Lecture 20a:

Under the Hood, Part 1: Implementing Message Passing

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2021

Today’s Theme

Message passing model (abstraction)

- Threads operate within their own private address spaces
- Threads communicate by sending/receiving messages
  - send: specifies recipient, buffer to be transmitted, and optional message identifier ("tag")
  - receive: sender, specifies buffer to store data, and optional message identifier
  - Sending messages is <u>the only way</u> to exchange data between threads 1 and 2

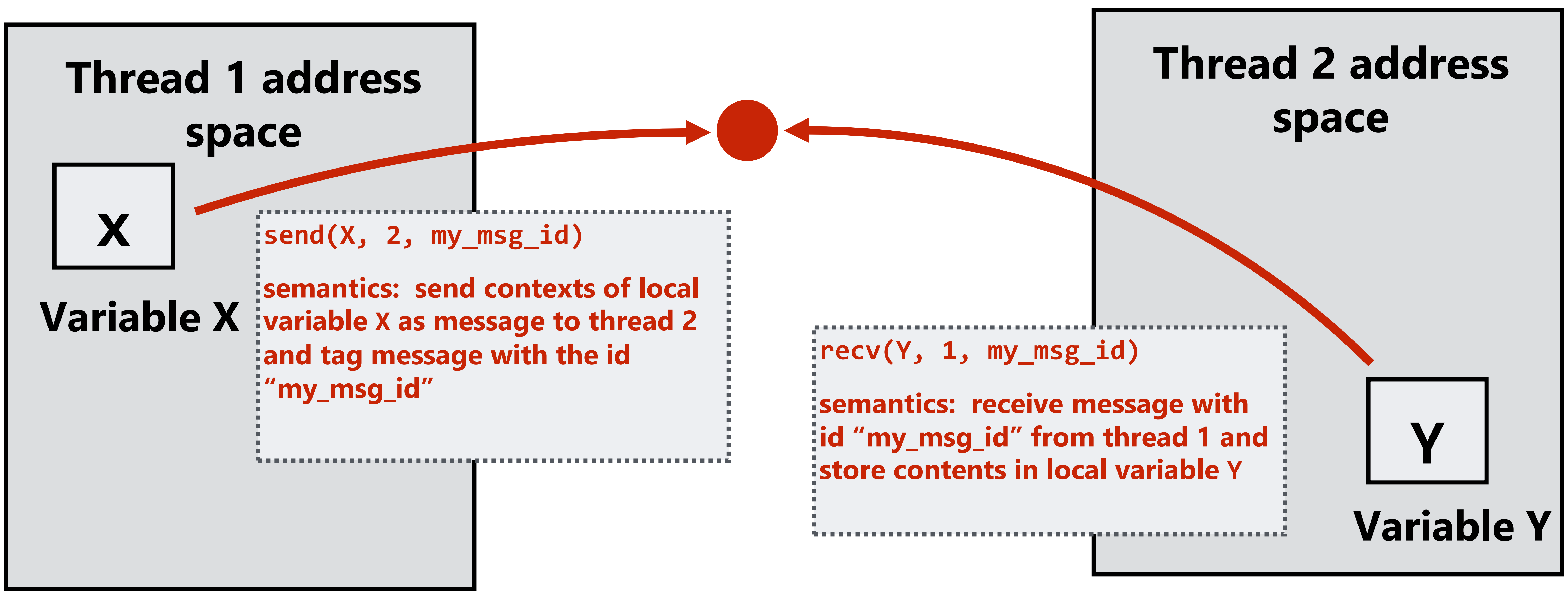
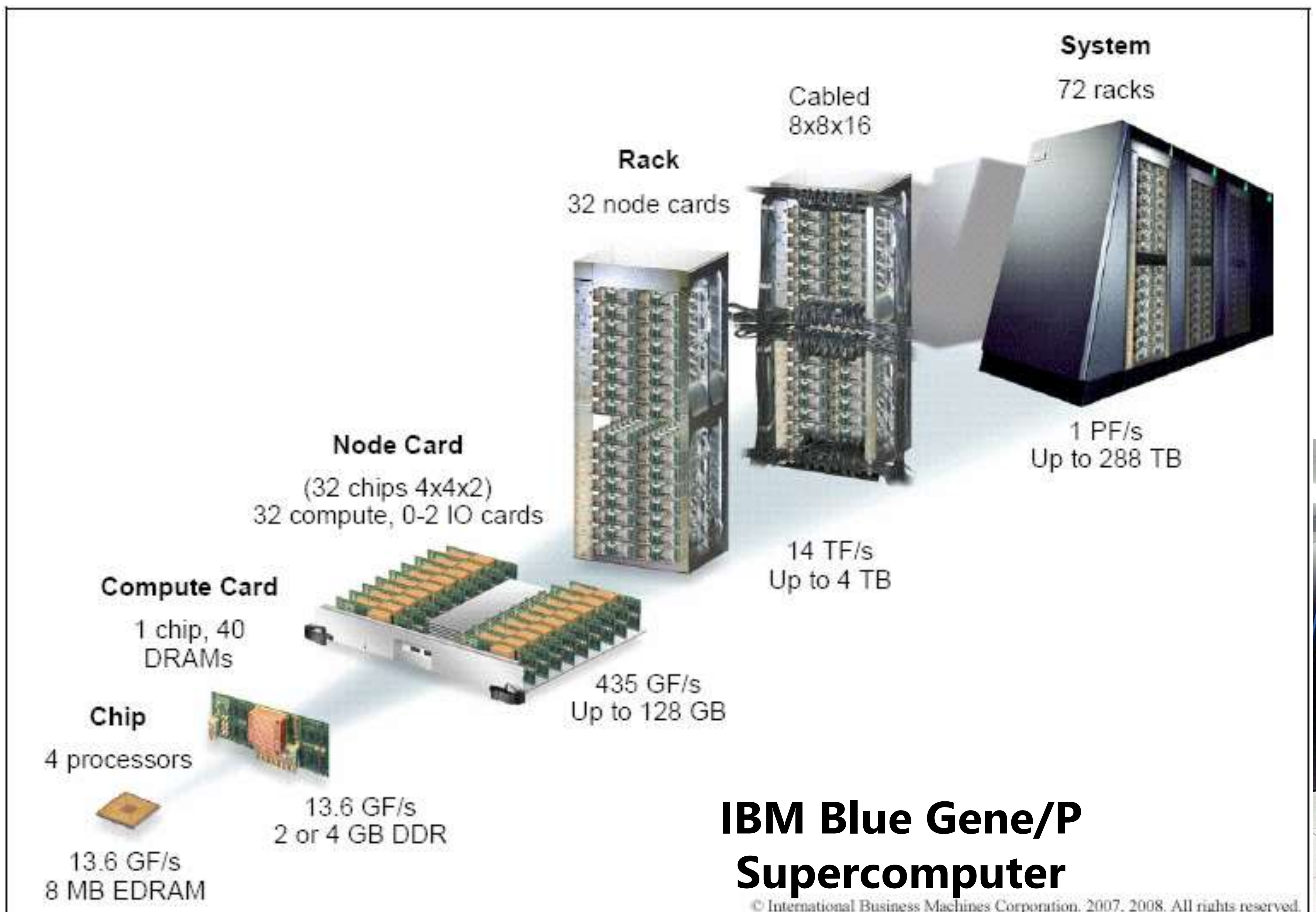
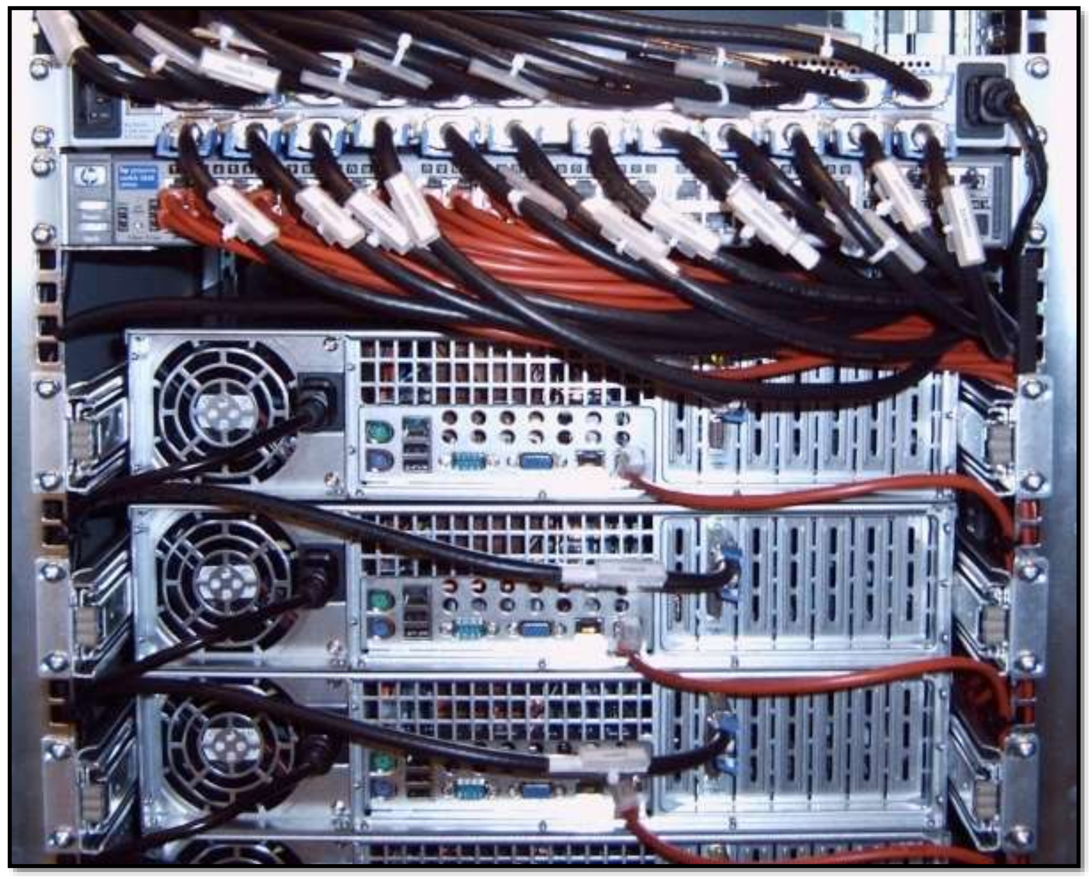


Illustration adopted from Culler, Singh, Gupta

Message passing systems

- Popular software library: MPI (message passing interface)
- Hardware need not implement system-wide loads and stores to execute message passing programs (need only be able to communicate messages)
  - Can connect commodity systems together to form large parallel machine (message passing is a programming model for clusters)

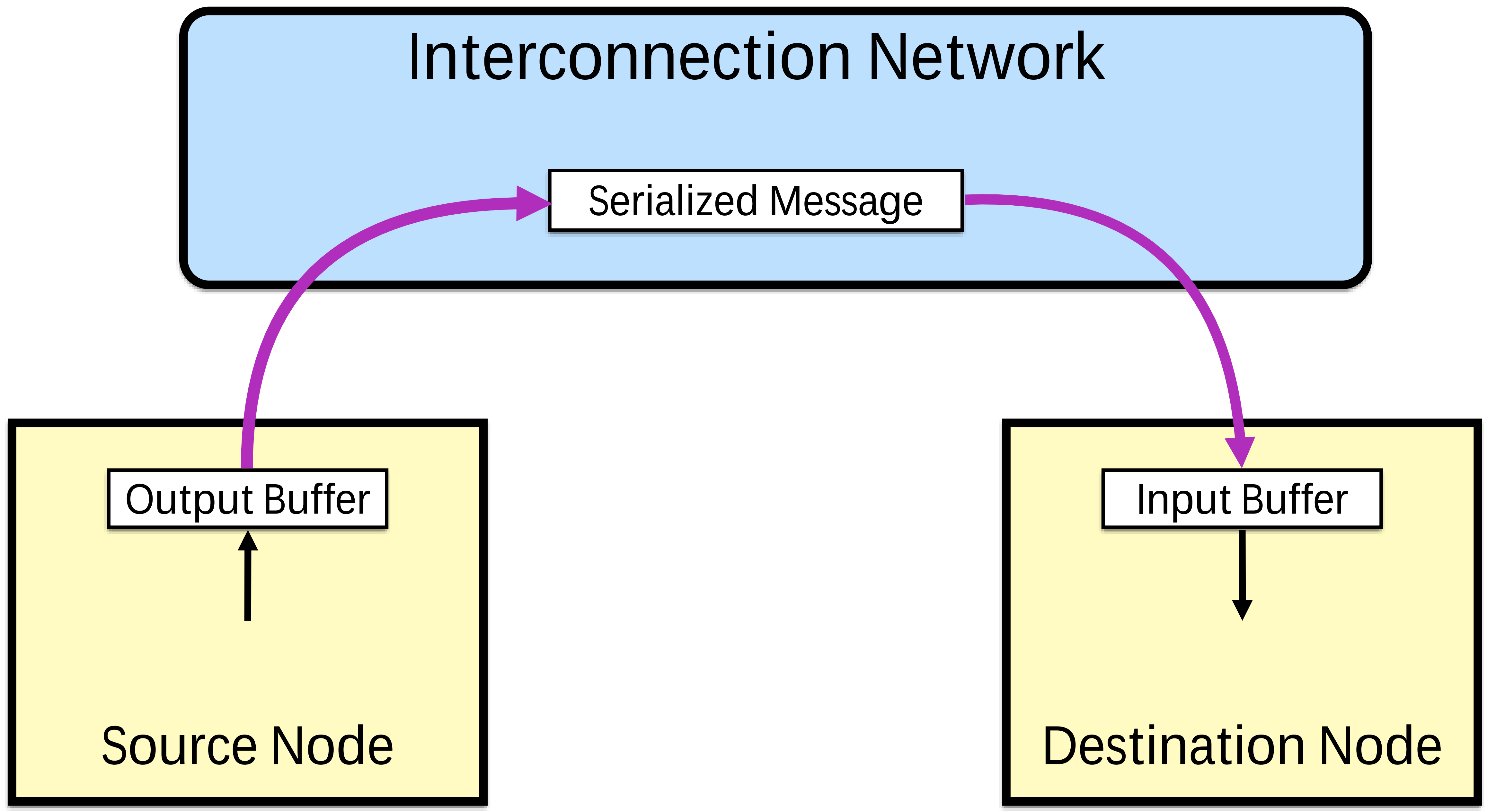




Cluster of workstations
(Infiniband network)

Image credit: IBM

Network Transaction



- **One-way transfer of information from a source output buffer to a destination input buffer**
  - **causes some action at the destination**
    - **e.g., deposit data, state change, reply**
  - **occurrence is not directly visible at source**

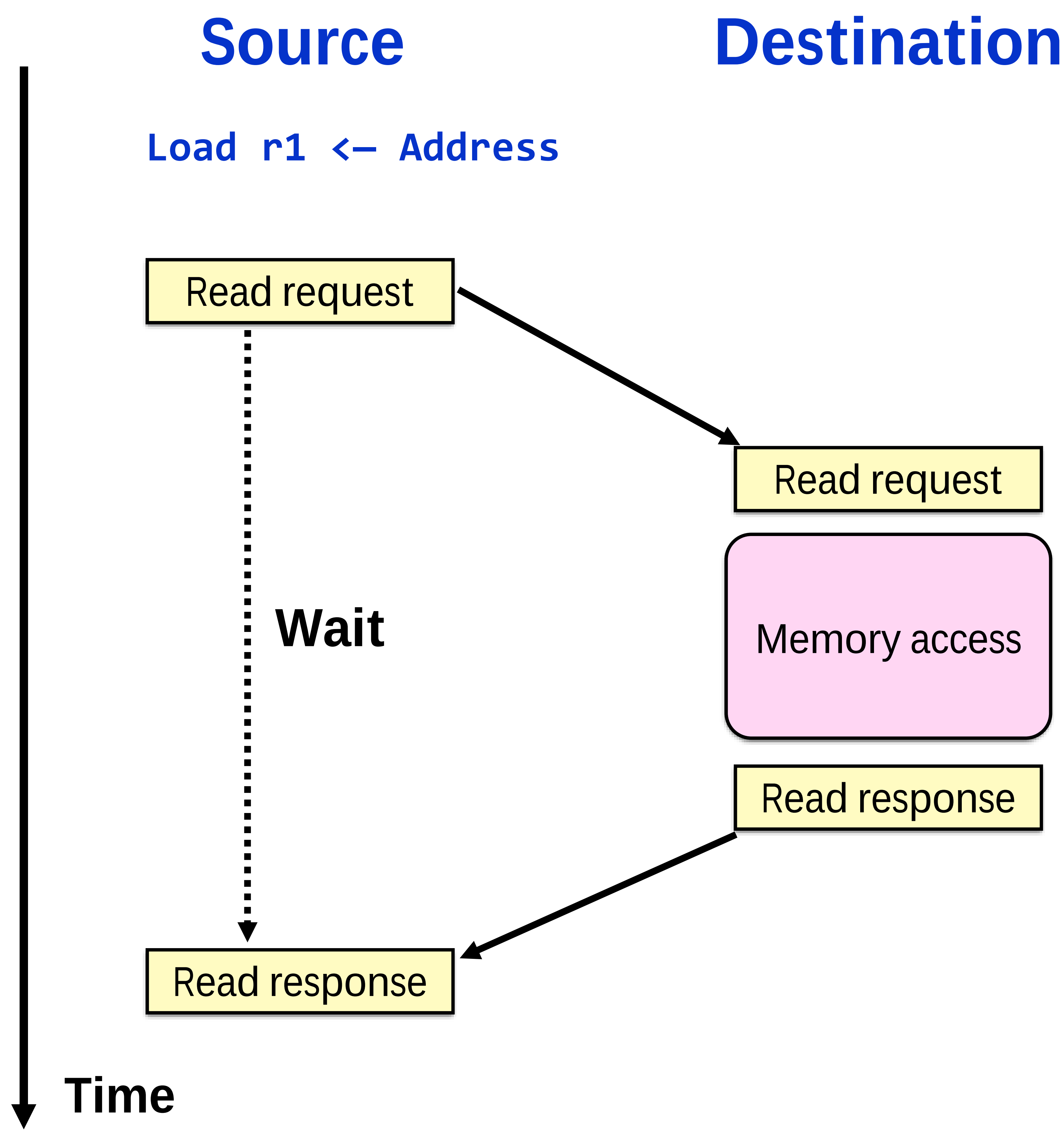
Shared Address Space Abstraction

(1) Initiate memory access
(2) Address translation
(3) Local/remote check
(4) Request transaction

(5) Remote memory access

(6) Reply transaction

(7) Complete memory access



- **Fundamentally a two-way request/response protocol**
  - **writes have an acknowledgement**

Key Properties of SAS Abstraction

- Source and destination addresses are specified by source of the request
  - a degree of logical coupling and trust
- No storage logically "outside the application address space(s)"
  - may employ temporary buffers for transport
- Operations are fundamentally request-response
- Remote operation can be performed on remote memory
  - logically does not require intervention of the remote processor

Message Passing Implementation Options

Synchronous:

- Send completes after matching receive and source data sent
- Receive completes after data transfer complete from matching send

Asynchronous:

- Send completes after send buffer may be reused

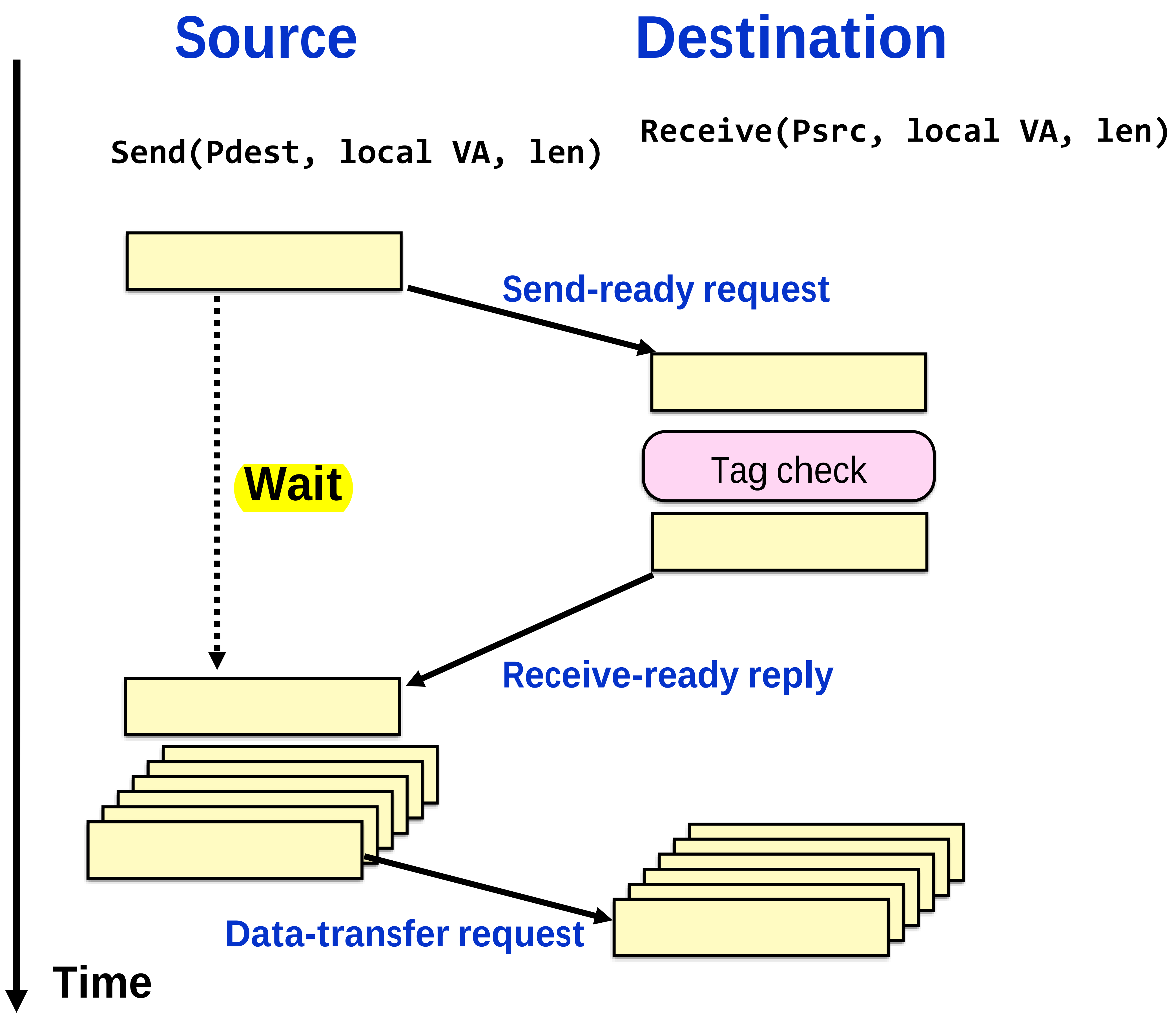
Synchronous Message Passing

(1) Initiate send
(2) Address translation
(3) Local/remote check
(4) Send-ready request

(5) Remote check for posted receive (assume success)

(6) Reply transaction

(7) Bulk data transfer
Source VA —> Dest VA

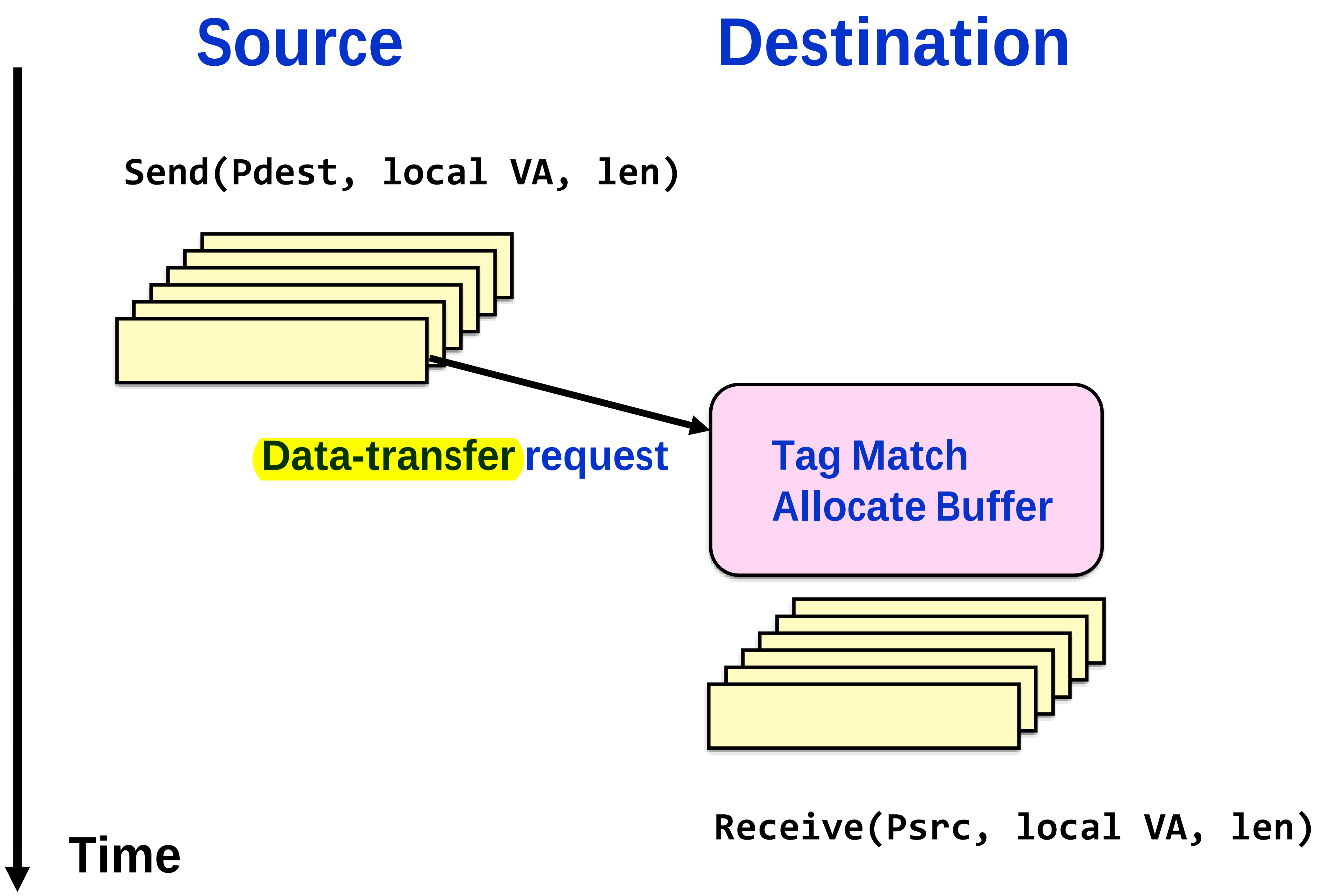


- Data is not transferred until target address is known
  - Limits contention and buffering at the destination
- Performance?

Asynchronous Message Passing: Optimistic

(1) Initiate send
(2) Address translation
(3) Local/remote check
(4) **Send data**

(5) Remote check for posted receive; on fail, **allocate data buffer**



- **<u>Good news:</u>**
  - **source does not stall waiting for the destination to receive**
- **<u>Bad news:</u>**
  - **storage is required within the message layer (?)**

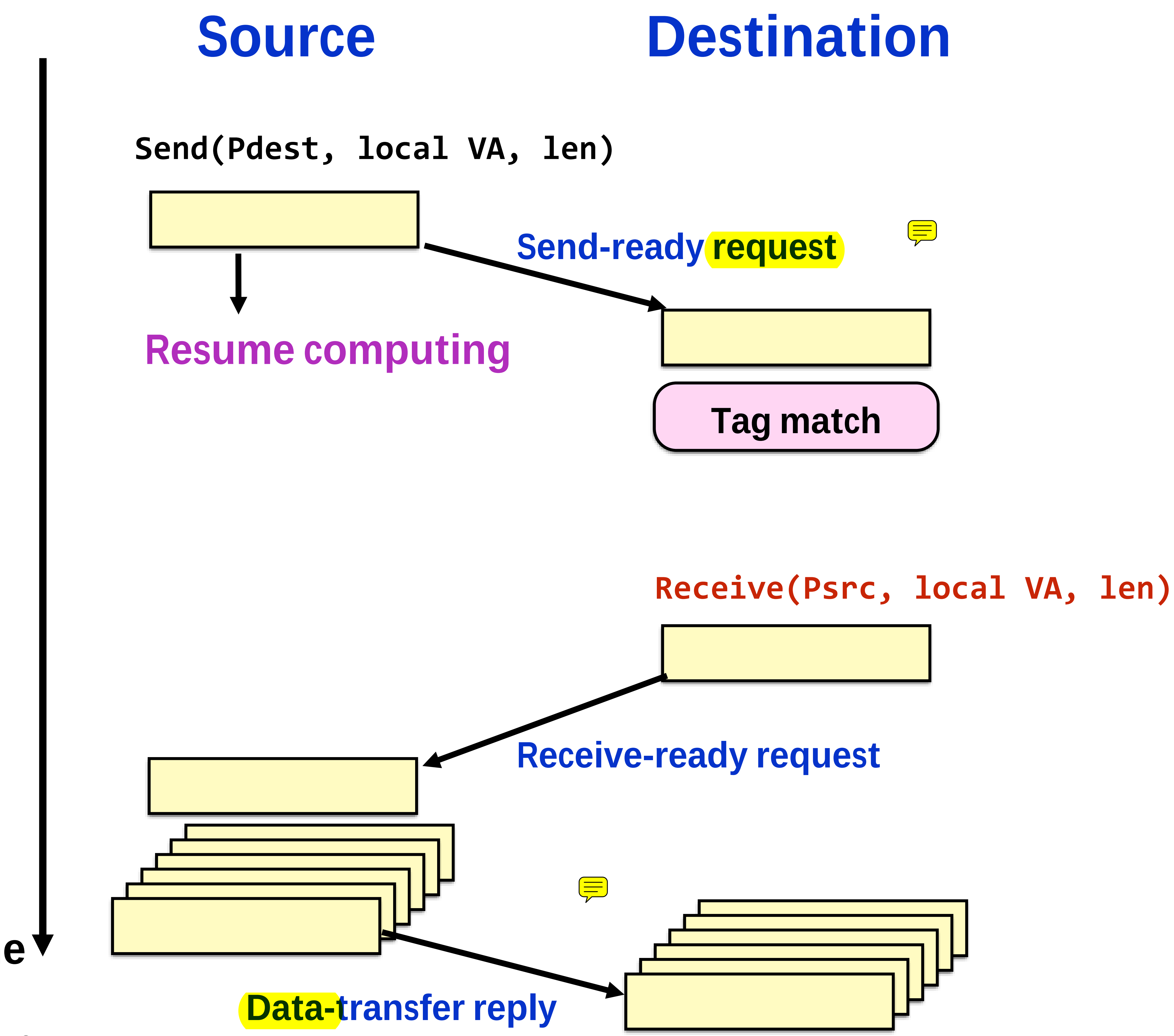
Asynchronous Message Passing: Conservative

(1) Initiate send
(2) Address translation
(3) Local/remote check
(4) Send-ready request

(5) Remote check for posted receive (assume fail); **record send-ready**

(6) Receive-ready request

(7) Bulk data reply
Source VA —> Dest VA



- **Where is the buffering?**
- **Contention control? Receiver-initiated protocol?**
- **What about short messages?**

Key Features of Message Passing Abstraction

- Source knows send address, destination knows receive address
  - after handshake they both know both
- Arbitrary storage "outside the local address spaces"
  - may post many sends before any receives
- Fundamentally a 3-phase transaction
  - includes a request / response
  - can use optimistic 1-phase in limited "safe" cases
    - credit scheme

Challenge: Avoiding Input Buffer Overflow

- This requires flow-control on the sources
- Approaches:
  1. Reserve space per source (credit)
     - when is it available for reuse? (utilize ack messages?)
  2. Refuse input when full
     - what does this do to the interconnect?
       - backpressure in a reliable network
       - tree saturation? deadlock?
       - what happens to traffic not bound for congested destination?
  3. Drop packets (?)
  4. ???

Challenge: Avoiding Fetch Deadlock

- Must continue accepting messages, even when cannot source msgs
  - what if incoming transaction is a request?
    - each may generate a response, which cannot be sent!
    - what happens when internal buffering is full?

Approaches:

1. Logically independent request/reply networks
   - physical networks
   - virtual channels with separate input/output queues
2. Bound requests and reserve input buffer space
   - K(P-1) requests + K responses per node
   - service discipline to avoid fetch deadlock?
3. NACK on input buffer full
   - NACK delivery?

Implementation Challenges: Big Picture

- One-way transfer of information
- No global knowledge, nor global control
  - barriers, scans, reduce, global-OR give fuzzy global state
- Very large number of concurrent transactions
- Management of input buffer resources
  - many sources can issue a request and over-commit destination before any see the effect
- Latency is large enough that you are tempted to "take risks"
  - e.g., optimistic protocols; large transfers; dynamic allocation

Lecture 20b:

Implementing Parallel Runtimes, Part 2

Parallel Computer Architecture and Programming
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Objectives

- What are the costs of using parallelism APIs?
- How do the runtimes operate?

Basis of Lecture

- This lecture is based on runtime and source code analysis of Intel's open source parallel runtimes
  - OpenMP – https://www.openmprtl.org/
  - Cilk – https://bitbucket.org/intelcilkruntime/intel-cilk-runtime

- And using the LLVM compiler
  - OpenMP – part of LLVM as of 3.8
  - CilkPlus: http://cilkplus.github.io/ ➔ OpenCilk: http://cilk.mit.edu

OpenMP and Cilk

- What do these have in common?
  - pthreads

- What benefit does abstraction versus implementation provide?

Simple OpenMP Loop Compiled

- What is this code doing?
- What do the OpenMP semantics specify?
- How might you accomplish this?

```
extern float foo( void );
int main (int argc, char** argv) {
    int i;
    float r = 0.0;
    #pragma omp parallel for schedule(dynamic) reduction(+:r)
    for ( i = 0; i < 10; i ++ ) {
        r += foo();
    }
    return 0;
}
```

Under the hood:

1. Scheduling
2. Work (in parallel)
3. Reduction
4. Barrier

Example from OpenMP runtime documentation

Simple OpenMP Loop Compiled

```
extern float foo( void );
int main (int argc, char** argv) {
   static int zero = 0;
   auto int gtid;
   auto float r = 0.0;
   __kmpc_begin( & loc3, 0 );
   gtid = __kmpc_global thread num( & loc3 );
   __kmpc_fork call( &loc7, 1, main_7_parallel_3, &r );
   __kmpc_end( & loc0 );
   return 0;
}
```

Call a (new) function in parallel with the argument(s)

Simple OpenMP Loop Compiled

- **OpenMP "microtask"**
  - Each thread runs the task
- **Initializes local iteration bounds and local reduction**
- **Each iteration receives a chunk and operates locally**
- **After finishing all chunks, combine into global reduction**

```
struct main_10_reduction_t_5 { float r_10_rpr; };

void main_7_parallel_3( int *gtid, int *btid, float *r_7_shp ) {
        auto int i_7_pr;
        auto int lower, upper, liter, incr;
        auto struct main_10_reduction_t_5 reduce;
        reduce.r_10_rpr = 0.F;
        liter = 0;
        __kmpc_dispatch_init_4( & loc7,*gtid, 35, 0, 9, 1, 1 );
        while ( __kmpc_dispatch_next_4( & loc7, *gtid, &liter,
           &lower, &upper, &incr) ) {
                for( i_7_pr = lower; upper >= i_7_pr; i_7_pr ++ )
                        reduce.r_10_rpr += foo();
        }
        switch( __kmpc_reduce_nowait( & loc10, *gtid, 1, 4,
           &reduce, main_10_reduce_5, &lck ) ) {
        case 1:
                *r_7_shp += reduce.r_10_rpr;
                __kmpc_end_reduce_nowait( & loc10, *gtid, &lck);
        break;
        case 2:
                __kmpc_atomic_float4_add( & loc10, *gtid,
                   r_7_shp, reduce.r_10_rpr );
        break;
        default:;
        }
}
```

Example from OpenMP runtime documentation

Simple OpenMP Loop Compiled

- All code combined

```
extern float foo( void );
int main (int argc, char** argv) {
        static int zero = 0;
        auto int gtid;
        auto float r = 0.0;
        __kmpc_begin( & loc3, 0 );
        gtid = __kmpc_global thread num( & loc3 );
        __kmpc_fork call( &loc7, 1, main_7_parallel_3, &r );
        __kmpc_end( & loc0 );
        return 0;
}

struct main_10_reduction_t_5 { float r_10_rpr; };
static kmp_critical_name lck = { 0 };
static ident_t loc10;

void main_10_reduce_5( struct main_10_reduction_t_5 *reduce_lhs,
struct main_10_reduction_t_5 *reduce_rhs )
{
        reduce_lhs->r_10_rpr += reduce_rhs->r_10_rpr;
}
```

```
void main_7_parallel_3( int *gtid, int *btid, float *r_7_shp ) {
        auto int i_7_pr;
        auto int lower, upper, liter, incr;
        auto struct main_10_reduction_t_5 reduce;
        reduce.r_10_rpr = 0.F;
        liter = 0;
        __kmpc_dispatch_init_4( & loc7,*gtid, 35, 0, 9, 1, 1 );
        while ( __kmpc_dispatch_next_4( & loc7, *gtid, &liter,
           &lower, &upper, &incr) ) {
                for( i_7_pr = lower; upper >= i_7_pr; i_7_pr ++ )
                        reduce.r_10_rpr += foo();
        }
        switch( __kmpc_reduce_nowait( & loc10, *gtid, 1, 4,
           &reduce, main_10_reduce_5, &lck ) ) {
        case 1:
                *r_7_shp += reduce.r_10_rpr;
                __kmpc_end_reduce_nowait( & loc10, *gtid, &lck);
        break;
        case 2:
                __kmpc_atomic_float4_add( & loc10, *gtid, r_7_shp,
                   reduce.r_10_rpr );
        break;
        default:;
        }
}
```

Example from OpenMP runtime documentation

Fork Call

- "Forks" execution and calls a specified routine (microtask)
- Determine how many threads to allocate to the parallel region
- Setup task structures
- Release allocated threads from their idle loop

Iteration Mechanisms

- Static, compile time iterations
  - __kmp_for_static_init
  - Compute one set of iteration bounds

- Everything else
  - __kmp_dispatch_next
  - Compute the next set of iteration bounds

OMP Barriers

- Two phase -> gather and release
  - Gather non-master threads pass, master waits
  - Release is opposite

- Barrier can be:
  - Linear (Centralized)
  - Tree
  - Hypercube
  - Hierarchical

OMP Atomic

- Can the compiler do this in a read-modify-write (RMW) op?

- Otherwise, create a compare-and-swap loop

```
T* val;
T update;
#pragma omp atomic
   *val += update;
```

If T is int, this is "lock add …".
If T is float, this is "lock cmpxchg …"

Why?

OMP Tasks

- #pragma omp task depend (inout:x) …

- Create microtasks for each task
  - Track dependencies by a list of address / length tuples
  - Ordered, dataflow scheduling of tasks on memory locations

- Allows dynamic creation of task graph for computations with irregular structure

Cilk

- Covered in Lecture 6
- We discussed the what and why, now the how

Simple Cilk Program Compiled

- What is this code doing?
- What do the Cilk semantics specify?
- Which is the child? Which is the continuation?

```
int fib(int n) {
  if (n < 2)
    return n;
  int a = cilk_spawn fib(n-1);
  int b = fib(n-2);
  cilk_sync;
  return a + b;
}
```

How to create a continuation?

- Continuation needs all of the state to continue
  - Register values, stack, etc.

- What function allows code to jump to a prior point of execution?

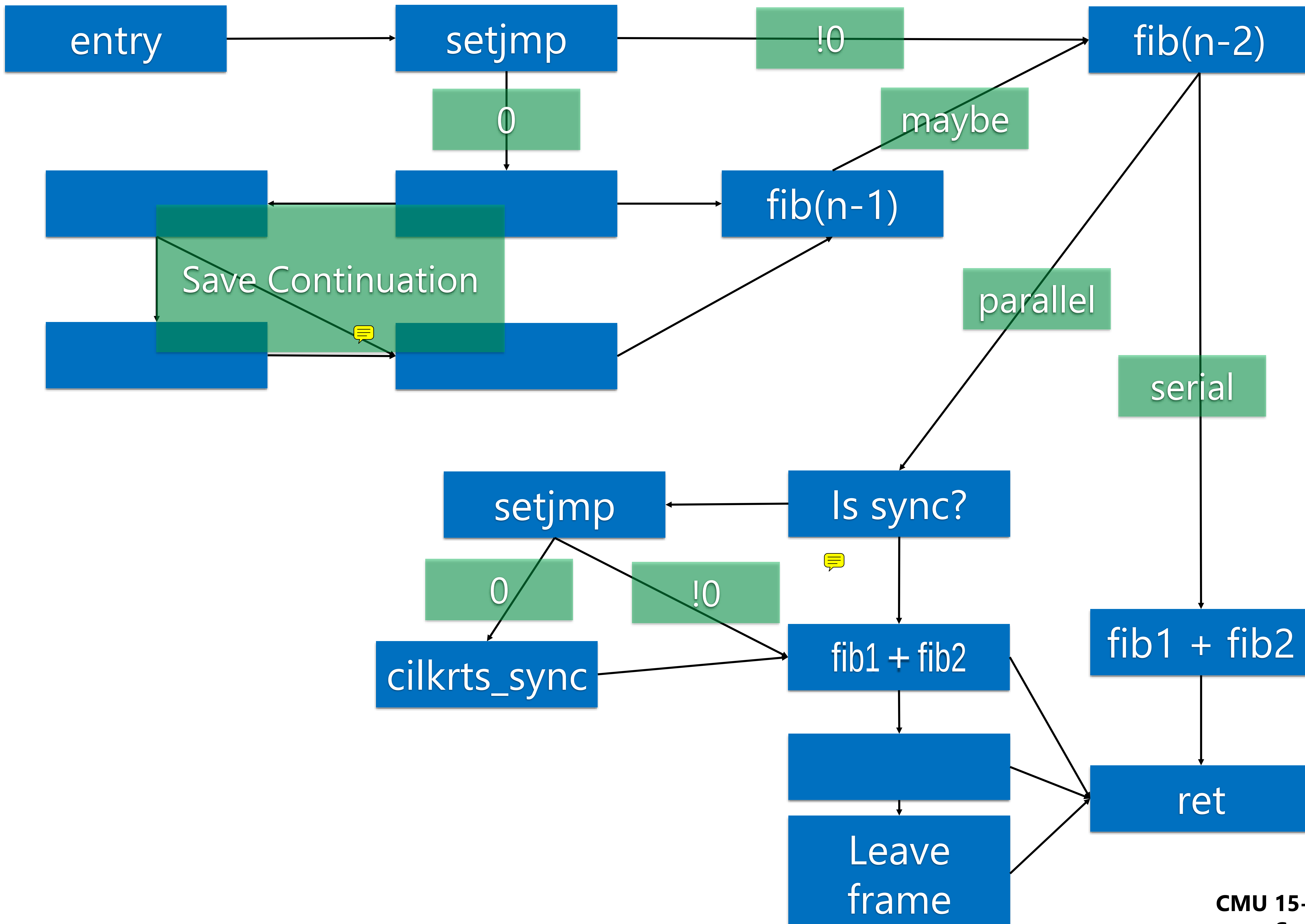
- Setjmp(jmp_buf env)
  - Save stack context
  - Return via longjmp(env, val)
  - Setjmp returns 0 if saving, val if returning via longjmp

Basic Block

- **Unit of Code Analysis**

- **Sequence of instructions**
  - **Execution can only enter at the first instruction**
    - **Cannot jump into the middle**
  - **Execution can only exit at the last instruction**
    - **Branch or Function Call**
    - **Or the start of another basic block (fall through)**

Simple Cilk Program Revisited



Cilk Workers

- While there may be work
  - Try to get the next item from our queue
  - Else try to get work from a random queue
  - If there is no work found, wait on semaphore

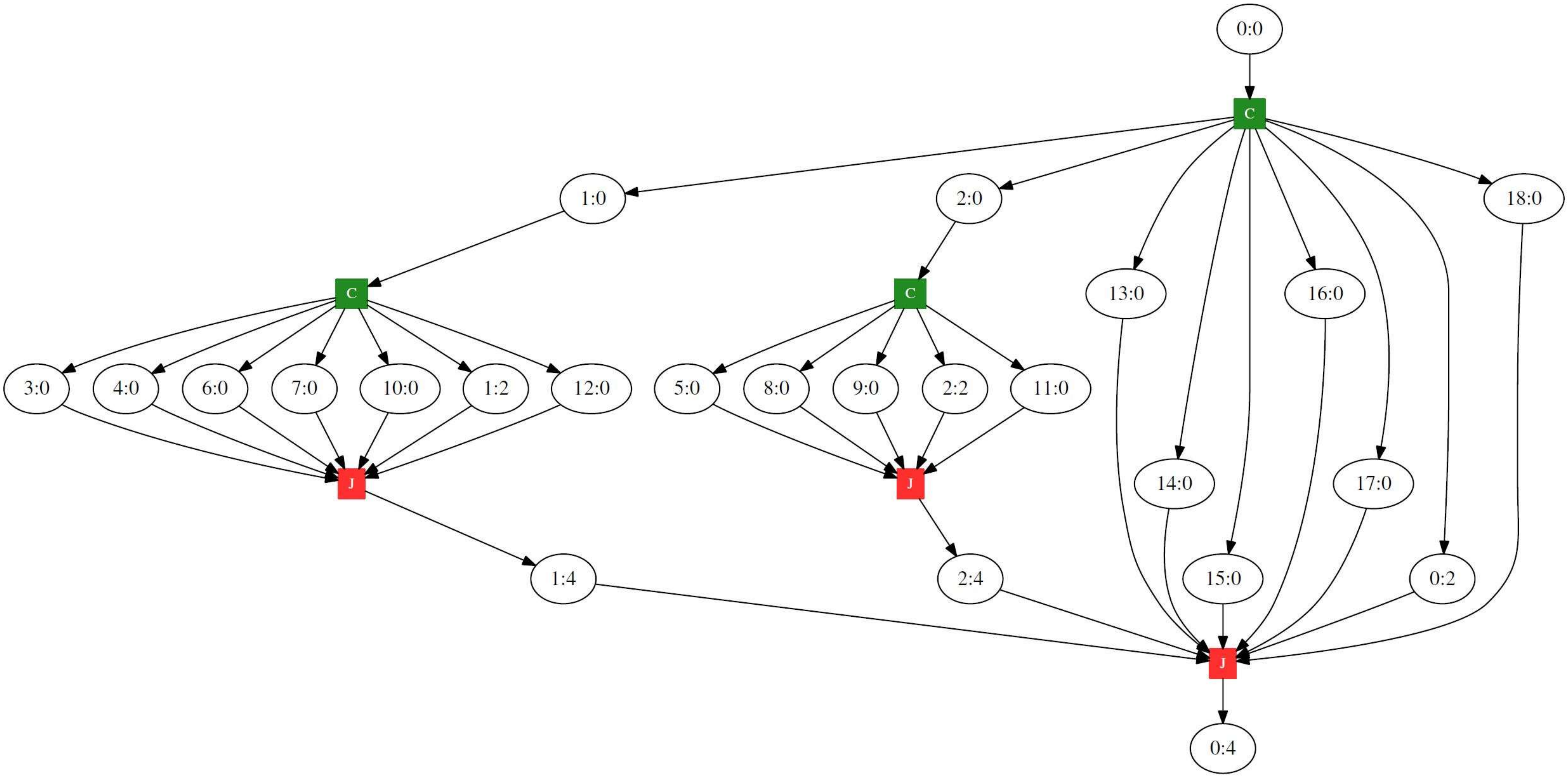
- If work item is found
  - Resume with the continuation's stack

Thread Local Storage

- Linux supports thread local storage
  - New: C11 - _Thread_local keyword
    - one global instance of the variable per thread
  - Compiler places values into .tbss
  - OS provides each thread with this space

- Since Cilk and OpenMP are using pthreads
  - These values are in the layer below them

OpenMP Example - Traced



Cilk Taskgraph – Fib - Traced