# Latest in OpenSHMEM: Specification, API, and Programming

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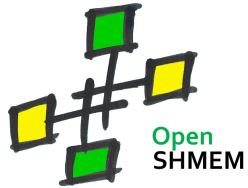
# Tutorial Outline




- The OpenSHMEM API
- Solving SAT with OpenSHMEM
- OpenSHMEM Serial to Parallel Code
  Distributed Hash Table
- OpenSHMEM implementation: from the hardware layer to the user layer

# The OpenSHMEM API

Graham Lopez
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Material: Swaroop Pophale

# Outline

- Background
- Introduction to OpenSHMEM
- History of SHMEM
- OpenSHMEM Effort
- OpenSHMEM Concepts
- OpenSHMEM API

# We assume …

- Knowledge of C
- Familiarity with parallel computing
- Linux/UNIX command-line

# Background

- Global vs. distributed Address Spaces
  - OpenMP has global (shared) space
  - MPI has partitioned space; private data exchanged via messages
  - OpenSHMEM uses “partitioned global address space” (PGAS)
    - Implemented as a library

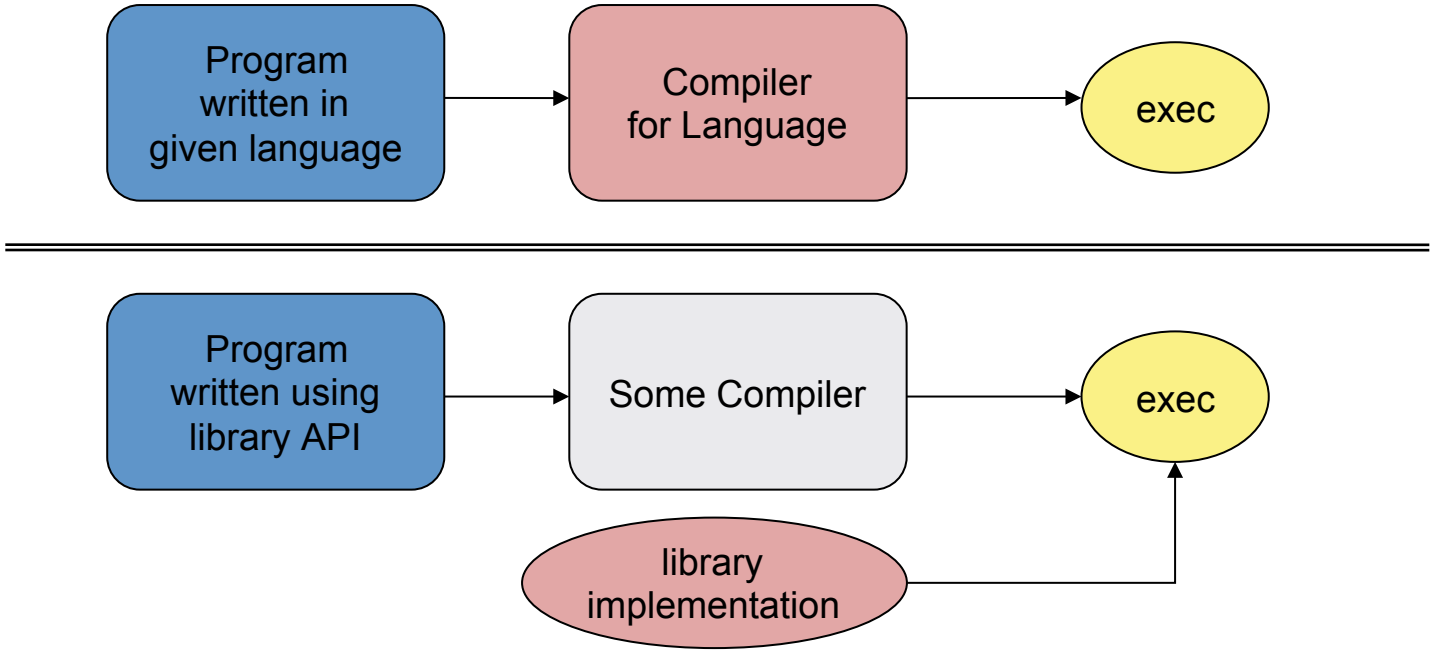
# Background

- SPMD – single program, multiple data
  - Program launches many processes
  - Each starts with the same code (SP)
  - But then typically operates on some specific part of the data (MD)
  - Processes may then communicate with each other
    - Share common data
    - Broadcast work
    - Collect results
    - Synchronization

# Background

- The PGAS family
  - Libraries include:
    - GASNet, ARMCI / Global Arrays, UCCS, CCI, GASPI/GPI, OpenSHMEM
  - Languages include:
    - Chapel, Titanium, X10, UPC, CAF
  - A language or library can be used on many machine types, their implementation hides differences & leverages features

# Background




PGAS Languages vs Libraries

# Background

| Languages | Libraries |
|---|---|
| Often more concise | More information redundancy in program |
| Requires compiler support | Generally not dependent on a particular compiler |
| More compiler optimization opportunities | Library calls are a "black box" to compiler, typically inhibiting optimization |
| User may have less control over performance | Often usable from many different languages through bindings |
| **Examples:** UPC, CAF, Titanium, Chapel, X10 | **Examples:** OpenSHMEM, Global Arrays, MPI-3 |

PGAS Languages vs Libraries

# Background

## PGAS Language - UPC

- A number of threads working independently in an SPMD fashion
- Number of threads specified at compile-time or run-time; program variable THREADS
  - MYTHREAD specifies thread index (0..THREADS-1)
  - upc_barrier is a global synchronization: all wait
  - upc_forall is the work sharing construct

- There are two compilation modes
  - Static and Dynamic threads mode

# Background

## Hello World in UPC

- Any legal C program is also a legal UPC program
- If you compile and run it as UPC with N threads, it will run N copies of the program.
- Example of a parallel hello world using UPC:

```
#include <upc.h>  /* needed for UPC extensions */
#include <stdio.h>

  main() {
    printf("Thread %d of %d: hello UPC world\n",
                                    MYTHREAD, THREADS);
  }
```

# Background

- PGAS Language - Coarray Fortran (CAF)
  - Multiple executing images
  - Explicit data decomposition and movement across images achieved by declaring and accessing coarrays
  - Image control statements
    - subdivide program into execution segments
    - determine partial ordering of segments among images
    - define scope for compiler optimization
  - Part of Fortran 2008 standard
  - Other languages enhancements (teams, expanded collectives and atomics, semaphore synchronization, resilience) are being considered for next revision

# Introduction to OpenSHMEM

- An SPMD parallel programming library
  - Library of functions similar in feel to MPI (e.g. shmem_get())
- Available for C / Fortran
- Used for programs that
  - perform computations in separate address spaces and
  - explicitly pass data to and from different processes in the program.
- The processes participating in shared memory applications are referred to as processing elements (PEs).
- OpenSHMEM routines supply remote data transfer, work-shared broadcast and reduction, barrier synchronization, and atomic memory operations.

# Introduction to OpenSHMEM

- An OpenSHMEM “Hello World”

```
#include <stdio.h>
#include <shmem.h>

int main (int argc, char **argv) {
  int me, npes;
  shmem_init (); /*Library Initialization*/
  me = shmem_my_pe ();
  npes = shmem_n_pes ();
  printf ("Hello World from PE %4d of %4d\n", me, npes);
  return 0;
}
```

# History of SHMEM

- Cray
  - SHMEM first introduced by Cray Research Inc. in 1993 for Cray T3D
  - Platforms: Cray T3D, T3E, PVP, XT series
- SGI
  - Owns the “rights” for SHMEM
  - Baseline for OpenSHMEM development (Altix)
- Quadrics (company out of business)
  - Optimized API for QsNet
  - Platform: Linux cluster with QsNet interconnect
- Others
  - HP SHMEM, IBM SHMEM
  - GPSHMEM (cluster with ARMCI & MPI support, old)

  - Note: SHMEM was not defined by any one standard.

# Divergent Implementations

- Many forms of initialization
  - Include header shmem.h to access the library
    - #include <shmem.h>
    - #include <mpp/shmem.h>
  - start_pes, shmem_init: Initializes the shmem portion of the program
  - my_pe: Get the PE ID of local processor
  - num_pes: Get the total number of PEs in the system

# Divergent Implementations

| SGI | | Quadrics | Cray | |
|---|---|---|---|---|
| **Fortran** | **C/C++** | **C/C++** | **Fortran** | **C/C++** |
| start_pes | start_pes(0) | shmem_init | start_pes | start_pes |
| | | | shmem_init | shmem_init |
| shmem_my_pe | shmem_my_pe | | shmem_my_pe | shmem_my_pe |
| shmem_n_pes | shmem_n_pes | | shmem_n_pes | shmem_n_pes |
| NUM_PES | _num_pes | num_pes | NUM_PES | |
| MY_PE | _my_pe | my_pe | | |

# Divergent Implementations

## Hello World (SGI on Altix)

```
#include <stdio.h>
#include <mpp/shmem.h>
int main(void)
{
   int me, npes;
   start_pes(0);
   npes = _num_pes();
   me = _my_pe();
   printf("Hello from %d of %d\n",
            me, npes);
   return 0;
}
```

## Hello World (Cray)

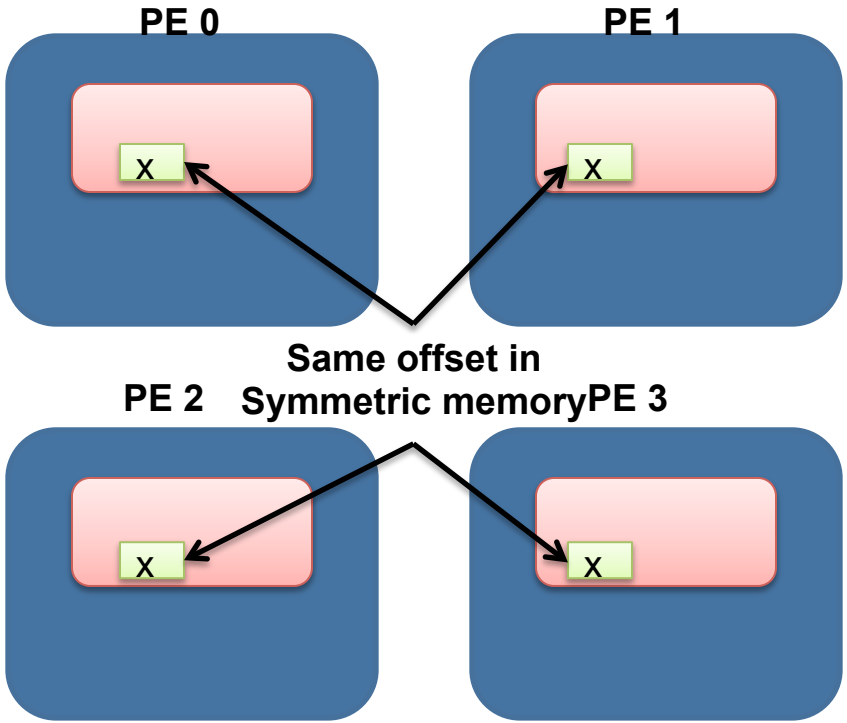
```
#include <stdio.h>
#include <shmem.h>
int main(void)
{
   int me, npes;
   shmem_init();
   npes = num_pes();
   me = my_pe();
   printf("Hello from %d of %d\n",
            me, npes);
   return 0;
}
```

# OpenSHMEM Concepts

- Symmetric Variables
  - Arrays or variables that exist with the **same name, size, type, and relative address** on all PEs.
  - The following kinds of data objects are  symmetric:
    - Fortran data objects in common blocks or with the **SAVE** attribute.
    - Non-stack C and C++ variables.
    - Fortran arrays allocated with **shpalloc**
    - C and C++ data allocated by **shmalloc**

# OpenSHMEM Concepts

```
int main (void)
{
    int *x;
    …
    shmem_init();
    …
    x = (int*)
    shmalloc(sizeof(*x));
    …
    …
    shmem_barrier_all();
    …
    shfree(x);
    return  0;
}
```




Dynamic allocation of Symmetric Data

# OpenSHMEM API

- Initialization, Query and Exit Routines
- Memory Management Routines
- Data transfers
- Synchronization mechanisms
- Collective communication
- Atomic Memory Operations

# OpenSHMEM Initialization, Query and Exit

**`void shmem_init(void)`**

- Same functionality as deprecated **`void start_pes(int n)`**
- Number of PEs taken from invoking environment
  - E.g. from MPI or job scheduler
- PEs numbered 0 .. (N – 1) in flat space

**`int shmem_n_pes(void)`**

- return number of PEs in this program

**`int shmem_my_pe(void)`**

- return “rank” of calling PE

**`void shmem_finalize(void)`**

- collective operation to exit the OpenSHMEM environment

**`void shmem_global_exit(int status)`**

- one PE may force all PEs to exit the OpenSHMEM environment

# OpenSHMEM Memory Management Routines

**`void *shmem_malloc(size_t size)`**

- Allocate symmetric memory on all PEs.

**`void *shmem_free(void *ptr)`**

- Deallocate symmetric memory.

**`void *shmem_realloc(void *ptr, size_t size)`**

- Resize the symmetric memory

**`void *shmem_align(size_t alignment, size_t size)`**

- Allocate symmetric memory with alignment

# OpenSHMEM Memory Management Routines

```
/* shmem_alloc() & shmem_free() */
#include <stdio.h>
#include <shmem.h>
int main (int argc, char **argv)
{
  int *v;
  shmem_init();
  v=(int *)shmem_malloc(sizeof(int));
  …
  …
  shmem_free(v);
  return 0;
}
```

# OpenSHMEM Accessibility

- **`int shmem_pe_accessible(int pe)`**
  - Can this PE talk to the given PE?

- **`int shmem_addr_accessible(void *addr, int pe)`**
  - Can this PE address the named memory location on the given PE?

- In SGI SHMEM used for mixed-mode MPI/SHMEM programs
  - In “pure” OpenSHMEM, could just return “1”

- Could in future be adapted for fault-tolerance

# OpenSHMEM Data Transfer

- Put
  - Single variable
    - `void shmem_TYPE_p(TYPE *target, TYPE value, int pe)`
      - TYPE = double, float, int, long, short
  - Contiguous object
    - `void shmem_TYPE_put(TYPE *target, const TYPE *source, size_t nelems, int pe)`
      - For C: TYPE = double, float, int, long, longdouble, longlong, short
      - For Fortran: TYPE = complex, integer, real, character, logical
    - `void shmem_putN(void *target, const void *source, size_t nelems, int pe)`
      - Storage Size (N bits) = 32, 64, 128, mem (any size)

**Target must be symmetric**

# OpenSHMEM Data Transfer

- Example: Cyclic communication via puts

```
/*Initializations*/
int src;
int *dest;
…..
shmem_init();
….
src  = me;
dest = (int *) shmem_malloc (sizeof (*dest));
nextpe = (me + 1) % npes; /*wrap around */

shmem_int_put (dest, &src, 1, nextpe);
…
shmem_barrier_all();
x = dest * 0.995 + 45 * y;
…
```

**Points To Remember**

- 'Destination' has to be symmetric
- Consecutive puts are not guaranteed to finish in order
- Put returns after the data has been copied out of the source
- Completion guaranteed only after synchronization

# OpenSHMEM Data Transfer

- Get
  - Single variable
    - **`TYPE shmem_TYPE_g(TYPE *target, TYPE value, int pe)`**
      - For C: TYPE = double, float, int, long, longdouble, longlong, short
      - For Fortran: TYPE=complex, integer, real, character, logical
  - Contiguous object
    - **`void shmem_TYPE_get(TYPE *target, const TYPE *source, size_t nelems, int pe)`**
      - For C: TYPE = double, float, int, long, longdouble, longlong, short
      - For Fortran: TYPE=complex, integer, real, character, logical
    - **`void shmem_getN(void *target, const void *source, size_t nelems, int pe)`**
      - Storage Size (N bits) = 32, 64,128, mem (any size)
  - Source must be symmetric data object

# OpenSHMEM Data Transfer

- Example: Summation at PE 0

```
/*Initializations*/
int *src, dest, sum;
...
shmem_init();
...
src  = (int *) shmem_malloc (sizeof (*src));
src = me; sum = me;
if(me == 0){
   for(int i = 1; i < num_pes(); i++){
     shmem_int_get(&dest, src, 1, i)
     sum = sum + dest;
   }
}
...
```

**Points To Remember**

- **'Source' has to be remotely accessible**
- **Consecutive gets finish in order**
- **The routines return after the data has been delivered to the 'dest' on the local PE**

# OpenSHMEM Data Transfer

- Strided put/get

```
void shmem_TYPE_iput(TYPE *target, const TYPE *source,
                     ptrdiff_t tst, ptrdiff_t sst,
                     size_t nelems, int pe)
```

- For C: TYPE = double, float, int, long, longdouble, longlong, short
- For Fortran: TYPE=complex, integer, real, character, logical
- tst and sst indicate stride between accesses of target and source resp.

# OpenSHMEM Data Transfer

```
int main()
{
  static short source[10] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
  short target[10];
  int i,me;
  for (i = 0; i < 10; i += 1) {
      target[i] = 666;
  }
  shmem_init();
  me = _my_pe ();
  if (me == 1){
   /* source[0,1,2,3] -> target[0,2,4,6] */
      shmem_short_iget (target, source, 2, 1, 4, 0);
  }
  shmem_barrier_all ();    /* sync sender and receiver */
  if (me == 1){
      for (i = 0; i < 10; i += 1){
          printf ("PE %d: target[%d] = %hd, source[%d] = %hd\n",
                   me, i, target[i], i, source[i]);
      }
  }
  shmem_barrier_all ();    /* sync before exiting */
  return 0;
}
```

**Output:**

```
PE 1: target[0] = 1, source[0] = 1
PE 1: target[1] = 666, source[1] = 2
PE 1: target[2] = 2, source[2] = 3
PE 1: target[3] = 666, source[3] = 4
PE 1: target[4] = 3, source[4] = 5
PE 1: target[5] = 666, source[5] = 6
PE 1: target[6] = 4, source[6] = 7
PE 1: target[7] = 666, source[7] = 8
PE 1: target[8] = 666, source[8] = 9
PE 1: target[9] = 666, source[9] = 10
```

# OpenSHMEM Data Transfer

- Put vs. Get
  - Put call completes when data is “being sent”
  - Get call completes when data is “stored locally”

  - Cannot assume put has written until later synchronization
    - Data still in transit
    - Partially written at target
    - Put order changed by e.g. network

  - Puts allow overlap
    - Communicate
    - Compute
    - Synchronize

# OpenSHMEM Synchronization

- Active Sets
  - Way to specify a subset of PEs
  - A triplet:
    - Start PE
    - Stride (log2)
    - Size of set
  - Limitations
    - Stride must be powers of 2
    - Only define ‘regular’ PE sub-groups

# OpenSHMEM Synchronization

- Barrier (Group synchronization)
  - **`void shmem_barrier_all()`**
    - Suspend PE execution until all PEs call this function
  - **`void shmem_barrier(int PE_start, int PE_stride, int PE_size, long *pSync)`**
    - Barrier operation on subset of PEs
  - pSync is a symmetric work array that allows different barriers to operate simultaneously

# OpenSHMEM Synchronization

- Conditional wait (P2P synchronization)
  - Suspend until local symmetric variable NOT equal to the value specified
  - **`void shmem_wait(long *var, long value)`**
  - **`void shmem_TYPE_wait(TYPE *var, TYPE value)`**
    - For C: TYPE = int, long, longdouble, longlong, short
    - For Fortran: TYPE = complex, integer, real, character, logical

- Specific conditional wait
  - Similar to the generic wait except the comparison can now be
    - >=, >, =, !=, <, <=
  - **`void shmem_wait_until(long *var, int cond, long value)`**
  - **`void shmem_TYPE_wait_until(TYPE *var, int cond, TYPE value)`**
    - TYPE = int, long, longlong, short

# OpenSHMEM Synchronization

```
#define GREEN 1
#define RED 0

int light=RED;
int main(int argc, char **argv)
{
    int me;
    shmem_init();
    me = shmem_my_pe();
    if(me==0){
        printf("me:%d. Stop on Red Light\n", me);
        shmem_int_wait(&light, RED); /* Is the light still red? */
        printf("me:%d. Now I may proceed\n", me);
    }
    if(me==1){
        sleep(1);
        light=GREEN;
        printf("me:%d. I've turn light to green.\n", me);
        shmem_int_put(&light, &light, 1, 0);
    }
    return 0;
}
```

```
Output:
me:0. Stop on Red Light
me:1. I've turned light to green
me:0. Now I may proceed
```

# OpenSHMEM Synchronization

- void shmem_fence()
  - Ensures ordering of outgoing write operations on a per-PE basis.

- void shmem_quiet()
  - Waits for completion of all outstanding remote writes and stores to symmetric data objects initiated from the calling PE.

# OpenSHMEM Synchronization

## Example Fence

```
...
if (shmem_my_pe() == 0) {
shmem_long_put(target, source, 3, 1); /*put1*/
shmem_long_put(target, source, 3, 2); /*put2*/
  shmem_fence();
shmem_int_put(&targ, &src, 1, 1);     /*put3*/
shmem_int_put(&targ, &src, 1, 2);     /*put4*/
}
...
```

put1 will be ordered to be delivered before put3

put2 will be ordered to be delivered before put4

## Example Quiet

```
...
shmem_long_put(target, source, 3, 1); /*put1*/
shmem_int_put(&targ, &src, 1, 2);     /*put2*/
  shmem_quiet();
shmem_long_get(target, source, 3, 1);
shmem_int_get(&targ, &src, 1, 2);
printf("target:{%d,%d,%d}\n",
        target[0],target[1],target[2]);
printf("targ: %d\n", targ); /*targ: 90*/
shmem_int_put(&targ, &src, 1, 1);     /*put3*/
shmem_int_put(&targ, &src, 1, 2);     /*put4*/
...
```

put1 & put2 will be delivered when quiet returns

# OpenSHMEM Collective Communication

- Broadcast
  - One-to-all symmetric communication
  - No update on root

- `void shmem_broadcastN(void *target, void *source,`
  `size_t nelems, int PE_root,`
  `int PE_start, int PE_stride,`
  `int PE_size, long *pSync)`

Storage Size (N bits) = 32, 64

# OpenSHMEM Collective Communication

Code snippet showing working of shmem_broadcast

```
...
int *target, *source;
target = (int *) shmalloc( sizeof(int) );
source = (int *) shmalloc( sizeof(int) );
*target = 0;
if (me == 0) {
    *source = 222;
}
else
    *source = 101;
shmem_barrier_all();
shmem_broadcast32(target, source, 1, 0, 0, 0, 4, pSync);

printf("target on PE %d is %d\n”, shmem_my_pe(), *target);
...
```

**Output:**
target on PE 0 is 0
target on PE 1 is 222
target on PE 2 is 222
target on PE 3 is 222

# OpenSHMEM Collective Communication

- Collection
  - Concatenates blocks of symmetric data from multiple PEs to an array in every PE
  - Each PE can contribute different amounts
  - ```
    void shmem_collectN(void *target, void *source,
                        size_t nelems, int PE_start,
                        int PE_stride, int PE_size,
                        long *pSync)
    ```

Storage Size (N bits) = 32, 64

  - Concatenation written on all participating PEs

  - shmem_fcollect variant
    - When all PEs contribute exactly same amount of data
    - PEs know exactly where to write data, so no offset lookup overhead
    ```

# OpenSHMEM Collective Communication

```
int sum;
int me,npe;
int main(int argc, char **argv)
{
    int i;
    long *pSync;
    int *pWrk, pWrk_size;
    shmem_inti();
    me = shmem_my_pe();
    npe = shmem_n_pes();
    pWrk = (int *) shmalloc (npe);
    pSync = (long *) shmalloc (SHMEM_REDUCE_SYNC_SIZE);
    for (i = 0; i < SHMEM_REDUCE_SYNC_SIZE; i += 1){
        pSync[i] = _SHMEM_SYNC_VALUE;
    }
    shmem_barrier_all();
    shmem_int_sum_to_all(&sum, &me, 1, 0, 0, npe, pWrk, pSync);
    shmem_barrier_all();
    printf("me:%d. Total sum of 'me' is %d\n", me, sum);
    return 0;
}
```

**Output:**

```
me:1. Total sum of 'me' is 45
me:2. Total sum of 'me' is 45
me:3. Total sum of 'me' is 45
me:4. Total sum of 'me' is 45
me:5. Total sum of 'me' is 45
me:6. Total sum of 'me' is 45
me:7. Total sum of 'me' is 45
me:8. Total sum of 'me' is 45
me:9. Total sum of 'me' is 45
me:0. Total sum of 'me' is 45
```

# OpenSHMEM Collective Communication

- Reductions
  - Perform commutative operation across symmetric data set
    - `void shmem_TYPE_OP_to_all(TYPE *target, TYPE *source, int nreduce, int PE_start, int PE_stride, int PE_size, TYPE *pWrk, long *pSync)`
    - Logical OP = and, or, xor
    - Extrema OP = max, min
    - Arithmetic OP = prod(uct), sum
    - TYPE = int, long, longlong, longdouble, short, complex
  - Reduction performed and stored on all participating PEs
  - pWrk and pSync allow interleaving

  - E.g. compute arithmetic mean across set of PEs
    - sum_to_all / PE_size

# OpenSHMEM Atomic Operations

- What does “atomic” mean anyway?
  - Indivisible operation on symmetric variable
  - No other operation can interpose during update

- But “no other operation” actually means…?
  - No other atomic operation
  - Can’t do anything about other mechanisms interfering
    - E.g. thread outside of OpenSHMEM program
    - Non-atomic OpenSHMEM operation

  - Why this restriction?
    - Implementation in hardware

# OpenSHMEM Atomic Operations

- Atomic Swap
  - Unconditional
    - `long shmem_swap(long *target, long value, int pe)`
    - `TYPE shmem_TYPE_swap(TYPE *target, TYPE value, int pe)`
      - TYPE = double, float, int, long, longlong
      - Return old value from symmetric target
  - Conditional
    - `TYPE shmem_TYPE_cswap(TYPE *target, TYPE cond, TYPE value, int pe)`
      - TYPE = int, long, longlong
      - Only if “cond” matches value on target

# OpenSHMEM Atomic Operations

- Arithmetic
  - increment (= add 1) & add value
  - `void shmem_TYPE_inc(TYPE *target, int pe)`
  - `void shmem_TYPE_add(TYPE *target, TYPE value, int pe)`
    - TYPE = int, long, longlong

  - Fetch-and-increment & fetch-and-add value
  - `TYPE shmem_TYPE_finc(TYPE *target, int pe)`
  - `TYPE shmem_TYPE_fadd(TYPE *target, TYPE value, int pe)`
    - TYPE = int, long, longlong
  - Return previous value at target on PE

# OpenSHMEM Atomic Operations

```
...
long *dest;
dest = (long *) shmalloc( sizeof(*dest) );
 *dest = me;
 shmem_barrier_all();
...
new_val = me;
 if (me == 1) {
    swapped_val = shmem_long_swap(target, new_val, 0);
    printf("%d: target = %d, swapped = %d\n",
                        me, *target, swapped_val);
 }
shmem_barrier_all();
...
```

# OpenSHMEM Atomic Operations

- Locks
  - Symmetric variables
  - Acquired and released to define mutual-exclusion execution regions
    - Only 1 PE can enter at a time
  - **`void shmem_set_lock(long *lock)`**
  - **`void shmem_clear_lock(long *lock)`**
  - **`int shmem_test_lock(long *lock)`**
    - Acquire lock if possible, return whether or not acquired
    - But don’t block…
  - Initialize lock to 0. After that managed by above API
  - Can be used for updating distributed data structures

# Solving SAT with OpenSHMEM

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# Background

The examples are based on http://ubcsat.dtompkins.com

- Code https://github.com/dtompkins/ubcsat
- OpenSHMEM based code https://github.com/shamisp/ubcsat/tree/shmem

Parallel solver algorithm is based on: *"Massively Parallel Local Search for SAT"*, Alejandro Arbelaez, Philippe Codognet

- Full paper: http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6495029&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel7%2F6493540%2F6495011%2F06495029.pdf%3Farnumber%3D6495029

# What is the SAT problem ?

$$F = (v11 \vee v12 \vee v13) \wedge (v21 \vee v22 \vee v23) \wedge \cdots \wedge (vn1 \vee vn2 \vee vn3)$$

Clause (3-SAT)

- Finding an assignment for all the variables such that all clauses are satisfied and $F$ is true
- NP-Complete

# How do we solve it

Local search !

Sparrow local search solver

- Winner of 2011 SAT competition
- Part of UBCAST framework
- https://github.com/dtompkins/ubcsat/tree/satcomp2011-sparrow

# Local Search for SAT

```
0: for try = 1 to MaxTries {
1:         A = variable-initialization(F)
2:         for Iteration = 1 to MaxFlips {
3:                 if A satisfies F then
4:                         return A
5:                 x = select-variable(A)
6:                 A = A with x flipped
7:         }
8: }
9: return “No solution”
```

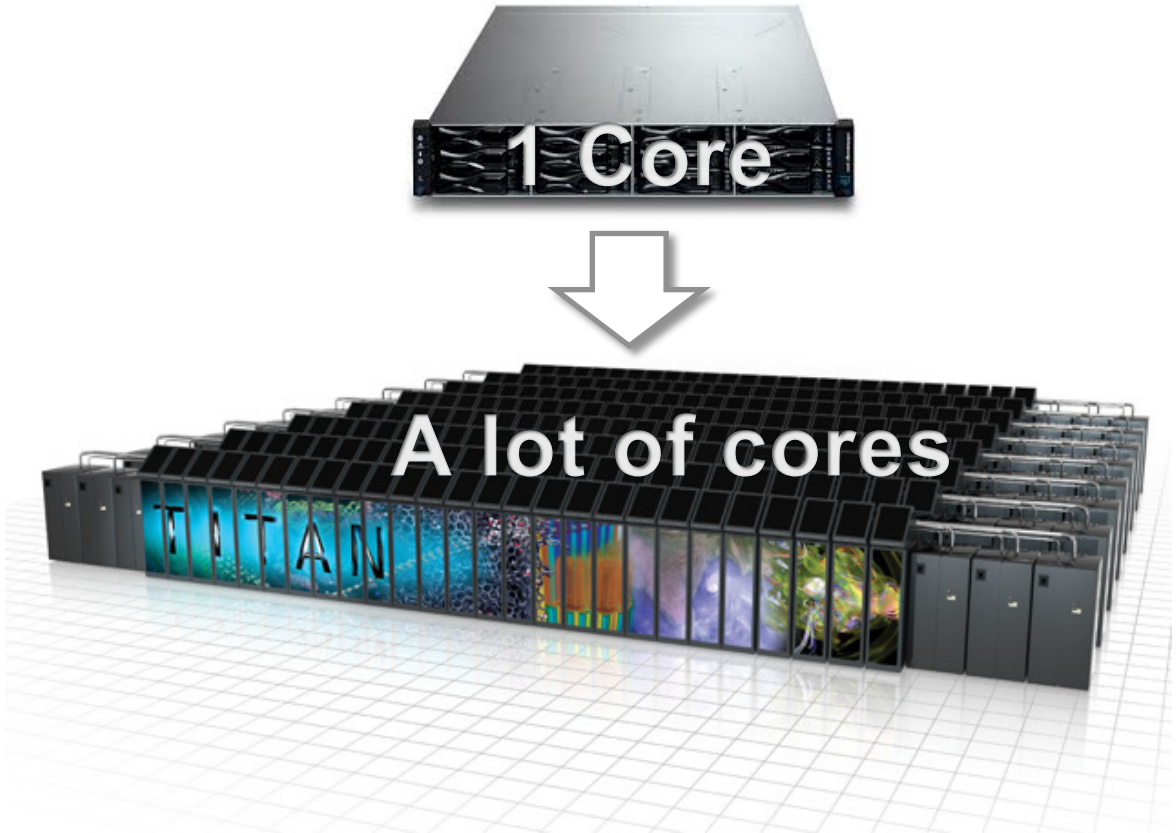
# Local Search for SAT

Starting point for the search

The “secret sauce”

```
for try = 1 to MaxTries {
        A = variable-initialization(F)
        for Iteration = 1 to MaxFlips {
                if A satisfies F then
                        return A
                x = select-variable(A)
                A = A with x flipped
        }
}
return “No solution”
```

# Parallel Local Search



# Portfolio-based Parallel Local Search

Each process uses unique SEED

```
0: Init-Seed(Process_ID)
0: for try = 1 to MaxTries {
1:         A = variable-initialization(F)
2:         for Iteration = 1 to MaxFlips {
3:                 if A satisfies F then
4:                         eureka-return(A)
5:                 x = select-variable(A)
6:                 A = A with x flipped
7:         }
8: }
9: return “No solution”
```

# Code Snippet

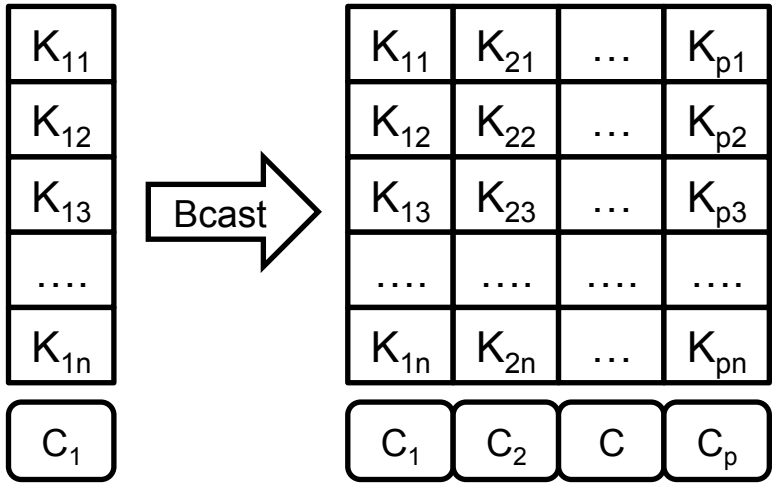
```
0: Init-Seed(Process_ID)
0: for try = 1 to MaxTries {
1:         A = variable-initialization(F)
2:         for Iteration = 1 to MaxFlips {
3:                 if A satisfies F then
4:                         eureka-return(A)
5:                 x = select-variable(A)
6:                 A = A with x flipped
7:         }
8: }
9: return “No solution”
```

```
start_pe(0);
seed = atoi(argv[2]) * (1+shmem_my_pe());
```

```
/* OpenSHMEM 1.2 */
shmem_global_exit(0);
```

```
/* OpenSHMEM 1.2 */
shmem_finalize();
```

# Portfolio-based Parallel Local Search Information Sharing




Probability

***ProbNormilizedW****(i=True)* where
i∈ [1,n]
n-number of variables
c-number unsatisfied clauses

$$ProbNormilizedW(i = true) = \frac{\sum_{x\in[1,p]} K_{xi} * NormW_x}{\sum_{x\in[1,p]} NormW_x}$$

$$NormW_x = \frac{|C| - C_x}{|C|}$$

$$x - \ PE\ , i - variable$$

# Information Sharing

```
0: Init-Seed(Process_ID)
0: for try = 1 to MaxTries {
1:         A = variable-initializ
2:         for Iteration = 1  o F
3:                 if A sa    ies
4:                            re
5:                 x =        va
6:                            x
7:
8: }
9: retur
```

```
start_pe(0);
seed = atoi(argv[2]) * (1+shmem_my_pe());
/* Vertor of values */
rem_aVarValue = shmalloc(iNumVars * sizeof(BOOL) *
shmem_n_pes());
if (rem_aVarValue == NULL) {
      fprintf(stderr, "Failed to allocate memory for rem_aVarValue\n");
      shmem_global_exit(1);
}
memset(rem_aVarValue, 0, sizeof(BOOL) * shmem_n_pes());
/* Cost of the current solution */
rem_iNumFalse = shmalloc(sizeof(UINT32) * shmem_n_pes());
if (rem_iNumFalse == NULL) {
      fprintf(stderr, "Failed to allocate memory for rem_iNumFalse\n");
      shmem_global_exit(1);
}
memset(rem_iN
/* Signal that da
```

$$ProbNormilizedW(i = true) = \frac{\sum_{x \in}}{\sum}$$

$$NormW_x = \frac{|C| - C}{|C|}$$

$x - PE, i - variabl$

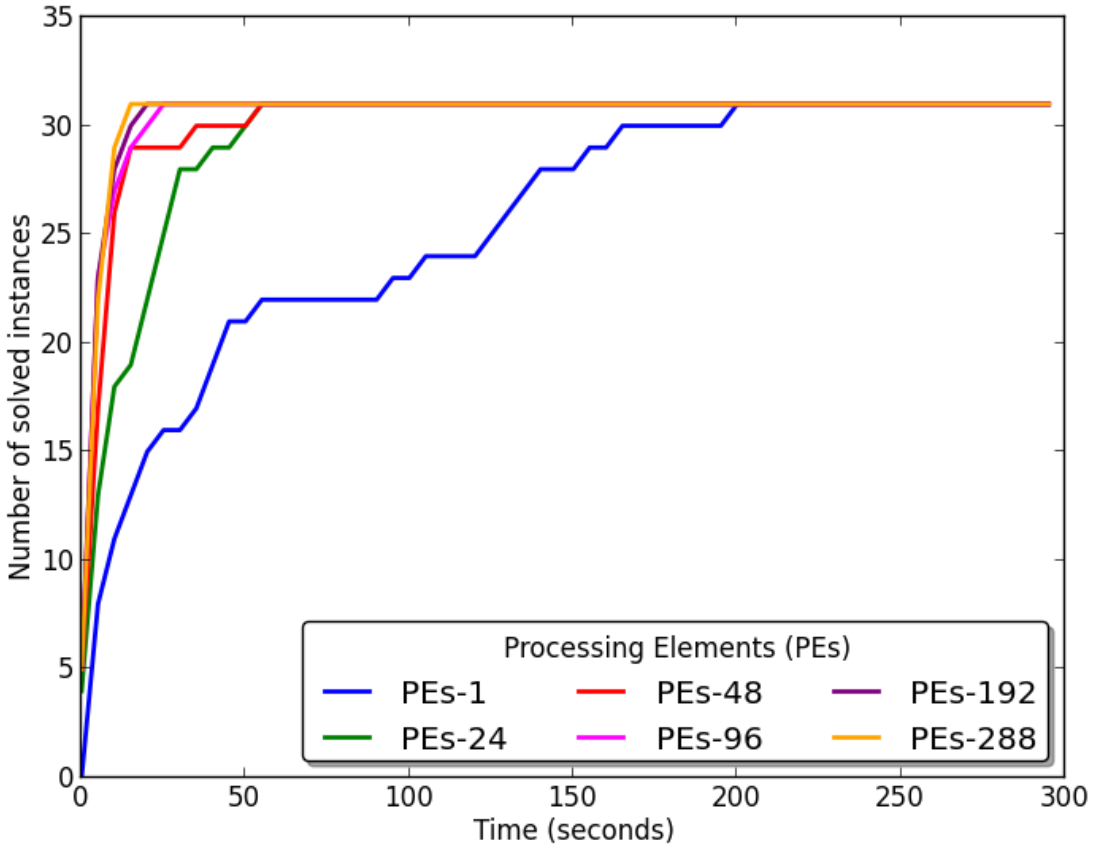
```
int i;
for (i = 0; i < shmem_n_pes(); i++) {
      shmem_putmem(get_rem_avar(shmem_my_pe(), 0),
                  aVarValue, iNumVars*sizeof(BOOL), i);
      shmem_putmem(get_rem_inum(shmem_my_pe()),
                  &iNumFalse,sizeof(UINT32), i);
        /* Announce update */
      shmem_fence();
      shmem_longlong_inc(&rem_counter[shmem_my_pe()],i);
}
```

# What Algorithm Performed the Best ?

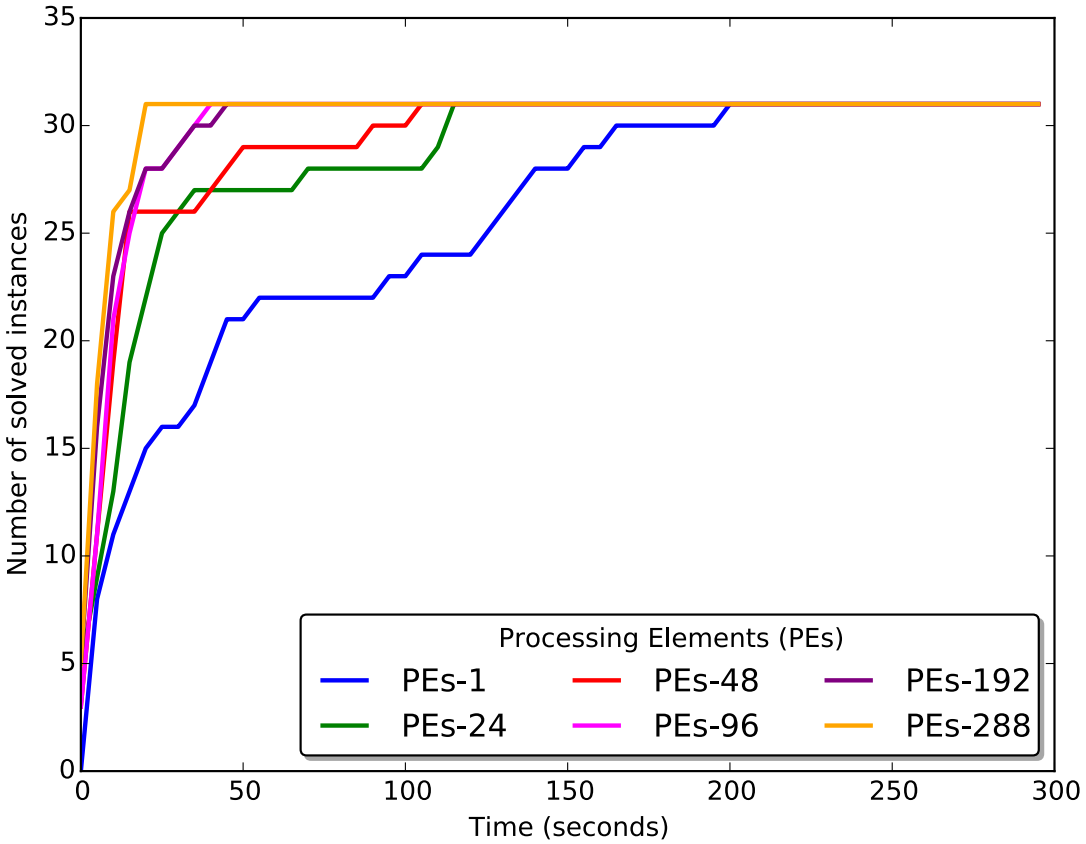
# Test-bed

- SGI Altix
- 12 nodes each one with 24 cores (288 cores in total)
- Processing Element (PE) per core
- InfiniBand interconnect
- 50 instances from SAT2011 (random)
- 3-SAT (x20), 5-SAT(x20), 7-SAT(x10)
- 3 iterations for each instance / median reported

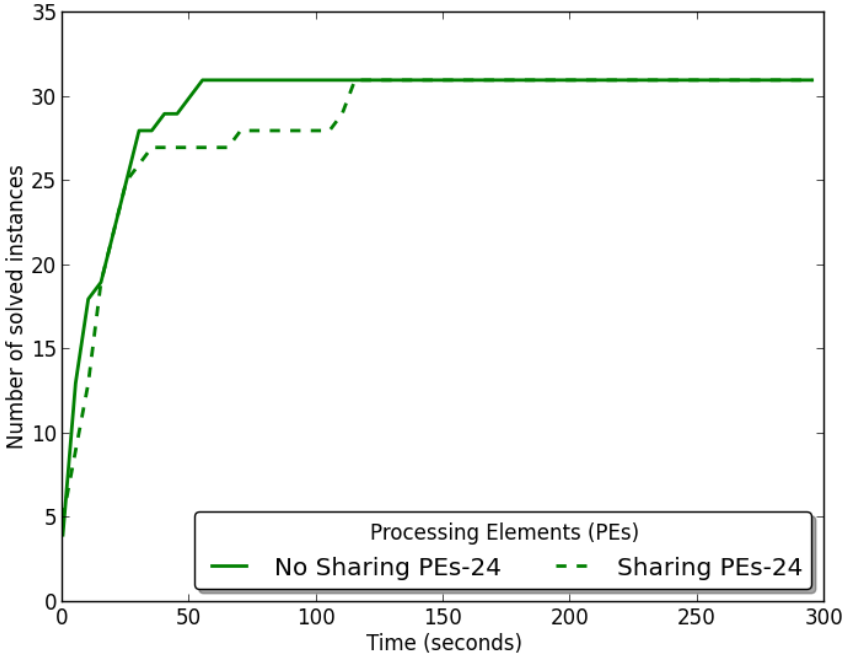
# Performance – No Information Sharing

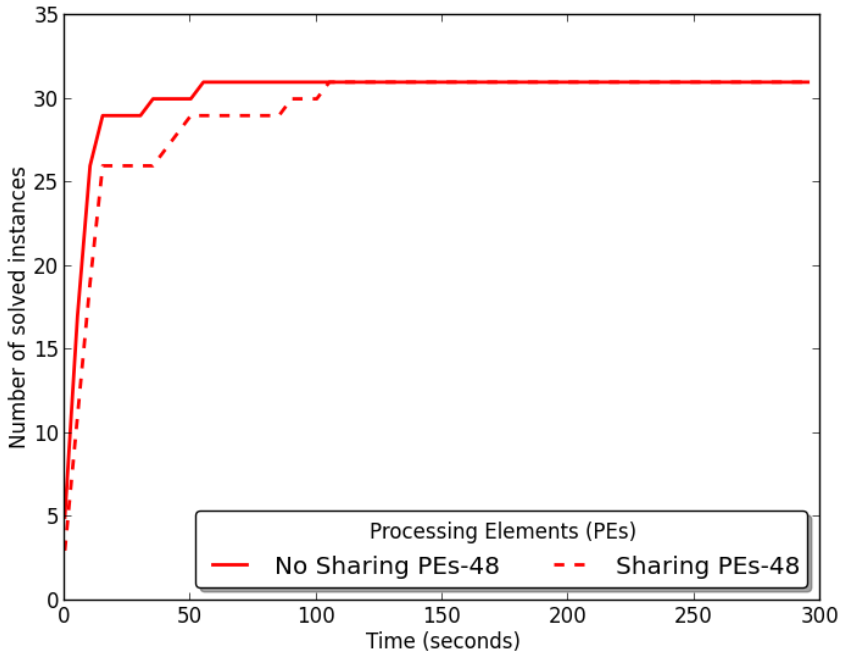


# Performance – Information Sharing

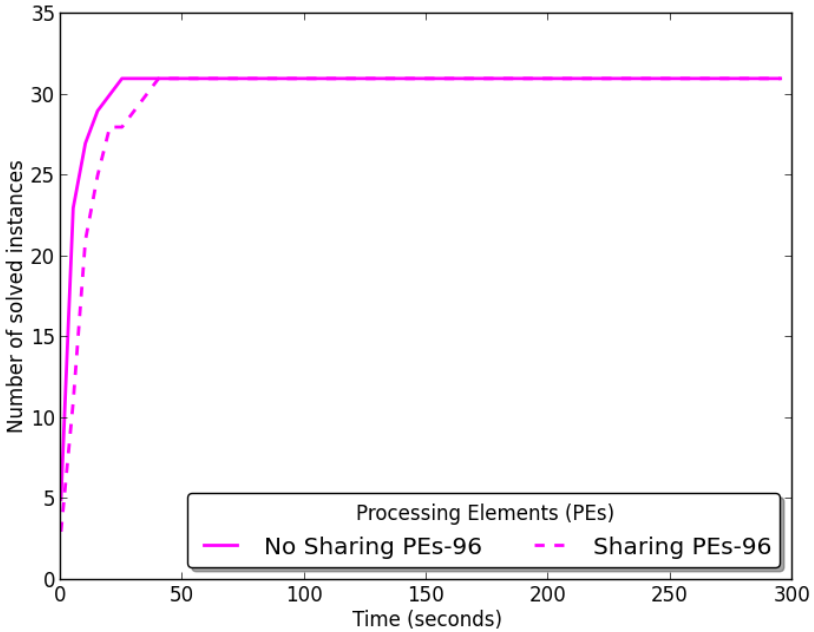


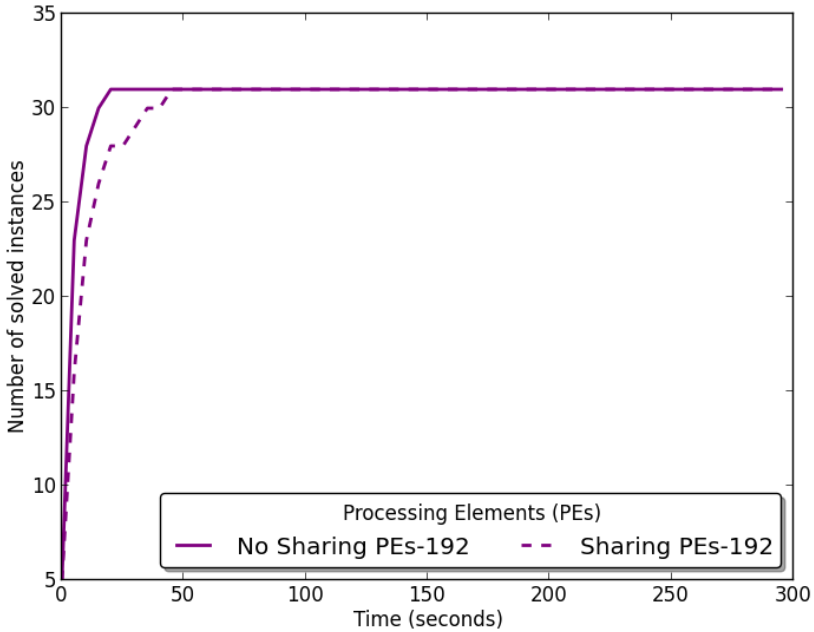
# Sharing VS No-sharing



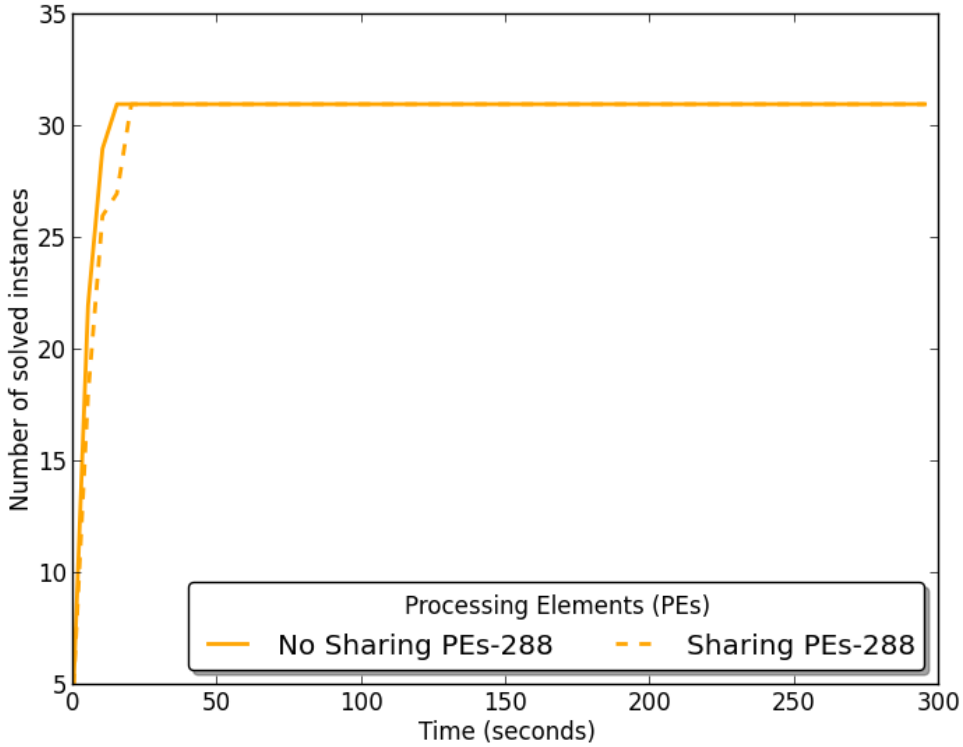



# Sharing VS No-sharing



# Sharing VS No-sharing



# Thanks !

Questions ?

# OpenSHMEM Serial to Parallel Code Conversion

# Distributed Hash Table (DHT)

Dounia Khaldi
University of Houston

# The Orbit Calculation Problem

- Application benchmark:
  - Group theory
  - Calculation of the orbits of a group G acting on a set M
  - Graph traversal problem, where each graph vertex is a group element
- For each graph vertex, compute some of its properties
- Which other graph vertices is a vertex connected to?

C. Maynard, “Comparing One-Sided Communication With MPI, UPC and SHMEM”, Cray Users Group (CUG), Tech. Rep., 2012.

# Notion of Orbit

**Input:** $m_0 \in M$, Group $G = \{g_i, 1 \le i \le r\}$
**Output:** A list L containing the elements of $m_0G$ ($G$-orbit of $m_0$)

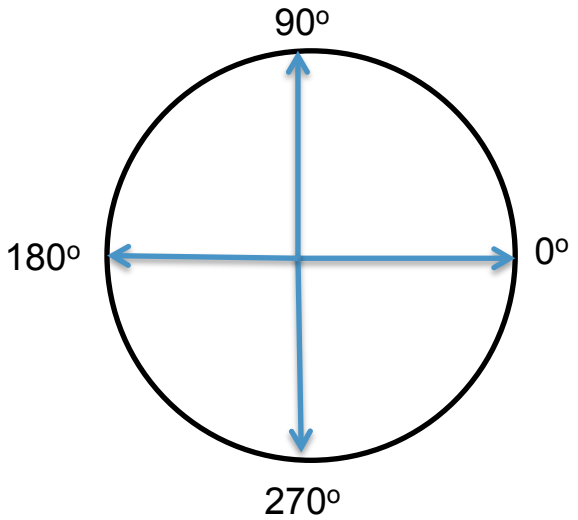
**Example:**

- **M** is a set of vectors
- **G** is a group of four 90° rotations

$$R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

- Composition of rotations corresponds to matrix multiplication
- **Orbit**: mG

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$



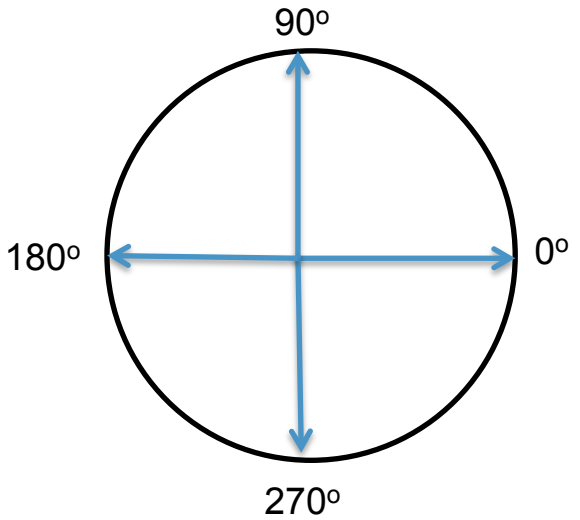

**G = {R(0°), R(90°), R(180°), R(270°) }**

# The Orbit Basic Algorithm

**Input:** $m_0 \in M$, Group $G = \{g_i, 1 \le i \le r\}$
**Output:** A list L containing the elements of $m_0G$ (G-orbit of $m_0$)

```
L := [m0]
for i from 1 to r do
    x := m0gi      // element of orbit of m0
    if x is not in L then
        append x to L
    end if
end for
return L
```

**DHT**



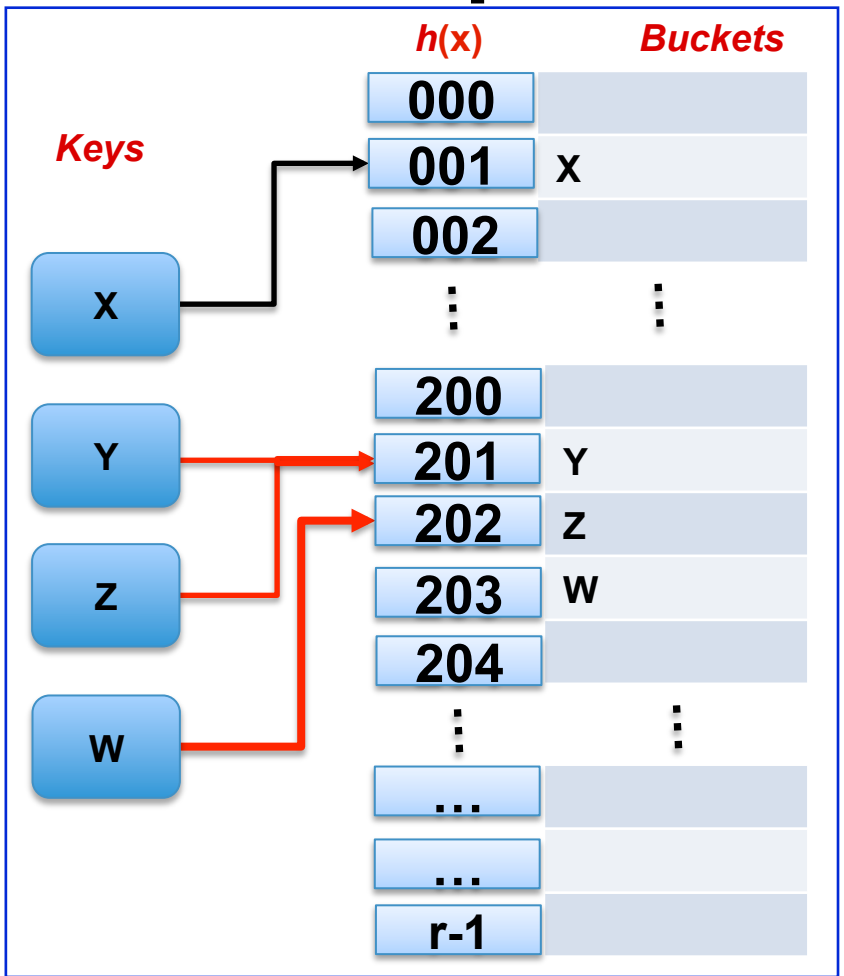

**G = {R(0°), R(90°), R(180°), R(270°) }**

F. Lübeck and M. Neunhöffer, “Enumerating large orbits and direct condensation”, Experiment. Math., vol. 10, no. 2, pp. 197–205, 2001.

# Orbit Calculation: Serial Hash Table

- Linear lookup of points in lists (sequential comparison) expensive for large orbits
- Hash table to keep track of whether a vertex has been visited
- Lookups using hash tables almost independent of the orbit length
- Limited to certain size of groups by the amount of memory available in serial implementation
- Parallel (distributed) implementation to allow larger orbits

# DHT: Open Addressing Strategy




**Implementation**

- **insert ()** puts new entry in the hash table if not present
- **lookup ()** searches for a key
- **delete ()** frees entry to remove from the hash table

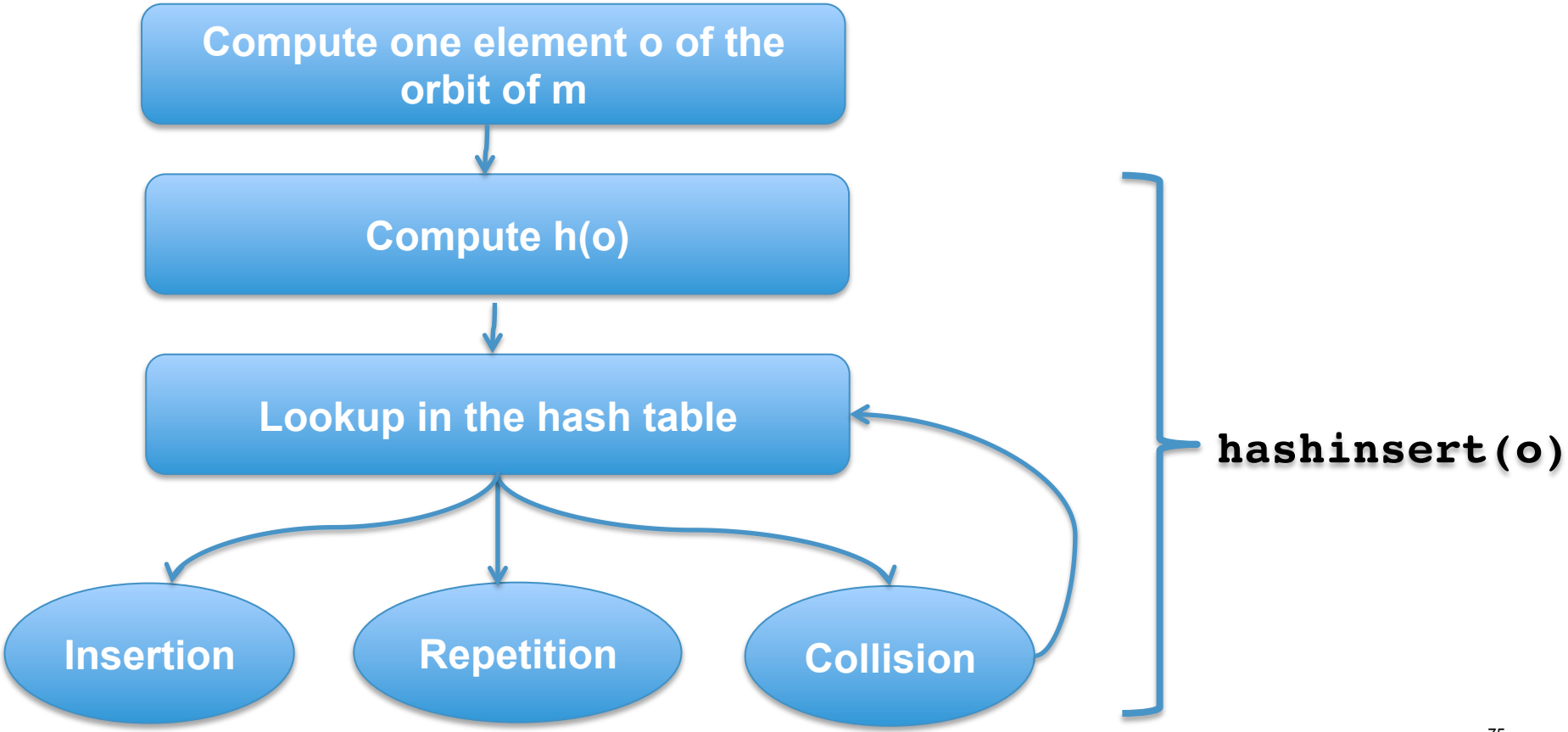
**Advantages**

- Lookup is fast
- Insertion is fast
- Unlike chaining, it cannot have more elements than table slots

**Disadvantage**

- Deletion should take into account collisions

# DHT: Sequential Code



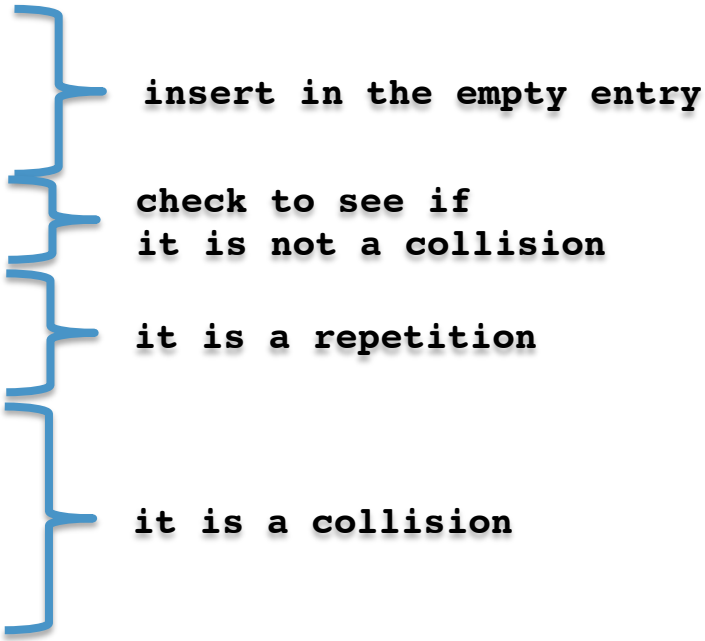
# DHT: Data Structures

- `hashtab`: the memory where to store the orbit
- `hashcount`: number of repetitions
- `hashlen`: max size of the orbit (r)
- `collisions`: number of collisions
- `dest_pos`: the index of an element of the orbit in `hashtab`
- `local_val`: the value of an element of `hashtab`

# DHT: Sequential Code (`hashinsert(o)`)

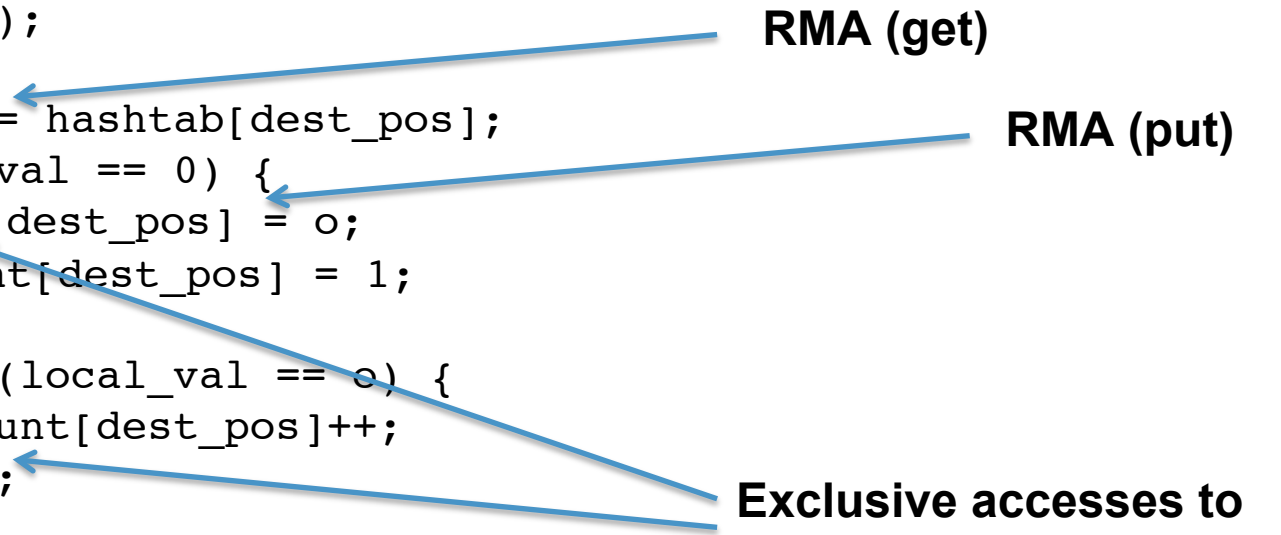
- Size of *G* (r: number of vertices): hashlen = r;

```
dest_pos = h(o);
while (1) {
    local_val = hashtab[dest_pos];
    if (local_val == 0) {
       hashtab[dest_pos] = o;
       hashcount[dest_pos] = 1;
       return;
    } else if (local_val == o) {
        hashcount[dest_pos]++;
        return;
    } else {
        collisions++;
        dest_pos++;
        if (dest_pos == hashlen)
            dest_pos = 0;
    }
}
```



# DHT: Sequential Code (`hashinsert(o)`)

```
dest_pos = h(o);
while (1) {
    local_val = hashtab[dest_pos];
    if (local_val == 0) {
       hashtab[dest_pos] = o;
       hashcount[dest_pos] = 1;
       return;
    } else if (local_val == o) {
        hashcount[dest_pos]++;
        return;
    } else {
        collisions++;
        dest_pos++;
        if (dest_pos == hashlen)
            dest_pos = 0;
    }
}
```

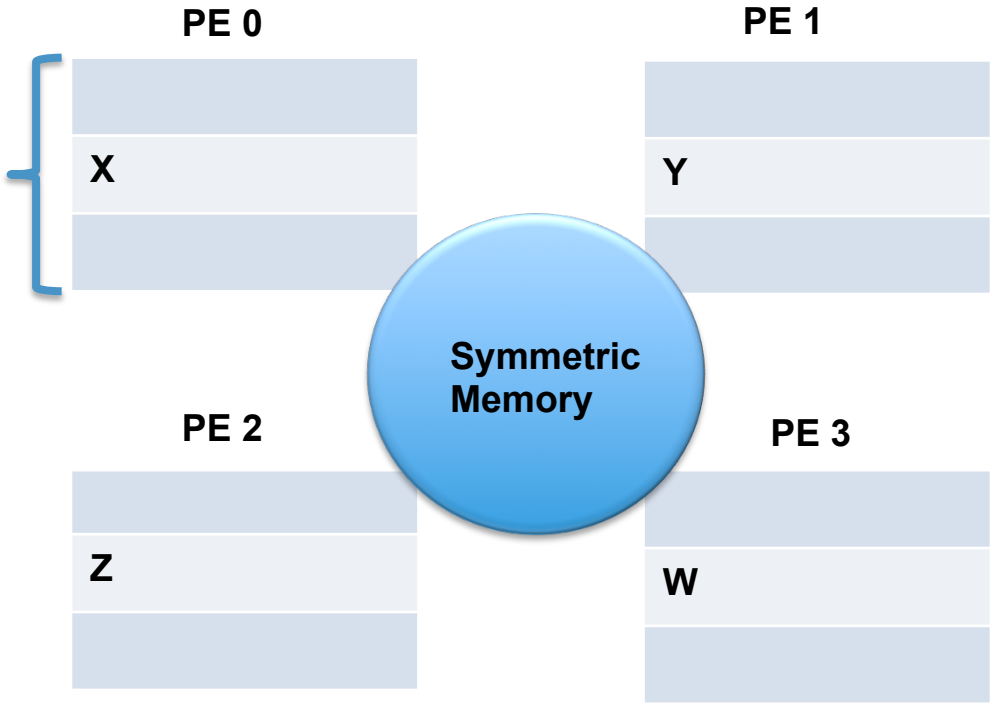


# Distributed Hash Table (DHT)

- The sender would know the identity of the receiver via hash, but not vice versa
- Larger hash tables created in parallel than can be done serially →
  much larger orbits
- Suitable for OpenSHMEM →
  requires RMA

# DHT: OpenSHMEM Code Initialization

**hashlen = r**




```
void inithash()
{
    npes = shmem_n_pes();
    mype = shmem_my_pe();
    hashlen = r;
    localhashlen = hashlen/npes;
    hashtab   = shmem_malloc( localhashlen * sizeof *hashtab );
    hashcount = shmem_malloc( localhashlen * sizeof *hashcount );
    pe_lock   = shmem_malloc( npes * sizeof *pe_lock );
    memset( pe_lock, 0, npes * sizeof *pe_lock);
}
```

# DHT: OpenSHMEM Code

```
#include <shmem.h>
//declaration of hashtab, hashcount,…
void orbit(m0,G)
{
   shmem_init();
   inithash();
   shmem_barrier_all();
   for (i = mype; i < hashlen; i+=npes) {
      hashinsert(apply(m0, g[i]));
   }
   shmem_barrier_all();
   finhash();
   shmem_finalize();
   return;
}
```

**Allocate symmetric variables**

**Free symmetric variables**

# DHT: OpenSHMEM Hash Finish

```
void finhash()
{
  shfree(hashtab);
  shfree(hashcount);
  shfree(pe_lock);
}
```

# DHT: OpenSHMEM Code Using Locks

## hashinsert(o)

```
hash = h(o);
while (1) {
   dest_pe = ceil(hash / localhashlen);
   dest_pos = hash - (dest_pe)*localhashlen;
   /* lock the data */
   shmem_set_lock(&pe_lock[dest_pe]);
   shmem_int_get(&local_val, &hashtab[dest_pos], 1, dest_pe);
```

# DHT: OpenSHMEM Code Using Locks

```
 /* check to see if o already exists */
 if (local_val == 0) {
   /* insert the entry */
   int one = 1;
   shmem_int_put(&hashtab[dest_pos], &o, 1, dest_pe);
   shmem_int_put(&hashcount[dest_pos], &one, 1, dest_pe);
   /* unlock before return */
   shmem_clear_lock(&pe_lock[dest_pe]);
   return;
}
else... // repetition or collision
```

# DHT: OpenSHMEM Code Using Locks

```
    /* check to see if it is not a collision */
    else if (local_val == 0) {
          /* it is a repetition */
          shmem_int_inc(&hashcount[dest_pos], dest_pe);
          shmem_clear_lock(&pe_lock[dest_pe]);
           return;
    } else { /* it is a collision */
          collisions++;
          hash++;
          if (hash == hashlen) {
             hash = 0;
          }
          shmem_clear_lock(&pe_lock[dest_pe]);
    }
}
```

# DHT: OpenSHMEM Code Using Locks

**shmem_int_cswap?**

```
hash = h(o);
while (1) {
   dest_pe = ceil(hash / localhashlen);
   dest_pos = hash - (dest_pe)*localhashlen;
   shmem_set_lock( &pe_lock[dest_pe] );
   shmem_int_get(&local_val, &hashtab[dest_pos], 1, dest_pe);
   if (local_val == 0) {
      int one = 1;
      shmem_int_put(&hashtab[dest_pos], &o, 1, dest_pe);
      shmem_int_put(&hashcount[dest_pos], &one, 1, dest_pe);
      /* unlock before return */
      shmem_clear_lock( &pe_lock[dest_pe] );
      return;
   }
   else...    //repetition or collision;
```

# DHT: OpenSHMEM Code Using Locks

```
/* check to see if it is a collision */
else if (local_val == 0) {
       /* its a repetition */
       shmem_int_inc(&hashcount[dest_pos], dest_pe);
       shmem_clear_lock( &pe_lock[dest_pe] );
        return;
} else { /* its a collision */
        collisions++;
        hash++;
        if (hash == hashlen) {
           hash = 0;
        }
        shmem_clear_lock( &pe_lock[dest_pe] );
  }
}
```

# DHT: OpenSHMEM Code Using AMO

```
hash = h(o);
while (1) {
   dest_pe = ceil(hash / localhashlen);
   dest_pos = hash - (dest_pe)*localhashlen;
   local_val = shmem_int_cswap(&hashtab[dest_pos],0,o,dest_pe);
   if (local_val == 0 || local_val == o) {
      /* update successful, so increment count and return */
      shmem_int_inc(&hashcount[dest_pos], dest_pe);
      return;
   }
   else
    /* it's a collision */
```

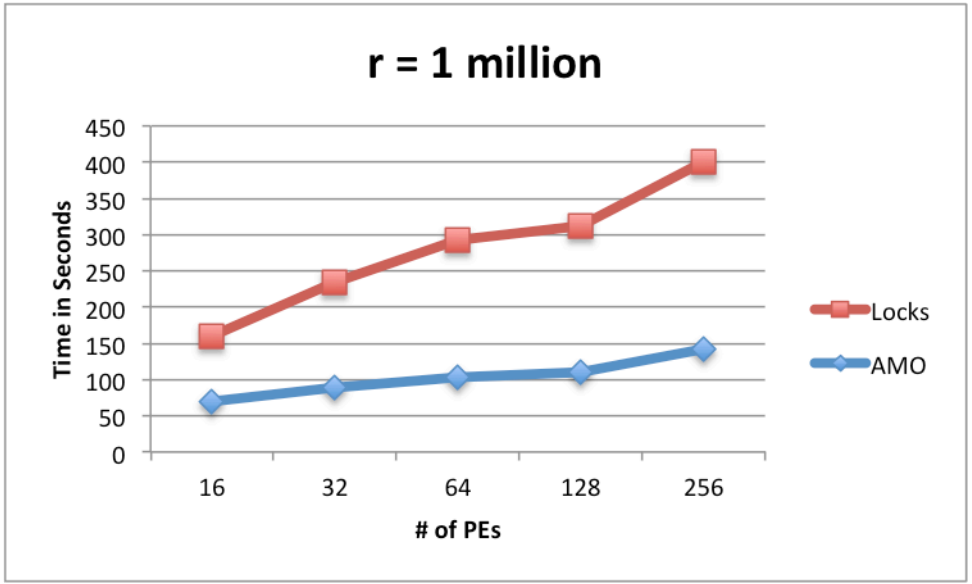
# DHT: OpenSHMEM Code Using AMO

```
   else { /* its a collision */
          collisions++;
          hash++;
          if (hash == hashlen) {
             hash = 0;
          }
    }
}
```

# DHT: Performance on Stampede using MVAPICH2-X

**Interconnect:**
InfiniBand Mellanox Switches/HCAs
**Cores/Node:** 16
- We used 16 PEs/nodes

**Version:** mvapich2-x/2.0b
ICC 13.1.0
CFLAGS= -O2



# DHT: Conclusion

- DHT: look up and store large orbits
- DHT: illustrative example of using OpenSHMEM (RMA, locks, atomics)
- Easy transition from sequential to parallel
- Use atomics if implementation is adapted

# OpenSHMEM Implementation Components and Characteristics

Manjunath Gorentla Venkata
ORNL

# OpenSHMEM Components and Characteristics

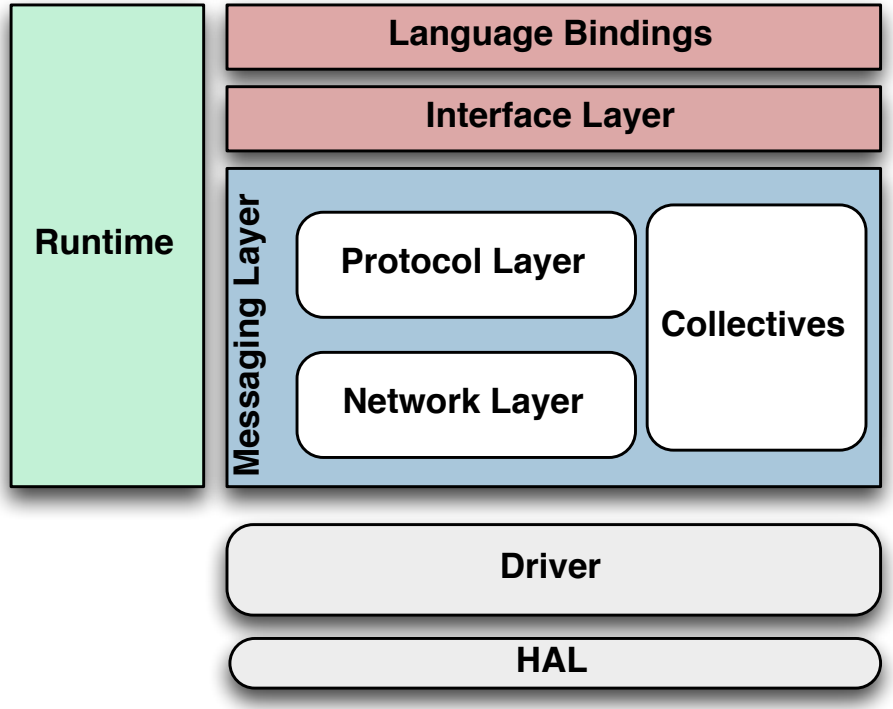
Goal:

Overview of components and its characteristics in a typical OpenSHMEM implementation

Expert level:

Introductory

# Components in a Typical OpenSHMEM Implementation



# Runtime Layer

Resides on the head node from which processes are launched, and typically a daemon resides in each node of the job

Functions

- Launches the job, leveraging job launchers such as rsh, ssh, slurm, pbs
- Provides out-of-band communication
- Fault detection and recovery
- Provides flexible process binding functionality

# Examples

## Launchers

- ALPS, SSH, Hydra

## Runtime Implementations

- STCI  - Runtime that supports fault-tolerance
- ORTE – Runtime for Open MPI
- PMI – Runtime for MPICH based implementations
- SLURM PMI, BG/L PMI, Simple PMI

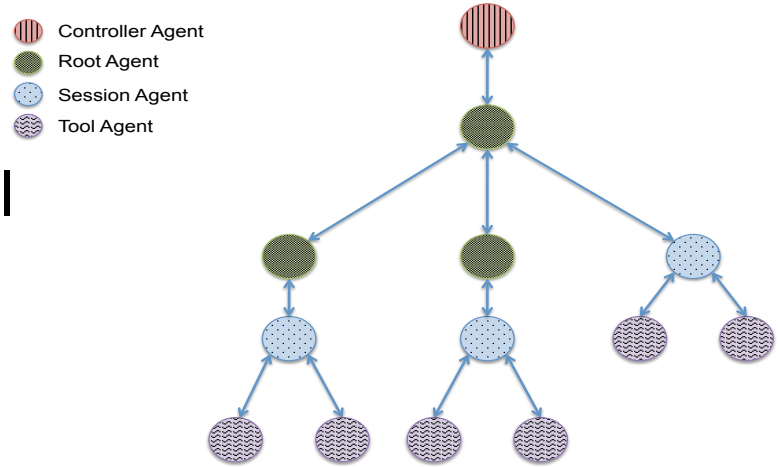
## Interfaces for abstracting various runtime layers

- Librte – Library interface for runtimes
- Process Manager Interface (PMI)

# Case Study: STCI

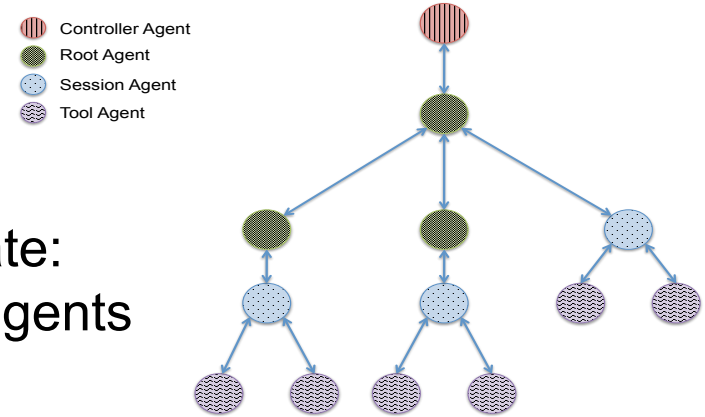
Components

- Agents
  - Controller, Root, Session, Tool
- Topology
  - Connects various agent components
  - Currently supports tree, meshes, BMGs

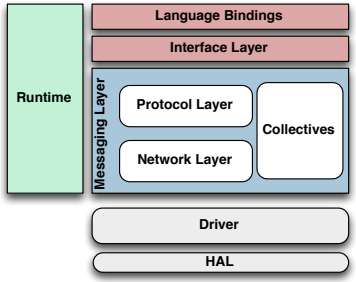


# Case Study: STCI

- Communication Substrate
  - Bootstrap communication substrate :
    - Self-bootstrapping
    - Reliable and ordered
  - Active message communication substrate:
    - Provides communication between agents after bootstrapping
- Fault tolerance : Enables communication even in the event of failed agents
  - Fault detection
  - Fault tolerant communication



# Messaging Layer




## Protocol Layer

- Implements semantics of the programming model
- Provides protocols to support the programming model semantics and achieve performance
- Provides message fragmentation and coalescing abilities
- RDMA Protocols, Active Messages, Atomics

## Network layer

- Transfers data between processing elements
- Typically hardware and network dependent, and this component requires to re-implementing for porting the message layer

# Example

## Programming model specific

- Mellanox SHMEM
- Open MPI /MPICH
- OpenSHMEM reference implementation

## Independent of Programming model

- UCCS/UCX
- PAMI
- MXM
- Libfabrics
- GASNet

# Case Study: UCX

Yossi will provide a detailed talk on UCX

# What Collective Operations ?

- Collective operations are global communication and synchronization operations in a parallel job

- Important component of a parallel system software stack
- Simulations are sensitive to collectives performance characteristics
- Simulations spend significant amount of time in collectives

# Examples

## Part of messaging layer

- OpenMPI – Tuned, Cheetah
- PAMI
- OpenSHMEM (reference implementation)

## Standalone Libraries

- LibNBC
- HCOL (derived from Cheetah)
- FCA


# Case Study : Cheetah

***Objectives***

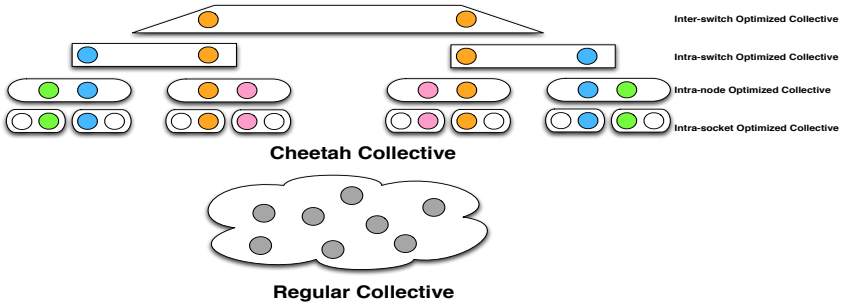
- Develop a high-performing and highly scalable collective operations library for multicore systems
- Develop collective offload mechanism for InfiniBand HCA
- Designed to support blocking and nonblocking semantics, and achieve high scalability and performance on modern multicore systems

http://www.csm.ornl.gov/cheetah

# Our Approach: Hierarchical Collectives

- A collective operation is a combination of multiple (layered) collective primitives.

- Group processes into multiple hierarchies to leverage architecture capabilities
- Build a collective by combining these basic collective primitives
- Progress independent collective primitives concurrently



# Definitions: Reduction Operations

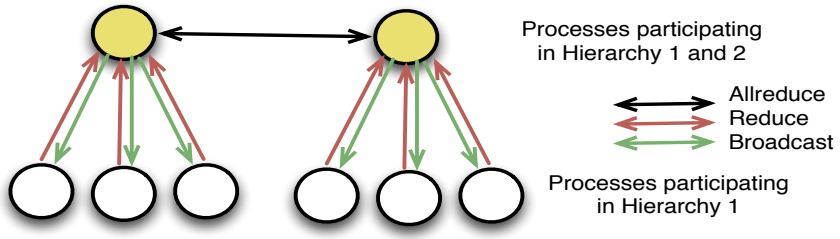
- Allreduce Operation: Combines the data from all participants with an operation, and distributes the results of the operation to all participants

- Reduce Operation: Combines the data from all participants with an operation, and the result is available only at the root

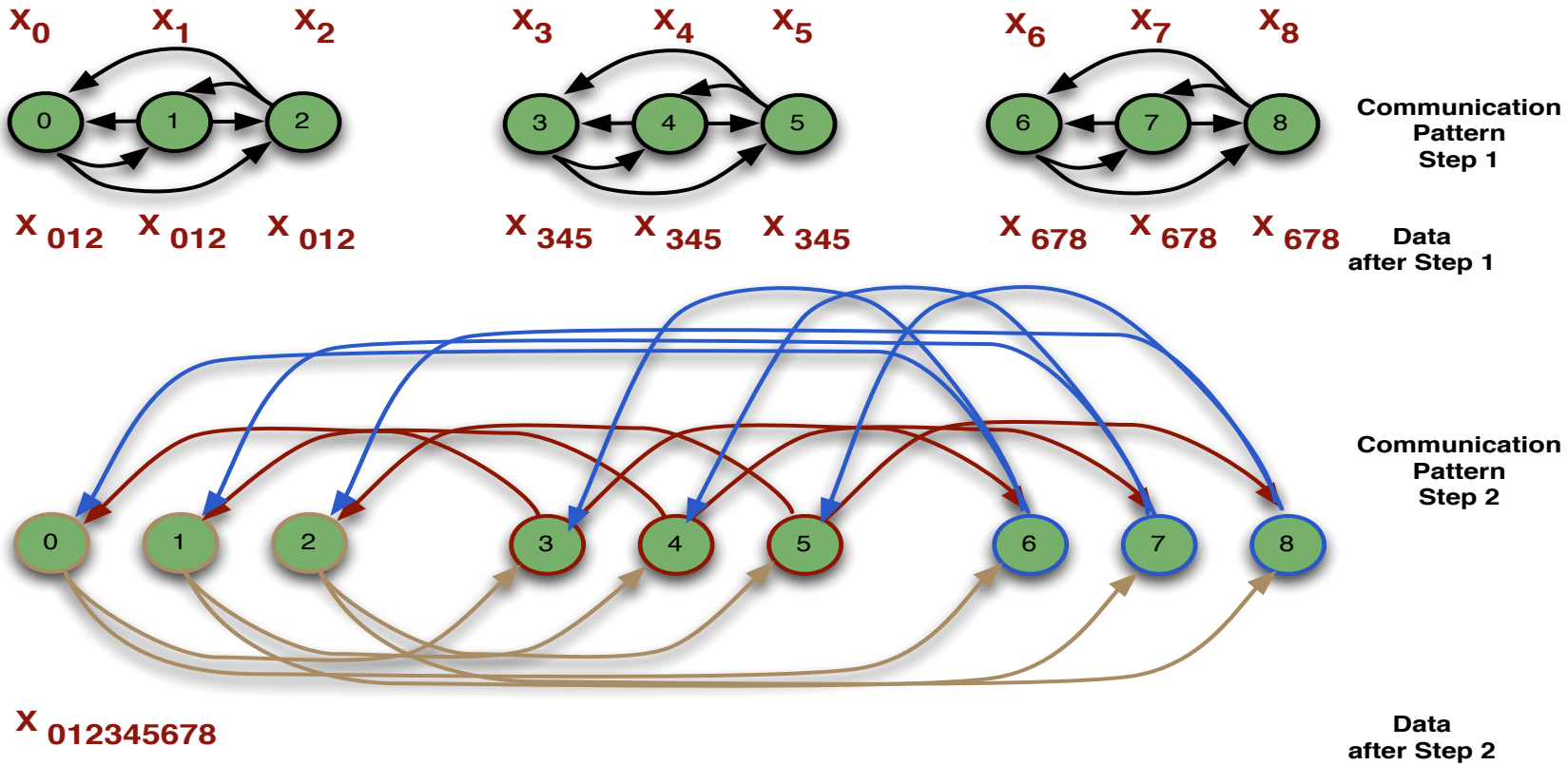
# Hierarchical Allreduce Collective Operation

- A hierarchical allreduce is implemented as a combination of the reduce, allreduce, and broadcast primitives
- n level Allreduce is a combination of three primitives
- Reduce ( first n-1 levels), Allreduce(nth level), Broadcast ( first n-1 levels)

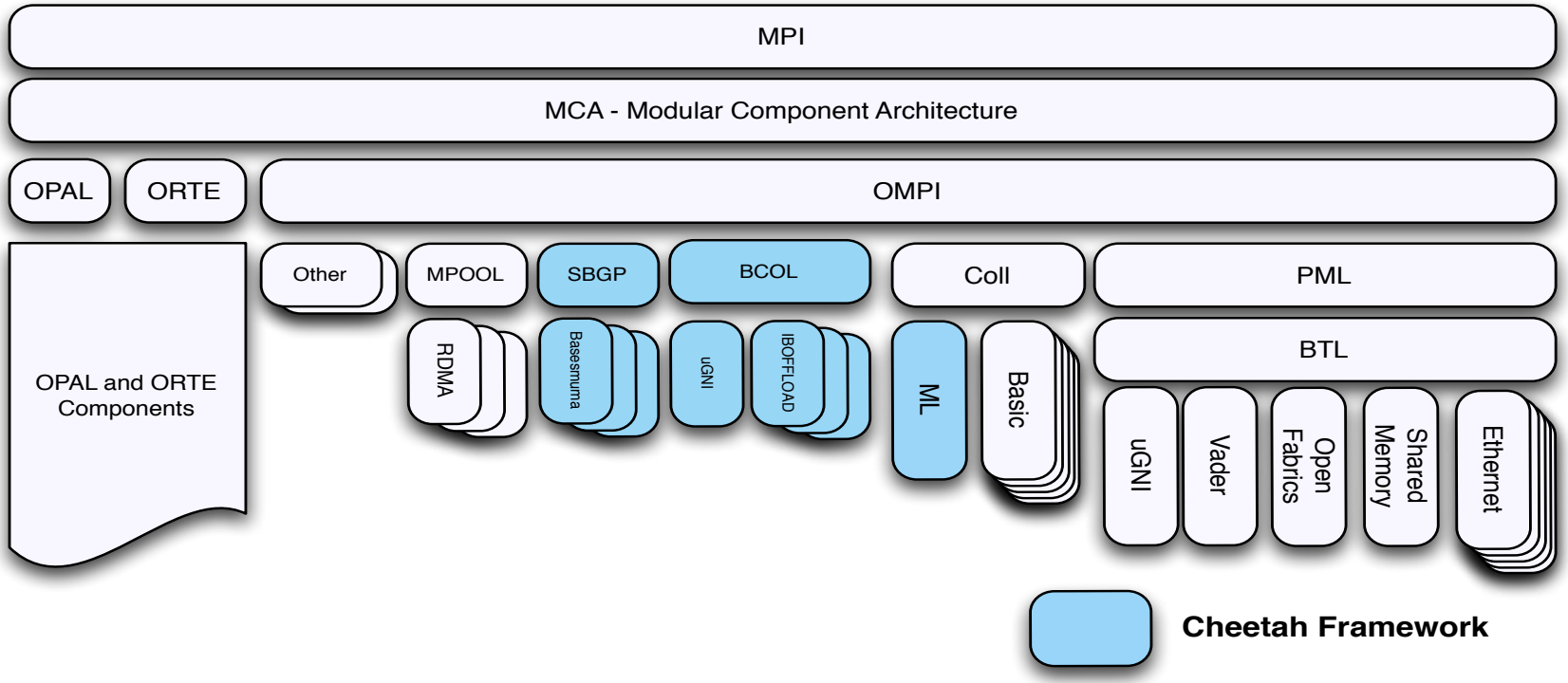
- Example: Interaction of the collective primitives in a 8-process allreduce collective operation



# Recursive K'ing Algorithm for Implementing Allreduce Primitive



# Cheetah : A Framework for implementing hierarchical collectives



# Driver

## Provides low level messaging functionality

- For RDMA networks it provides – RDMA Read, Write, Atomic interfaces
- Provide thin layer of active messages on RDMA network

## The functionality is accessible through well-defined interface

- The interfaces are well-defined, but might change more rapidly

## The lowest interface to the network interface

- It is not typically portable across the same hardware or different hardware

# Examples

Verbs

- Driver for InfiniBand

uGNI

- Driver for Cray's Gemini and Aries NICs
- Primarily used for implementing MPI

DMAPP

- Driver for Cray's Gemini and Aries NICs
- Primarily used for implementing PGAS models

# Case Study : Verbs

## What is Verbs ?

- A low level abstraction of the network device, and is close to bare metal for many HCAs
- Provides RDMA functionality for the upper-layer protocols

## Why use Verbs ?

- Low-level interface - for portability, performance and scalability
- Provides kernel bypass

# Case Study: Verbs (Continued)

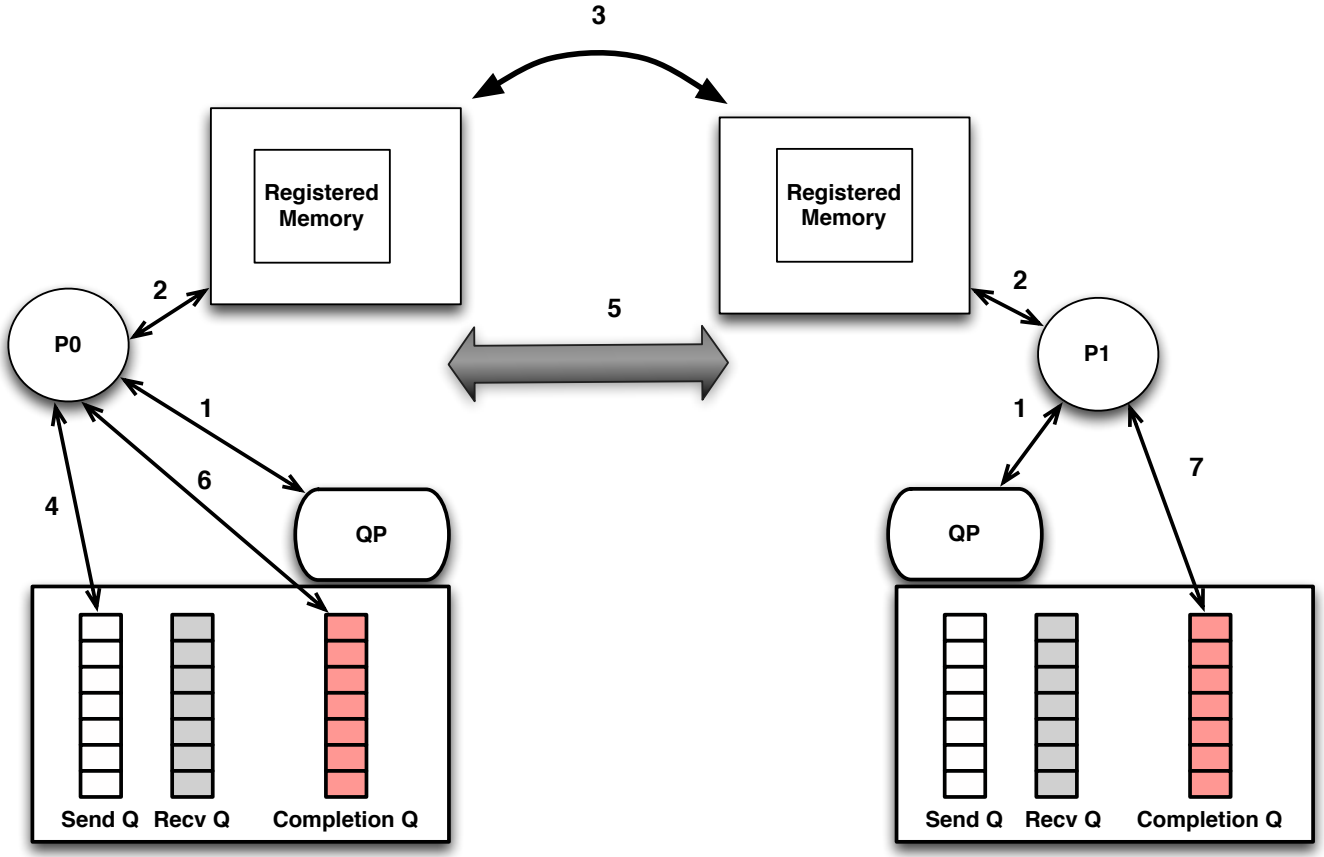
Constructs

- Objects : QPs, SQ, RQ, CQ, Memory Region
- Functions:

Control Functions : Create, Destroy, Modify, Query, Work with events

Data Functions : Post Send, Recv, Poll CQ, Request for completion event

# Example of Message Transfer using Verbs on InfiniBand

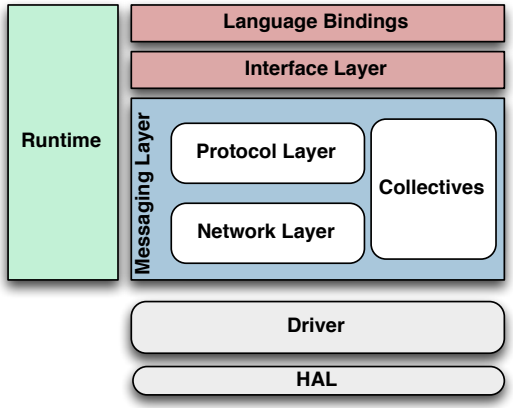


# References


- https://zcopy.wordpress.com/2010/10/08/quick-concepts-part-1-—-introduction-to-rdma/
- http://www.digitalvampire.org/rdma-tutorial-2007/slides.pdf
- http://www.csm.ornl.gov/workshops/openshmem2013/documents/presentations_and_tutorials/Tutorials/Verbs%20programming%20tutorial-final.pdf

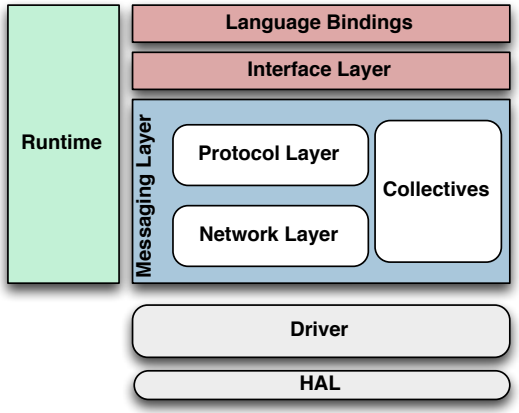
# Stack Trace: shmem_put call (First Packet)

#0 0x00007f2694bcc160 in ibv_create_qp ()
#1 0x00007f2694e0040c in qp_create_one ()
#2 0x00007f2694e001dd in qp_create_all ()
#3 0x00007f2694dff7af in oob_module_start_connect ()
#4 0x00007f2694df43fa in check_endpoint_state ()
#5 0x00007f2694df41ef in mca_tl_openib_put_short_nb ()
#6 0x0000000000403352 in uccs_put_contiguous_short_nb ()
#7 0x0000000000403169 in uccs_put ()
#8 0x0000000000403049 in __shmem_comms_put ()
#9 0x00000000004034a2 in shmem_int_put ()
#10 0x0000000000403f7c in shmem_int_p ()
#11 0x0000000000402054 in main ()



# Stack Trace: shmem_put call (Subsequent Packets)

```
#0  ibv_post_send ()
#1  0x00007fe21fe3d32e in mca_tl_openib_put_short_nb ()
#2  0x0000000000403366 in uccs_put_contiguous_short_nb ()
#3  0x000000000040317d in uccs_put ()
#4  0x000000000040305d in __shmem_comms_put ()
#5  0x00000000004034b6 in shmem_int_put ()
#6  0x0000000000403f90 in shmem_int_p ()
#7  0x0000000000402068 in main ()
```



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# Latest in OpenSHMEM: Specification, API, and Programming

**Presenters:**
Graham Lopez, Dounia Khaldi, Pavel Shamis, Manjunath Gorentla Venkata