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DPHPC: Locks

Recitation session

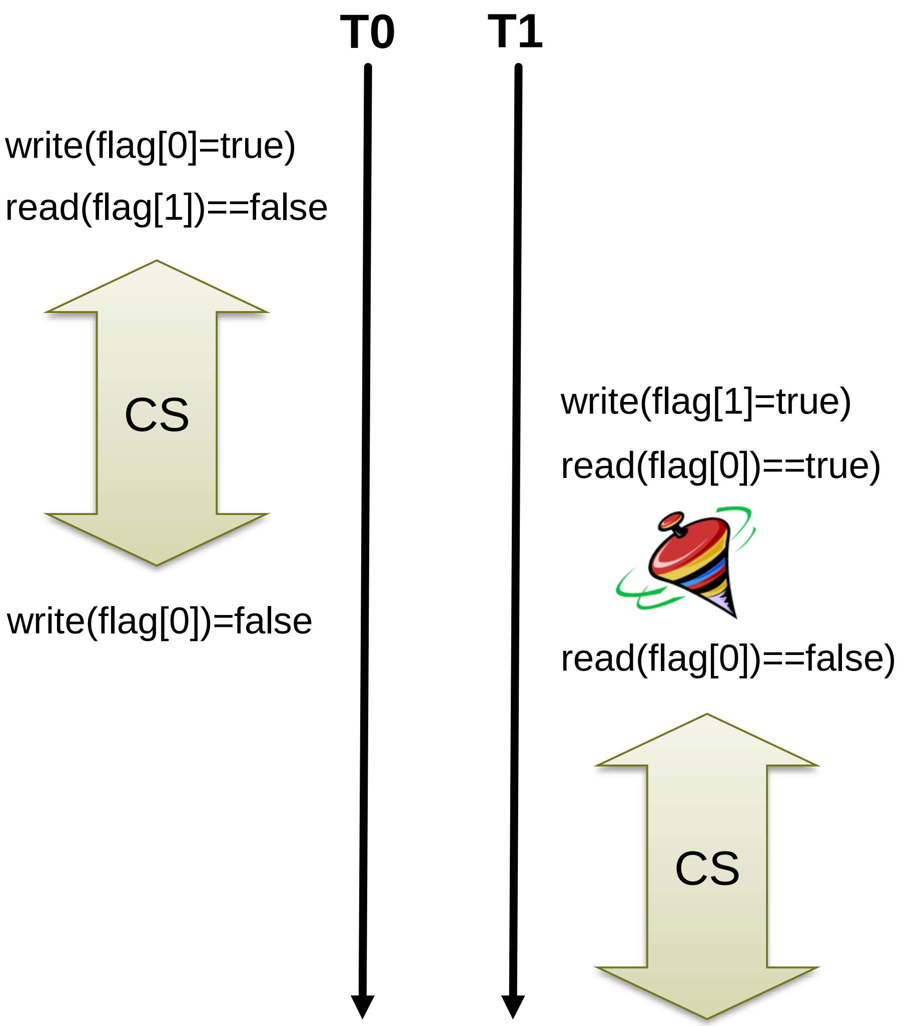
Systems@ETH zürich

2-threads: LockOne

```
volatile int flag[2];

void lock() {
  int j = 1 - tid;
  flag[tid] = true;
  while (flag[j]) {} // wait
}

void unlock() {
  flag[tid] = false;
}
```



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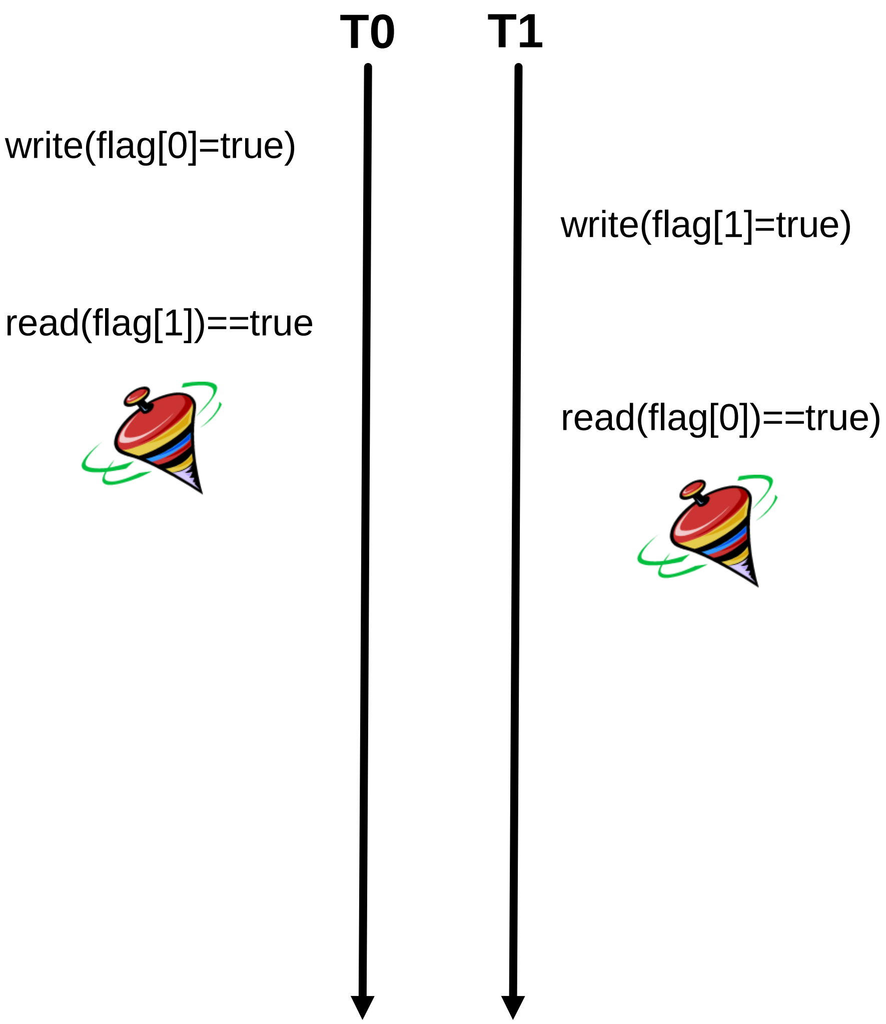
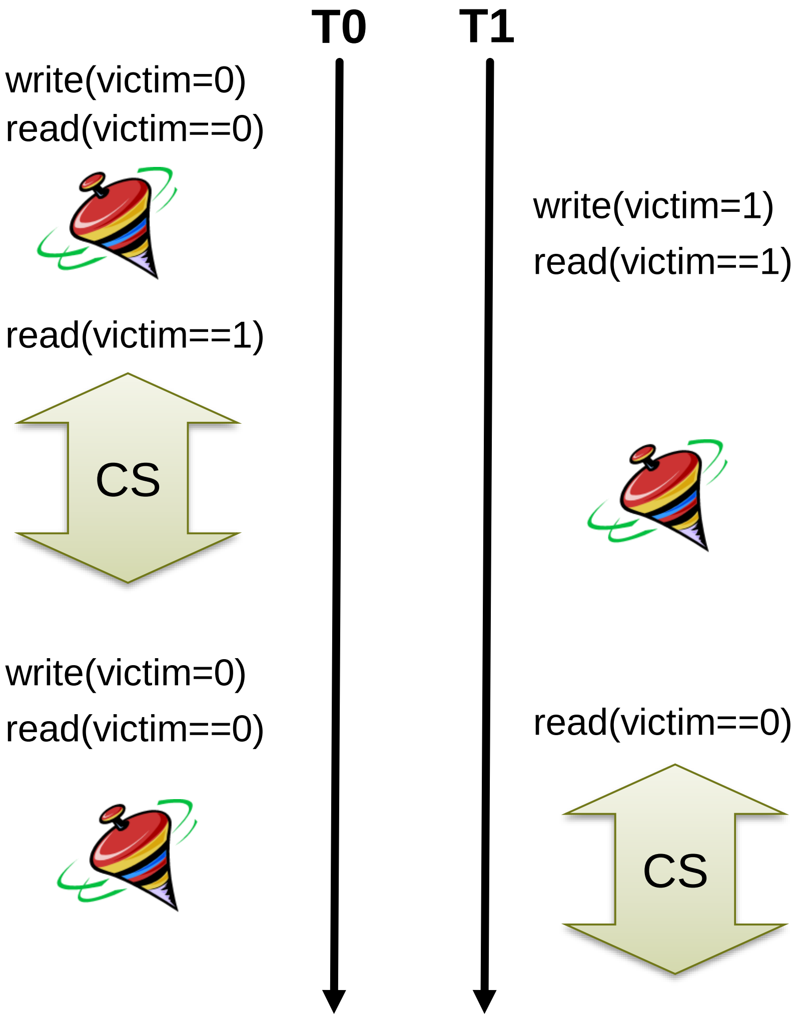


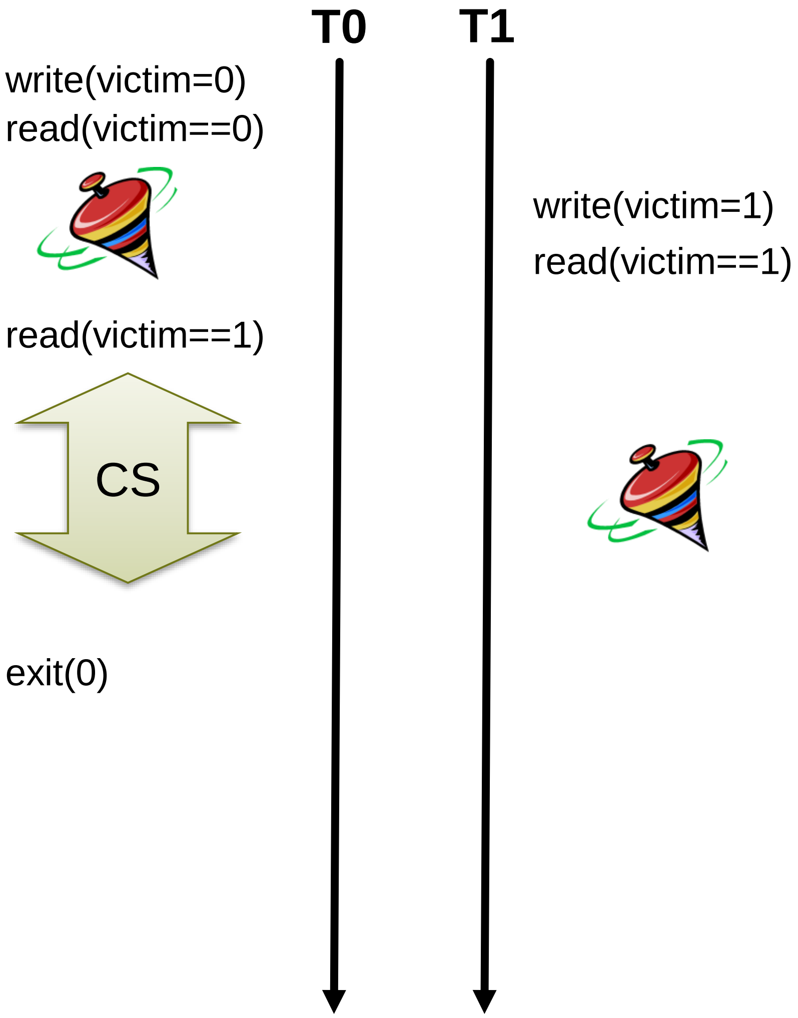
2-threads: LockTwo

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```



2-threads: LockTwo

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```

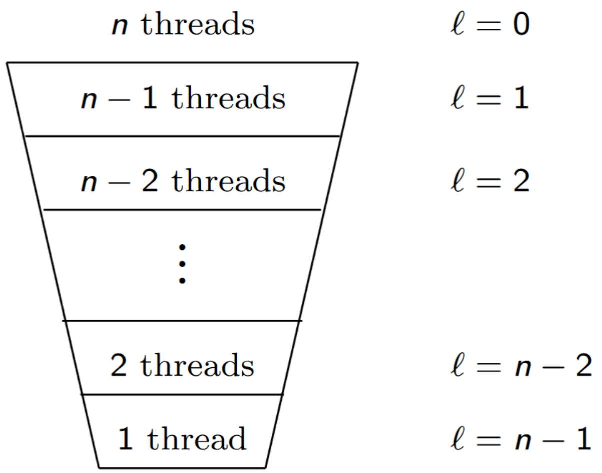


2-threads: Peterson lock

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;       // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

N-threads: Filter Lock

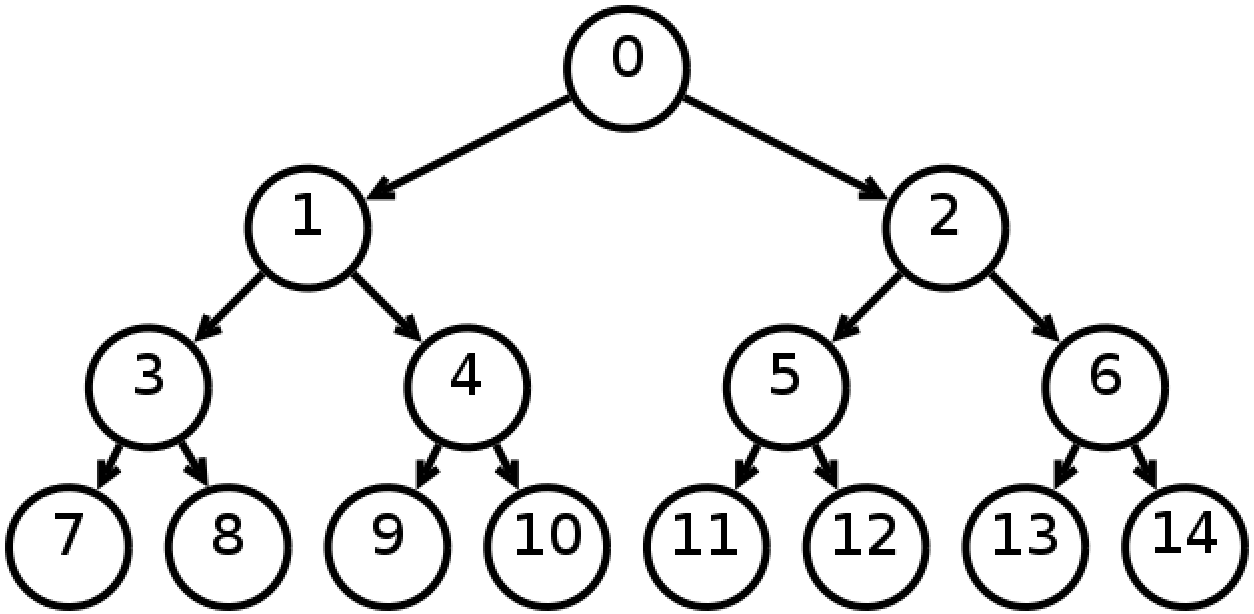
```
volatile int level[n] = {0,0,…,0}; // highest level a thread tries to enter
volatile int victim[n]; // the victim thread, excluded from next level
void lock() {
  for (int i = 1; i < n; i++) { // attempt level i
    level[tid] = i;
    victim[i] = tid;
    // spin while conflicts exist
    while ((∃k != tid) (level[k] >= i && victim[i] == tid )) {};
  }
}

void unlock() {
  level[tid] = 0;
}
```



- **At least one thread trying to enter level L succeeds**
- **If more than one thread is trying to enter level L, then at least one is blocked (waits at that level)**

N-threads: Peterson locks in a binary tree

- **Another way to generalize the Peterson lock to n>=2 threads is to use a binary tree, where each node holds a Peterson lock for two threads.**
  - Threads start at a leaf in the tree, and move one level up when they acquire the lock at a node.
  - A thread that holds the lock of the root can enter its critical section.
  - When a thread exits its critical section, it releases the locks of nodes that it acquired.



First-Come-First-Served Locks

- Doorway: bounded number of steps
- Waiting: unbounded number of steps

- $D_A^j \rightarrow D_B^k$, then $CS_A^j \rightarrow CS_B^k$

N-threads: Bakery lock

```
volatile int flag[n] = {0,0,…,0};
volatile int label[n] = {0,0,….,0};

void lock() {                                              Doorway
  flag[tid] = 1; // request
  label[tid] = max(label[0], ...,label[n-1]) + 1; // take ticket
  while ((∃k != tid)(flag[k] && (label[k],k) <* (label[tid],tid))) {};
}
public void unlock() {
  flag[tid] = 0;
}c
```

- What happens if two threads execute their doorways concurrently?
  - Lexicographical order helps us!

- A thread could see a set of labels that never existed in memory at the same time

Flaky Lock

Programmers at the Flaky Computer Corporation designed the protocol shown below to achieve n-thread mutual exclusion. **Does this protocol satisfy mutual exclusion? Is it starvation-free? Is it deadlock-free?**

```
class Flaky implements Lock {
    private int turn ;
    private boolean busy = false ;
    public void lock () {
        int me = ThreadID .get ();
        do {
            do {
                turn = me;
            } while ( busy );
            busy = true ;
        } while ( turn != me);
    }
    public void unlock () {
        busy = false ;
    }
}
```

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DPHPC: MPI RMA

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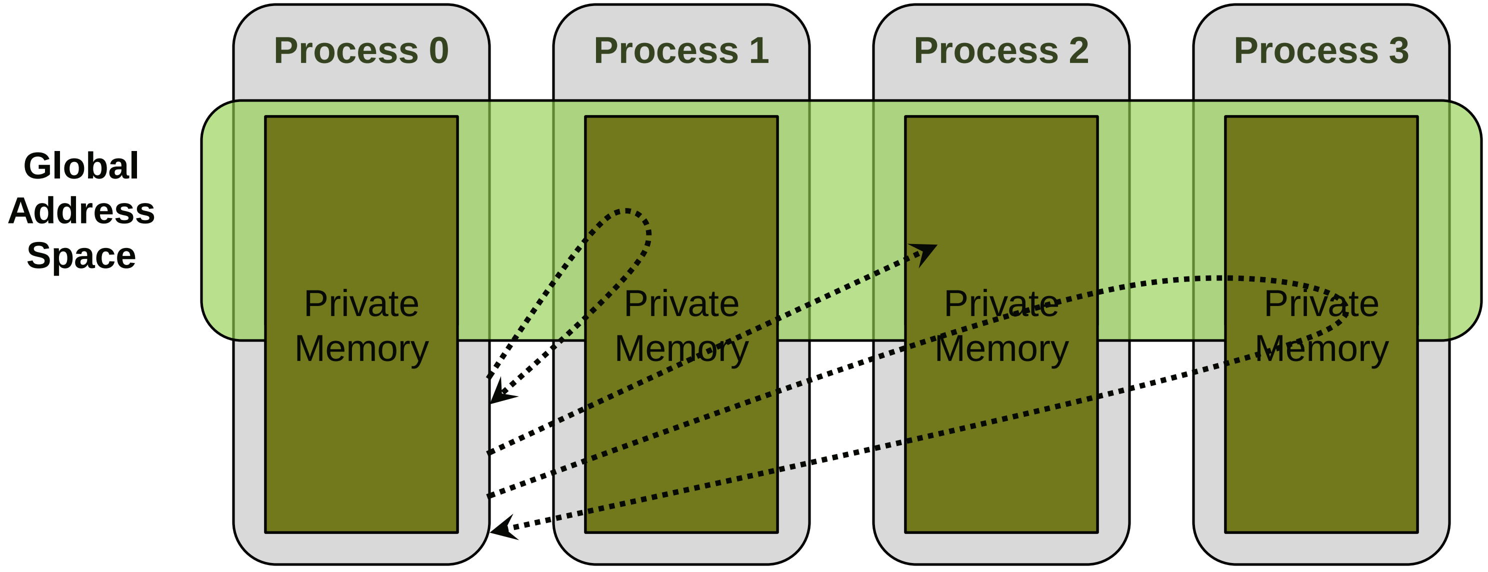
Slides credits: Pavan Balaji, Torsten Hoefler

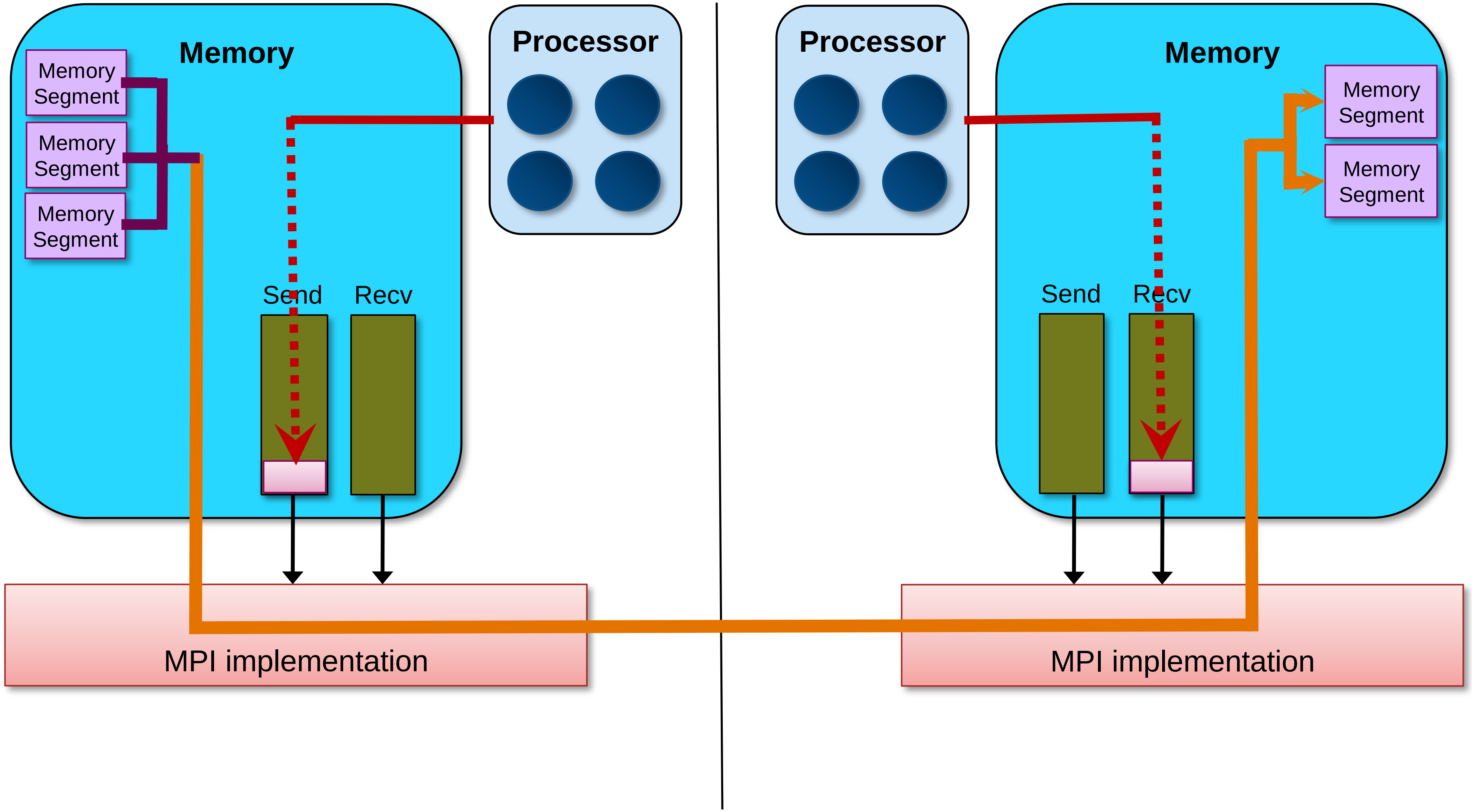
https://htor.inf.ethz.ch/teaching/mpi_tutorials/isc16/hoefler-balaji-isc16-advanced-mpi.pdf

One-sided Communication

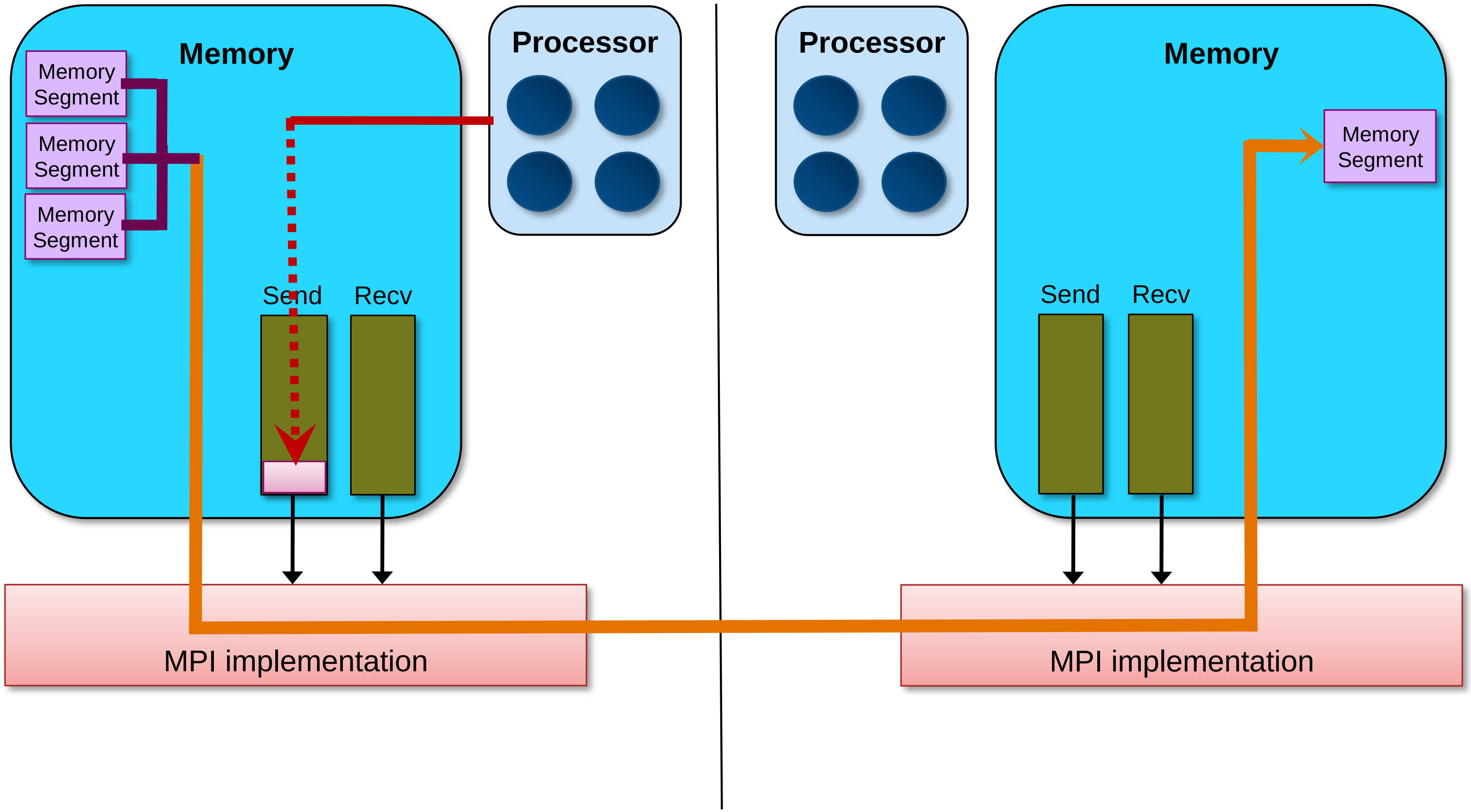
- **The basic idea of one-sided communication models is to decouple data movement with process synchronization**
  - Should be able move data without requiring that the remote process synchronize
  - Each process exposes a part of its memory to other processes
  - Other processes can directly read from or write to this memory



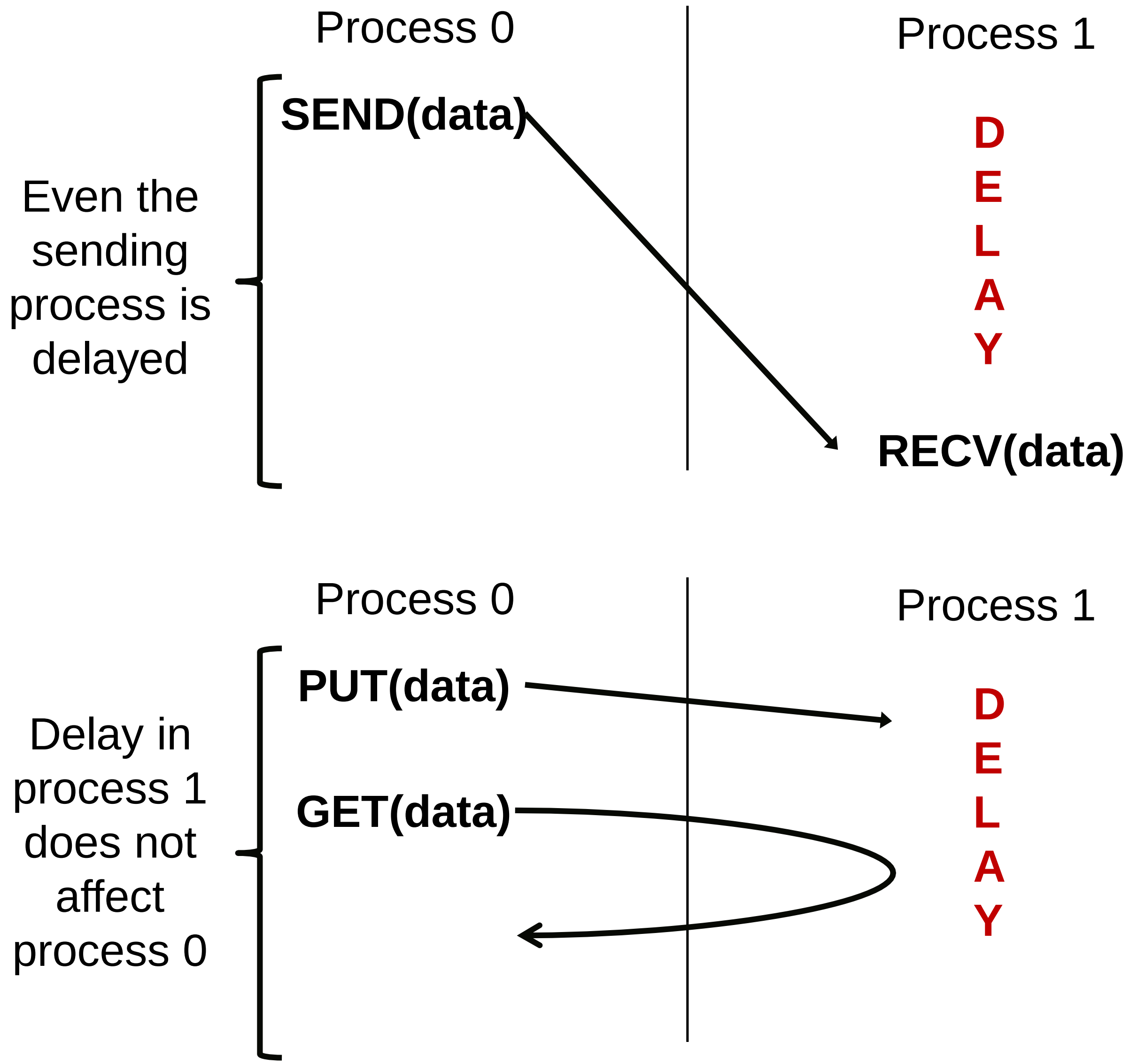
Two-sided Communication Example



One-sided Communication Example



Comparing One-sided and Two-sided Programming

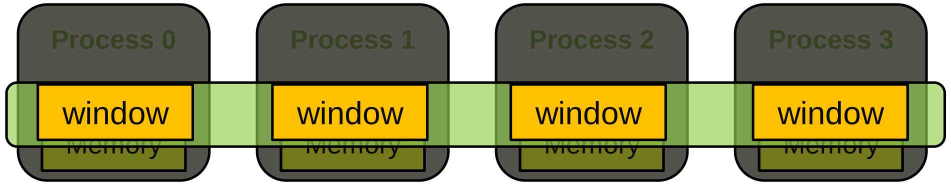


What we need to know in MPI RMA

- How to create remote accessible memory?
- Reading, Writing and Updating remote memory
- Data Synchronization
- Memory Model

Creating remotely accessible memory

- **Any memory used by a process is, by default, only locally accessible**
  - X = malloc(100);



- **Once the memory is allocated, the user has to make an explicit MPI call to declare a memory region as remotely accessible**
  - MPI terminology for remotely accessible memory is a "**window**"
  - A group of processes collectively create a "window"
- **Once a memory region is declared as remotely accessible, all processes in the window can read/write data to this memory without explicitly synchronizing with the target process**

Window creation models

- **Four models exist**
  - MPI_WIN_CREATE

    You already have an allocated buffer that you would like to make remotely accessible
  - MPI_WIN_ALLOCATE

    You want to create a buffer and directly make it remotely accessible
  - MPI_WIN_CREATE_DYNAMIC

    You don't have a buffer yet, but will have one in the future

    You may want to dynamically add/remove buffers to/from the window
  - MPI_WIN_ALLOCATE_SHARED

    You want multiple processes on the same node share a buffer

MPI_WIN_CREATE

```
MPI_Win_create(void *base, MPI_Aint size,
               int disp_unit, MPI_Info info,
               MPI_Comm comm, MPI_Win *win)
```

- **Expose a region of memory in an RMA window**
  - Only data exposed in a window can be accessed with RMA ops.
- **Arguments:**
  - base - pointer to local data to expose
  - size - size of local data in bytes (nonnegative integer)
  - disp_unit - local unit size for displacements, in bytes (positive integer)
  - info - info argument (handle)
  - comm - communicator (handle)
  - win - window (handle)

Example with MPI_WIN_CREATE

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);

    /* create private memory */
    MPI_Alloc_mem(1000*sizeof(int), MPI_INFO_NULL, &a);
    /* use private memory like you normally would */
    a[0] = 1;  a[1] = 2;

    /* collectively declare memory as remotely accessible */
    MPI_Win_create(a, 1000*sizeof(int), sizeof(int),
                        MPI_INFO_NULL, MPI_COMM_WORLD, &win);

    /* Array ‘a’ is now accessibly by all processes in
     * MPI_COMM_WORLD */

    MPI_Win_free(&win);
    MPI_Free_mem(a);
    MPI_Finalize(); return 0;
}
```

MPI_WIN_ALLOCATE

```
MPI_Win_allocate(MPI_Aint size, int disp_unit,
                 MPI_Info info, MPI_Comm comm,
                 void *baseptr, MPI_Win *win)
```

- **Create a remotely accessible memory region in an RMA window**
  - Only data exposed in a window can be accessed with RMA ops.
- **Arguments:**
  - size - size of local data in bytes (nonnegative integer)
  - disp_unit - local unit size for displacements, in bytes (positive integer)
  - info - info argument (handle)
  - comm - communicator (handle)
  - baseptr - pointer to exposed local data
  - win - window (handle)

Example with MPI_WIN_ALLOCATE

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);

    /* collectively create remote accessible memory in a window */
    MPI_Win_allocate(1000*sizeof(int), sizeof(int), MPI_INFO_NULL,
                     MPI_COMM_WORLD, &a, &win);

    /* Array ‘a’ is now accessible from all processes in
     * MPI_COMM_WORLD */

    MPI_Win_free(&win); // will also free the buffer memory

    MPI_Finalize(); return 0;
}
```

MPI_WIN_CREATE_DYNAMIC

```
MPI_Win_create_dynamic(MPI_Info info, MPI_Comm comm,
                       MPI_Win *win)
```

- **Create an RMA window, to which data can later be attached**
  - Only data exposed in a window can be accessed with RMA ops
- **Initially "empty"**
  - Application can dynamically attach/detach memory to this window by calling MPI_Win_attach/detach
  - Application can access data on this window only after a memory region has been attached
- **Window origin is MPI_BOTTOM**
  - Displacements are segment addresses relative to MPI_BOTTOM
  - Must tell others the displacement after calling attach

Example with MPI_WIN_CREATE_DYNAMIC

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);
    MPI_Win_create_dynamic(MPI_INFO_NULL, MPI_COMM_WORLD, &win);

    /* create private memory */
    a = (int *) malloc(1000 * sizeof(int));
    /* use private memory like you normally would */
    a[0] = 1;  a[1] = 2;

    /* locally declare memory as remotely accessible */
    MPI_Win_attach(win, a, 1000*sizeof(int));

    /* Array 'a' is now accessible from all processes */

    /* undeclare remotely accessible memory */
    MPI_Win_detach(win, a);  free(a);
    MPI_Win_free(&win);

    MPI_Finalize(); return 0;
}
```

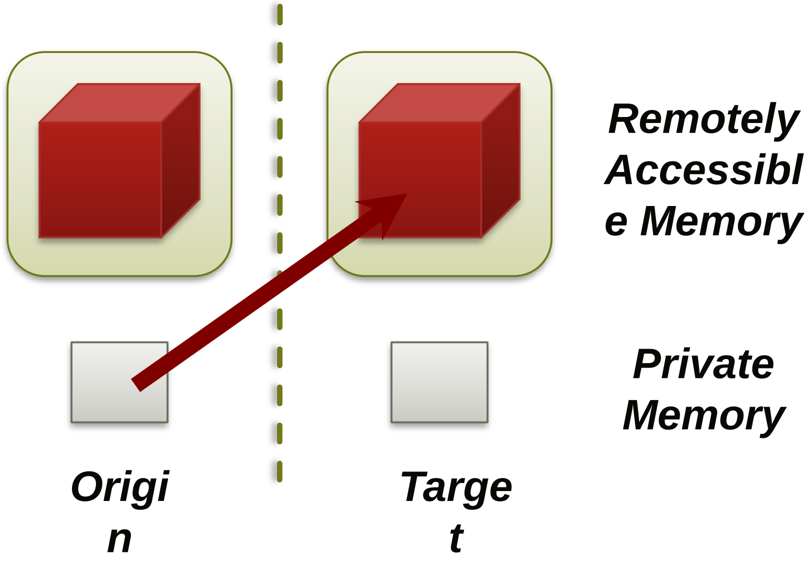
Data movement

- **MPI provides ability to read, write and atomically modify data in remotely accessible memory regions**
  - MPI_PUT
  - MPI_GET
  - MPI_ACCUMULATE `(atomic)`
  - MPI_GET_ACCUMULATE `(atomic)`
  - MPI_COMPARE_AND_SWAP `(atomic)`
  - MPI_FETCH_AND_OP `(atomic)`

Data movement: *Put*

```
MPI_Put(void *origin_addr, int origin_count,
        MPI_Datatype origin_dtype, int target_rank,
        MPI_Aint target_disp, int target_count,
        MPI_Datatype target_dtype, MPI_Win win)
```

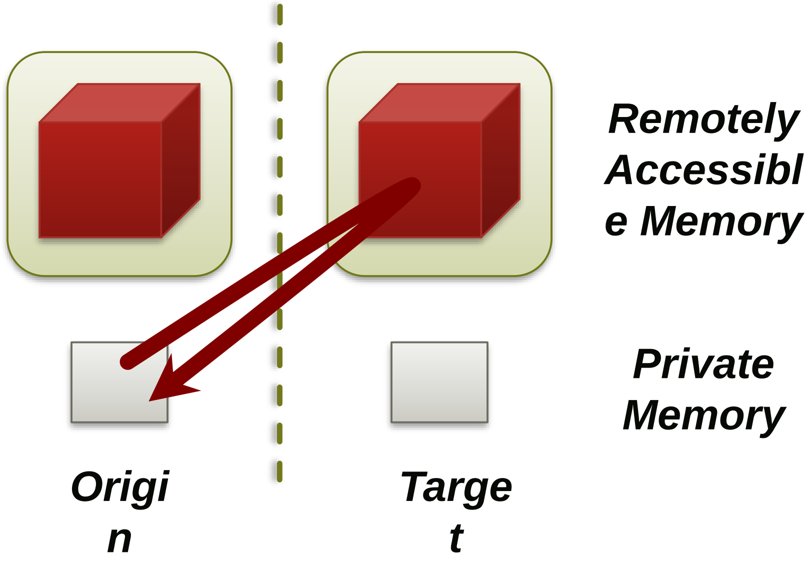
- **Move data <u>from</u> origin, <u>to</u> target**
- **Separate data description triples for origin and target**



Data movement: *Get*

```
MPI_Get(void *origin_addr, int origin_count,
        MPI_Datatype origin_dtype, int target_rank,
        MPI_Aint target_disp, int target_count,
        MPI_Datatype target_dtype, MPI_Win win)
```

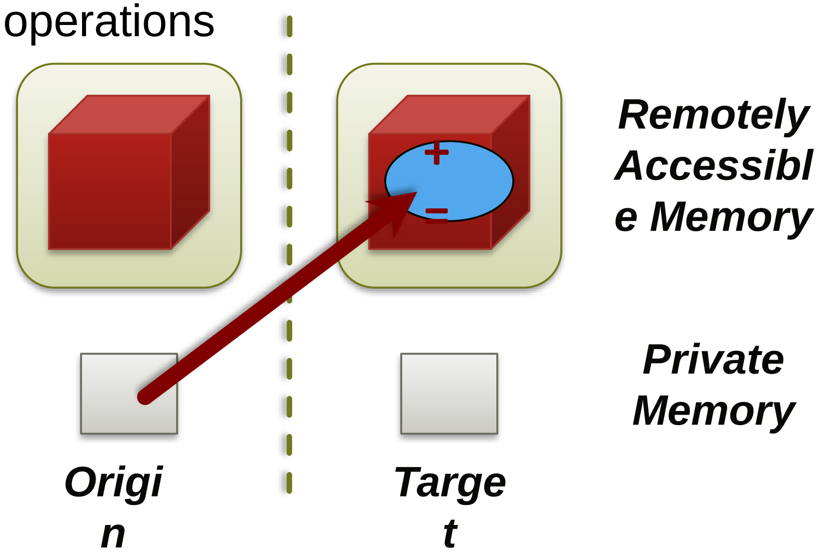
- **Move data to origin, from target**
- **Separate data description triples for origin and target**



Atomic Data Aggregation: *Accumulate*

```
MPI_Accumulate(void *origin_addr, int origin_count,
        MPI_Datatype origin_dtype, int target_rank,
        MPI_Aint target_disp, int target_count,
        MPI_Datatype target_dtype, MPI_Op op, MPI_Win win)
```

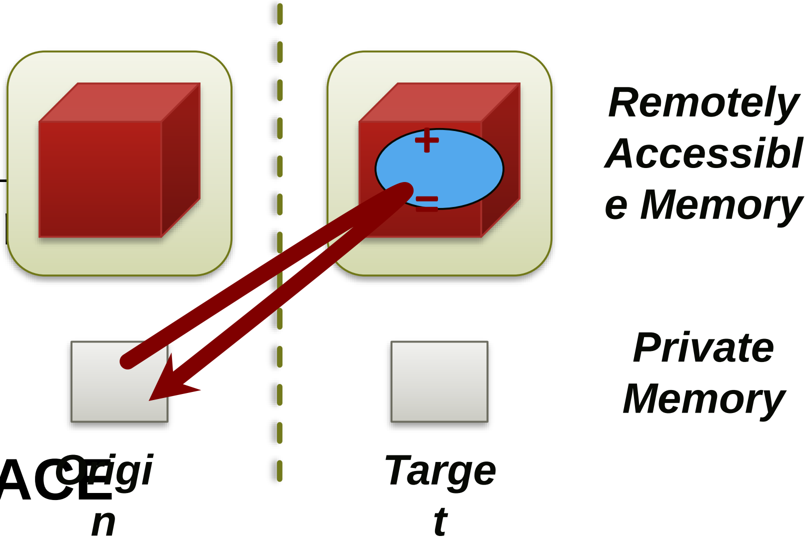
- **Atomic update operation, similar to a put**
  - Reduces origin and target data into target buffer using op argument as combiner
  - Op = MPI_SUM, MPI_PROD, MPI_OR, MPI_REPLACE, …
  - Predefined ops only, no user-defined operations
- **Different data layouts between target/origin OK**
  - Basic type elements must match
- **Op = MPI_REPLACE**
  - Implements *f(a,b)=b*
  - Atomic PUT



Atomic Data Aggregation: *Get Accumulate*

```
MPI_Get_accumulate(void *origin_addr, int origin_count,
        MPI_Datatype origin_dtype, void *result_addr,
        int result_count, MPI_Datatype result_dtype,
        int target_rank, MPI_Aint target_disp,
        int target_count, MPI_Datatype target_dype,
        MPI_Op op, MPI_Win win)
```

- **Atomic read-modify-write**
  - Op = MPI_SUM, MPI_PROD, MPI_OR, MPI_REPLACE, MPI_NO_OP, …
  - Predefined ops only
- **Result stored in target buffer**
- **Original data stored at result_**
- **Different data layouts between target/origin OK**
  - Basic type elements must match
- **Atomic get with MPI_NO_OP**
- **Atomic swap with MPI_REPLACE**



Atomic Data Aggregation: *CAS and FOP*

```
MPI_Fetch_and_op(void *origin_addr, void *result_addr,
       MPI_Datatype dtype, int target_rank,
       MPI_Aint target_disp, MPI_Op op, MPI_Win win)
```

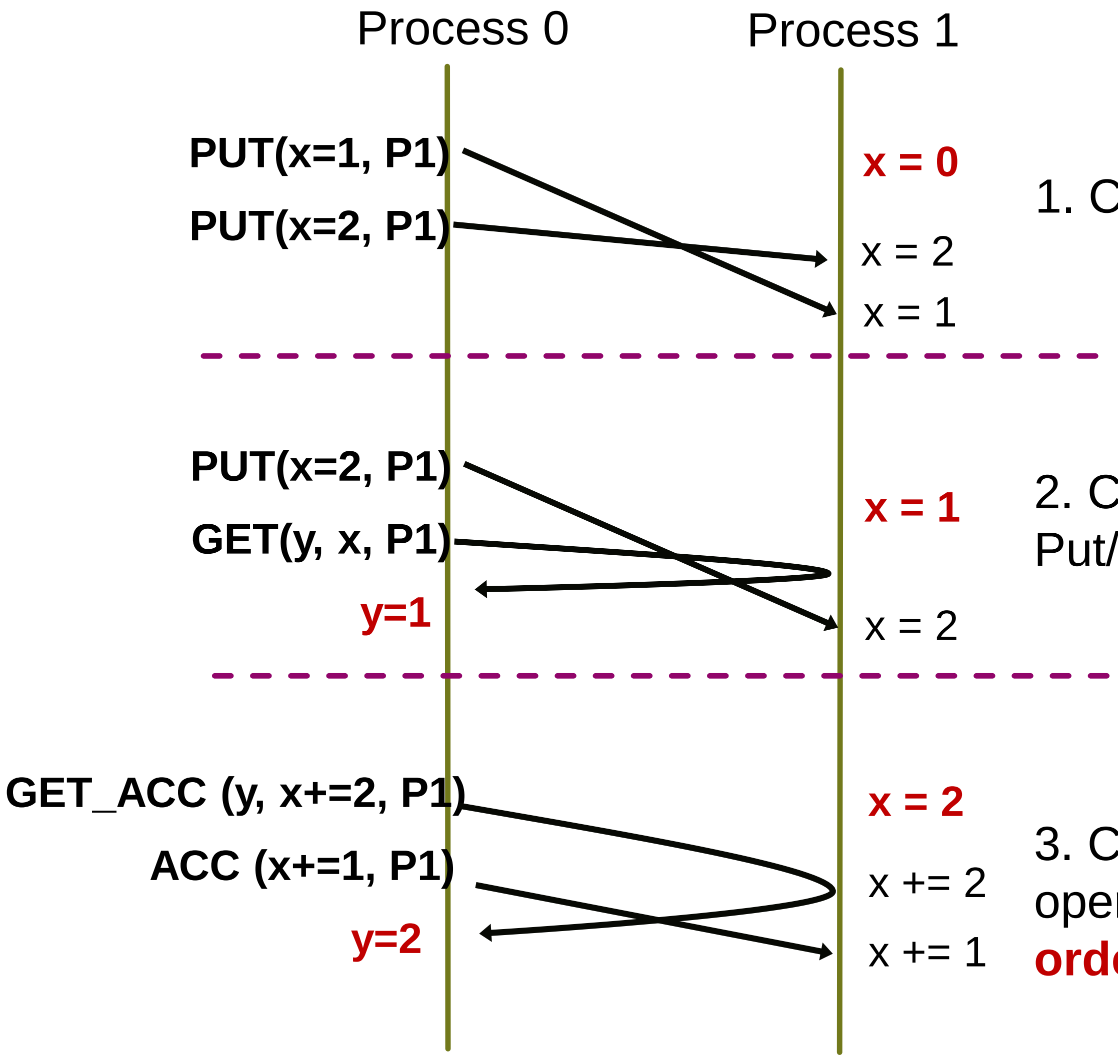
```
MPI_Compare_and_swap(void *origin_addr, void *compare_addr,
       void *result_addr, MPI_Datatype dtype, int target_rank,
       MPI_Aint target_disp, MPI_Win win)
```

- **FOP: Simpler version of MPI_Get_accumulate**
  - All buffers share a single predefined datatype
  - No count argument (it's always 1)
  - Simpler interface allows hardware optimization
- **CAS: Atomic swap if target value is equal to compare value**

Ordering of Operations in MPI RMA

- **No guaranteed ordering for Put/Get operations**
- **Result of concurrent Puts to the same location undefined**
- **Result of Get concurrent Put/Accumulate undefined**
  - Can be garbage in both cases
- **Result of concurrent accumulate operations to the same location are defined according to the order in which the occurred**
  - Atomic put: Accumulate with op = MPI_REPLACE
  - Atomic get: Get_accumulate with op = MPI_NO_OP
- **Accumulate operations from a given process are ordered by default**
  - User can tell the MPI implementation that (s)he does not require ordering as optimization hint
  - You can ask for only the needed orderings: RAW (read-after-write), WAR, RAR, or WAW

Examples with operation ordering



1. Concurrent Puts: **undefined**

2. Concurrent Get and Put/Accumulates: **undefined**

3. Concurrent Accumulate operations to the same location : **ordering is guaranteed**

RMA Synchronization Models

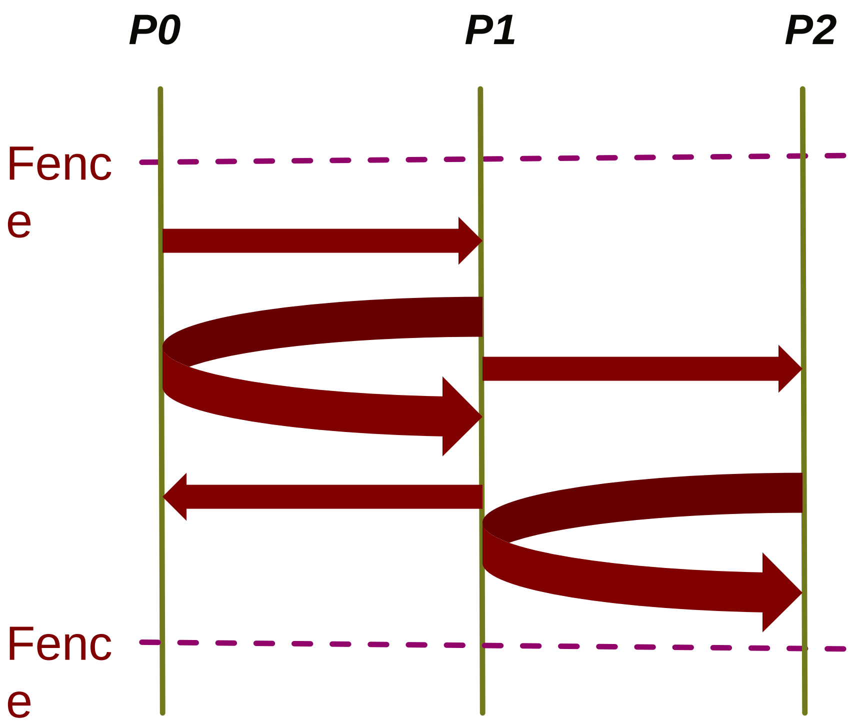
- **RMA data access model**
  - When is a process allowed to read/write remotely accessible memory?
  - When is data written by process X is available for process Y to read?
  - RMA synchronization models define these semantics
- **Three synchronization models provided by MPI:**
  - Fence (active target)
  - Post-start-complete-wait (generalized active target)
  - Lock/Unlock (passive target)
- **Data accesses occur within “epochs”**
  - *Access epochs*: contain a set of operations issued by an origin process
  - *Exposure epochs*: enable remote processes to update a target’s window
  - Epochs define ordering and completion semantics
  - Synchronization models provide mechanisms for establishing epochs

    E.g., starting, ending, and synchronizing epochs

Fence: Active Target Synchronization

```
MPI_Win_fence(int assert, MPI_Win win)
```

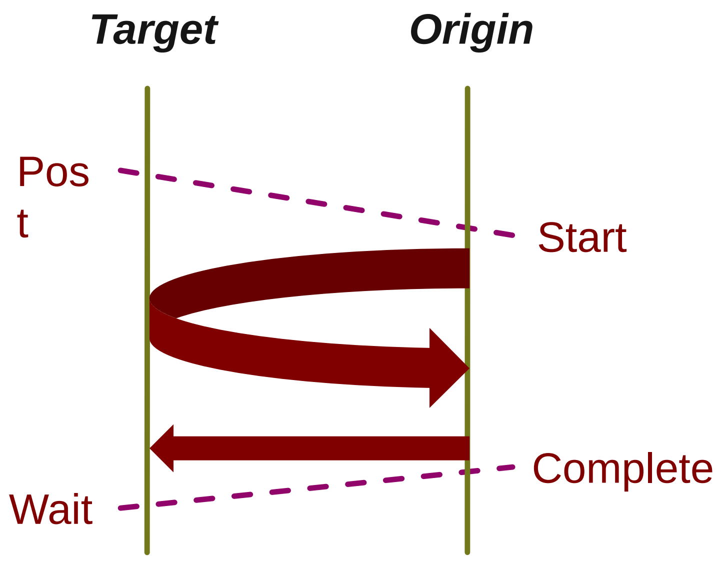
- Collective synchronization model
- Starts *and* ends access and exposure epochs on all processes in the window
- All processes in group of “win” do an MPI_WIN_FENCE to open an epoch
- Everyone can issue PUT/GET operations to read/write data
- Everyone does an MPI_WIN_FENCE to close the epoch
- All operations complete at the second fence synchronization



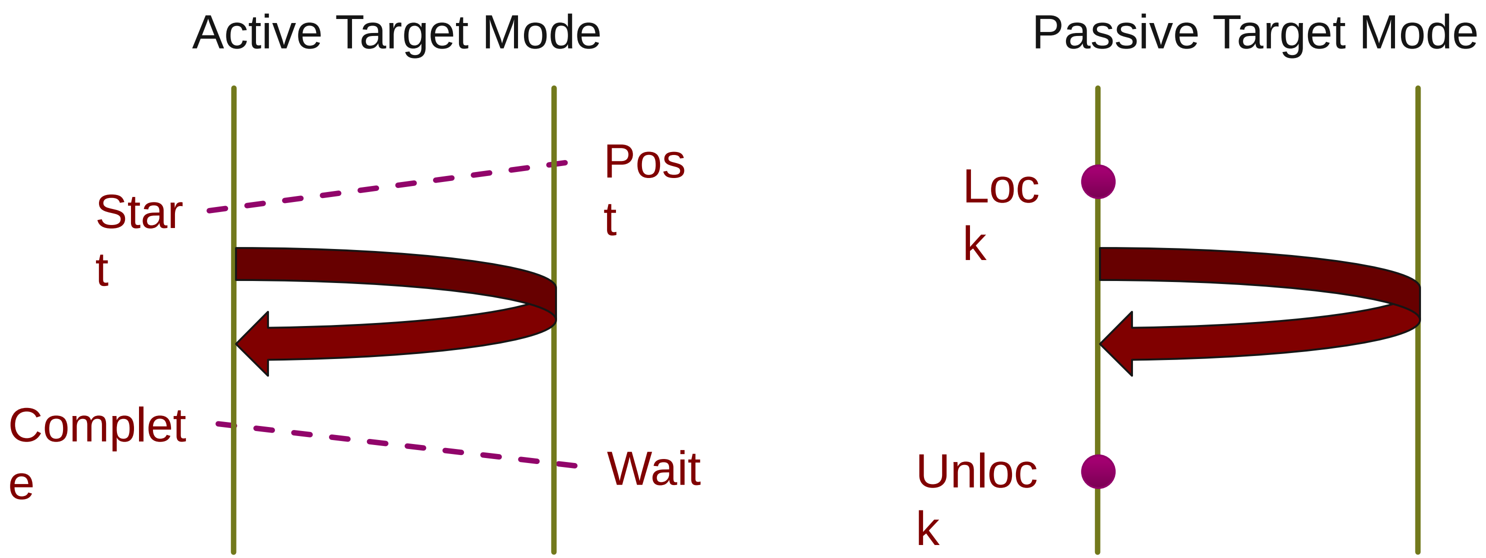
PSCW: Generalized Active Target Synchronization

```
MPI_Win_post/start(MPI_Group grp, int assert, MPI_Win win)
MPI_Win_complete/wait(MPI_Win win)
```

- **Like FENCE, but origin and target specify who they communicate with**
- **Target: Exposure epoch**
  - Opened with MPI_Win_post
  - Closed by MPI_Win_wait
- **Origin: Access epoch**
  - Opened by MPI_Win_start
  - Closed by MPI_Win_complete
- **All synchronization operations may block, to enforce P-S/C-W ordering**
  - Processes can be both origins and targets



Lock/Unlock: Passive Target Synchronization



- **Passive mode: One-sided, *asynchronous* communication**
  - Target does **not** participate in communication operation
- **Shared memory-like model**

Passive Target Synchronization

```
MPI_Win_lock(int locktype, int rank, int assert, MPI_Win win)
```

```
MPI_Win_unlock(int rank, MPI_Win win)
```

```
MPI_Win_flush/flush_local(int rank, MPI_Win win)
```

- **Lock/Unlock: Begin/end passive mode epoch**
  - Target process does not make a corresponding MPI call
  - Can initiate multiple passive target epochs to different processes
  - Concurrent epochs to same process not allowed (affects threads)
- **Lock type**
  - SHARED: Other processes using shared can access concurrently
  - EXCLUSIVE: No other processes can access concurrently
- **Flush: Remotely complete RMA operations to the target process**
  - After completion, data can be read by target process or a different process
- **Flush_local: Locally complete RMA operations to the target process**

Advanced Passive Target Synchronization

```
MPI_Win_lock_all(int assert, MPI_Win win)
```

```
MPI_Win_unlock_all(MPI_Win win)
```

```
MPI_Win_flush_all/flush_local_all(MPI_Win win)
```

- **Lock_all: Shared lock, passive target epoch to all other processes**
  - Expected usage is long-lived: lock_all, put/get, flush, …, unlock_all
- **Flush_all – remotely complete RMA operations to all processes**
- **Flush_local_all – locally complete RMA operations to all processes**

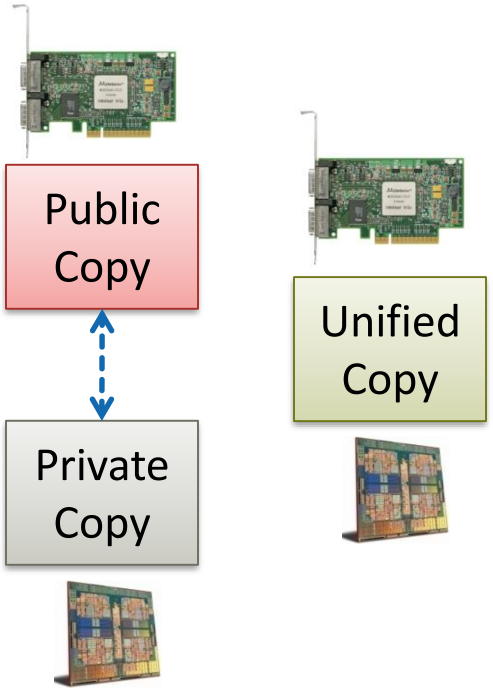
Which synchronization mode should I use, when?

- **RMA communication has low overheads versus send/recv**
  - Two-sided: Matching, queuing, buffering, unexpected receives, etc…
  - One-sided: No matching, no buffering, always ready to receive
  - Utilize RDMA provided by high-speed interconnects (e.g. InfiniBand)
- **Active mode: bulk synchronization**
  - E.g. ghost cell exchange
- **Passive mode: asynchronous data movement**
  - Useful when dataset is large, requiring memory of multiple nodes
  - Also, when data access and synchronization pattern is dynamic
  - Common use case: distributed, shared arrays
- **Passive target locking mode**
  - Lock/unlock – Useful when exclusive epochs are needed
  - Lock_all/unlock_all – Useful when only shared epochs are needed

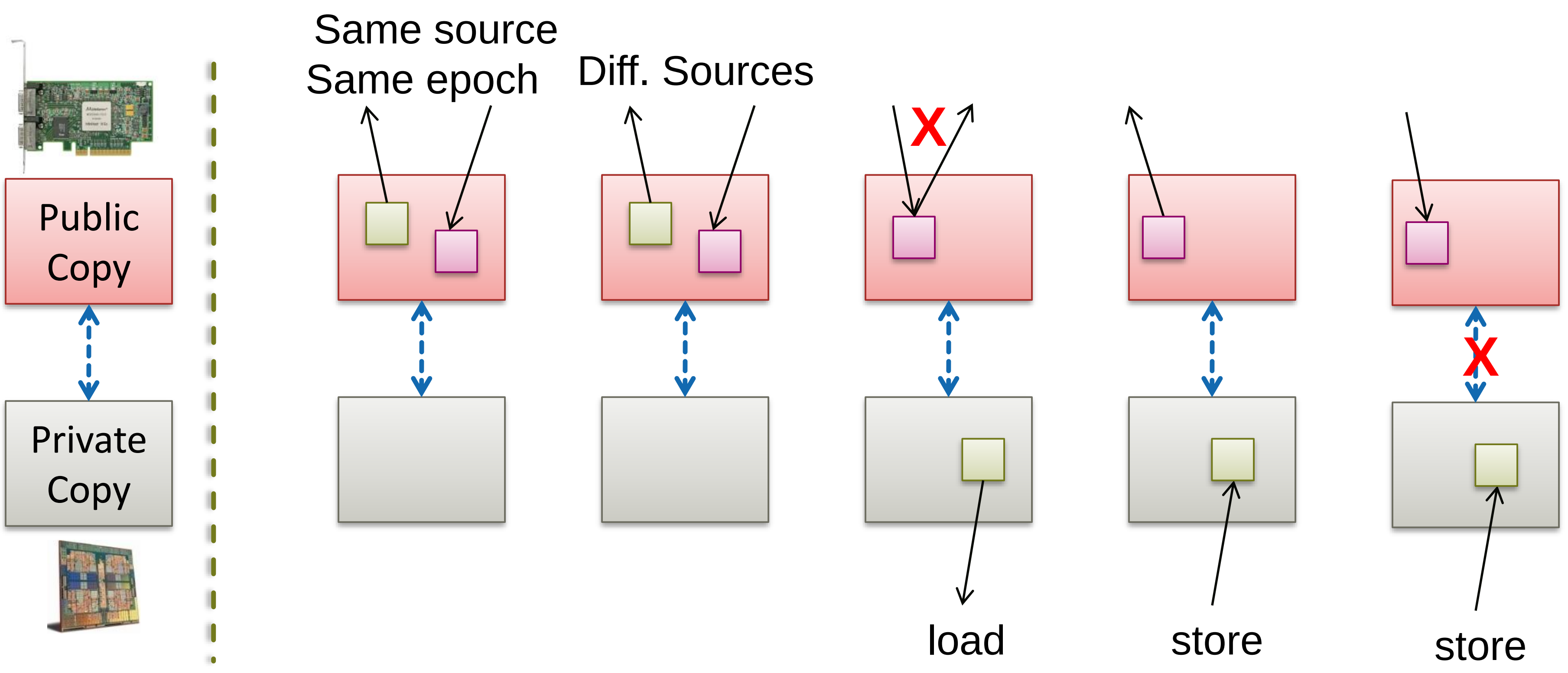
MPI RMA Memory Model

- **MPI-3 provides two memory models: separate and unified**
- **MPI-2: Separate Model**
  - Logical public and private copies
  - MPI provides software coherence between window copies
  - Extremely portable, to systems that don't provide hardware coherence
- **MPI-3: New Unified Model**
  - Single copy of the window
  - System must provide coherence
  - Superset of separate semantics

    E.g. allows concurrent local/remote access
  - Provides access to full performance potential of hardware

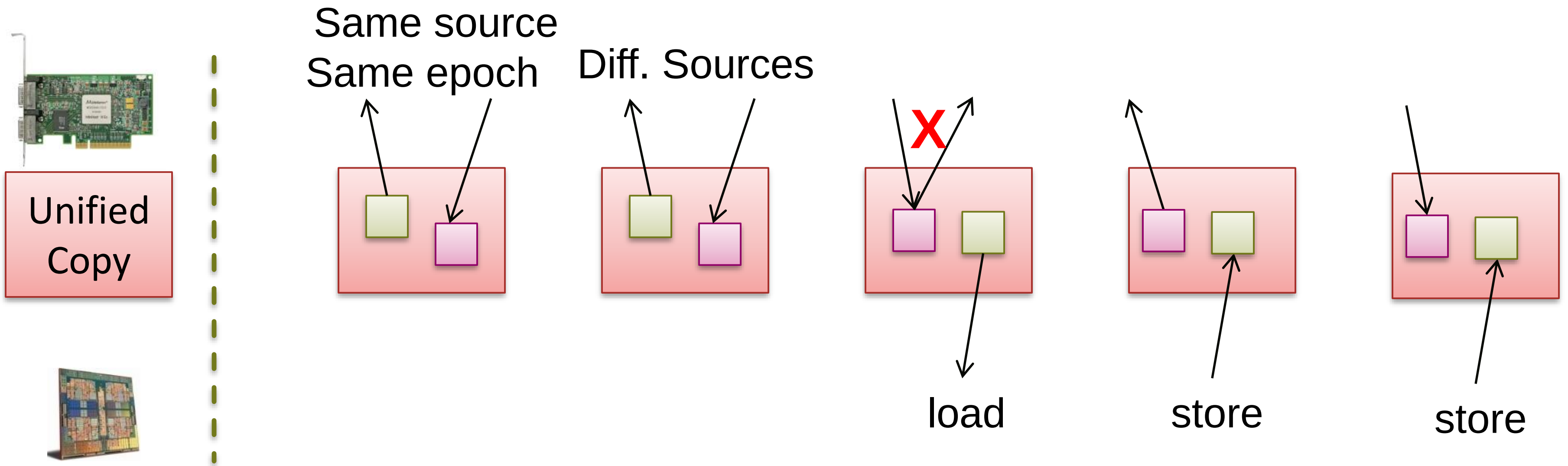


MPI RMA Memory Model (separate windows)



- Very portable, compatible with non-coherent memory systems
- Limits concurrent accesses to enable software coherence

MPI RMA Memory Model (unified windows)



- **Allows concurrent local/remote accesses**
- **Concurrent, conflicting operations are allowed (not invalid)**
  - Outcome is not defined by MPI (defined by the hardware)
- **Can enable better performance by reducing synchronization**