A Deadlock Detection Concept for OpenMP Tasks and Fully-Hybrid MPI-OpenMP Applications

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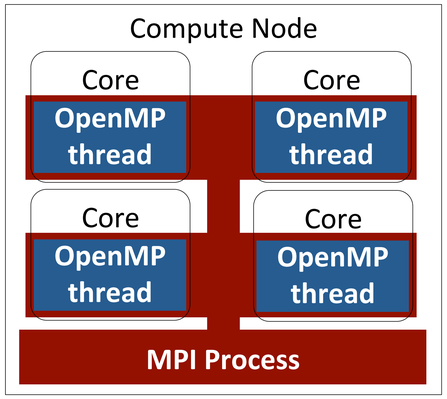
Current high performance computing applications often combine the Message Passing Interface (MPI) with threaded parallel programming paradigms, e.g., OpenMP. MPI allows fully hybrid applications in which multiple threads of a process issue MPI operations concurrently. Little study on deadlock conditions for this combined use exists. We propose a wait-for graph approach to understand and detect deadlock for such fully hybrid applications. It specifically considers OpenMP 3.0 tasking support to incorporate OpenMP's task-based execution model. Our model creates dependencies with deadlock criteria that can be visualized to support comprehensive deadlock reports. We use a model checking approach to investigate wide ranges of valid execution states of example programs to verify the soundness of our wait-for graph construction.

MPI, OpenMP, Tasks, and Hardware

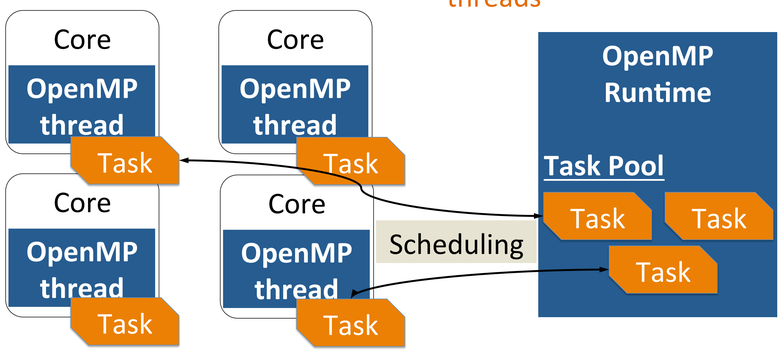
- Increasing core counts per compute node



⇒ **Process**:
From MPI, execute the same program, distinct virtual memory, message communication

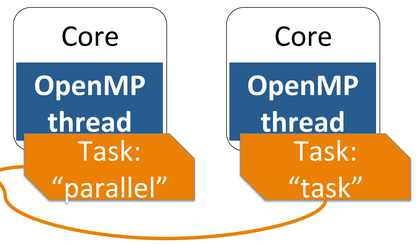
⇒ **Thread**:
From OpenMP, share memory within their process

⇒ **Task**:
Managed by OpenMP runtime, executes on threads

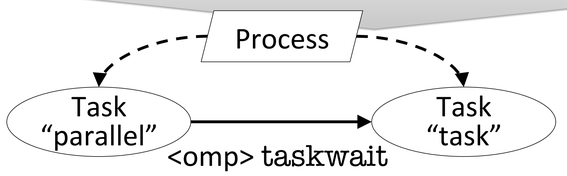


OpenMP Tasks and Deadlocks

```
1 #pragma omp parallel
2 {
3 #pragma omp task
4   {
5     ... /*Do something*/
6   } /*end: omp task*/
7 #pragma omp taskwait
8 } /*end: omp parallel*/
```



Wait-For Graph Construction Rules



Deadlock?
⇒No

Is my MPI-OpenMP application deadlocked?

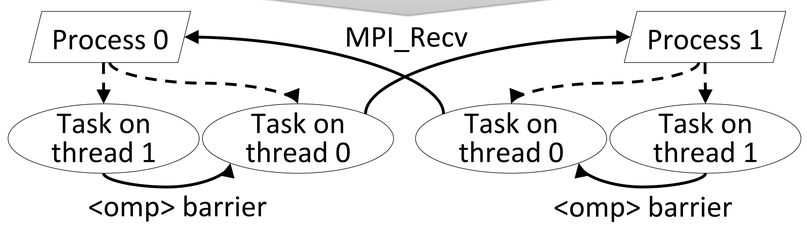
Wait-For Graph (WFG) Construction Rules

I. Each MPI process i get one node in the WFG
II. Each task t_i of a process gets one node in the WFG
III. A node for process i waits for all of its task nodes t_i (OR semantic)
IV. An unscheduled task t_i waits for its parent process i (with AND semantic)
V. If any task t_i is at a task scheduling point, ignore rule IV. for all tasks that could replace t_i
VI. Model individual wait-for dependencies for MPI/OpenMP directives active on tasks
VII. MPI Dependencies target process nodes, not task nodes

OpenMP-MPI Deadlock

Process 0		Process 1	
Thread 0	Thread 1	Thread 0	Thread 1
MPI_Recv(from:1)		MPI_Recv(from:0)	
#pragma omp barrier		#pragma omp barrier	
	MPI_Send(to:1)		MPI_Send(to:0)

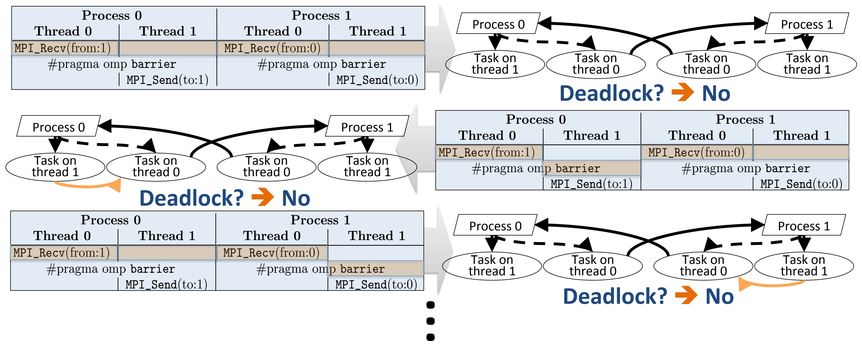
Wait-For Graph Construction Rules



Deadlock?
⇒Yes

Soundness

- Are the construction rules sound ?
- Approach: Enumerate a large set of
  - ⇒Evaluate large numbers of application execution states
  - ⇒Apply construction rules to these states
  - ⇒Test WFG for deadlock
  - ⇒Compare result to expectation => Should this state have a deadlock or not?
  - ⇒We demonstrate no false positives/negatives for 13 examples



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