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Probabilistic Diagnosis of Performance Faults in Large-Scale Parallel Applications

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Developing Resilient HPC Applications is Challenging

MTTF of hours in Future Exascale Supercomputers

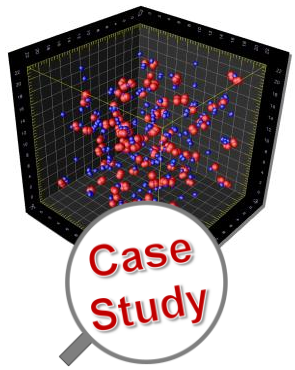
Faults come from:
Hardware
Software
Network

Software bugs from:
Application
Libraries
OS & Runtime system

Multiple manifestations:
Hangs, crashes
Silent data corruption
Applications is slower than usual

Some Faults Manifest Only at Large Scale

Molecular dynamics simulation code (ddcMD)



Fault Characteristics

- Application hangs with 8,000 MPI tasks
- Only fails in Blue Gene/L
- Manifestation was intermittent
- Large amount of time spent on fixing the problem
- *Out technique isolated the origin of the problem in a few seconds*

Why Do We Need New Debugging Tools?

Current Tools

-Old (breakpoint) technology (>30 years old)

- Manual process to find bugs

- Poor scalability

Future Tools

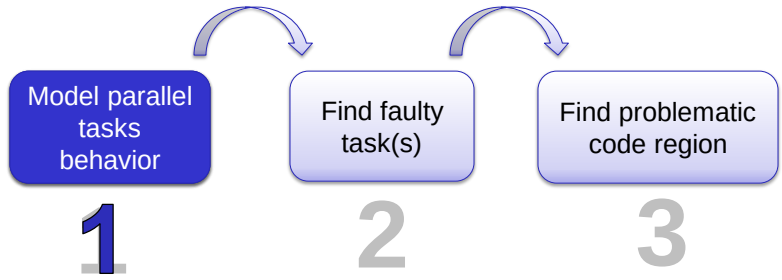
- Automatic problem determination

- Less human intervention in determining failure root cause

- Scalable (~millions of processes)

Approach Overview

- We focus on pinpointing the origin of performance faults:
  - Application hangs
  - Execution is slower than usual
- Could have multiple causes:
  - Deadlocks, slower code regions, communication problems, etc.



Summarizing Execution History

- HPC applications generate a large amount of traces
- Use a probabilistic model to summarize traces
- We model control flow behavior of MPI tasks
  - Allow us to find the least progressed task

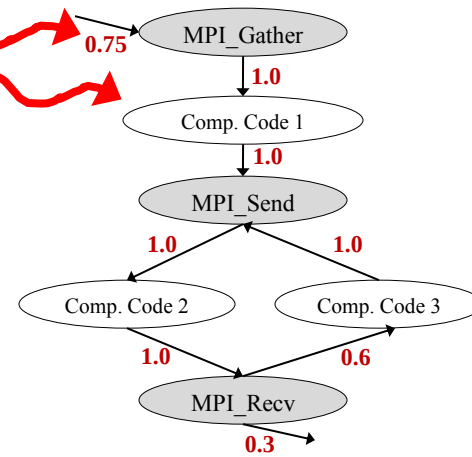
Each MPI Tasks is Modeled as a Markov Model

Sample code

```
foo() {
   MPI_gather( )
   // Computation code
   for (…) {
      // Computation code
      MPI_Send( )
      // Computation code
      MPI_Recv( )
      // Computation code
   }
```

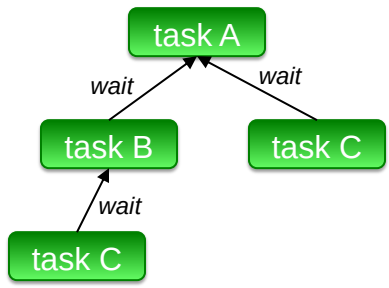
MPI calls wrappers:
- Gather call stack
- Create states in the model

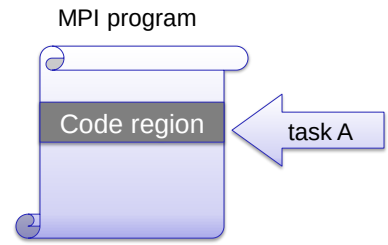
Markov Model



Approach Overview

The Progress Dependence Graph





- Facilitates finding the origin of performance faults
- Allows programmer to focus on the origin of the problem:
  - The *least progressed task*

What Tasks are Progress Dependent On Other Tasks?

Point-to-Point Operations

Task X:

```
// computation code...

MPI_Recv(…, taskY, …)

// ...
```

- Task X depends on task Y

- Dependency can be obtained from MPI calls parameters and request handlers

Collective Operations

Task X:

```
// computation code ...

MPI_Reduce(…)

// ...
```

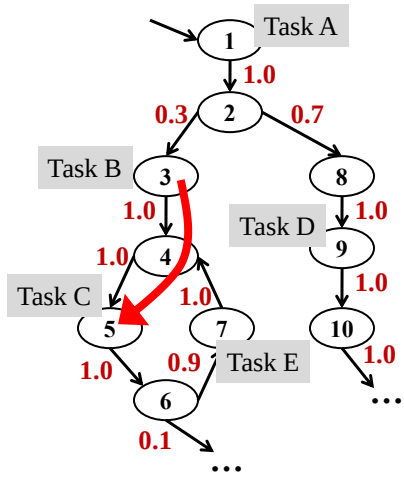
- Multiple implementations (e.g., binomial trees)

- A task can reach MPI_Reduce and continue

- Task X could block waiting for another task (less progressed)

Probabilistic Inference of Progress-Dependence Graph

Sample Markov Model



Progress dependence between tasks B and C?

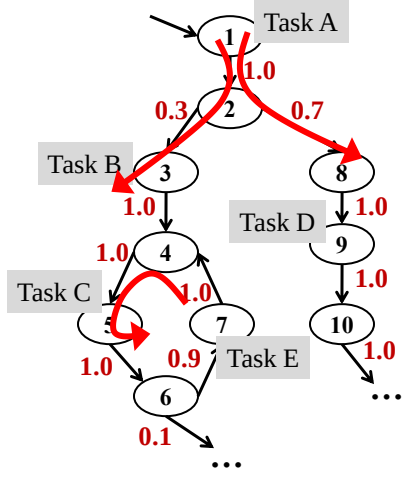
Probability(3 -> 5) = 1.0
Probability(5 -> 3) = 0

Task C is likely waiting for task B
(A task in 3 always reaches 5)

C has progressed further than B

Resolving Conflicting Probability Values

Sample Markov Model



Dependence between tasks B and D?

Probability(3 -> 9) = 0
Probability(9-> 3) = 0
The dependency is null

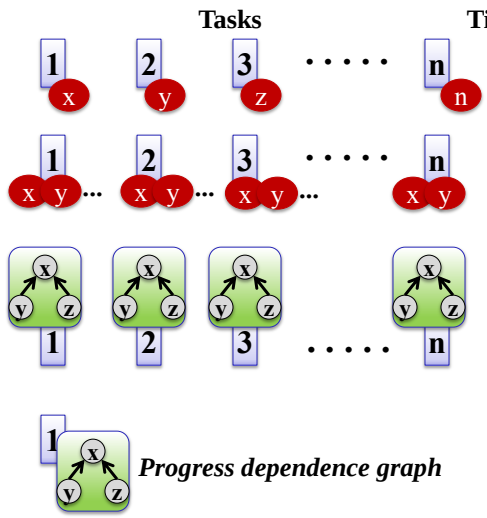
Dependence between tasks C and E?

Probability(7 -> 5) = 1.0
Probability(5-> 7) = 0.9

Heuristic: Trust the highest probability

C is likely waiting for E

Distributed Algorithm to Infer the Graph



All-reduction of current states

All tasks know the state of others

Build (locally) progress-dependence graph

Reduction of progress-dependence graphs

Reductions are O(log #tasks)

Reduction Operations: *Graph Dependencies Unions*

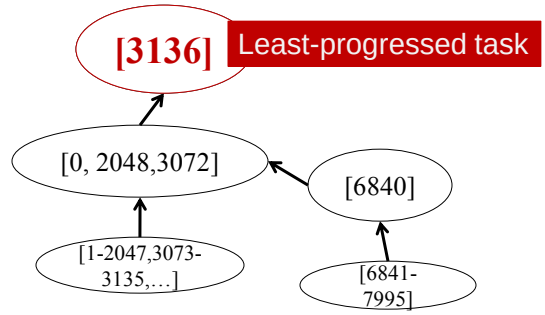
Examples of reduction operations
X → Y: X is progress dependent on Y

Task A	Task B	Result
X → Y	X → Y	X → Y (Same dependence)
X → Y	Null	X → Y (First dominates)
X → Y	Y → X	Undefined (or Null)
Null	Null	Null

Case Study

Bug Progress Dependence Graph

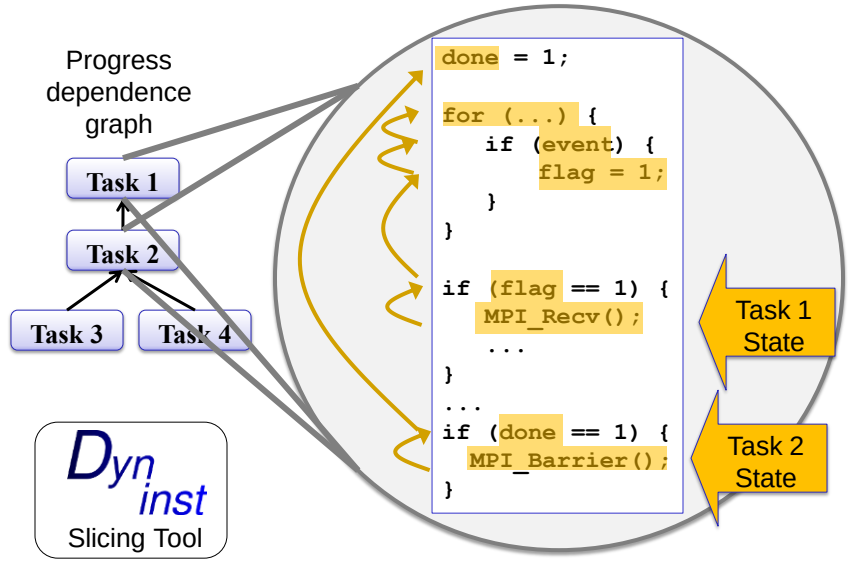
Hang with ~8,000 MPI tasks in BlueGene/L



- Our tool finds that task 3136 is the origin of the hang
  - *How did it reach its current state?*

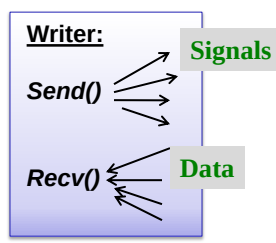
Approach Overview

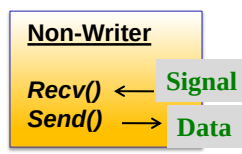
Finding the Faulty Code Region: *Program Slicing*



Code to Handle Buffered I/O in DDCMD

Case Study






```
dataWritten = 0
for (…) {
   Probe(…, &flag,…)
   if (flag == 1) {
      Recv()
      Send()
      dataWritten = 1
   }
   Send()
   Recv()
   // Write data
}
if (dataWritten == 0) {
   Recv()
   Send()
}
Reduce()
Barrier()
```

Check if another writer asks for data

Slice With Origin of the Bug

Case Study

```
dataWritten = 0
for (…) {
    Probe(…, &flag,…)
    if (flag == 1) {
        Recv()
        Send()
        dataWritten = 1
    }
    Send()
    Recv()
    // Write data
}
if (dataWritten == 0) {
    Recv()
    Send()
}
Reduce()
Barrier()
```

Least-progressed task State

Dual condition occurs in BlueGene/L

- *A task is a writer and a non-writer*

`MPI_Probe` checks for *source, tag and comm* of a message

- *Another writer intercepted wrong message*

Programmer used unique MPI tags to isolate different I/O groups

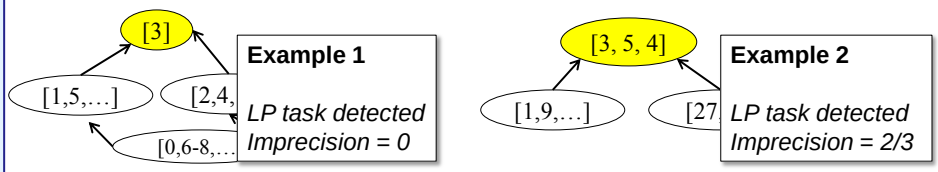
Fault Injections Methodology

- Faults injected in Two Sequoia benchmarks:
  - AMG-2006
  - LAMMPS
- We injected a hang in random MPI tasks:
  - 20 user function calls, 5 MPI calls
  - Only injected in executed functions
  - Functions are selected randomly

Accurate Detection of Least-Prog. Tasks

- Least-progressed task detection recall:
  - Cases when LP task is detected correctly
- Imprecision:
  - % of extra tasks in LP tasks set

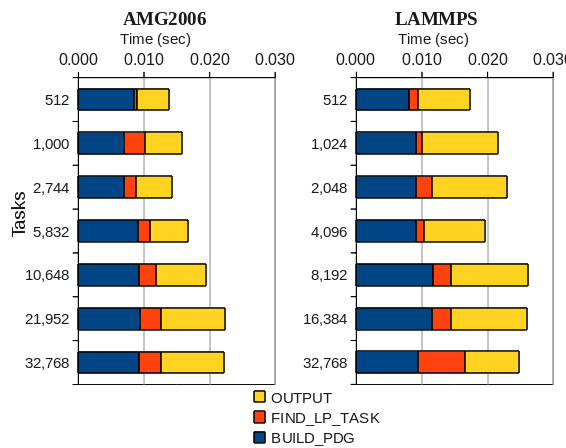
Example Runs: **64 tasks, fault injected in task 3**



- Overall results:
  - Average LP task detection recall is 88%
  - 86% of injections has imprecision of zero

Performance Results:

Least-Prog. Task Detection Takes a Fraction Of A Second



Performance Results:
Slowdown Is Small For a Variety of Benchmarks

Benchmark	Slowdown	Memory-usage Increase
LAMMPS	1.59	6.11
AMG2006	1.46	10.36
BT	1.08	3.75
SP	1.67	5.14
CG	1.14	2.21
FT	1.05	1.01
LU	1.39	5.37
MG	1.04	1.04

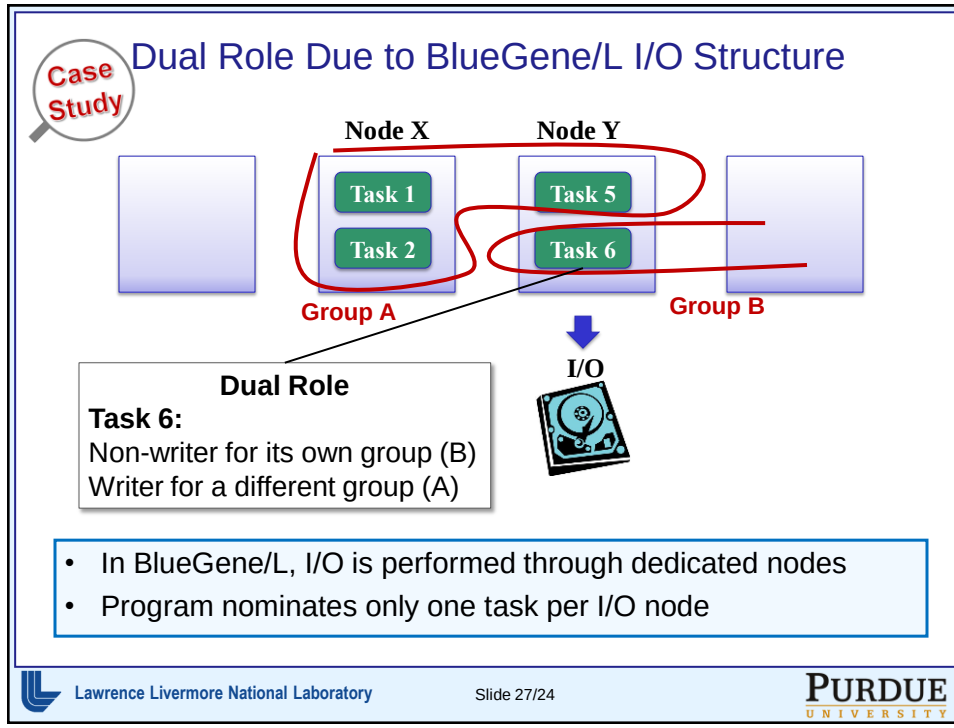
- Tested slowdown with NAS Parallel and Sequoia benchmarks
  - Maximum slowdown of ~1.67
- Slowdown depends on number of MPI calls from different contexts

Conclusions

- Our debugging approach diagnose faults in HPC applications
- *Novelties:*
  - *Compression of historic control-flow behavior*
  - *Probabilistic inference of the least-progressed tasks*
  - *Guided application of program slicing*
- Distributed debugging method is scalable
  - Takes fraction of a second with 32,000 BlueGene/P tasks
- Successful evaluation with hard-to-detect bug and representative benchmarks

Thank you!

Backup Slides


Case Study
Dual Role Due to BlueGene/L I/O Structure
Node X
Node Y
Task 1
Task 2
Task 5
Task 6
Group A
Group B
I/O
Dual Role
Task 6:
Non-writer for its own group (B)
Writer for a different group (A)
• In BlueGene/L, I/O is performed through dedicated nodes
• Program nominates only one task per I/O node
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