Process-in-Process: Techniques for Practical Address-Space Sharing

HPDC'18, Tempe Arizona
June 14, Arizona

Atsushi Hori (Riken) and Min Si (ANL)
B. Gerofi, M. Takagi, Y. Ishikawa (Riken),
J. Dayal (Intel), P. Balaji (ANL)

Motivation

- Conventional In-node Parallel Execution Models
  - Multi-Process: MPI
  - Multi-Thread: OpenMP
- Pros
  - Multi-Process: Privatized variables
  - Multi-Thread: Easy to exchange info.
- Cons
  - Multi-Process: Hard to exchange data
  - Multi-Thread: Locks on shared variables
- The rise of Many-Core
  - makes above cons worse

Conventional Parallel Execution Models

		Address Space	
		Isolated	Shared
Variables	Privatized	Multi-Process (MPI)	
	Shared	*N/A*	Multi-Thread (OpenMP)

- Pros
  - Multi-Process: Privatized variables
  - Multi-Thread: Easy to exchange data
- Cons
  - Multi-Process: Hard to exchange data
  - Multi-Thread: Locks on shared variables

Take the best of two worlds

		Address Space	
		Isolated	Shared
Variables	Privatized	Multi-Process (MPI)	***3rd Exec. Model***
	Shared	*N/A*	Multi-Thread (OpenMP)

- Pros
  - 3rd Model
    - Privatized variables
    - Easy to exchange data
- Cons
  - ~~Multi-Process: Hard to exchange data~~
  - ~~Multi-Thread: Locks on shared variables~~

Take the best of two worlds

		Address Space	
		Isolated	Shared
Variables	Privatized	Multi-Process (MPI)	***3rd Exec. Model***
	Shared	*N/A*	Multi-Thread (OpenMP)

- Pros
  - 3rd Model
    - Privatized variables
    - Easy to exchange data
- Cons

Variables and Data are SHARABLE

3rd Model Implementations

- Two Approaches
  - Process Approach
    - SMARTMAP (SNL) — Kitten OS
    - PVAS (Riken) — Patched Linux
  - Thread Approach
    - MPC (CEA) — Compiler

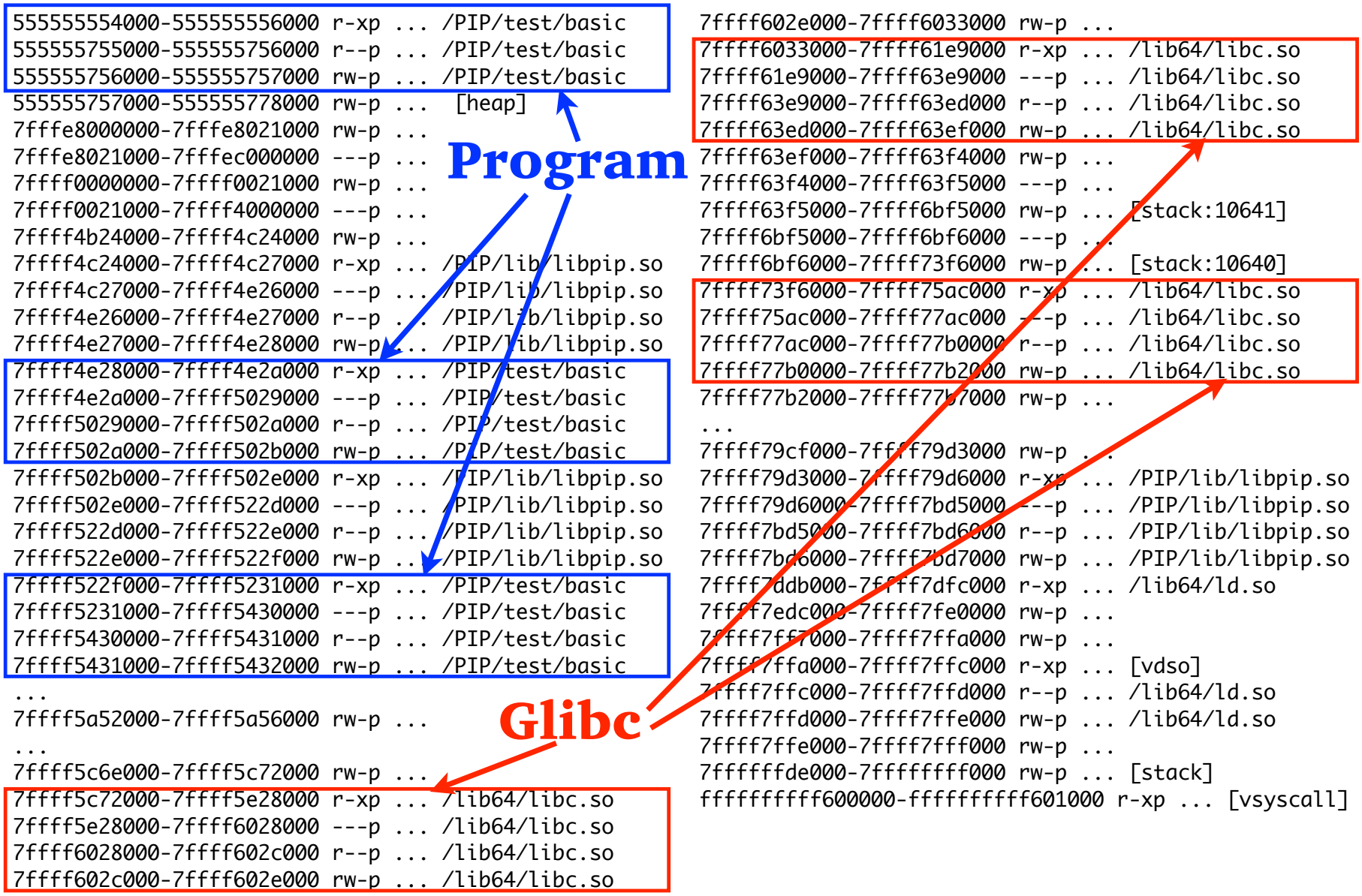
- None of them is portable nor practical

- Our Goal:
  - Can we implement it at user-level ?
    - more portable and practical

Process-in-Process (PiP)

- User-Level Implementation
- 3 Technical Elements
  1. dlmopen() - not dlopen()
     - creates a new (symbol) name space for linking
     - can privatize statically allocated variables
  2. Position Independent Executable (PIE)
     - can load multiple programs in the same virtual address space
  3. clone() or pthread_create()
     - creates kernel threads to run on the same virtual address space
- PiP has only 3K LOC

/proc/*/maps **Example of PiP**



OpenMP, MPI and PiP

OpenMP

```
int main() {
  int tid, seed, i;
  srand(1);
#pragma omp parallel …
  {
    seed = 1;
    tid = omp_get_thread_num();
    for ( i=0; i<3; i++ ) {
#pragma omp barrier
      printf( "<%d> %d : %d\n", tid,
          rand(), rand_r(&seed) ); }
  }
  return 0;
}
```

MPI

```
int main( … ) {
  int i, rank, seed = 1;
  MPI_Init( … );
  MPI_Comm_rank( …, &rank );
  srand(1);
  for ( i=0; i<3; i++ ) {
    MPI_Barrier( … );
    printf( "<%d> %d : %d\n", rank,
        rand(), rand_r(&seed) ); }
  MPI_Finalize();
  return 0;
}
```

PiP

```
pthread_barrier_t barrier, *barrp;
int main() {
  int i, pipid, seed = 1;
  pip_init( &pipid, … );
  if ( pipid == 0 ) {
    pthread_barrier_init( &barrier,
            NULL, ntasks );
    pip_export( &barrier );
    barrp = &barrier;
  } else {
    do {
      pip_import( 0, (void**) &barrp );
    } while( barrp == NULL ); }
  srand(1);
  for ( i=0; i<3; i++ ) {
    pthread_barrier_wait( barrp );
    printf( "<%d> %d : %d\n", pipid,
      rand(), rand_r(&seed) );
  }
  pip_fin();
  return 0;
}
```

OpenMP, MPI and PiP

OpenMP

```
int main() {
  int tid, seed, i;
  srand(1);
#pragma omp parallel …
  {
    seed = 1;
    tid = omp_get_thread_num();
    for ( i=0; i<3; i++ ) {
#pragma omp barrier
      printf( "<%d> %d : %d\n", tid,
          rand(), rand_r(&seed) ); }
  }
  return 0;
}
```

MPI

```
int main( … ) {
  int i, rank, seed = 1;
  MPI_Init( … );
  MPI_Comm_rank( …, &rank );
  srand(1);
  for ( i=0; i<3; i++ ) {
    MPI_Barrier( … );
    printf( "<%d> %d : %d\n", rank,
        rand(), rand_r(&seed) ); }
  MPI_Finalize();
  return 0;
}
```

PiP

```
pthread_barrier_t barrier, *barrp;
int main() {
  int i, pipid, seed = 1;
  pip_init( &pipid, … );
  if ( pipid == 0 ) {
    pthread_barrier_init( &barrier,
            NULL, ntasks );
    pip_export( &barrier );
    barrp = &barrier;
  } else {
    do {
      pip_import( 0, (void**) &barrp );
    } while( barrp == NULL ); }
  srand(1);
  for ( i=0; i<3; i++ ) {
    pthread_barrier_wait( barrp );
    printf( "<%d> %d : %d\n", pipid,
      rand(), rand_r(&seed) );
  }
  pip_fin();
  return 0;
}
```

PiP Programming

OpenMP

	rand()	rand_r()
<0>	1681692777	476707713
<0>	424238335	1186278907
<0>	596516649	505671508
<1>	1804289383	476707713
<1>	1957747793	1186278907
<1>	1649760492	505671508
<2>	846930886	476707713
<2>	1714636915	1186278907
<2>	719885386	505671508

MPI and PiP

	rand()	rand_r()
<0>	1804289383	476707713
<0>	846930886	1186278907
<0>	1681692777	505671508
<1>	1804289383	476707713
<1>	846930886	1186278907
<1>	1681692777	505671508
<2>	1804289383	476707713
<2>	846930886	1186278907
<2>	1681692777	505671508

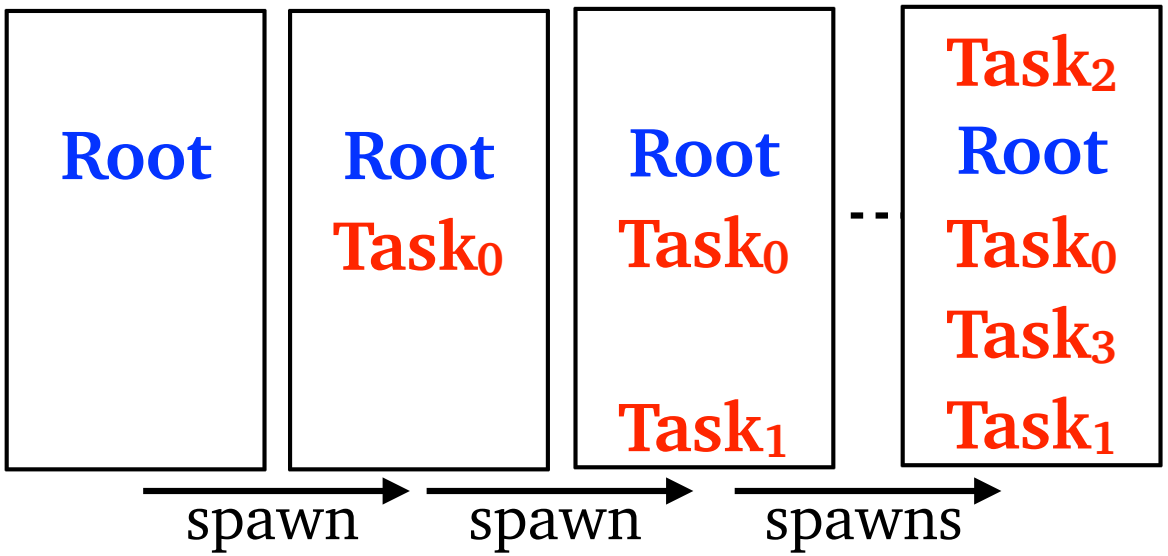
- pthread_barrier (and pthread_mutex) works with PiP
  - VAS is shared
- The sequence of rand() is the same with MPI
  - Variables are privatized
- pip_import() and pip_export()

PiP

```
pthread_barrier_t barrier, *barrp;
int main() {
  int i, pipid, seed = 1;
  pip_init( &pipid, … );
  if ( pipid == 0 ) {
    pthread_barrier_init( &barrier,
            NULL, ntasks );
    pip_export( &barrier );
    barrp = &barrier;
  } else {
    do {
      pip_import( 0, (void**) &barrp );
    } while( barrp == NULL ); }
  srand(1);
  for ( i=0; i<3; i++ ) {
    pthread_barrier_wait( barrp );
    printf( "<%d> %d : %d\n", pipid,
      rand(), rand_r(&seed) );
  }
  pip_fin();
  return 0;
}
```

How PiP Works

- Root Process
  - Spawn Tasks
- PiP Task
  - Share the same VAS with root
  - PIE



- PiP Execution Mode
  - Process mode clone()
  - Thread mode pthread_create()

✓ In either mode, variables are privatized

✓ pthread_create() is more portable than clone()

Potability

Table 2: Experimental platform hardware information

Name	CPU	# Cores	Clock	Memory	Network
Wallaby	Xeon E5-2650 v2	8×2(×2)	2.6GHz	64 GiB	ConnectX-3
OFP†	Xeon Phi 7250	68(×4)	1.4GHz	96(+16) GiB	Omni-Path
K [44]	SPARC64 VIIIfx	8	2.0GHz	16 GiB	Tofu

Table 3: Experimental platform software information

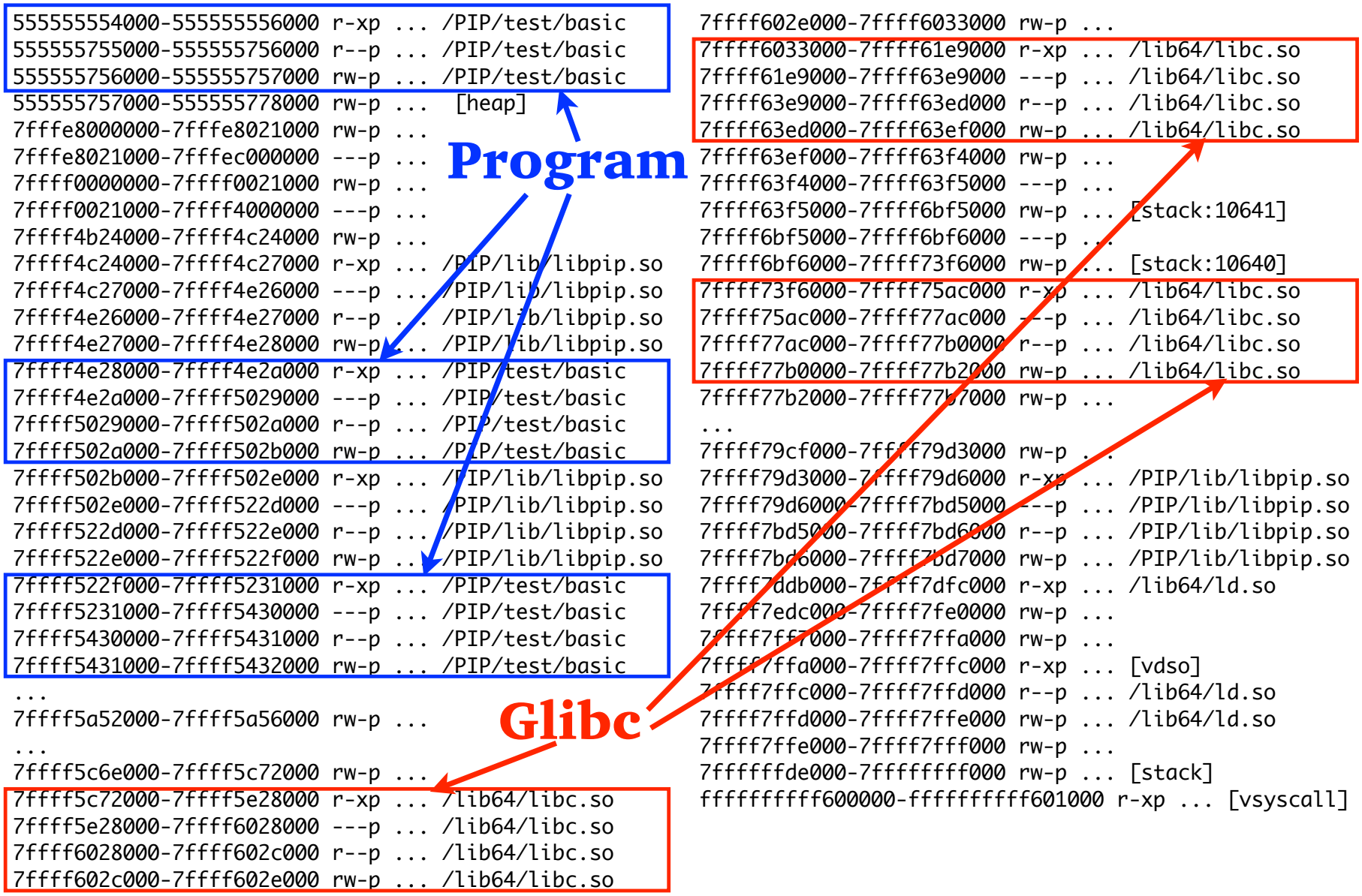
Name	OS	Glibc	PiP Exec. Mode(s)
Wallaby	Linux (CentOS 7.3)	w/ patch	process and thread
Wallaby	McKernel+CentOS 7.3	w/ patch	thread only
OFP†	Linux (CentOS 7.2)	w/ patch	process and thread
K	XTCOS	w/o patch	process and thread

✓ **Glibc Patch: dlmopen() can create up to 16 name spaces**

✓ **McKernel is a multi-kernel developed at Riken**

- **PiP also works on Arm64/Linux**

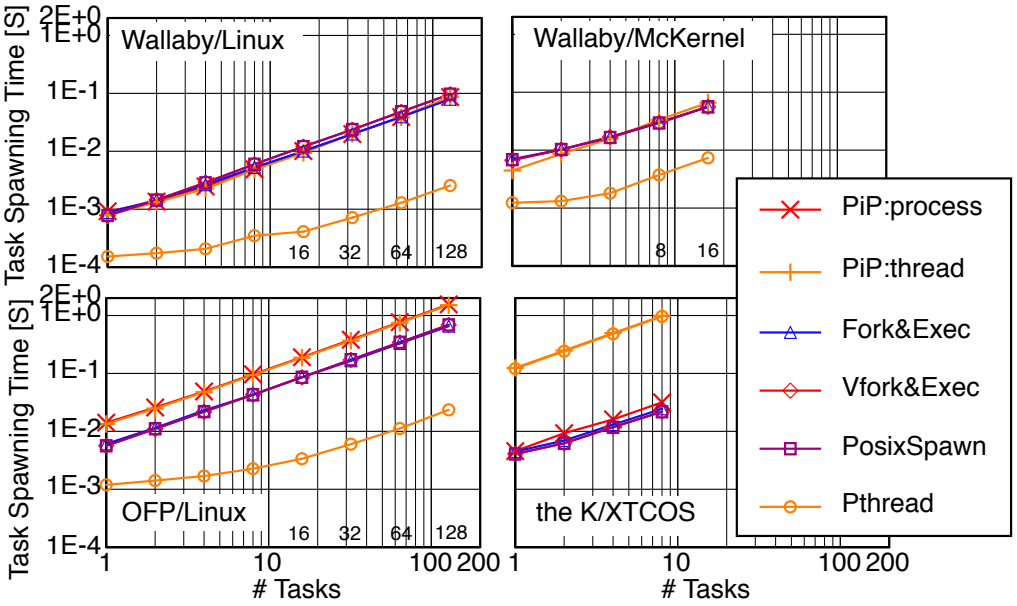
/proc/*/maps **Example of PiP**



PiP Basic Performance

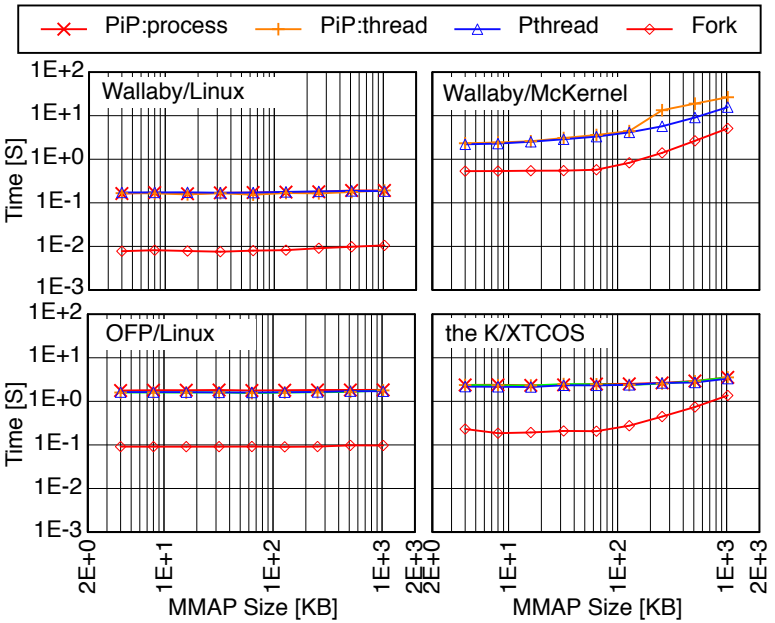
- A larger number of memory segments MAY affect task spawning time and/or mmap() time
- Spawn: Almost equal to processes
- mmap(): Almost equal to pthreads

Task Spawning Time



Better

mmap() Time (10 tasks)

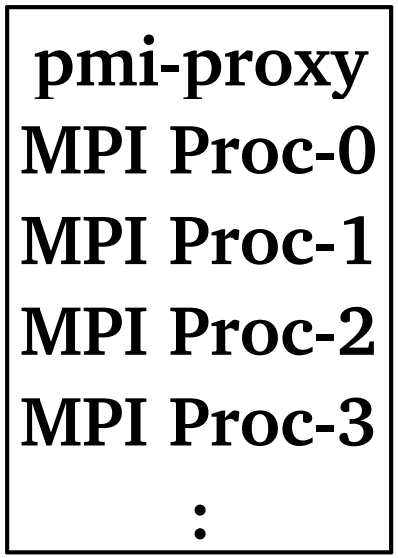


PiP-aware MPI Prototype

- PiP Root: Hydra process manager
- PiP Tasks: MPI Processes
- PiP Mode: Process Mode

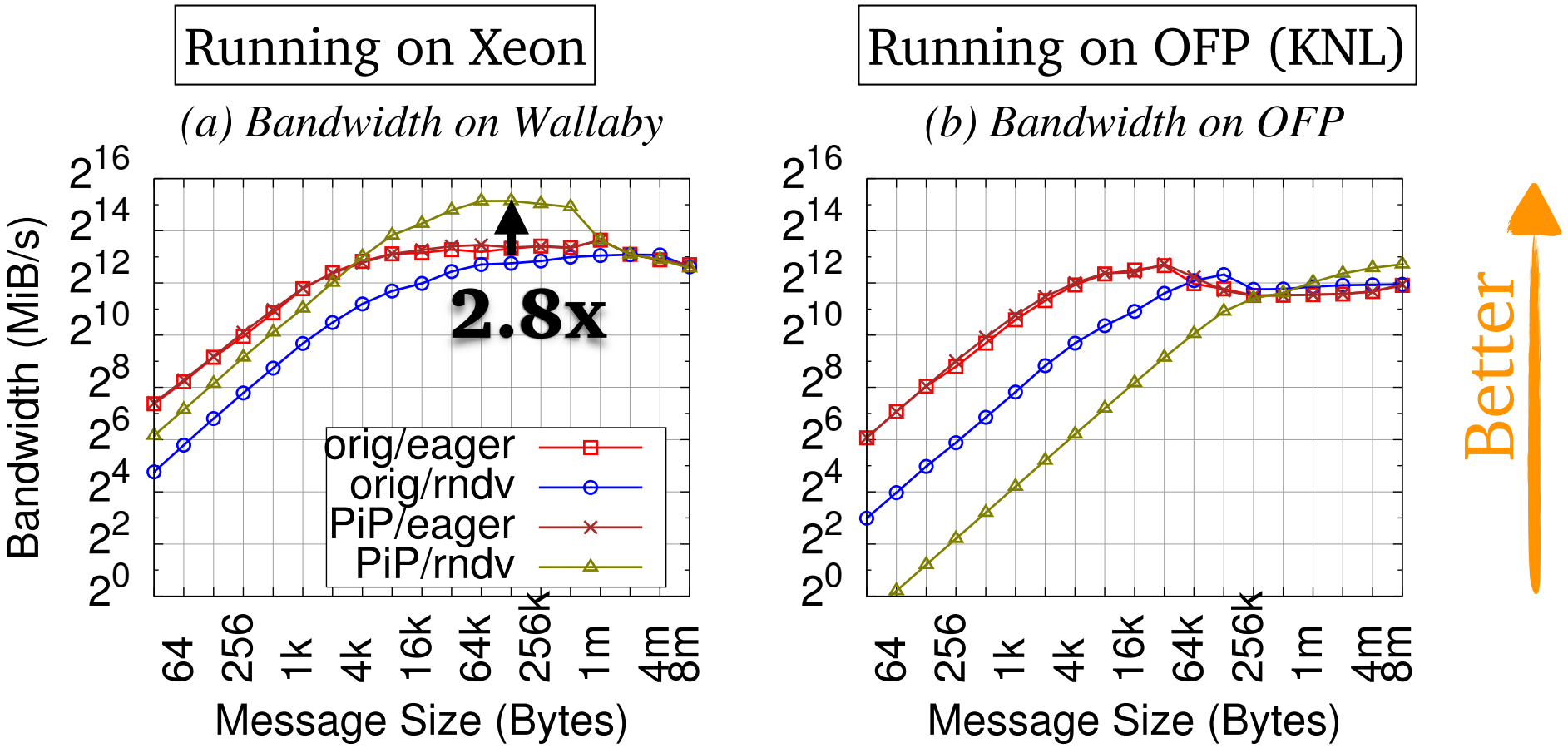
- Base MPI: MPICH (v3.3a3)

- PiP-aware MPI Optimizations
  - Pt2Pt rendezvous protocol
    - Before: 2 copies
    - After: 1 copy
  - MPI_Win_allocate_shared()
    - Before: Allocate POSIX shmem and broadcast
    - After: malloc() at root and broadcast



MPI Pt2Pt (Intra-Node) Performance

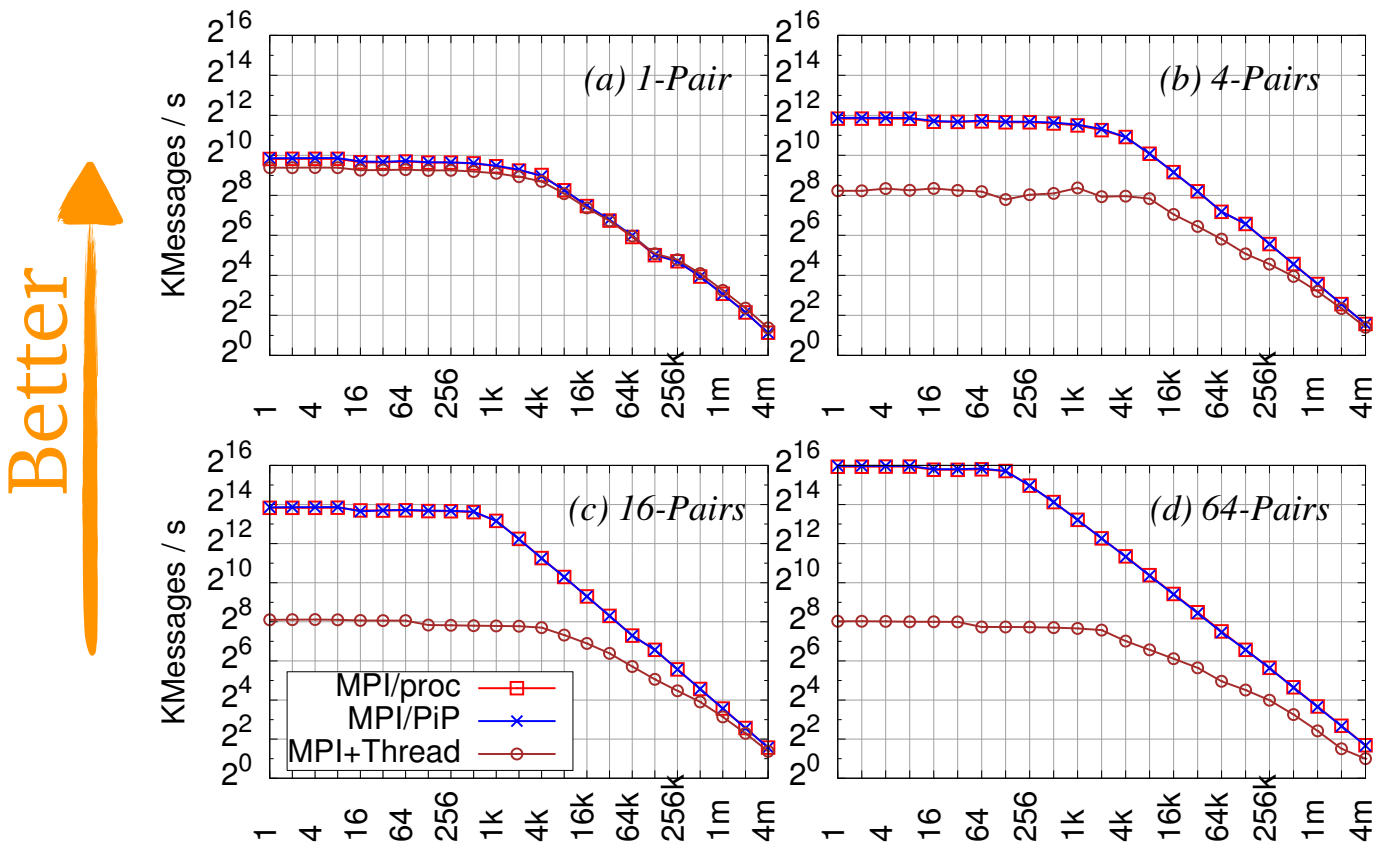
- PiP rendezvous protocol outperform 2.8x
  - IMB Ping-Pong benchmark (Intra-Node)



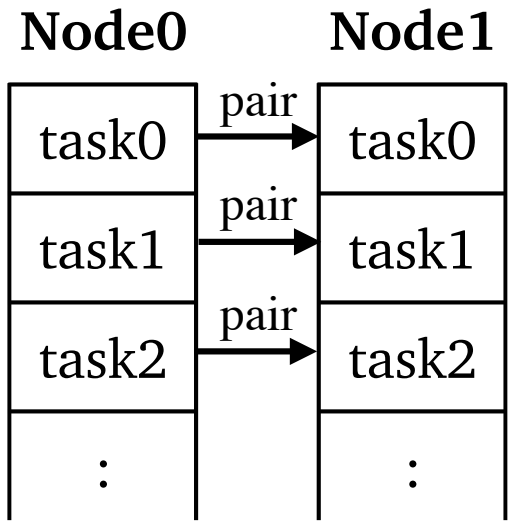
Note: The results of orig/eager and PiP/eager are overlapped.

MPI Multithreaded (Inter-Node) Performance

- Modified **osu_mbw_mr** benchmark program
  - to compare MPI+Thread and PiP-aware MPI



Note: The results of MPI/proc and MPI/PiP are overlapped in the four graphs.

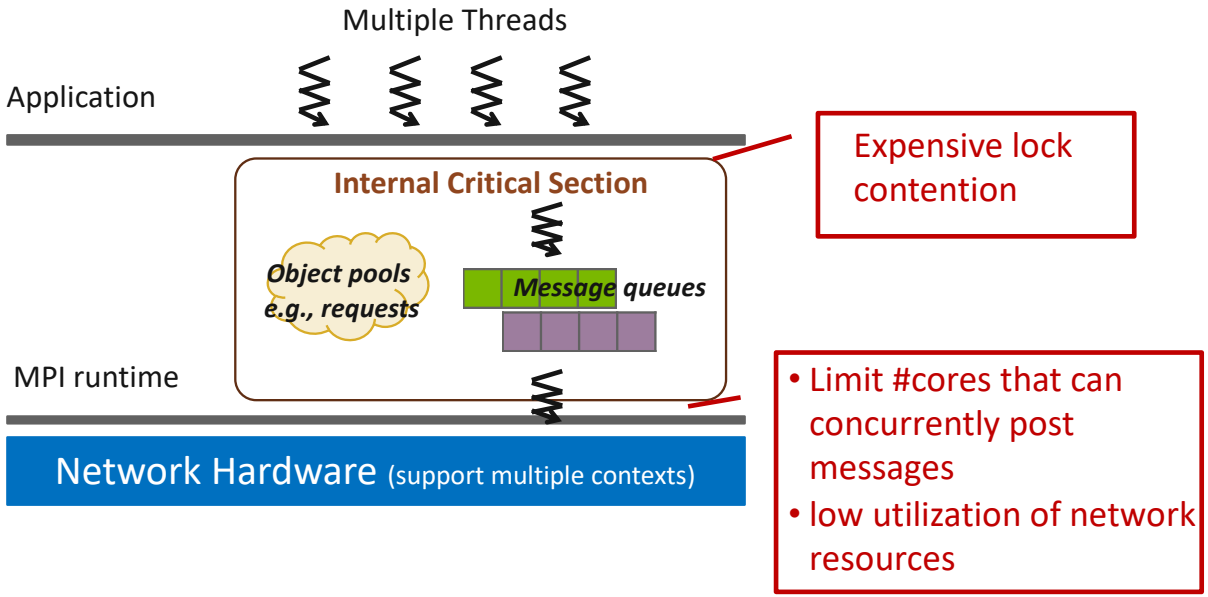


Running on OFP (KNL)

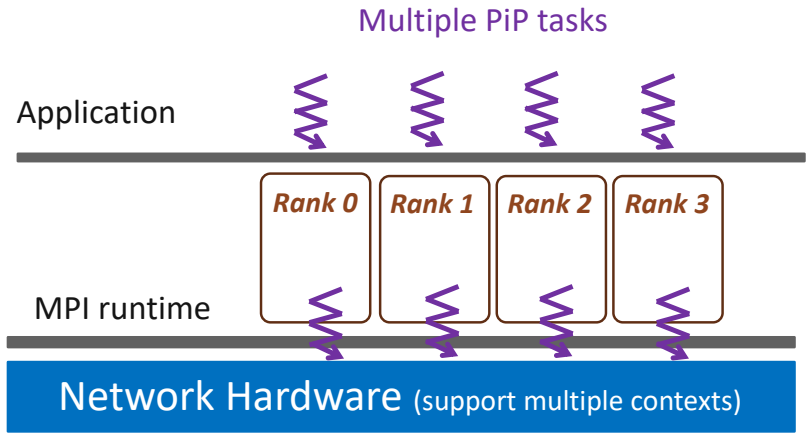
Figure 11: Multipair message rate between two OFP nodes

Why PiP is better ?

- MPI standard does not allow threaded comm.

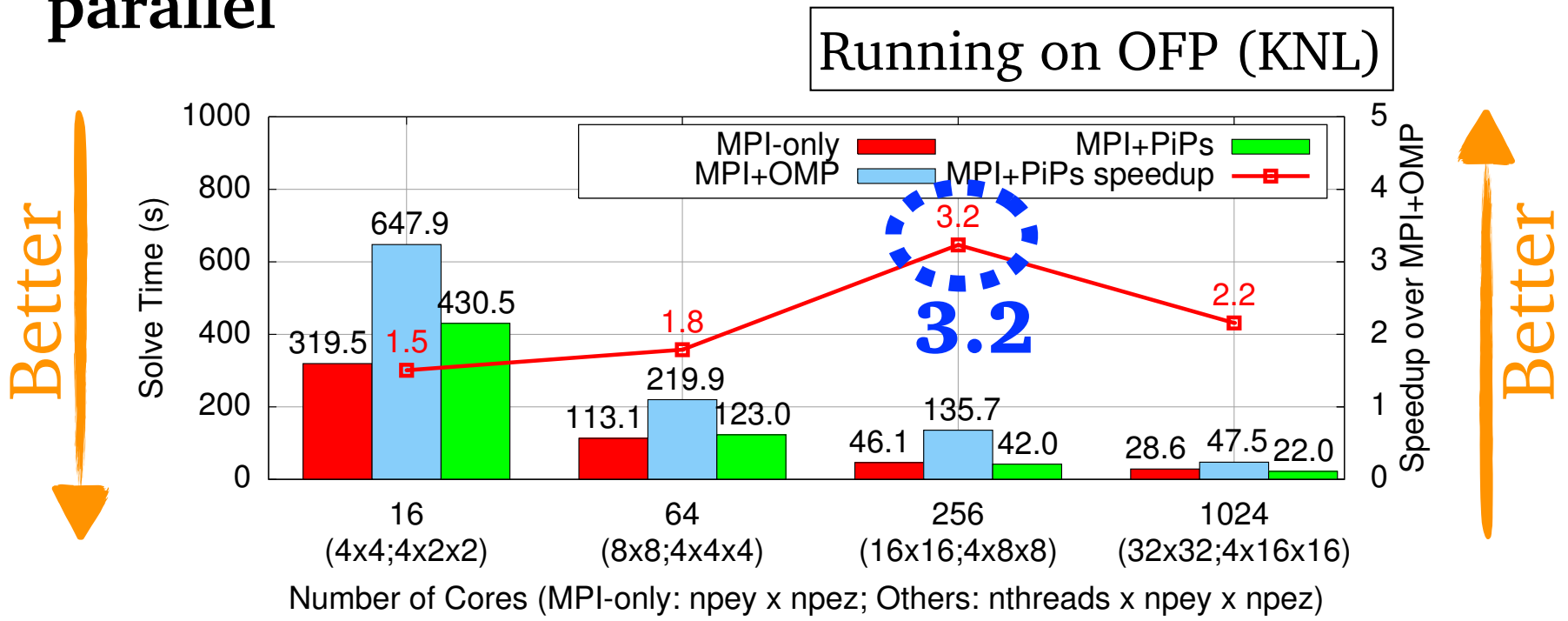


- Each PiP task has its own MPI lib. and they can run in parallel

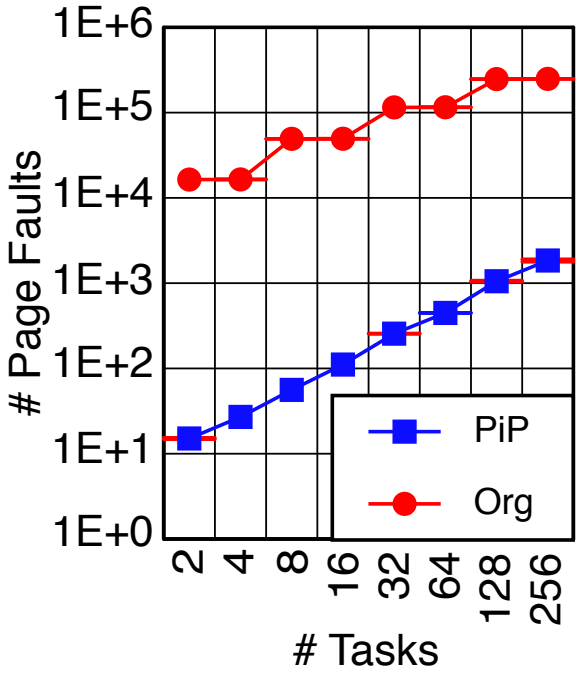


SNAP

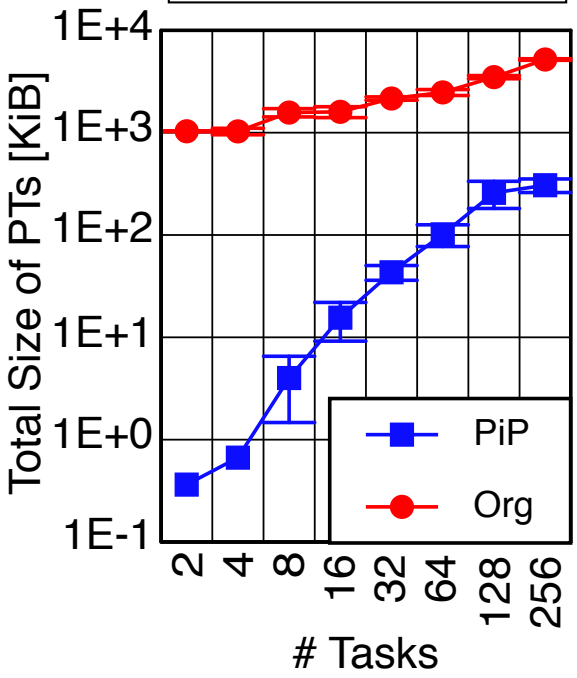
- Before: MPI + OpenMP
  - SNAP call MPI functions from each OpenMP thread
  - Only one communication takes place at a time
- After: MPI + PiP
  - Each PiP task can perform communication in parallel



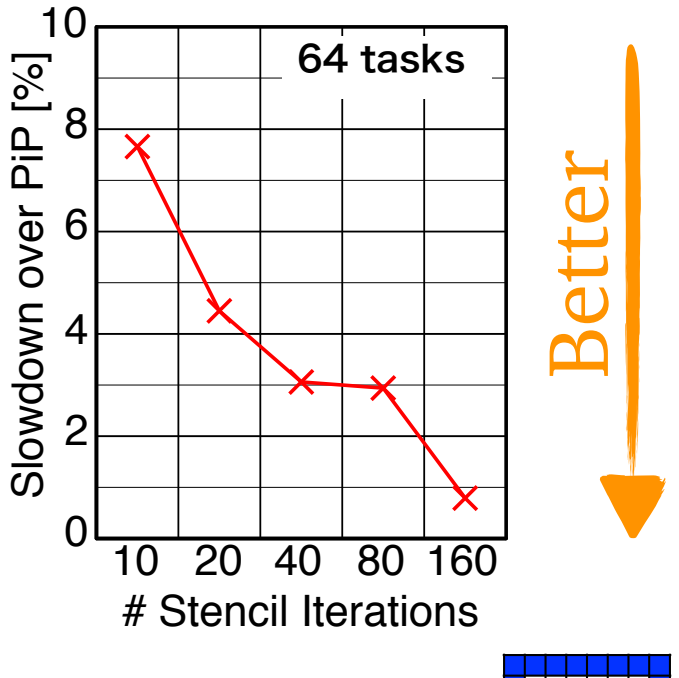
MPI_Win_allocate_shared()



not in the paper



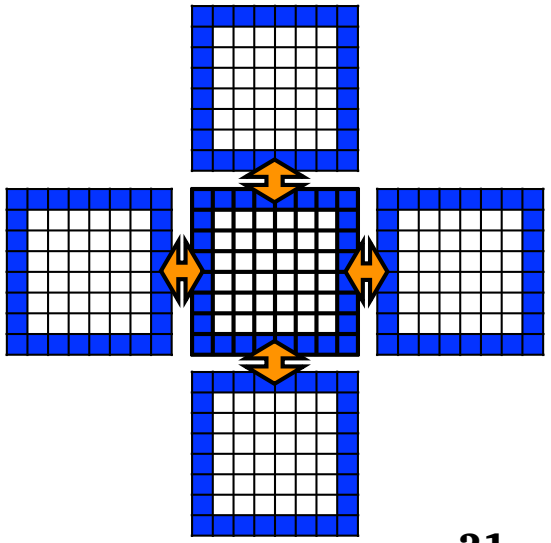
not in the paper



- **Org:** POSIX Shmem (Memory Mapping)
- **PiP:** VAS Sharing

5P Stencil (double, 8K x 8K), Xeon Phi (KNL)

Example program stencil_mpi_shmem.c in Advanced MPI Programming - Tutorial at SC14. http://www.mcs.anl.gov/~thakur/sc14-mpi-tutorial



Memory Mapping vs. PiP

- Memory Mapping Technique (POSIX Shmem, XPMEM, …)
  - ➡ OH of sub-PT creation (create, attach, etc.)
  - ➡ OH of maintaining coherency (page fault)
  - ➡ Each process must have PT entries - $O(N^2)$
- ✳ Those OH can be avoided by using PiP
  Because Page table is shared

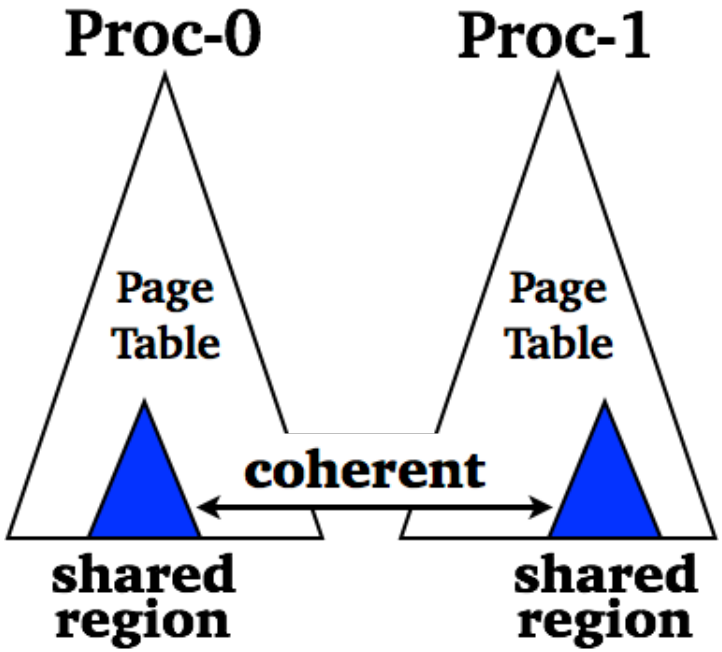


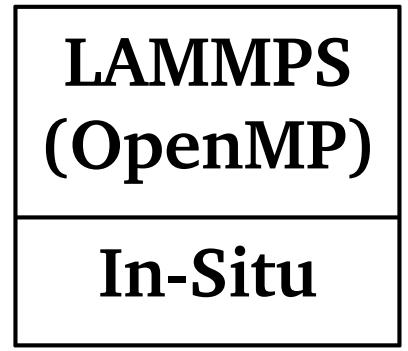
Table 5. Overhead of XPMEM and POSIX shmem functions (Xeon/Linux)

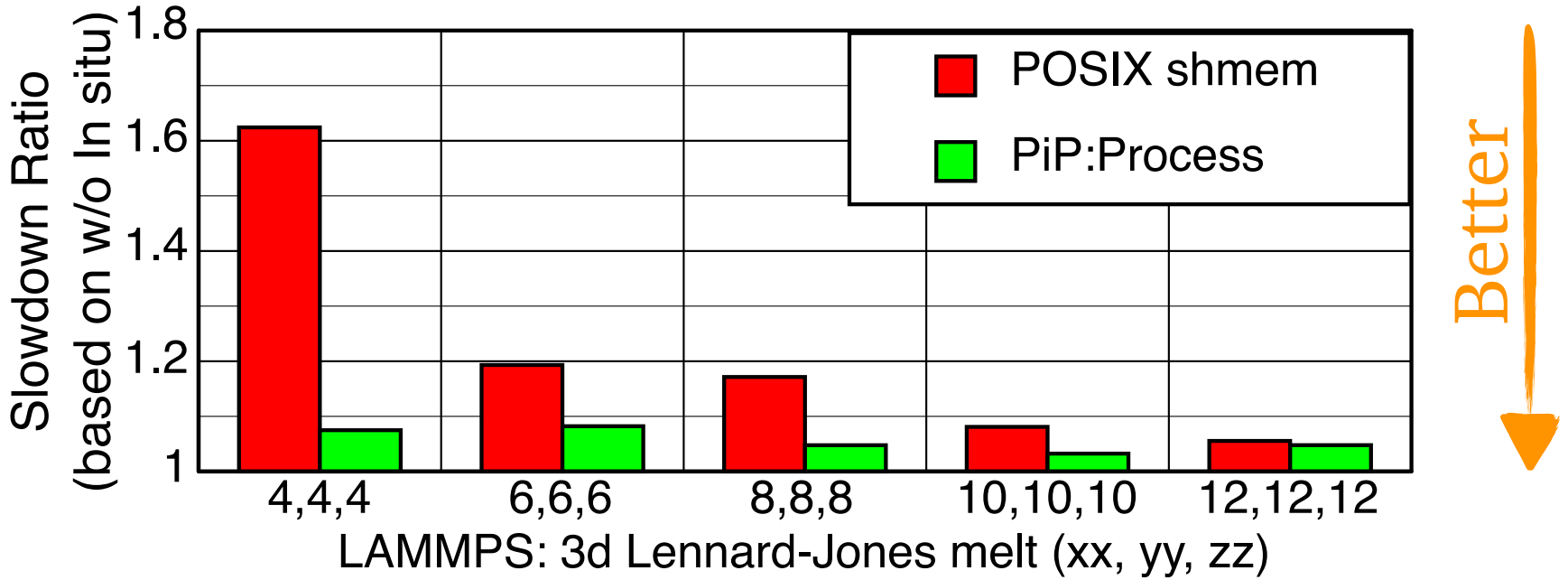
XPMEM	Cycles
xpmem_make()	1,585
xpmem_get()	15,294
xpmem_attach()	2,414
xpmem_detach()	19,183
xpmem_release()	693

	POSIX Shmem	Cycles
Sender	shm_open()	22,294
	ftruncate()	4,080
	mmap()	5,553
	close()	6,017
Receiver	shm_open()	13,522
	mmap()	16,232
	close()	16,746

LAMMPS with In-Situ

- Before: LAMMPS + In-Situ
  - Using POSIX shmem -> 2 Copies
- After: LAMMPS + In-Situ (as a PiP task)
  - LAMMPS passes a pointer to In-Situ and In-Situ copies simulation data -> 1 Copy





Summary

- PiP provides the 3rd execution model at user-level
  - Portable (on most Linux compatible OS)
    - dlmopen(), PIE, and clone() or pthread_create()
  - Practical
    - Runs on big machines (K and OFP) in operation
- PiP outperforms Memory Mapping Techniques
  - Setup cost
  - Page fault overhead
  - Page table size
- PiP Showcases
  - PiP-aware MPI — pt2pt, MPI_Win_allocate_shared()
  - MPI+PiP outperforms MPI+OpenMP
  - More efficient In-Situ implementation

FAQs

- ✓ It is crazy to mix programs, I cannot debug
  - Can't you debug multi-thread programs ?
  - Do not mix independent programs.
    Mix communicating and/or interacting programs.
- ✓ Is PiP a Programming Model ?
  - No, it is a execution model
- ✓ If I use huge pages, PiP has no advantage
  - PiP can work with huge pages
  - Pit falls of using huge pages
    - Transparent Huge Pages may hinder execution
    - Other huge page techniques require extra programming
    - More memory consumption
- ✓ We are already happy with MPI and OpenMP, no need of PiP
  - PiP is for people who are not happy with them.
- ✓ PiP+OpenMP works ?
  - In PiP Process Mode: YES. In Thread Mode, it depends.