COS 318: Operating Systems

Message Passing

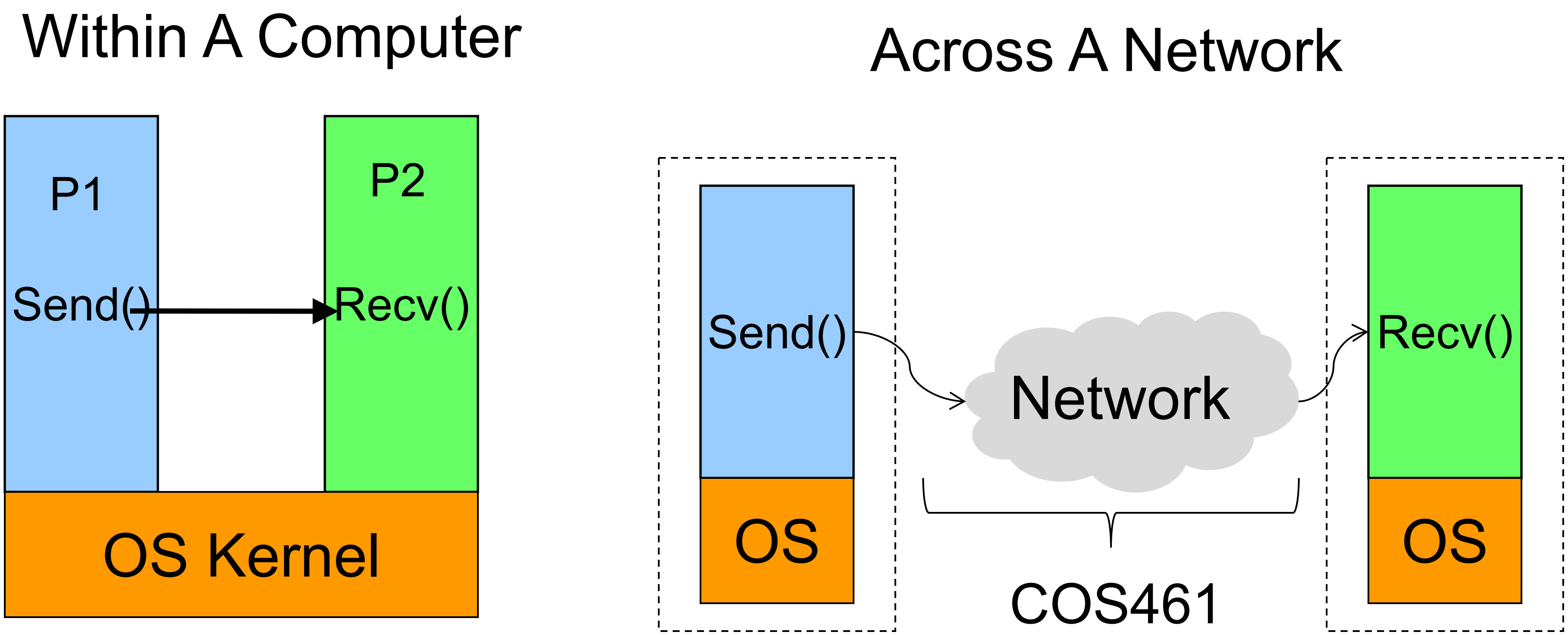
Motivation

- Locks, semaphores, monitors are good but they only work under the shared-address-space model
  - Threads in the same process
  - Processes that share an address space
- We have assumed that processes/threads communicate via shared data (counter, producer-consumer buffer, …)
- How to synchronize and communicate among processes with different address spaces?
  - Inter-process communication (IPC)
- Can we have a single set of primitives that work for all cases: single machine OS, multiple machines same OS, multiple machines multiple OS, distributed?

With No Shared Address Space

- No need for explicit mutual exclusion primitives
  - Processes cannot touch the same data directly
- Communicate by sending and receiving explicit messages: Message Passing
- Synchronization is implicit in message passing
  - No need for explicit mutual exclusion
  - Event ordering via sending and receiving of messages
- More portable to different environments, though lacks some of the convenience of a shared address space
- Typically, communication in consummated via a send and a matching receive

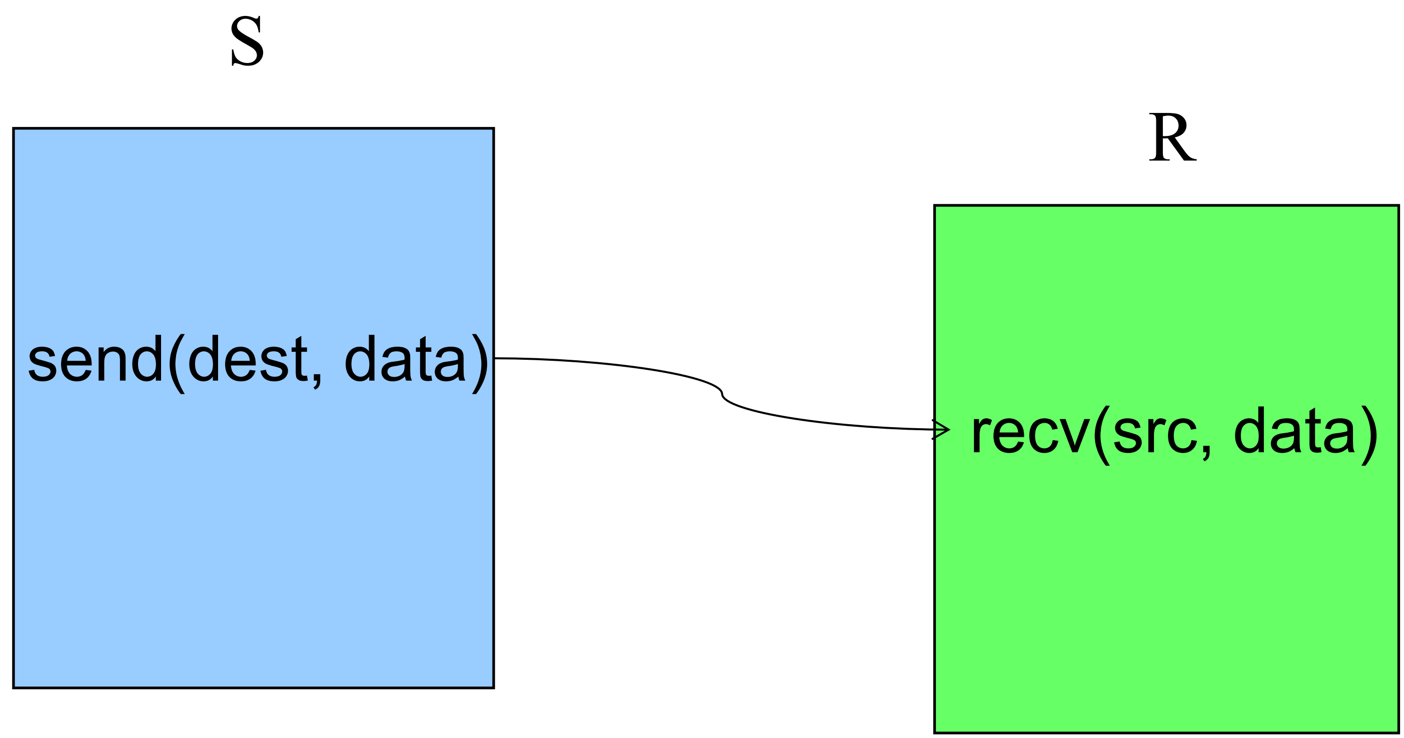
Sending A Message



P1 can send to P2, P2 can send to P1

Simple Send and Receive

```
send( dest, data ), receive( src, data )
```

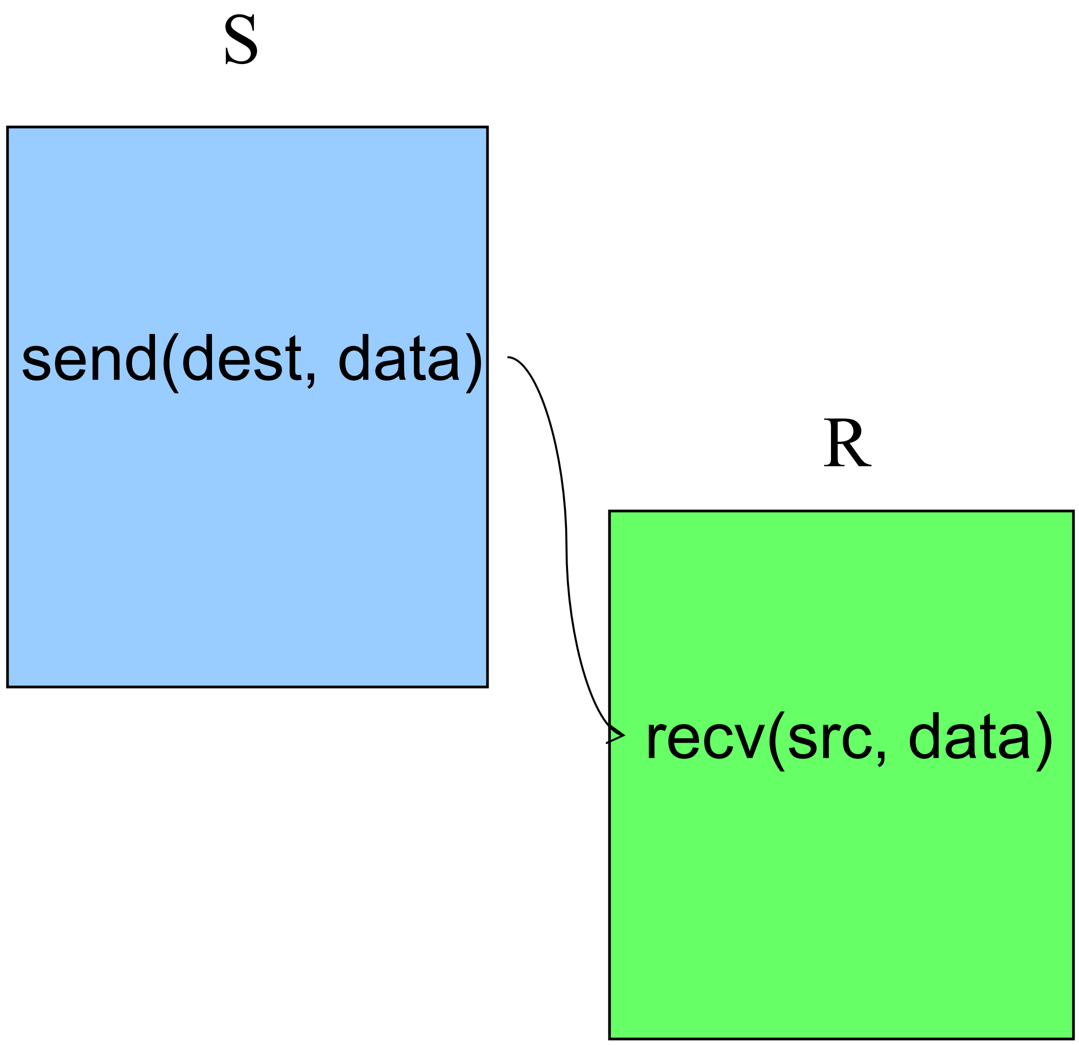


- Send "data" specifies where the data are in sender's address space
- Recv "data" specifies where the incoming message data should be put in receiver's address space

Simple API

```
send( dest, data ), receive( src, data )
```

- Destination or source
  - Direct address: node Id, process Id
  - Indirect address: mailbox, socket, channel, …
- Data
  - Buffer (addr) and size
  - Anything else that specifies the source or destination data



Simple Semantics

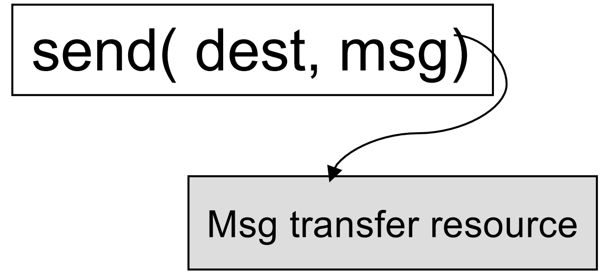
- Send call does not return until data have been copied out of source data structure
  - Could be to destination process/machine, or to OS buffer, … (there are variants depending on this)
  - At that point, source data structure can be safely overwritten without changing the data carried by the message
- Receive does not return until data have been received and copied into destination data structure
- This is called Synchronous Message Passing
  - Makes synchronization implicit and easy
  - But processes wait around a lot for send and receive calls to return, so can hurt performance

Issues/options

- Asynchronous vs. synchronous
- Buffering of messages
- Matching of messages
- Direct vs. indirect
- Data alone, or function invocation?
- How to handle exceptions (when bad things happen)?

Synchronous vs. Asynchronous Send

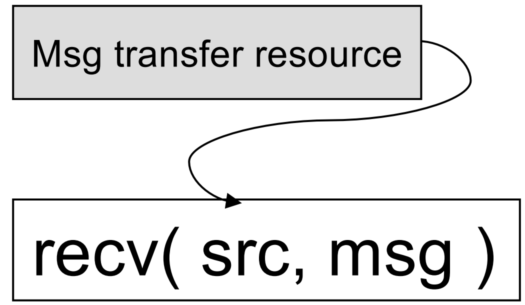
- Synchronous
  - Send will not return until data are copied out of source data structure
  - If a buffer is used for messaging and it is full, block
- Asynchronous
  - Return before data are copied out of source data structure
  - Completion of send or of copy:
    - Applications must check status
    - Notify or signal the application
  - Block on full buffer




```
status = async_send( dest, msg )
…
if !send_complete( status )
    wait for completion;
…
use msg data structure;
…
```

Synchronous vs Asynchronous Receive

- Synchronous
  - Return data if there is a message in incoming buffer
  - If not, buffer

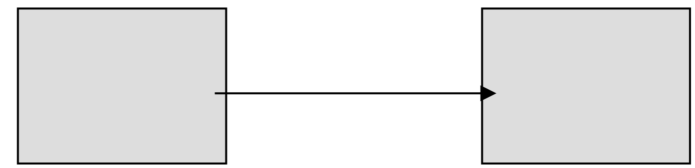


- Asynchronous
  - Return data if there is a message
  - Return status if there is no message (probe)

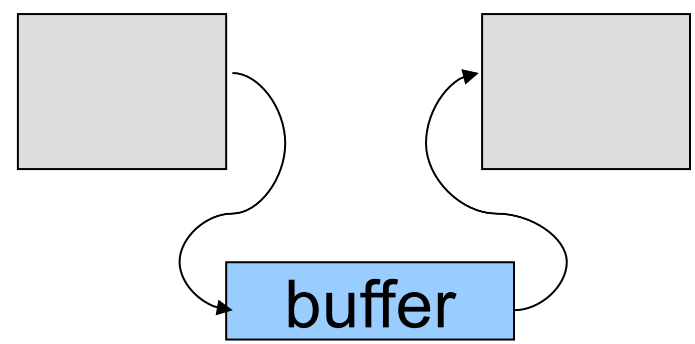
```
/* consume if available, or move on */
status = async_recv( src, msg );
if ( status == SUCCESS )
    consume msg;

/* At some point, wait for message */
while ( probe(src) != haveMSG )
    wait for msg arrival;
recv( src, msg );
consume msg;
```

Buffering

Buffer holds message contents so sender and receiver can be decoupled



- No buffering
  - Sender must wait until the receiver receives message
  - Rendezvous on each msg
- Finite buffer
  - Sender blocks on buffer full



Synchronous Send/Recv Within a System

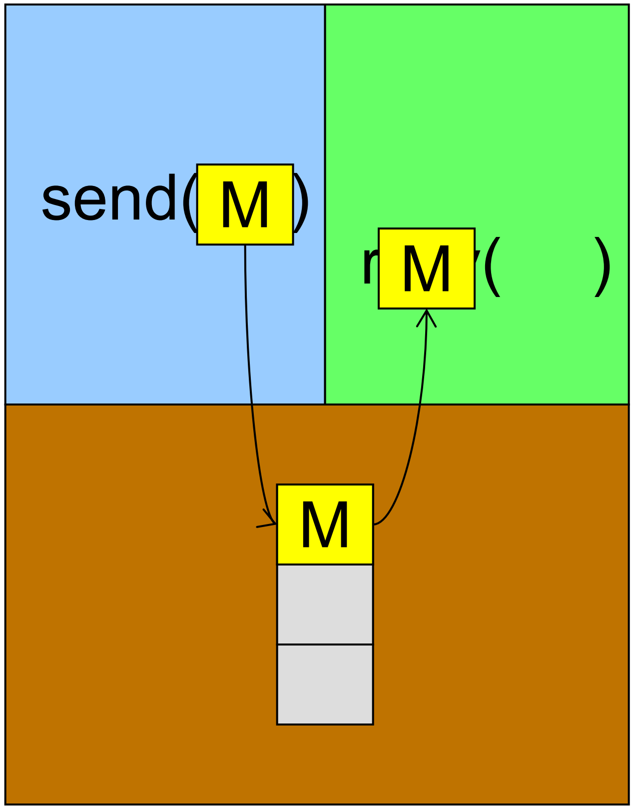
Synchronous send:

- Call send system call with M
- Send system call:
  - No buffer in kernel: block
  - Copy M to kernel buffer

Synchronous recv:

- Call recv system call
- Recv system call:
  - No M in kernel: block
  - Copy to user buffer

How to manage kernel buffer?



On distributed machines/OSes, buffers at one/both ends

What if Buffers Fill Up?

- Make processes wait (can be hard to do when they are on different machines)
- Drop messages
- Don’t send fast enough to fill up buffers: flow control
- Credits
  - Receivers provide credits based on space availability
  - Senders don’t send unless they have the credits to do so

Direct Addressing Example

```
Producer(){
   ...
   while (1) {
      produce item;
      recv(Consumer, &credit);
      send(Consumer, item);
   }
}
```

```
Consumer(){
   ...
   for (i=0; i<N; i++)
      send(Producer, credit);
   while (1) {
      recv(Producer, &item);
      send(Producer, credit);
      consume item;
   }
}
```

- Q: Does this work?
- Would it work with multiple producers and 1 consumer?
- Would it work with 1 producer and multiple consumers?
- What about multiple producers and multiple consumers?

Indirect Addressing Example

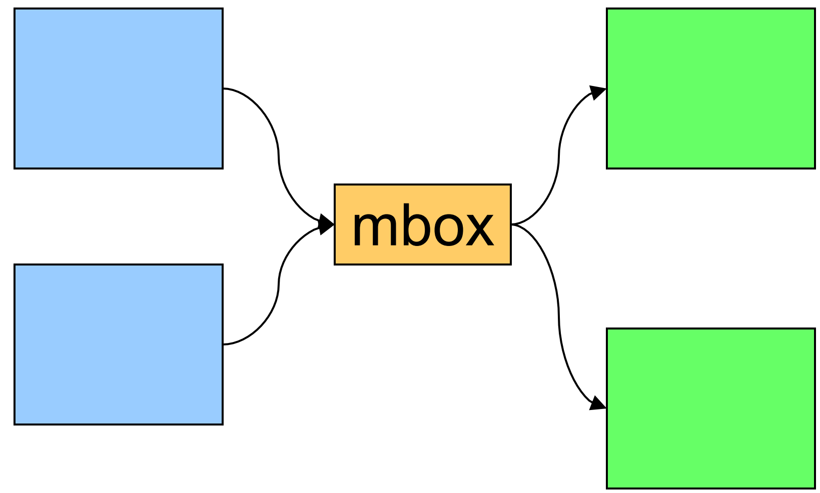
```
Producer(){
  ...
  while (1) {
    produce item;
    recv(prodMbox, &credit);
    send(consMbox, item);
  }
}
```

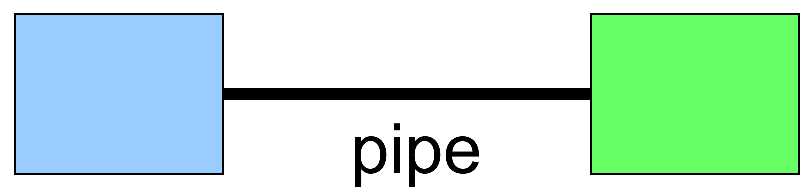
```
Consumer(){
  ...
  for (i=0; i<N; i++)
    send(prodMbox, credit);
  while (1) {
    recv(consMbox, &item);
    send(prodMbox, credit);
    consume item;
  }
}
```

- Would it work with multiple producers and 1 consumer?
- Would it work with 1 producer and multiple consumers?
- What about multiple producers and multiple consumers?

Indirect Communication

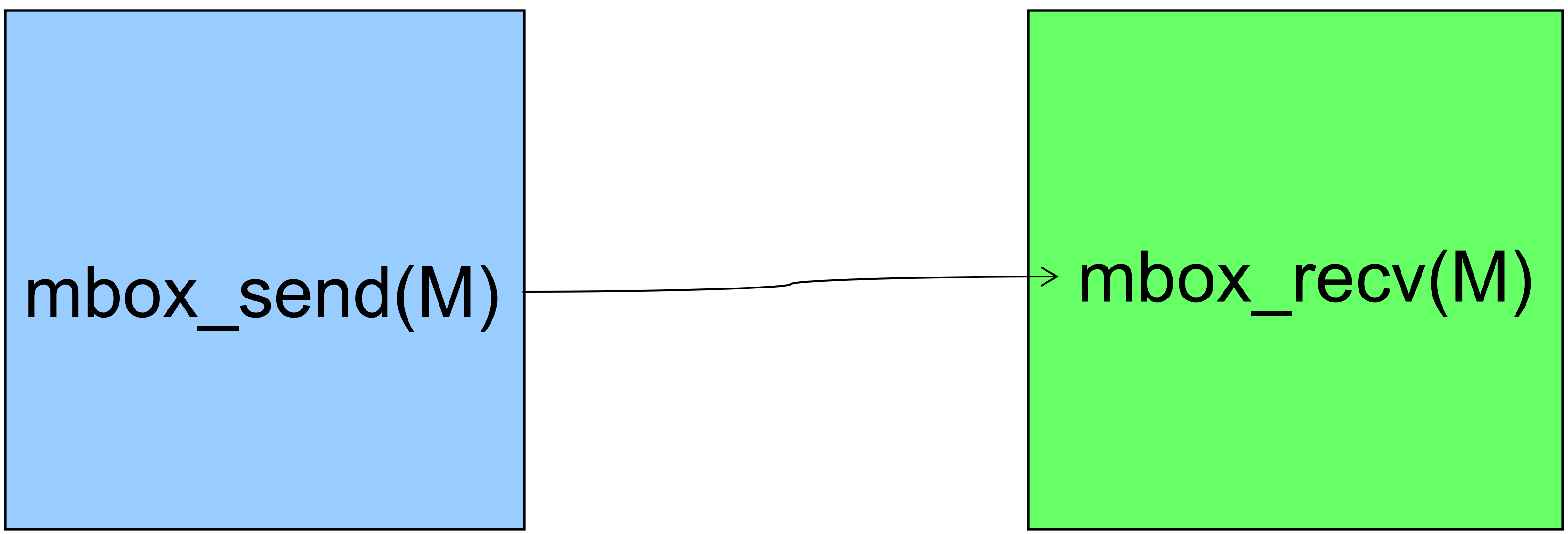
- Names
  - mailbox, socket, channel, …
- Properties
  - Some allow one-to-one (e.g. pipe)
  - Some allow many-to-one or one-to-many communications (e.g. mailbox)





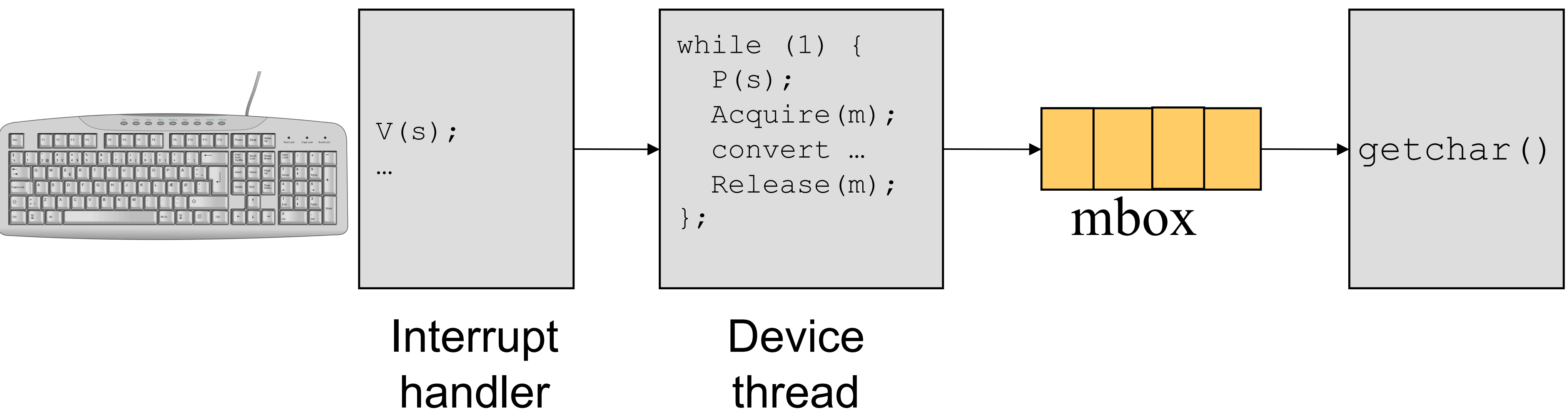
Mailbox Message Passing

- Message-oriented 1-way communication
- Data structure
  - Mutex, condition variable, buffer for messages
- Operations
  - Init, open, close, send, receive, …
- Does the sender know when receiver gets a message?



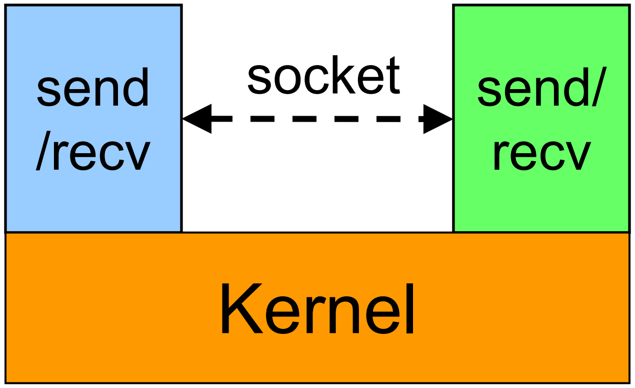
Example: Keyboard Input

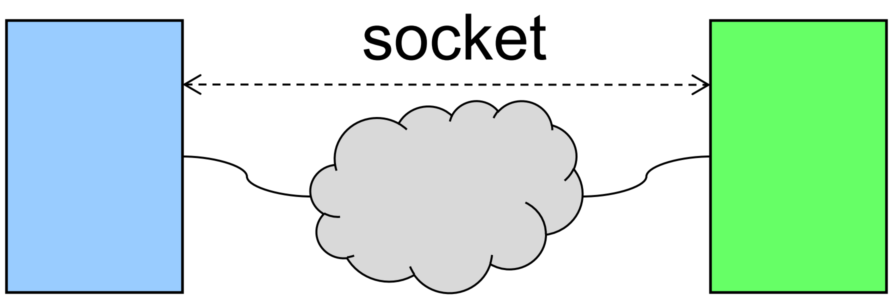
- Interrupt handler
  - Get the input characters and give to device thread
- Device thread
  - Generate a message and send it to mailbox of an input process



Sockets

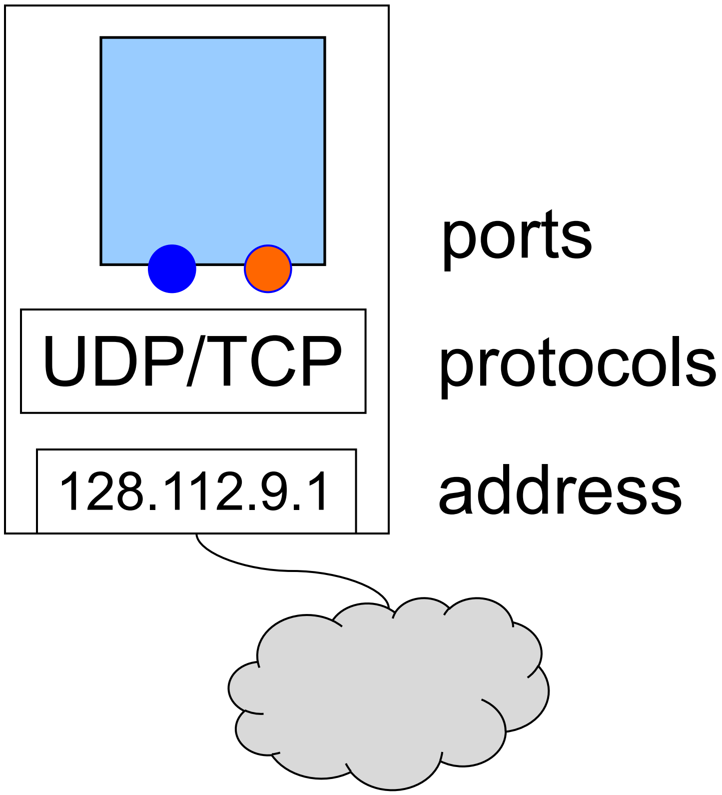
- Sockets
  - Bidirectional (unlike mailbox)
  - Unix domain sockets (IPC)
  - Network sockets (over network)
  - Same APIs
- Two types
  - Datagram Socket (UDP)
    - Collection of messages
    - Best effort
    - Connectionless
  - Stream Socket (TCP)
    - Stream of bytes (like pipe)
    - Reliable
    - Connection-oriented



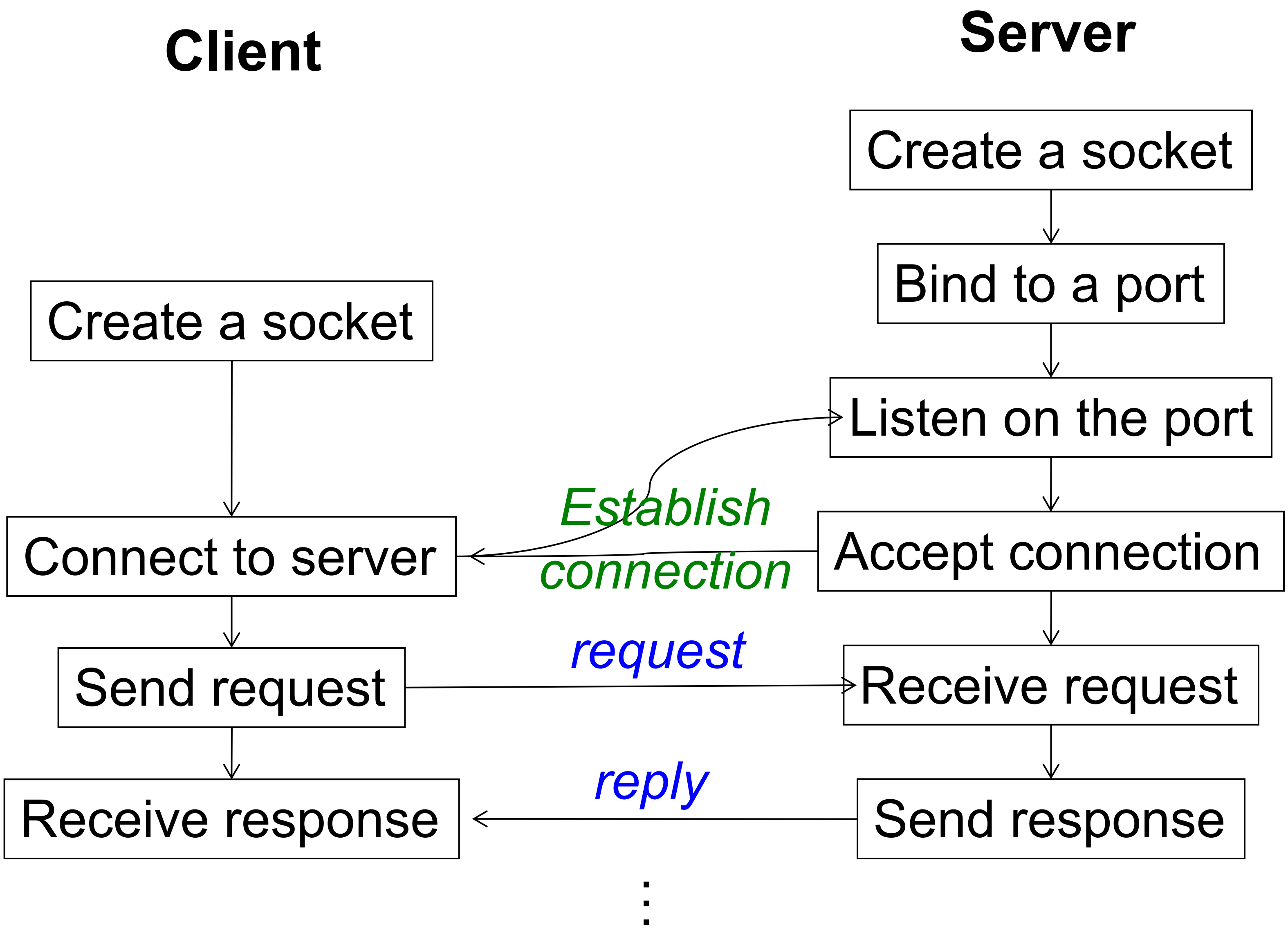


Network Socket Address Binding

- A network socket binds to
  - Host: IP address
  - Protocol: UDP/TCP
  - Port:
    - Well known ports (0..1023), e.g. port 80 for Web
    - Unused ports available for clients (1025..65535)
- Q: Why do we need ports?
  - Indirection: No need to know which process to communicate with
  - Updating software on one side won't affect another side



Communication with Stream Sockets



Sockets API

- Create and close a socket
  - sockid = socket(af, type, protocol);
  - sockerr = close(sockid);
- Bind a socket to a local address
  - sockerr = bind(sockid, localaddr, addrlength);
- Negotiate the connection
  - listen(sockid, length);
  - accept(sockid, addr, length);
- Connect a socket to destimation
  - connect(sockid, destaddr, addrlength);
- Message passing
  - send(sockid, buf, size, flags);
  - recv(sockid, buf, size, flags);

Unix pipes

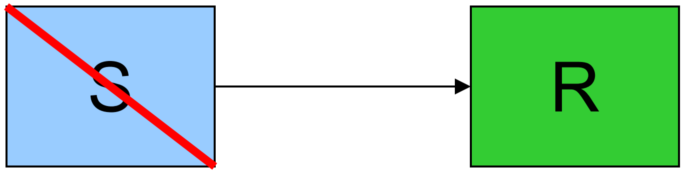
- An output stream connected to an input stream by a chunk of memory (a queue of bytes).

- Send (called write) is non-blocking
- Receive (called read) is blocking

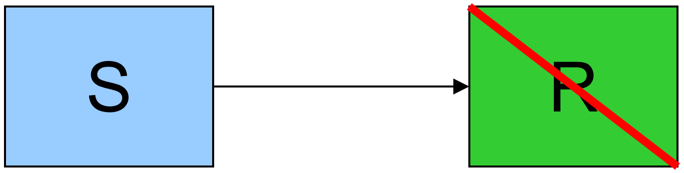
- Buffering is provided by OS

What if things go bad?

- R waits for a message from S, but S has terminated
  - R may be blocked forever

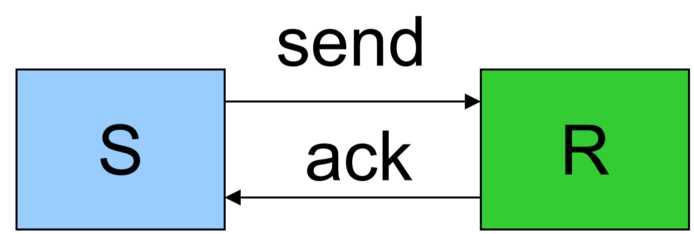


- S sends a message to R, but R has terminated
  - S has no buffer and will be blocked forever



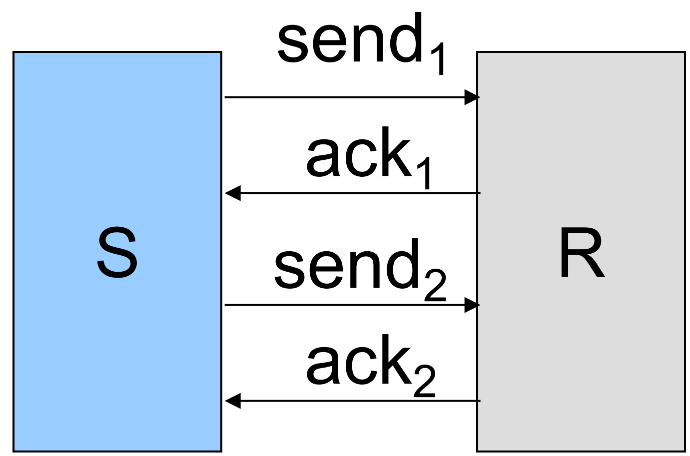
Exception: Message Loss

- Use ack and timeout to detect and retransmit a lost message
  - Receiver sends an ack for each msg
  - Sender blocks until an ack message is back or timeout
    status = send(dest, msg, timeout);
  - If timeout happens and no ack, then retransmit the message
- Issues
  - Duplicates
  - Losing ack messages

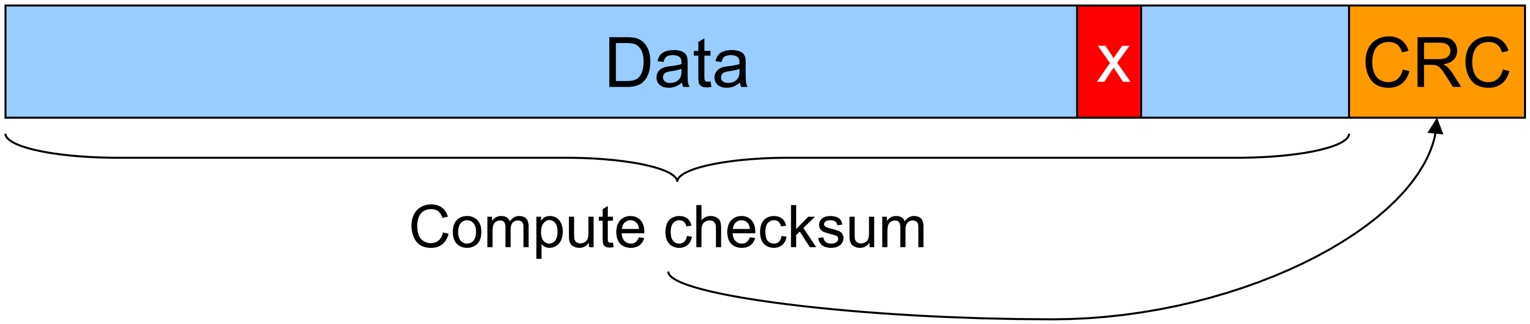


Exception: Message Loss, contd.

- Retransmission must handle
  - Duplicate messages on receiver side
  - Out-of-sequence ack messages on sender side
- Retransmission
  - Use sequence number for each message to identify duplicates
  - Remove duplicates on receiver side
  - Sender retransmits on an out-of-sequence ack
- Reduce ack messages
  - Bundle ack messages
  - Piggy-back acks in send messages



Exception: Message Corruption



- Detection
  - Compute a checksum over the entire message and send the checksum (e.g. CRC code) as part of the message
  - Recompute a checksum on receive and compare with the checksum in the message
- Correction
  - Trigger retransmission
  - Use correction codes to recover

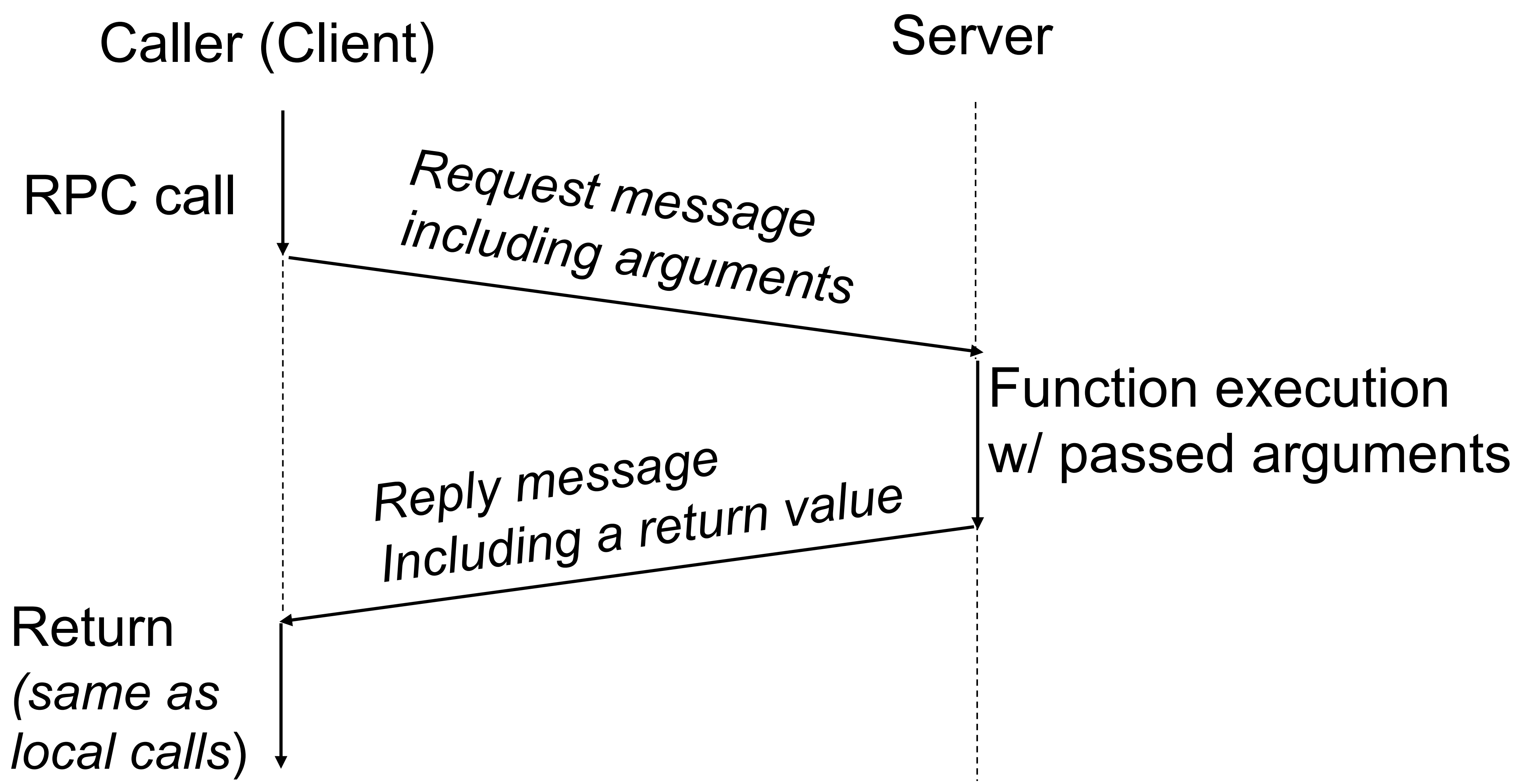
Message Passing Interface (MPI)

- A message-passing library for parallel machines
  - Implemented at user-level for high-performance computing
  - Portable
- Basic (6 functions)
  - Works for most parallel programs
- Large (125 functions)
  - Blocking (or synchronous) message passing
  - Non-blocking (or asynchronous) message passing
  - Collective communication
- References
  - http://www.mpi-forum.org/

Remote Procedure Call (RPC)

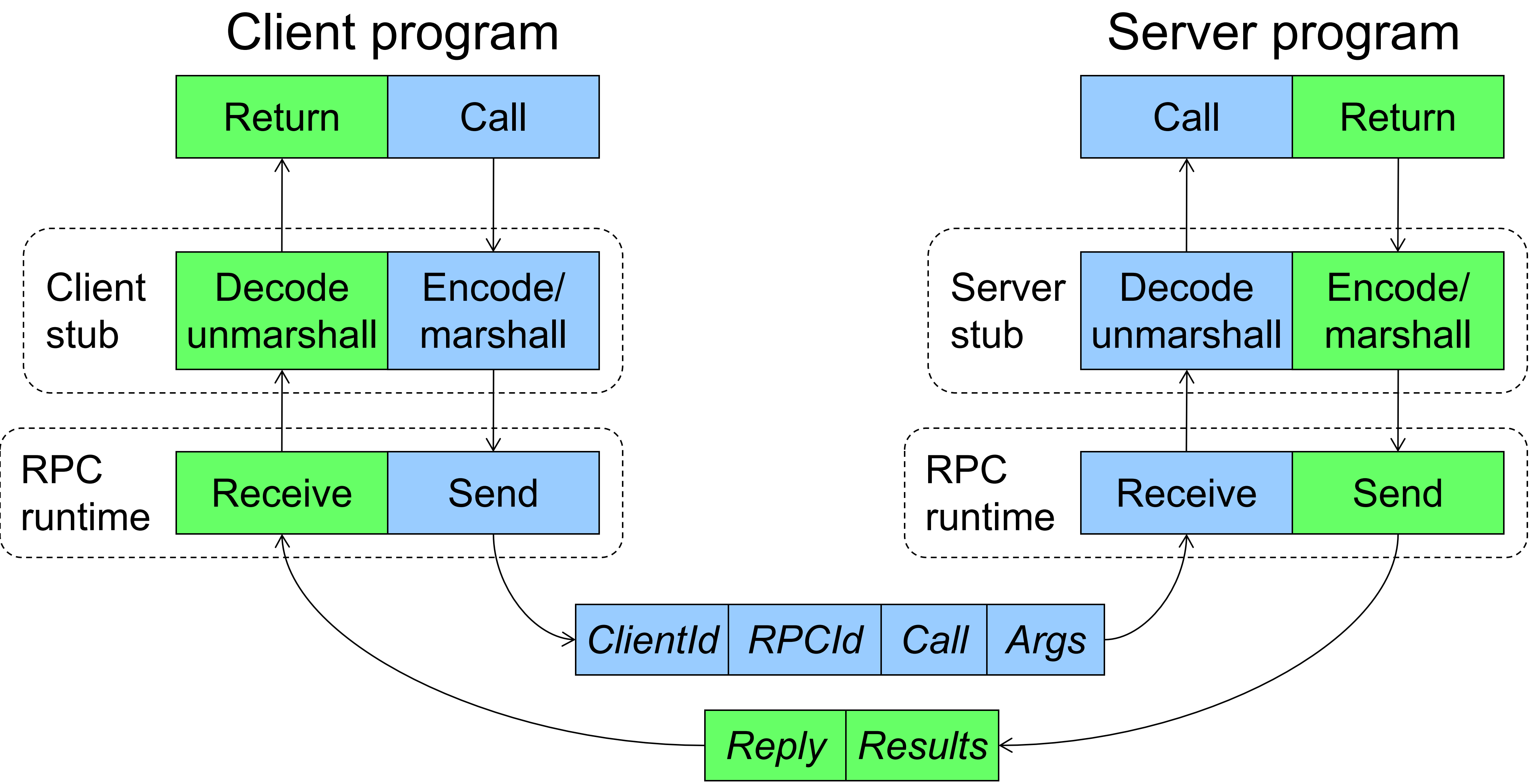
- Make remote procedure calls
  - Similar to local procedure calls
  - Examples: SunRPC, Java RMI
- Restrictions
  - Call by value
  - Call by object reference (maintain consistency)
  - Not call by reference
- Different from mailbox, socket or MPI
  - Remote execution, not just data transfer
- References
  - B. J. Nelson, Remote Procedure Call, PhD Dissertation, 1981
  - A. D. Birrell and B. J. Nelson, Implementing Remote Procedure Calls, ACM Trans. on Computer Systems, 1984

RPC Model



Compile time type checking and interface generation

RPC Mechanism



Summary

- Message passing
  - Move data between processes
  - Implicit synchronization
  - Many API design alternatives (Socket, MPI)
  - Indirection is helpful
- Implementation and Semantics
  - Synchronous method is most common
  - Asynchronous method provides overlapping, but required careful design and implementation decisions
  - Indirection makes implementation flexible
  - Exception needs to be carefully handled
- RPC
  - Remote execution like local procedure calls
  - With constraints in terms of passing data

Appendix:
Message Passing Interface (MPI)

Hello World using MPI

```
#include "mpi.h"
#include <stdio.h>

int main( int argc, char *argv[] )
{
    int rank, size;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &rank );
    MPI_Comm_size( MPI_COMM_WORLD, &size );
    printf( "I am %d of %d\n", rank, size );
    MPI_Finalize();
    return 0;
}
```

Initialize MPI environment

Return my rank

Return # of processes

Last call to clean up

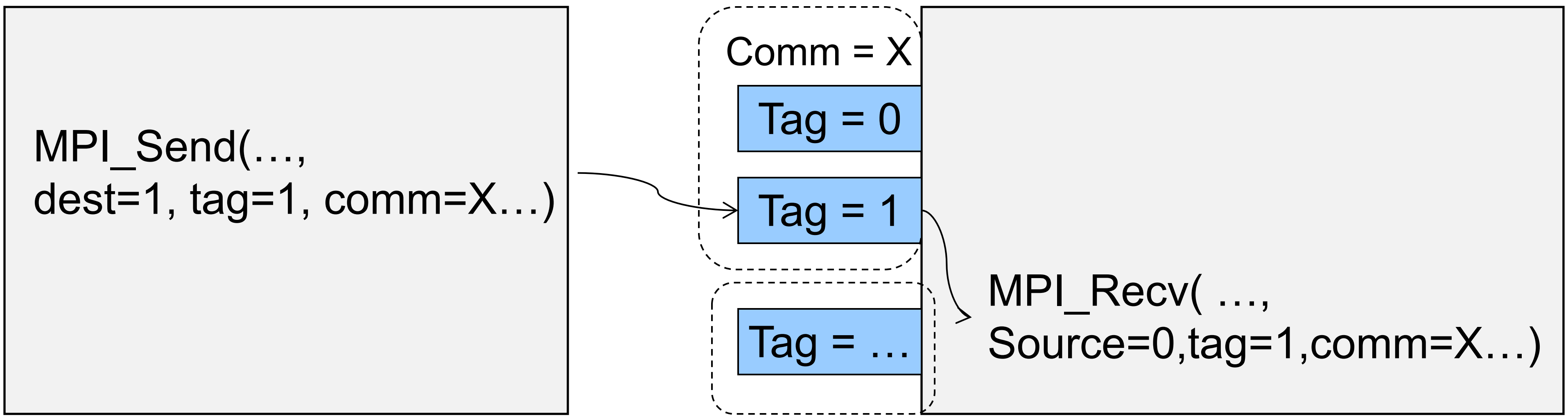
Blocking Send

- MPI_Send(buf, count, datatype, dest, tag, comm)
  - **buf** address of send buffer
  - **count** # of elements in buffer
  - **datatype** data type of each send buffer element
  - **dest** rank of destination
  - **tag** message tag
  - **comm** communicator
- This routine **may** block until the message is received by the destination process
  - Depending on implementation
  - But will block until the user source buffer is reusable
- More about message tag later

Blocking Receive

- MPI_Recv(buf, count, datatype, source, tag, comm, status)
  - **buf** address of receive buffer (output)
  - **count** maximum # of elements in receive buffer
  - **datatype** datatype of each receive buffer element
  - **source** rank of source
  - **tag** message tag
  - **comm** communicator
  - **status** status object (output)
- Receive a message with the specified tag from the specified comm and specified source process
- MPI_Get_count(status, datatype, count) returns the real count of the received data

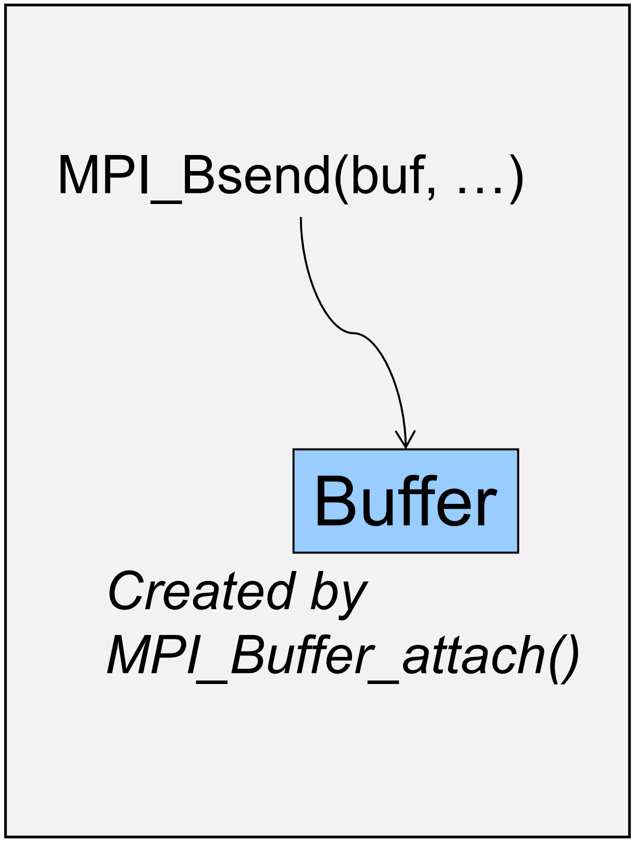
More on Send & Recv



- Can send from source to destination directly
- Message passing must match
  - Source rank (can be MPI_ANY_SOURCE)
  - Tag (can be MPI_ANY_TAG)
  - Comm (can be MPI_COMM_WORLD)

Buffered Send

- MPI_Bsend(buf, count, datatype, dest, tag, comm)
  - **buf** address of send buffer
  - **count** # of elements in buffer
  - **Datatype** type of each send element
  - **dest** rank of destination
  - **tag** message tag
  - **comm** communicator
- May buffer; user can use the user send buffer right away
- MPI_Buffer_attach(), MPI_Buffer_detach creates and destroy the buffer



- MPI_Ssend: Returns only when matching receive posted. No buffer needed.
- MPI_Rsend: assumes received posted already (programmer's responsibility)

Non-Blocking Send

- MPI_Isend(buf, count, datatype, dest, tag, comm, *request)
  - **request** is a handle, used by other calls below
- Return as soon as possible
  - Unsafe to use buf right away
- MPI_Wait(*request, *status)
  - Block until send is done
- MPI_Test(*request, *flag,*status)
  - Return the status without blocking

```
MPI_Isend(…)
  Work to do
MPI_Wait(…)
```

```
MPI_Isend(…)
  Work to do
MPI_Test(…, flag,…);
while ( flag == FALSE) {
    More work
}
```

Non-Blocking Recv

- MPI_Irecv(buf, count, datatype, dest, tag, comm, *request, ierr)
- Return right away
- MPI_Wait()
  - Block until finishing receive
- MPI_Test()
  - Return status
- MPI_Probe(source, tag, comm, flag, status, ierror)
  - Is there a matching message?

```
MPI_Irecv(…)
    Work to do
MPI_Wait(…)
```

```
MPI_Probe(…)
while ( flag == FALSE) {
    More work
}
MPI_Irecv(…)
or MPI_recv(…)
```