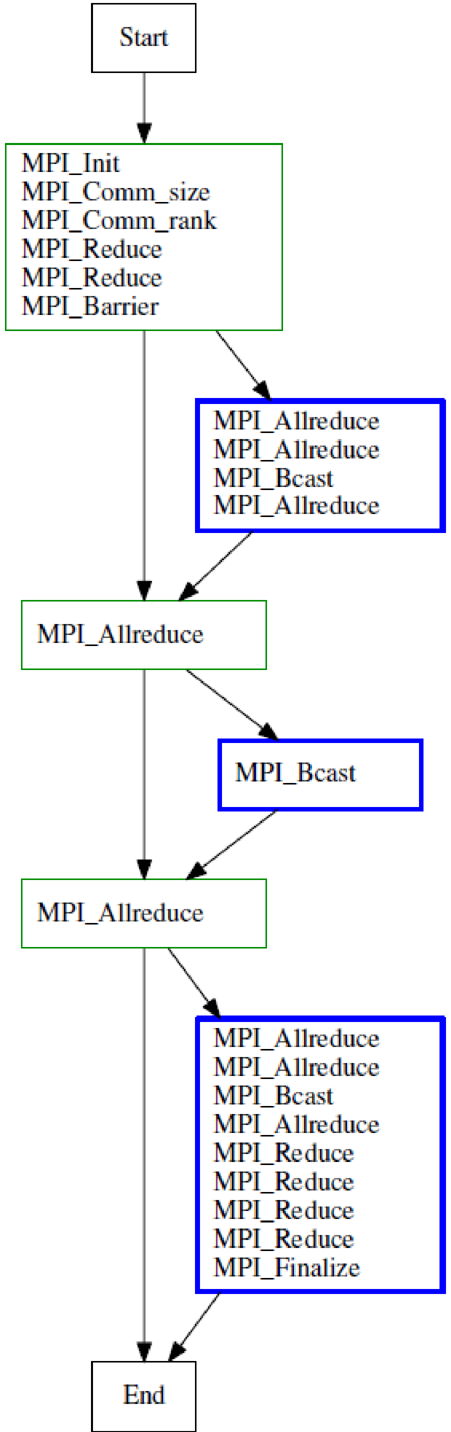

Summary

- DiffTrace situates HPC debugging around whole program trace diffing
  - Provides user-selectable filters
  - Summarizes loops based on the state-of-the-art algorithms
  - Condenses summarized traces into concept lattices
  - Obtains similarity matrices and hierarchically clusters traces
  - Detects, ranks and highlights most salient differences w.r.t. normal execution
- DiffTrace addresses missing features in existing tools

Future Work

- Optimize DiffTrace components to exploit multi-core CPUs
- Convert ParLOT traces into known formats such as OTF2 to mine temporal properties of functions
- Conduct systematic bug injection to evaluate use of concept lattices and loop structures as features for bug classification (via ML and NN)
- Take up more challenging and real-world examples to evaluate DiffTrace against similar tools, and release it to the community.

Thanks.
Any questions?