OpenSHMEM

http://www.openshmem.org/site/

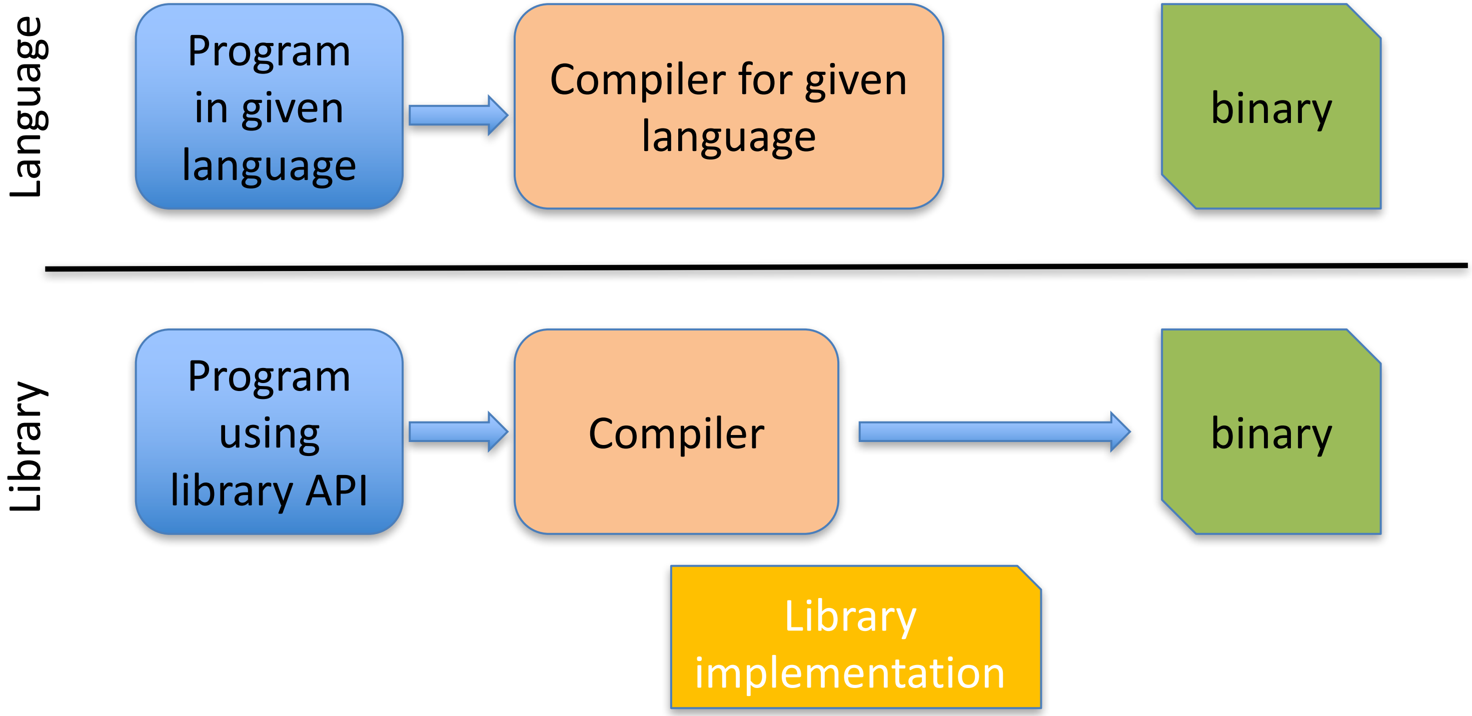
George Bosilca

Parallel Programming Models

- What exactly means parallel: An extension to concurrency where things happens on different locations (processors)
- One simple way to differentiate programming models is by their address space: global vs. distributed
  - Global: the address space is reachable by every process (think threading or OpenMP)
  - Distributed: each process address space is private, access only goes through specialized API (MPI)
  - Middle ground: partitioned global address (PGAS descendants) where some parts are private and some shared

The PGAS family

- Libraries: GASNet, ARMCI / Global Arrays, GASPI/GPI, OpenSHMEM
- Languages: Chapel, Titanuim, X10, UPC, CoArray Fortran


Language
Program in given language
Compiler for given language
binary
Library
Program using library API
Compiler
binary
Library implementation

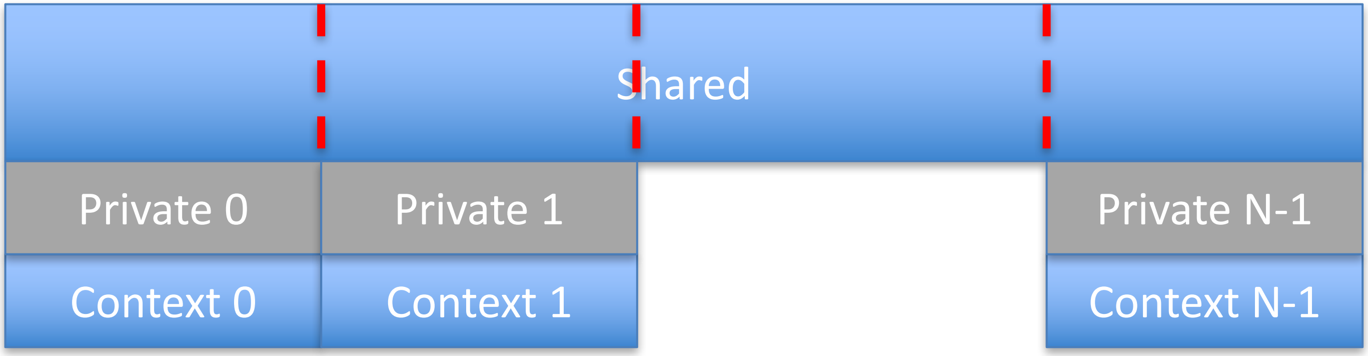
PGAS Languages vs Libraries

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

Courtesy Dr. Barbara Chapman

PGAS

- Execution entities share a common shared memory region distributed among all participants



Unified Parallel C (UPC)

- Language defines a “physical” association between execution contexts (UPC threads) and shared data items called “affinity”
  - Scalars data is affine with execution context 0
  - Standard data distribution concepts applies: cyclic, block and block-cyclic
- All interactions with shared data explicitly managed by the application developer.
  - UPC provides a toolbox of basic primitives: locks, barriers, fences.
- Load balancing is done using the forall concept

CoArray Fortran

- SPMD-like: multiple images, each with it’s own index (similar to rank in MPI), exists
- Each image execute independently of the others … but the same program
- Synchronizations between images is explicit
- An “object” (data) has the same name in all images
- An image can only work in local data
- An image moves remote data to local data, using explicit CAF syntax.
- No data movement outside this concept is allowed.

Symmetrical Hierarchical MEMory

- SPMD application developed in C, C++ and Fortran
- Similar to CAF: programs perform computations in their own address space but
  - Explicitly communicate data and synchronize with the other processes
- A process participating in SHMEM applications are called processing elements (PE)
- SHMEM provides remote one-sided data transfer, some basic collective concepts (broadcast and reduction), specialized synchronizations and atomic memory operation (remote memory)

History of SHMEM

- Originator: similar time-frame as MPI
  - SHMEM in 1993 by Cray Research (for Cray T3D)
  - SGI incorporated Cray SHMEM in their Message Passing Toolkit (MPT)
  - Quadrics optimized it for QsNet. First come to the Linux world
  - Many others: GSHMEM, University of Florida; HP, IBM, GPSHMEM (ARMCI).
- Unlike MPI, SHMEM was not defined by a standard. A loose API was used instead..
  - In other words, while all implementations manipulated similar concepts they were all different.
  - A push for standardization was necessary (OpenSHMEM)

OpenSHMEM

- An effort to create a standardized SHMEM library API with a [clear] well-defined behavior
- SGI SHMEM API is the baseline for OpenSHMEM 1.0
- A forum to discuss and extend the SHMEM standard with critical new capabilities
  - http://openshmem.org/site/
  - As of September 2016 the Open SHMEM standard reached version 1.3

Everything evolves around

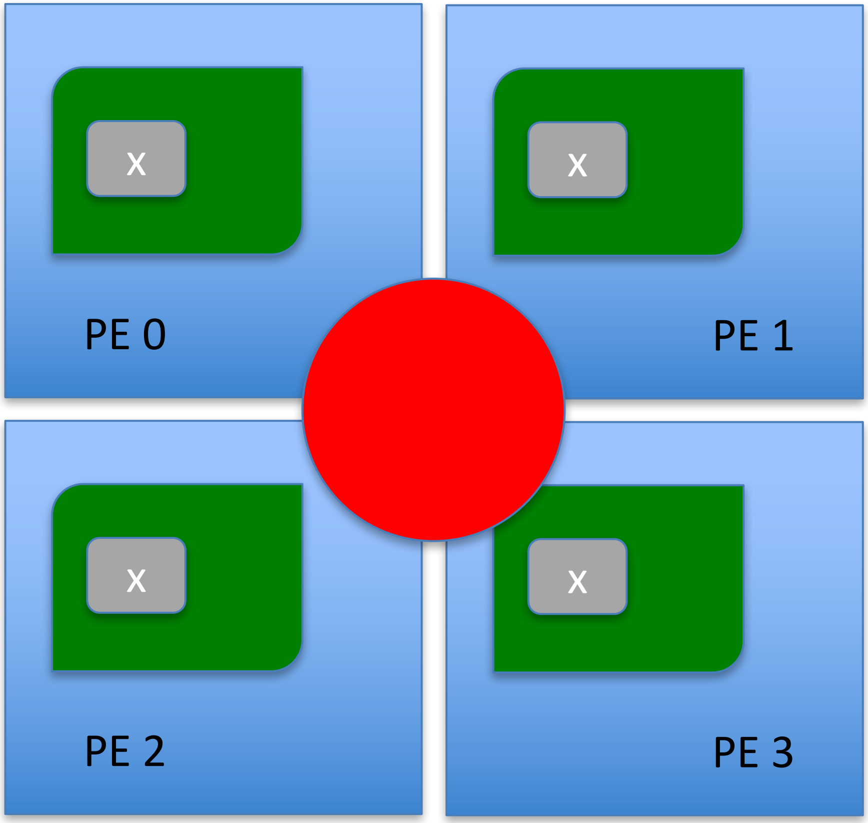
- Remote Direct Memory Access (RDMA)
  - RDMA allows one PE to access certain variables of another PE without interrupting the other PE
  - These data transfers are completely asynchronous
  - They can take advantage of hardware support
- Terminology
  - PE: processing element, a numbered process
  - Origin: process that performs the call
  - Remote_pe: process on each the memory is accessed
  - Source: array which the data is copied from
  - Target: array which the data is copied to
- The key concept here is the symmetric variables
  - Force the applications to be SPMD

Symmetric Variables

- Scalars or arrays that exists with the same size, type, and relative address on all PEs.
- They can either be
  - Global (static variables, or local variables)
  - Dynamically allocated and maintained by the SHMEM library
- With little help from the Operating System, the following types of objects can be made symmetric:
  - Fortran data objects: common blocks and SAVE attributes
  - Non-stack C and C++ variables
  - Fortran arrays allocated with shpalloc
  - C and C++ data allocated by shmalloc

Example (dynamic allocation)

```
int main (void)
{
  int *x;
 …
  start_pes(4);
 …
  x = (int*) shmalloc(sizeof(x));
 …
  shmem_barrier_all();
 …
  shfree(x);
  return 0;
}
```



OpenSHMEM primitives

- Initialization and Query
- Symmetric Data Management
- Data transfers: puts and gets (RDMA)
- Synchronization: barrier, fence, quiet
- Collective: broadcast, collection (allgather), reduction
- Atomic Memory Operations
  - Mutual Exclusion
  - Swap, add, increment, fetch
- Distributed Locks
  - Set, free and query
- Accessibility Query Routines
  - PE accessible, Data accessible

Main Concept

- As the data transfers are one-sided, it is difficult to maintain a consistent view of the state of the parallel application
  - Only local completion is known, and only in some cases
  - Example: put operation
- Synchronization primitives should be used to enforce completion of communication steps

Initialization and Query

- **void** start_pes(**int** npes);
- **int** shmem_my_pe(**void**);
- **int** shmem_n_pes(**void**);
- **void** shmem_finalize(**void**);
- **void** shmem_global_exit(**int** status);
  - Allows any PE to abort the entire application
    - Similar to MPI_Abort
- **int** shmem_pe_accessible(**int** pe);
- **int** shmem_addr_accessible(**void** *addr, **int** pe);
- **void** *shmem_ptr(**void** *target, **int** pe);
  - Only if the target process is running from the same executable (symmetry of the global variables)

Your first OpenSHMEM application

```c
#include <stdio.h>
#include <shmem.h> /* The shmem header file */
int
main (int argc, char *argv[])
{
   int nprocs, me;
   start_pes (4);
   nprocs = shmem_n_pes (); me = shmem_my_pe ();
   printf ("Hello from %d of %d\n", me, nprocs); return 0;
}
```

```
Hello from 0 of 4
Hello from 2 of 4
Hello from 3 of 4
Hello from 1 of 4
```

Symmetric Data Management

- Allocate symmetric, remotely accessible blocks (the call are extremely similar to their POSIX counterpart)
  - void *shmalloc(size_t size);
  - void shfree(void *ptr);
  - void *shrealloc(void *ptr, size_t size);
  - void *shmemalign(size_t alignment, size_t size);
  - extern long malloc_error;
- These calls are collective, which means all processes involved in the execution must make them
  - This is a simple way to ensure the symmetry of all dynamically allocated variables

Remote Memory Access - PUT

- void shmem_<type>_p(<type>* target,
  <type> value, int pe);
  void shmem_<type>_put(<type>* target,
  const <type> *source, size_t len, int pe);

- Type can be: floating point [double, float], integer [short, int, long, longdouble, longlong]
- void shmem_putXX(void *target,
  const void *source, size_t len, int pe);
- XX can be: 32, 64, 128
- void shmem_putmem(void *target,
  const void *source, size_t len, int pe);
  - Byte level function

Remote Memory Access - PUT

- Moves data from local memory to remote memory:
  - Target: remotely accessible object where the data will be moved
  - Source: local data object containing the data to be copied
  - Len: number of elements in the source (and target) array. The type of elements (from the function name) will decide how much data will be transferred
  - Pe: the target PE for the operation
- If there is only one data to copy there is an alias shmem_<type>_p
- Consecutive PUT are not guarantee to complete in order
- PUT return once the data has been copied away from the local buffer (but not necessarily after the data has been delivered)
- Remote completion only guarantee after synchronization

Example - PUT

```
..
long source[10] = { 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 };
static long target[10];

start_pes(2);

if ( _my_pe() == 0 ) {
  /* put 10 words into target on PE 1 */
  shmem_long_put(target, source, 10, 1);
}
shmem_barrier_all(); /* sync sender and receiver */

if (_my_pe() == 1) {
  for( i = 0; i < 10; i++ )
    printf("target[i] on PE %d is %d\n", i, _my_pe(), target[i]);
}
...
```

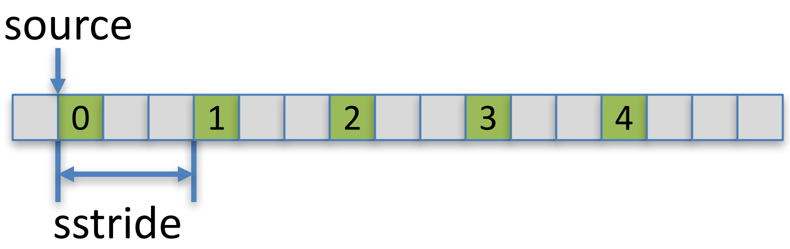
Target should be in a symmetric memory

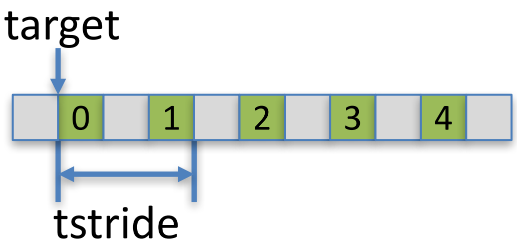
Without synchronization the target PE does not know when the data is available

No assumption about the order of operations should be made

Remote Memory Access - IPUT

- void shmem_<TYPE>_iput(<TYPE> *target,
  const <TYPE> *source, ptrdiff_t tstride,
  ptrdiff_t sstride, size_t nelems, int pe);
- Same idea as PUT plus
  - tstride: the stride between elements on the target array
  - sstride: the stride between elements on the source array





Remote Memory Access - GET

- <type> shmem_<type>_g(<type>* target, int pe);
  void shmem_<type>_get(<type>* target,
  const <type> *source, size_t len, int pe);

- Type can be: floating point [double, float], integer [short, int, long, longdouble, longlong]
- void shmem_getXX(void *target,
  const void *source, size_t len, int pe);
- XX can be: 32, 64, 128
- void shmem_getmem(void *target,
  const void *source, size_t len, int pe);
  - Byte level function

Remote Memory Access - GET

- Moves data from remote memory to local memory:
  - Target: local data object containing the data to be copied
  - Source: remotely accessible object where the data will be moved
  - Len: number of elements in the source (and target) array. The type of elements (from the function name) will decide how much data will be transferred
  - Pe: the source PE for the operation
- If there is only one data to copy there is an alias shmem_<type>_g
- Consecutive GET complete in order

Example - GET

```
..
long source;
static long target[10];

start_pes(2);
source = _my_pe();

if ( _my_pe() == 0 ) {
  /* get 1 words from each target PE */
 for( t = 0; t <  _num_pe(); t++)
    shmem_long_get(target + t, &source, 1, t);
}
shmem_barrier_all(); /* sync sender and receiver */

if ( _my_pe() == 0 ) {
  for( i = 0; I < _num_pe(); i++ )
    printf("target[%d] on PE %d is %d\n", i, target[i], target[i]);
}
...
```

Target should be in a symmetric memory

No need for synchronization after the call. The call is blocking it returns once the operation is completed

Consecutive gets complete in order

Example - GET

```
..
long source;
static long target[10];

start_pes(2);
source = _my_pe();

if ( _my_pe() == 0 ) {
  /* get 1 words from ea
 for( t = 0; t <
   shmem                                    , 1, t);
}
                          sync sender and receiver */

           _pe() == 0 ) {
  for( i = 0; I < _num_pe(); i++ )
   printf("target[%d] on PE %d is %d\n", i, target[i], target[i]);
}
…
```

This example is WRONG !!!

Example - GET

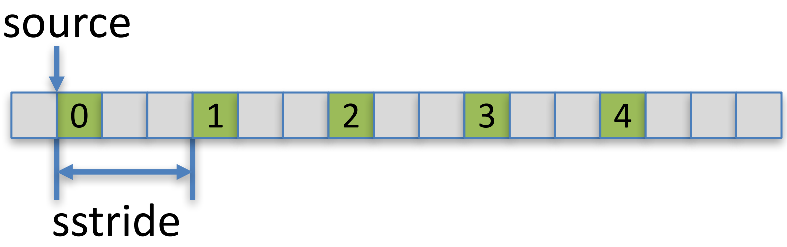
```
..
long source;
static long target[10];

start_pes(2);
source = _my_pe();
shmem_barrier_all(); /* sync sender and receiver */
if ( _my_pe() == 0 ) {
  /* get 1 words from each target PE */
  for( t = 0; t <  _num_pe(); t++)
    shmem_long_get(target + t, &source, 1, t);
}
shmem_barrier_all(); /* sync sender and receiver */

if ( _my_pe() == 0 ) {
  for( i = 0; I < _num_pe(); i++ )
    printf("target[%d] on PE %d is %d\n", i, target[i], target[i]);
}
...
```

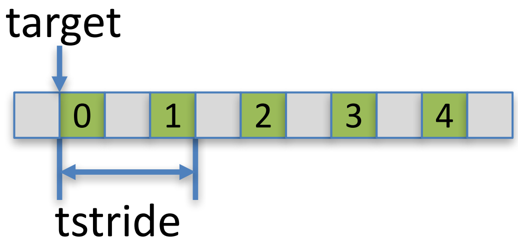
This barrier is needed to ensure proper initialization for source on all Pes.

Not needed

Remote Memory Access - IGET

- void shmem_<TYPE>_iget(<TYPE> *target, const <TYPE> *source, ptrdiff_t tstride, ptrdiff_t sstride, size_t nelems, int pe);
- Expand the capabilities of GET with
  - tstride: the stride between elements on the target array
  - sstride: the stride between elements on the source array





Non-blocking RMA operations

- Add _nbi (_NBI in Fortran) to any PUT and GET call
  - The transfer order is issued, but no assumptions about the data transfers should be made until the next ***shmem_quiet***.
  - No order between operations is enforced in the absence of more specific synchronizations (such as fence).

Remote Memory Access

- Put vs. Get
  - Put call completes when data is “being sent”
  - Get call completes when data is “stored locally”
- Cannot assume put data has been transferred until later synchronization
  - Data still in transit
  - Partially written at target
  - The delivery of words in a put operation can happen in any order
- Puts allow overlap
  - Communicate / Compute / Synchronize

Collective Operations: Barrier_all

- void shmem_barrier_all(void)
  - Barrier between all PE. All operations issued before the barrier are completed upon return.
  - This operation complete al remote shmem_<type>_add and put.

0	1	2	3
4	5	6	7
7	8	9	A
B	C	D	E

Active Sets

- What if not all processes want to be involved in an operation ?
  - Think 2D matrices where collective behavior is desired by line or by column
- It provides a regular definition of a group of processes
  - Composed by a tuple
    (start, log stride[power of 2], size of the set)
  - PE_start = 0, logPE_stride = 0, PE_size = 4
    Set: PE0, PE1, PE2, PE3
  - PE_start = 0, logPE_stride = 1, PE_size = 4
    Set: PE0, PE2, PE4, PE6
  - PE_start = 2, logPE_stride = 2, PE_size = 3
    Set: PE2, PE6, PE10
  - {PEx, where x = PE_start + k * 2 ^ logPE_stride,
    with k = 0 .. PE_size}

Collective Operations: Barrier

- void shmem_barrier(int PE_start,
  int logPE_stride, int PE_size, long *pSync)
- Define a barrier on a log (base 2) group of PE
- pSync: must be a symmetric array of type long, that is dedicated for the operation (of size __SHMEM_BARRIER_SYNC_SIZE). Upon entry it must contain __SHMEM_SYNC_VALUE. Upon return it will contain the same value.
- pSync is used internally for coordination and should not be modified during the operation on any PE.

Example: Barrier

```
#include <stdio.h>
#include <shmem.h>
long pSync[_SHMEM_BARRIER_SYNC_SIZE];
int x = 10101;

int main(void)
{
    int me, npes;
    for (int i = 0;
           i < _SHMEM_BARRIER_SYNC_SIZE; i += 1) {
        pSync[i] = _SHMEM_SYNC_VALUE;
    }
    start_pes(0);
    me = _my_pe();
    npes = _num_pes();
    if(me % 2 == 0) {
        x = 1000 + me;
        /*put to next even PE in a circular fashion*/
        shmem_int_p(&x, 4, me+2%npes);
        /*synchronize all even pes*/
        shmem_barrier(0, 1, (npes/2 + npes%2), pSync);
    }
    printf("%d: x = %d\n", me, x);
    return 0;
}
```

Collective Operations: Broadcast

- void shmem_broadcastXX(void *target,
  const void *source, size_t nlong,
  int PE_root, int PE_start, int logPE_stride,
  int PE_size, long *pSync);
  - XX can be 32 or 64
  - Similar concept to MPI_Bcast: broadcast a block of data from one PE to others PE
  - The participants group is defined bu the PE_root, PE_start, logPE_stride and PE_size.
  - The PE_root is a zero-based ordinal with respect to the active set of participants
  - pSync should follow the same rules as for the barrier

Collective Operations: Reductions

- void shmem_<type>_<op>_to_all(
  <type> *dest, <type>*source, int nreduce, int PE_start, int logPE_stride, int PE_size, <type>*pWrk, long *pSync);
  - Type might be: short, int, long, longlong, float, double
  - Op might be: and, or, xor, max, min, sum, prod
  - Dest and source must not overlap
  - pWrk must be a symmetric array of the same size as dest

Collective Operations: Gather

- void shmem_collectXX(void *target,
  const void *source, size_t nelems,
  int PE_start, int logPE_stride, int PE_size,
  long *pSync);
  - In C XX might be 32 or 64 (In fortran 4, 8, 16, 32, 64)
- Concatenates blocks of data from multiple PEs to an array in every PE (similar to MPI_Allgather)
- The group of participants is defined by the PE_start, logPE_stride and PE_size
- The data is concatenated based on the PE index in the active set
- 2 versions depending if the number of elements is the same on all PE (shmem_fcollectXX) or if they are different (shmem_collectXX)

Collective Operations: AlltoAll

- void shmem_alltoallXX(void *dest,
  const void *source, size_t nelems,
  int PE_start, int logPE_stride, int PE_size,
  long *pSync);
  - In C XX might be 32 or 64 (same in Fortran)
- each PE exchanges a fixed amount of data with all other PEs in the *Active set* (similar to MPI_Alltoall)
- The group of participants is defined by the PE_start, logPE_stride and PE_size
- The data is concatenated based on the PE index in the active set
- A strided version exists (shmem_alltoallsXX) where you can specify a stride for both the source and dest buffers (basically a vector of length 1 with a specified stride)

Point-to-point synchronizations

- void shmem_<type>_wait(<type> *var,
    int value);
  void shmem_<type>_wait_until(<type> *var,
    int cond, int value);
- Blocking function waiting until the condition on the *var is true with respect to the value
- The condition can be: equal, not equal, greater than, less or equal than, less than, greater or equal to

Example

```
#include <shmem.h>
#define GREEN 1
#define RED 0

int light=RED;

int main(int argc, char **argv) {
    int me; start_pes(0);
    me = _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);

    } else if( me == 1 ) {

        sleep(10);
        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
```

Memory Ordering Operations

- As most of the operations are not synchronizing there is a need for enforcing ordering
  - Basically a remote happen-before type of relationship between code blocks
  - void shmem_quiet(void): wait for completion of all outstanding Put, AMO and store operation issues by the PE
  - void shmem_fence(void): assure ordering of delivery of Put, AMO and store operations. All operation prior to the call to shmem_fence are guaranteed to be ordered to be delivered before any subsequent Put, AMO or store operation.
- Beware: the meaning of these synchronizations are purely local (i.e. barriers are needed for global scope)

Example

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

long target[10] = {0};
int targ = 0;
int main(void)
{
    long source[10] = { 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 };
    int src = 99;
    start_pes(0);
    if (_my_pe() == 0) {
        shmem_long_put(target, source, 10, 1); /*put1*/
        shmem_long_put(target, source, 10, 2); /*put2*/
        shmem_fence();
        shmem_int_put(&targ, &src, 1, 1); /*put3*/
        shmem_int_put(&targ, &src, 1, 2); /*put4*/
    }
    shmem_barrier_all(); /* sync sender and receiver */
    printf("target[0] on PE %d is %d\n", _my_pe(), target[0]);
    return 1;
}
```

Example shmem_quiet

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

long target[10] = {0};
int targ = 0;
int main(void)
{
   long source[10] = { 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 };
   int src = 99;
   start_pes(0);
   shmem_long_put(target, source, 3, 1);
   shmem_int_put(&targ, &src, 1, 2);




   shmem_long_get(target, source, 3, 1);
   shmem_int_get(&targ, &src, 1, 2);
   return 0;
}
```

Example shmem_quiet

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

long target[10] = {0};
int targ = 0;
int main(void)
{
   long source[10] = { 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 };
   int src = 99;
   start_pes(0);
   shmem_long_put(target, source, 3, 1);
   shmem_int_put(&targ, &src, 1, 2);

   shmem_quiet();

   shmem_long_get(target, source, 3, 1);
   shmem_int_get(&targ, &src, 1, 2);
   return 0;
}
```

Iget example

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

short source[10] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};

int main() {
 short target[10];
 int i, me;
 for (i = 0; i < 10; target[i++] = 666);
 start_pes (0);

 if (1 == (me = _my_pe ()) )
  shmem_short_iget (target, source, 2, 1, 4, 0); /* s[0,1,2,3] -> t[0,2,4,6] */

 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; }
```

Atomic Memory Operations (AMO)

- One-sided mechanism that combines memory update operations with atomicity guarantee
- Two types of AMO routines:
  - Non-fetch: update the remote memory in a single atomic operation. No completion is imposed as there is no local return value related to the operation.
  - Fetch-and-operate: combine memory update and fetch operations in a single atomic operation.The routines return after the data has been fetched and locally delivered.

AMO: fetch: CSWAP

- <type> shmem_<type>_cswap(<type>* target, <type> cond, <type>value, int pe);
  - type: int, long, longlong
  - The function returns the old value of *target
  - Target: remotely accessible integer data object to be updated
  - Cond: the value to be compared with. If the remote target and the cond value are equal, then value is swaped into the remote target. Otherwise, the remote target is unchanged.

AMO: fetch: SWAP

- <type> shmem_<type>_swap(<type>* target, <type>value, int pe);
  - type: float, double, int, long, longlong
  - The function returns the old value of *target
  - Target: remotely accessible integer data object to be updated
  - the remote target is swaped with value into the remote target

AMO: fetch: FINC, FADD

- <type> shmem_<type>_finc(<type> *target, int pe);
- <type> shmem_<type>_fadd(<type> *target, <type> value, int pe);
  - Atomic fetch-and-increment/add on the remote data object with 1/value
  - Returns the previous value in *target

AMO: non-fetch: INC, ADD

- void shmem_<type>_inc(<type> *target,
  int pe);
- void shmem_<type>_add(<type> *target,
  <type> value, int pe);
  - Atomic increment/add on the remote data object with 1/value
  - Returns … nothing

Locking Routines

- Similar to mutexes but for distributed settings
  - Work in First Come First serve mode
- **void** shmem_clear_lock(**volatile long** *lock);
  - Release the owned lock
- **void** shmem_set_lock(**volatile long** *lock);
  - Acquire the lock, blocks until the lock has been released by the prior owner and succesfully acquired by the PE
- **int** shmem_test_lock(**volatile long** *lock);
  - Return 1 if the lock is currently owned by another PE. Otherwise the lock is acquired and the return is 0.

Example

```
#include <shmem.h>

long L = 0;

int main(int argc, char **argv) {
    int me, slp = 1;
    shmem_init();
    me = shmem_my_pe();
    shmem_barrier_all();

    if (me == 1)
        sleep (3);

    shmem_set_lock(&L);
    printf("%d: sleeping %d second%s...\n", me, slp, slp == 1 ? "" : "s");
    sleep(slp);
    printf("%d: sleeping...done\n", me);
    shmem_clear_lock(&L);
    shmem_barrier_all();
    return 0; }
```