Inter-Process Communication: Message Passing

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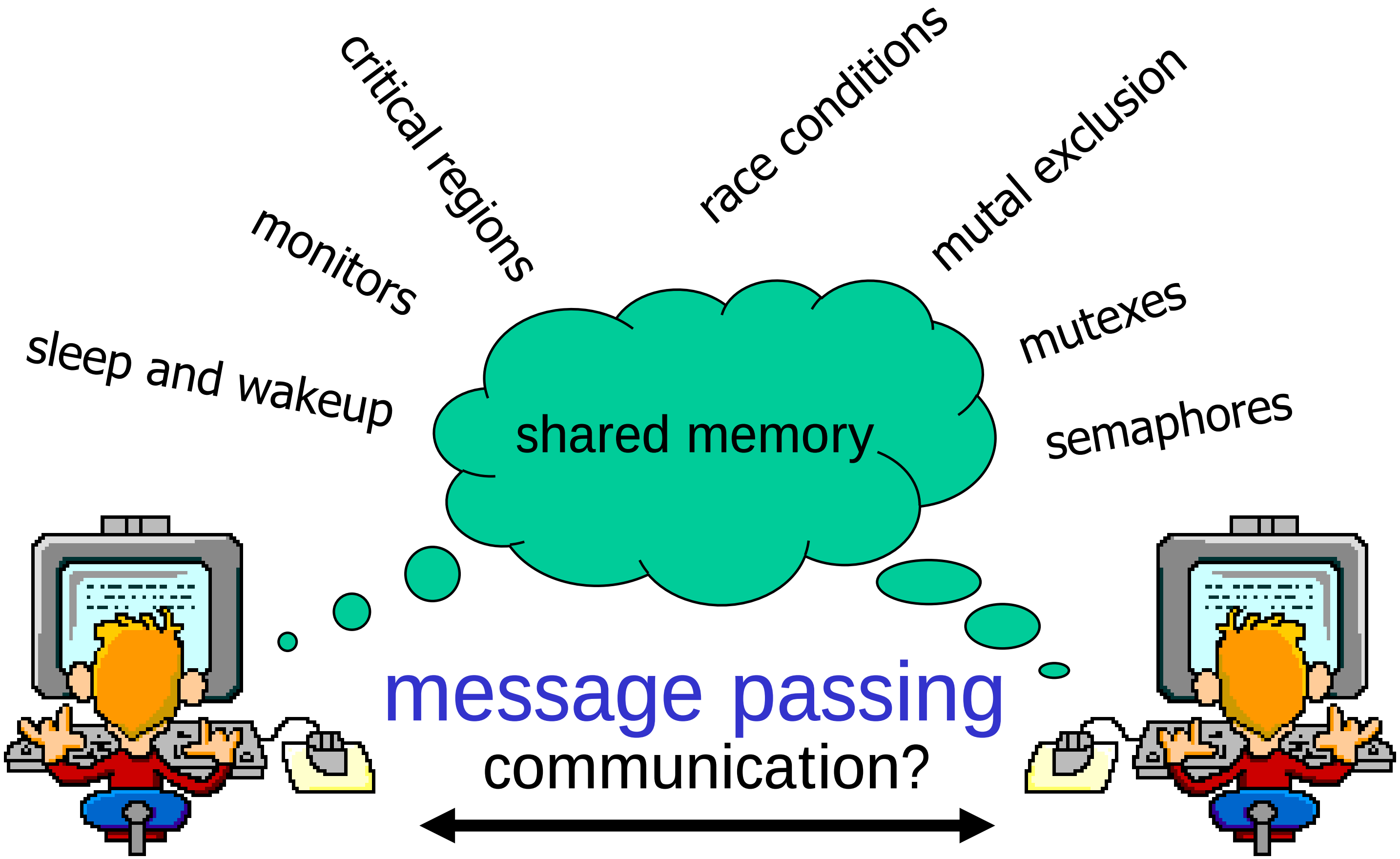
With slides from Pål Halvorsen, Kai Li, and Andrew S. Tanenbaum

Big Picture


critical regions
race conditions
mutal exclusion
monitors
mutexes
sleep and wakeup
shared memory
semaphores
message passing
communication?

Message Passing API

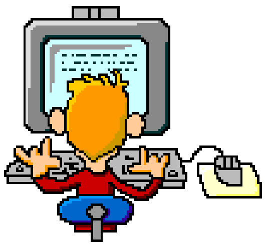
- Generic API
  - `send( dest, &msg )`
  - `recv( src, &msg )`
- What should the "`dest`" and "`src`" be?
  - pid
  - file: e.g. a (named) pipe
  - port: network address, pid, etc
  - no src: receive any message
  - src combines both specific and any
- What should "`msg`" be?
  - Need both buffer and size for a variable sized message

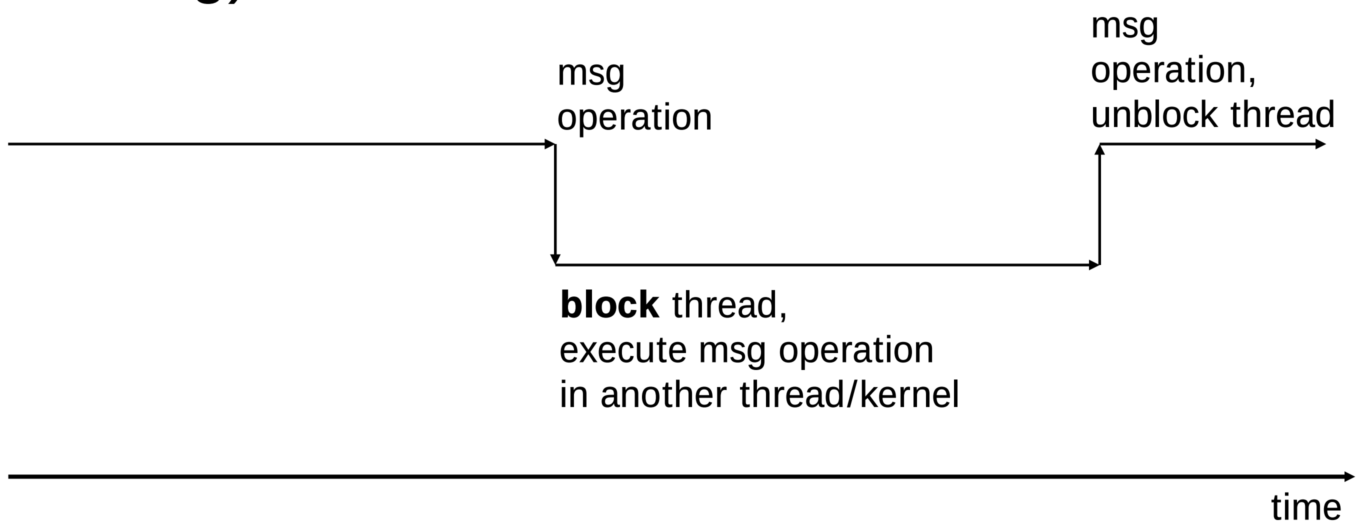
Issues

- Asynchronous vs. synchronous
- Direct vs. indirect
- How are links established?
- Can a link be associated with more than two processes?
- How many links can there be between any pair?
- What is the capacity of a link?
- What is the size of a message?
- Is a link unidirectional or bidirectional?

Asynchronous vs. Synchronous

- Synchronous (blocking):

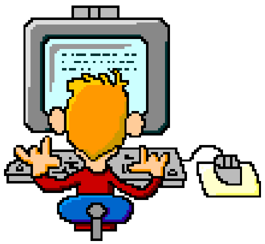


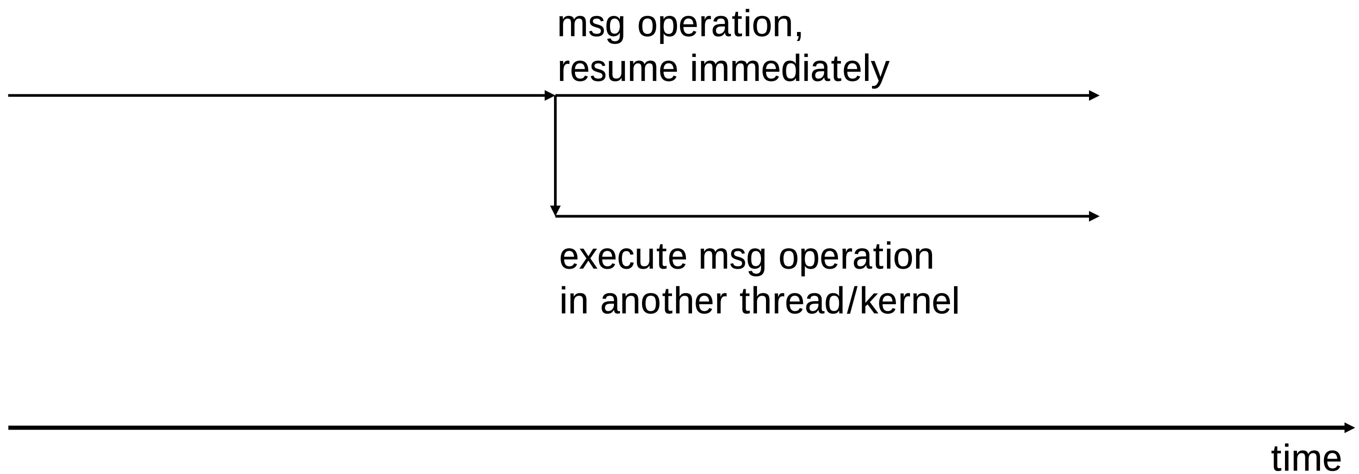


  – thread is blocked until message primitive has been performed
  – may be blocked for a very long time

Asynchronous vs. Synchronous

- Asynchronous (non-blocking):





  - thread gets control back immediately
  - thread can run in parallel other activities
  - thread cannot reuse buffer for message before message is received
  - how to know when to start if blocked on full/empty buffer?
    - poll
    - interrupts/signals
    - ...

Asynchronous vs. Synchronous

- Send semantic:
  - Synchronous
    - Will not return until data is out of its source memory
    - Block on full buffer
  - Asynchronous
    - Return as soon as initiating its hardware
    - Completion
      - Require application to check status
      - Notify or signal the application
    - Block on full buffer

- Receive semantic:
  - Synchronous
    - Return data if there is a message
    - Block on empty buffer
  - Asynchronous
    - Return data if there is a message
    - Return null if there is no message

Buffering

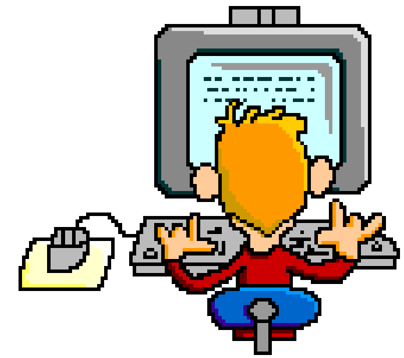
- No buffering
  - synchronous
  - Sender must wait until the receiver receives the message
  - Rendezvous on each message

- Buffering
  - asynchronous or synchronous

  - Bounded buffer
    - Finite size
    - Sender blocks when the buffer is full
    - Use mesa-monitor to solve the problem?

  - Unbounded buffer
    - “Infinite” size
    - Sender never blocks

Direct Communication



- Must explicitly name the sender/receiver (“`dest`” and “`src`”) processes

- A buffer at the receiver
  - More than one process may send messages to the receiver
  - To receive from a specific sender, it requires searching through the whole buffer

- A buffer at each sender
  - A sender may send messages to multiple receivers

Message Passing:
Producer-Consumers Problem

```
void producer(void)
{
   while (TRUE) {
       …
       produce item;
       …
       send( consumer, item );
   }
}
```

```
void consumer(void)
{
   while (TRUE) {
       recv( producer, item );
       …
       consume item;
       …
     }
}
```

Message Passing:
Producer-Consumers Problem with N messages

```
#define N 100                                /* number of slots in the buffer */

void producer(void)
{
    int item;
    message m;                               /* message buffer */

    while (TRUE) {
        item = produce_item( );              /* generate something to put in buffer */
        receive(consumer, &m);               /* wait for an empty to arrive */
        build_message(&m, item);             /* construct a message to send */
        send(consumer, &m);                  /* send item to consumer */
    }
}

void consumer(void)
{
    int item, i;
    message m;

    for (i = 0; i < N; i++) send(producer, &m);  /* send N empties */
    while (TRUE) {
        receive(producer, &m);               /* get message containing item */
        item = extract_item(&m);             /* extract item from message */
        send(producer, &m);                  /* send back empty reply */
        consume_item(item);                  /* do something with the item */
    }
}
```

Indirect Communication

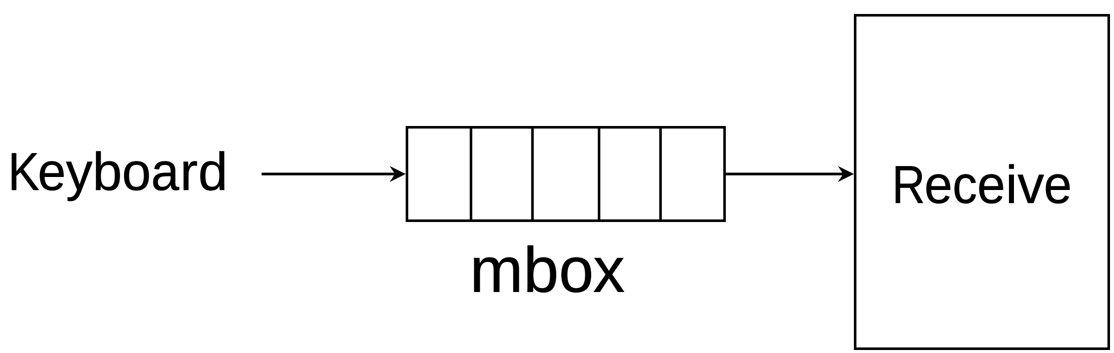
- “`dest`” and “`src`” are a shared (unique) mailbox

- Use a mailbox to allow many-to-many communication
  - Requires open/close a mailbox before using it

- Where should the buffer be?
  - A buffer and its mutex and conditions should be at the mailbox

Using Message-Passing

- What is message-passing for?
  - Communication across address spaces
  - Communication across protection domains
  - Synchronization
- Use a mailbox to communicate between a process/thread and an interrupt handler: fake a sender



Process Termination

- P waits for a message from Q, but Q has terminated
  - Problem: P may be blocked forever
  - Solution:
    - P checks once a while
    - Catch the exception and informs P
    - Send ack message

- P sends a message to Q, but Q has terminated
  - Problem: P has no buffer and will be blocked forever
  - Solution:
    - Check Q's state and cleanup
    - Catch the exception and informs P

Message Loss & Corruption

- Unreliable service
  - best effort, up to the user to
- Detection
  - Acknowledge each message sent
  - Timeout on the sender side
- Retransmission
  - Sequence number for each message
  - Retransmit a message on timeout
  - Retransmit a message on out-of-sequence acknowledgement
  - Remove duplication messages on the receiver side

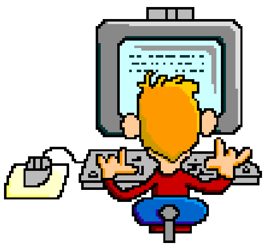
Linux Mailboxes

- Messages are stored as a sequence of bytes
- System V IPC messages also have a type
- Mailboxes are implemented as message queues sorting messages according to FIFO
- Can be both blocking and non-blocking (`IPC_NOWAIT`)
- The next slides have some simplified (pseudo) code
  - Linux 2.4.18
  - several parts missing
  - the shown code may block holding the queue lock
  - waiting queues are more complex
  - ...

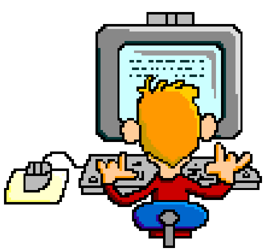
Linux Mailboxes

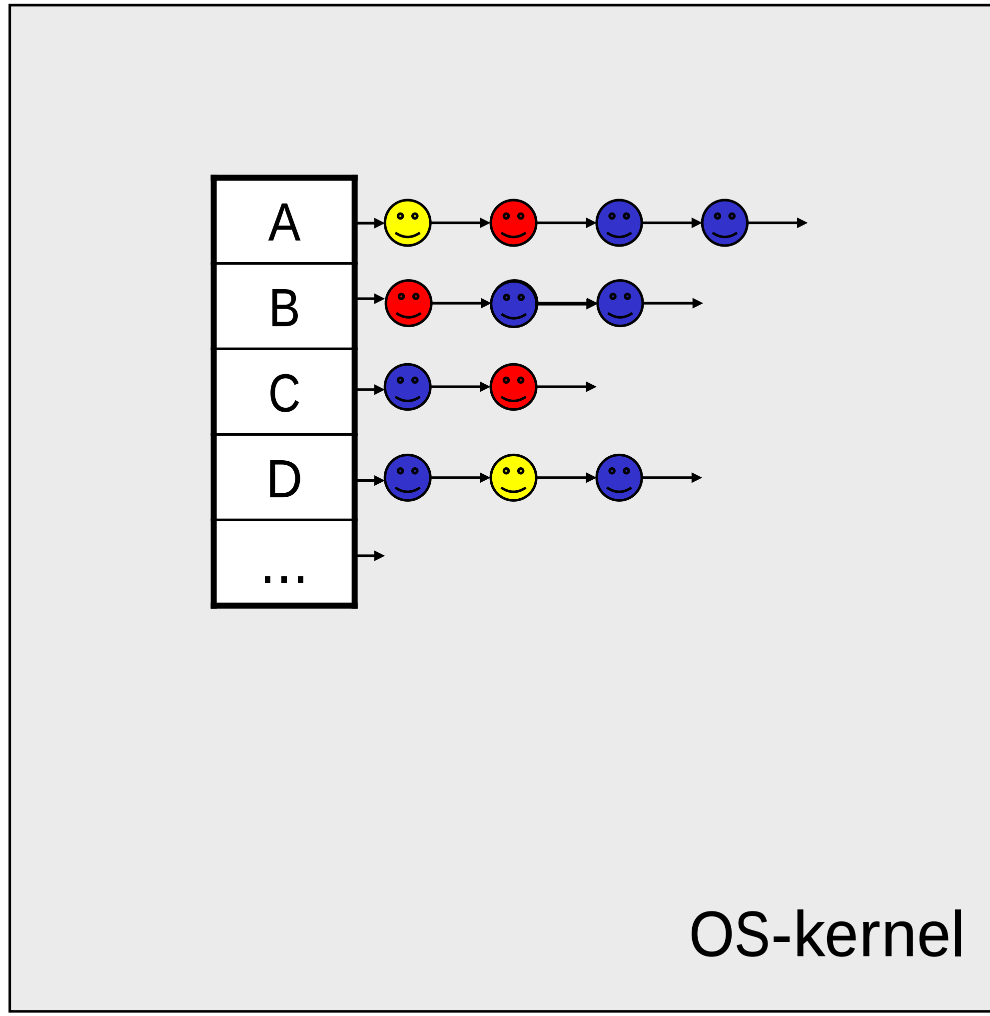
- Example:

`msgsnd(A,`  `, ...)`



`msgrcv(B,`  `, ...)`





Linux Mailboxes

- One `msq_queue` structure for each present queue:

```
struct msg_queue {
        struct kern_ipc_perm q_perm;    /* access permissions */
        time_t q_stime;                 /* last msgsnd time */
        time_t q_rtime;                 /* last msgrcv time */
        time_t q_ctime;                 /* last change time */
        unsigned long q_cbytes;         /* current number of bytes on queue */
        unsigned long q_qnum;           /* number of messages in queue */
        unsigned long q_qbytes;         /* max number of bytes on queue */
        pid_t q_lspid;                  /* pid of last msgsnd */
        pid_t q_lrpid;                  /* last receive pid */
        struct list_head q_messages;
        struct list_head q_receivers;
        struct list_head q_senders;
};
```

- Messages are stored in the kernel using the `msg_msg` structure:

```
struct msg_msg {
        struct list_head m_list;
        long  m_type;               /* message type */
        int   m_ts;                 /* message text size */
        struct msg_msgseg* next;    /* next pointer */
};
```

NOTE: the message is stored immediately after this structure - no pointer is necessary

Linux Mailboxes

- Create a message queue using the `sys_msgget` system call:

```
long sys_msgget (key_t key, int msgflg)
{
   ...
   create new message queue and set access permissions
   ...
}
```

- To manipulate a queue, one uses the `sys_msgctl` system call:

```
long sys_msgctl (int msqid, int cmd, struct msqid_ds *buf)
{
   ...
    switch (cmd) {
         case IPC_INFO:
             return info about the queue, e.g., length, etc.
         case IPC_SET:
             modify info about the queue, e.g., length, etc.
         case IPC_RMID:
             remove the queue
   }
   ...
}
```

Linux Mailboxes

- Send a message to the queue using the `sys_msgsnd` system call:

```
long sys_msgsnd (int msqid, struct msgbuf *msgp, size_t msgsz, int msgflg)
{
   msq = msg_lock(msqid);
   ...

   if ((msgsz + msq->q_cbytes) > msq->q_qbytes)
         insert message the tail of msq->q_messages *msgp, update msq
   else
         put sender in waiting senders queue (msq->q_senders)

   msg_unlock(msqid);
   ...
}
```

Linux Mailboxes

- Receive a message from the queue using the `sys_msgrcv` system call:

```
long sys_msgrcv (int msqid, struct msgbuf *msgp, size_t msgsz,
                            long msgtyp, int msgflg)
{
   msq = msg_lock(msqid);
   ...
   search msq->q_messages for first message matching msgtype
   if (msg)
         store message in msgbuf *msgp, remove message from msgbuf *msgp, update msq
   else
         put receiver in waiting receivers queue (msq->q_receivers)

   msg_unlock(msqid);
   ...
}
```

   – the `msgtyp` parameter and `msgflg` flag determine which messages to retrieve:
      - = 0: return first message
      - > 0: first message in queue with `msg_msg.m_type = msgtyp`
      - > 0 & `MSG_EXCEPT`: first message in queue with `msg_msg.m_type != msgtyp`

Our Mailbox

- We make it simpler than Linux
  - Deliver messages in FIFO order

- Mailbox $\Rightarrow$ buffer space
  - Finite space

- Main purpose:
  - Send
  - Receive
- Maintenance:
  - Init
  - Open
  - Close
  - Statistics

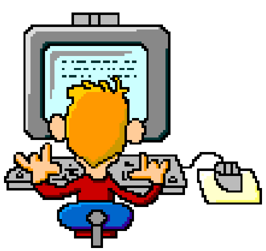
Linux Pipes

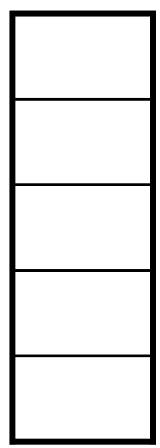
- Classic IPC method under UNIX:
  `> ls -l | more`
  - shell runs two processes `ls` and `more` which are linked via a pipe
  - the first process (`ls`) writes data (e.g., using `write`) to the pipe and the second (`more`) reads data (e.g., using `read`) from the pipe

- the system call `pipe( fd[2] )` creates one file descriptor for reading (`fd[0]`) and one for writing (`fd[1]`) - allocates a temporary inode and a memory page to hold data

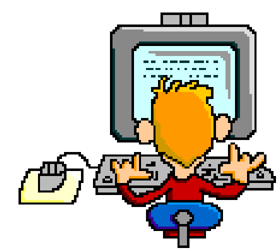
```
struct pipe_inode_info {
    wait_queue_head_t wait;
    char *base;
    unsigned int len;
    unsigned int start;
    unsigned int readers, writers;
    unsigned int waiting_readers, waiting_writers;
    unsigned int r_counter, w_counter;
}
```

`ls`





`more`



Linux: Mailboxes vs. Pipes

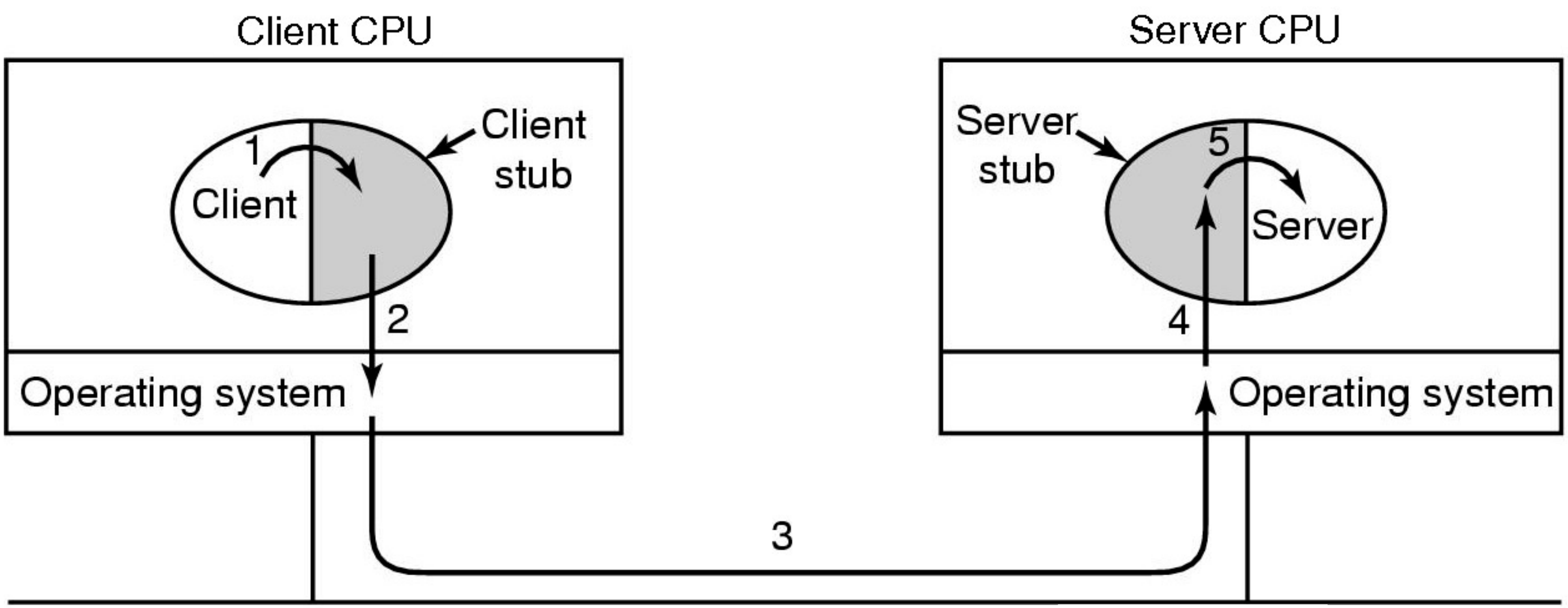
- Are there any differences between a mailbox and a pipe?
  - Message types
    - mailboxes may have messages of different types
    - pipes do not have different types
  - Buffer
    - pipes – one or more pages storing messages contiguously
    - mailboxes – linked list of messages of different types
  - Termination
    - pipes exists only as long as some have open the file descriptors
    - mailboxes must often be closed
  - More than two processes
    - a pipe **often** (not in Linux) implies one sender and one receiver
    - many can use a mailbox

Performance

- Performance is an important issue
  (at least when sender and receiver is on one machine), e.g.:
  - shared memory and using semaphores
  - mailboxes copying data from source to mailbox and
    from mailbox to receiver
- Can one somehow optimize the message passing?

Remote Procedure Call

- Message passing uses I/O
- Idea of RPC is to make function calls
- Small libraries (stubs) and OS take care of communication



Remote Procedure Call

Implementation Issues:

- Cannot pass pointers - call by reference becomes copy-restore
- Marshaling - packing parameters
- Weakly typed languages - client stub cannot determine size
- Not always possible to determine parameter types
- Cannot use global variables - may get moved to remote machine/protection domain

Summary

- Many ways to perform IPC on a machine
- Direct message passing or
  message passing using mailboxes
- Paradigms not covered here include
  - Distributed Shared Memory (DSM), Textbook 558-563
  - Linda (Distributed Shared Tuple Space), Textbook 584-587
  - PubSub, Textbook 586