Systems Design and Implementation

I.2 – Communication

System Architecture Group, SS 2009

University of Karlsruhe

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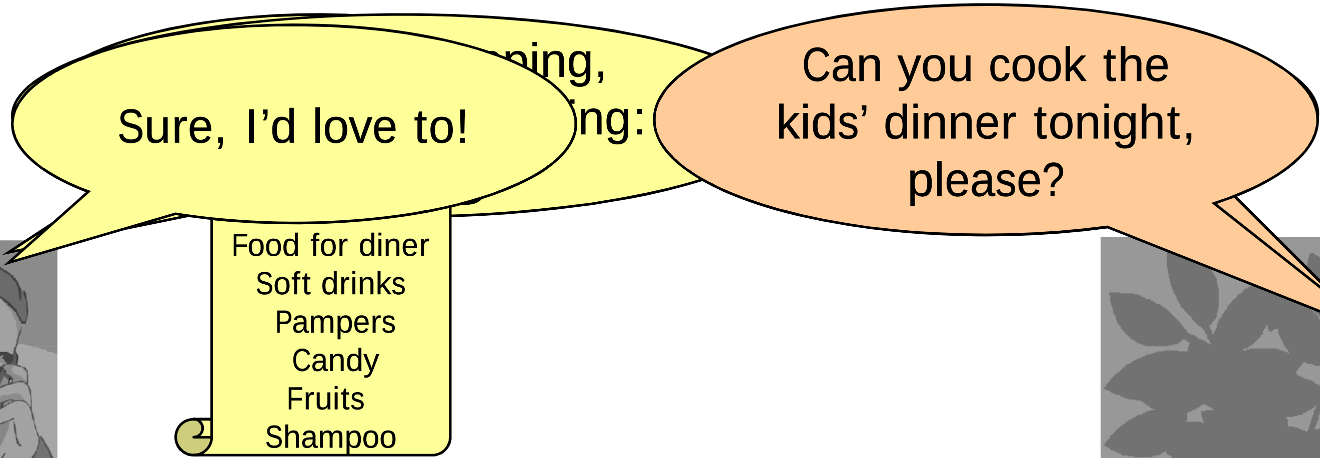
Overview

- Introduction
- Communication in monolithic systems
  - UNIX
- Communication in multi-server systems
  - Mach
  - L4
  - VMs

Why communicate?



- Synchronization
- Data Transfer
- Control Transfer

How communicate?

- Data transfer
  - Shared data
    - Shared memory, storage, registers, ...
    - Implicit, unsynchronized communication
  - Messages
    - Send, receive
    - Explicit communication
- Control transfer
  - Procedure call: call/ret
  - Safe procedure call: sysenter/sysexit, int 0x80/iret
  - Remote Procedure call: RPC
  - Based on
    - Shared code segments
    - Special primitives

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Communication principles

- Addressing modes:
  - Addressing senders/receivers:
    - Semaphores, sockets
  - Addressing communication facility
    - Pipes, mailboxes, ...
  - Unicast, Anycast, Multicast, Broadcast
  - Design Considerations:
    - Complexity
    - Communication model
      - Dispatcher/worker
      - Mailing list
      - Telephone

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Communication principles

- Message transfer
  - Coyping
  - By reference
    - Shared memory / storage
    - Using memory mapping techniques
  - Design considerations
    - Pass-by-reference requires shared storage
    - Copying incurs overhead (time and space)
    - Memory mapping as well (modifying pagetable mappings)
    - Copying may be required to ensure integrity
      - Kernel can’t checksum network packets in user-accessible memory
      - Can’t pass references to untrusted clients

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Communication principles

- Synchronous or not?
  - Synchronous
    - All parties are involved *at the same time*
    - Telephone, RPC
  - Asynchronous
    - Senders submit messages, receiver processes them some other time
    - Mail, message queues
  - Design considerations:
    - Complexity:
      - Asynchronous communication may require buffering
    - Availability of communication partners:
      - No need for e-mail, I'm always reachable via mobile

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Communication principles

- Blocking vs. non-blocking communication:
  - Blocking
    - Sender may block until message has been delivered / received / processed
    - Receiver may block until message has arrived
    - Enable synchronous communication if partners not always ready
    - Use timeouts to signal errors

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Communication principles

- Blocking vs. non-blocking communication:
  - Non-blocking
    - Sender returns after submission
    - Receiver returns independent of message status
    - Can use interrupts for signaling completion/message availability
  - Design considerations:
    - Importance of temporal synchronization with partners
      - Can I continue without a message having been processed?
    - Communication latency
      - How long does sending a message take?
      - Can I overlap I/O processing with other computation?

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Communication principles

- Buffered vs. unbuffered:
  - Communication facility provides buffers for
    - Asynchronous, non-blocking communication
    - Lossy communication channels
  - Design considerations
    - Importance of preserving (temporarily) undeliverable messages
      - I don't care if you're not online to see the video broadcast
    - Availability of buffer space
    - Buffer management
      - E.g.: Underflow/overflow handling -- Block sender/receiver? Return an error?

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Communication in Monolithic Operating Systems

Communication in Monolithic OSes

- Vertical communication
  - User/kernel
    - Safety requirements
      - No arbitrary control transfer
      - No arbitrary data sharing
      - Need well-defined semantics
    - Partially shared data
      - Kernel hidden from user, but not vice-versa
    - Safe procedure call
      - System call/return
      - kernel→user, user→kernel
      - Shared argument data, but no shared code
    - Asynchronous control transfer
      - Signals, callbacks, ...
      - kernel→user only
      - shared code
    - Implicit addressing of kernel

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Communication in Monolithic OSes

- Vertical communication
  - Kernel/devices
    - Safety requirements ignored, kernel is trusted
    - (Partially) shared data
      - I/O registers, DMA, ...
    - Control transfer
      - in, out, ...
      - kernel→device
    - Interrupts
      - Device→kernel

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Communication in Monolithic OSes

- Horizontal communication
  - User/user
    - Safety requirements
      - No arbitrary data sharing
    - Kernel-provided abstractions
      - Messages
        - pipes, fifos, ipc, sockets, ...
      - Shared data
        - (Explicitly) shared memory
  - Kernel/kernel
    - No safety requirements, kernel is trusted
    - Shared data (global state and knowledge)
    - Direct control transfer (call/ret)

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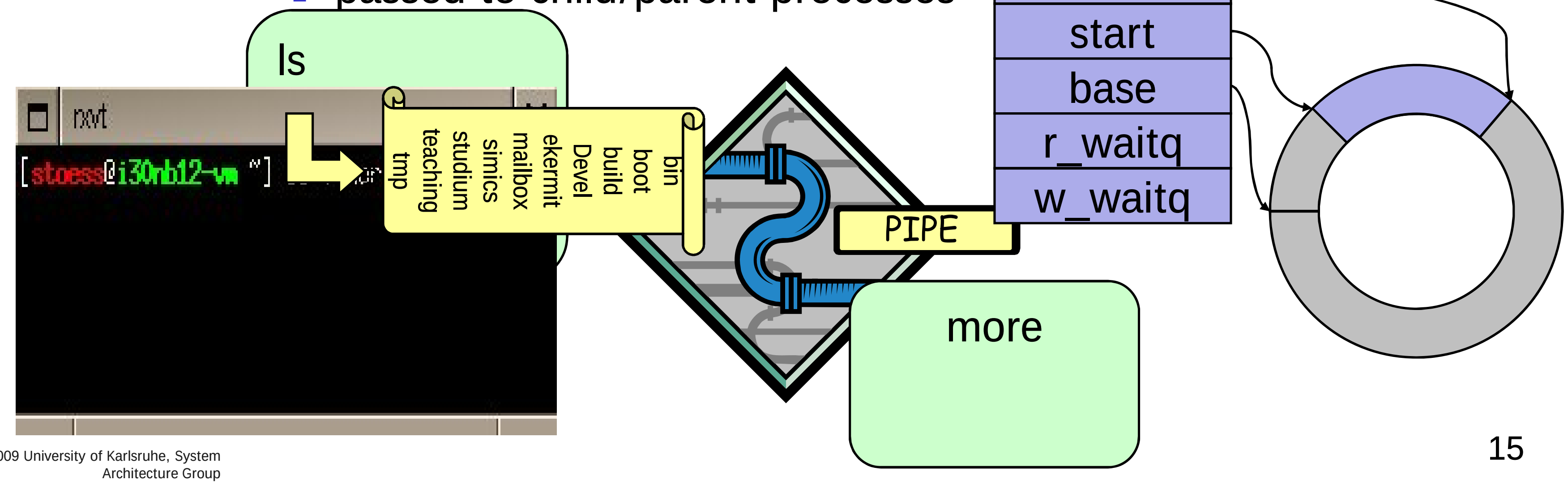
Communication primitives in UNIX

- Example: Pipe
  - Linear, byte-oriented, unidirectional data stream
  - Asynchronous, buffered communication
    - Ring-buffer of fixed size
    - Atomic write for data < buffer size
  - Blocking and non-blocking variants
    - Can block on full/empty buffer
  - Addressing: process-local handle
    - local file handle
    - passed to child/parent processes



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Communication primitives in UNIX

- Addressed via global handle
- Mapped to file system
- open()/close() for creating and removing FIFOs

- Manage access rights via file system permissions

Communication primitives in UNIX

- Reading from a pipe/FIFO

<table>
<tr><td rowspan="3">pipe size p</td><td colspan="3">At least one writing process</td><td rowspan="3">no writing process</td></tr>
<tr><td colspan="2">blocking read</td><td rowspan="2">non-blocking read</td></tr>
<tr><td>sleeping writer</td><td>no sleeping writer</td></tr>
<tr><td>p = 0</td><td rowspan="2">Copy n bytes, return n; wait on empty buffer</td><td>Wait for some data, copy it, return its size</td><td>Return -EAGAIN</td><td>Return 0</td></tr>
<tr><td>0 < p < n</td><td colspan="3">Copy p bytes, return p</td></tr>
<tr><td>p ≥ n</td><td colspan="4">Copy n bytes, return n; (p-n bytes will be left in the buffer)</td></tr>
</table>

- Writing to a pipe/FIFO

<table>
<tr><td rowspan="2">available buffer space u</td><td colspan="2">at least one reading process</td><td rowspan="2">no reading process</td></tr>
<tr><td>blocking write</td><td>nonblocking write</td></tr>
<tr><td>u < n ≤ bufsize</td><td rowspan="2">Wait until n-u bytes freed, copy n bytes, return n.</td><td>Return -EAGAIN</td><td rowspan="2">Send SIGPIPE signal and return -EPIPE</td></tr>
<tr><td>n > bufsize</td><td>if u>0, copy u bytes, return; else return -EAGAIN</td></tr>
<tr><td>u ≥ n</td><td colspan="3">copy n bytes and return n.</td></tr>
</table>

Source: Daniele Bovet and Marco Cesati. ***Understanding the Linux kernel*** . O'Reilly & Associates, Inc.. 2nd edition. p639-640

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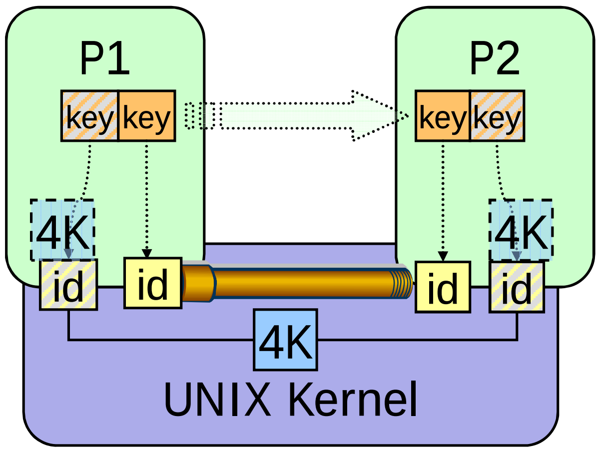
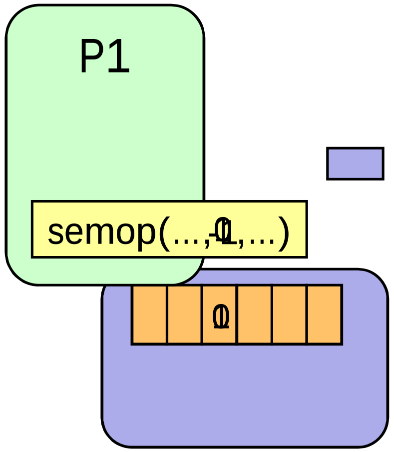
Communication primitives in UNIX

- System V IPC
  - Set of communication mechanisms for
    - Synchronization: *semaphores*
    - Message passing: *message queues*
    - Sharing memory: *IPC shared memory*
  - Addressed via global and local handles
    - 32-bit ipc key
      - Chosen by programmer
      - User-defined namespace
      - Passed around
    - 32-bit ipc reference identifier
      - Chosen and used by kernel
      - Unique in the system
      - (Can be passed around as well)



Communication primitives in UNIX

- IPC Semaphores
  - Synchronization via “atomic counting”
    - Consists of one or more primitive semaphores
    - Atomically incremented/decremented variables
  - Operations
    - semget(key): creates/resolves semaphore
    - semctl(id): initialize/force/destroy semaphore
    - semop(id, sem_op[]): operations on primitive semaphores
      - All operations performed atomically and simultaneously
      - atomic decrement (enter)
      - atomic increment (leave)
      - wait for zero
      - non-blocking and blocking variants
  - Undoable semaphores
    - Undo reservations of dying processes
    - Process can mark operations as undoable
    - Kernel tracks operations
    - Requires per-process list of semaphores



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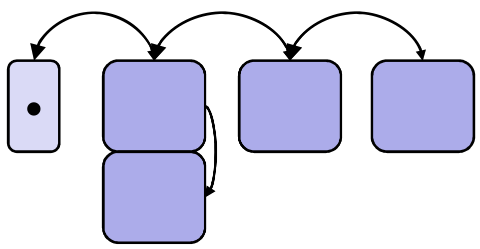
Communication primitives in UNIX

- IPC Message queues
  - Asynchronous, buffered messages
    - Requires user-kernel copying
  - Typed, FIFO-ordered message queues
    - Maximum number of queues
    - Maximum size of queue (16K)
    - Maximum size of messages (8K)
  - Operations
    - msgget(key): create/resolve message queue
    - msgsend(id)
    - msgreceive(id)
    - Blocking and non-blocking variants (on full/empty queues)
  - Implementation
    - Linked list of messages
    - Messages are broken into sub-pages



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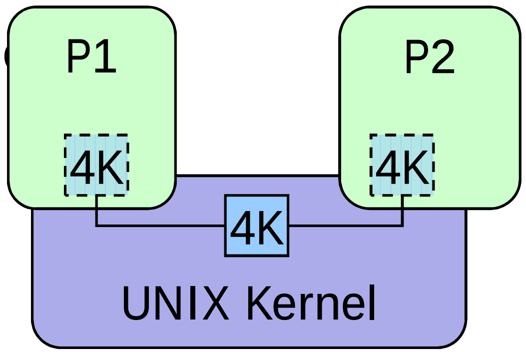
Communication primitives in UNIX

- IPC Shared Memory
  - Memory segment shared between processes
  - May be used for asynchronous, implicit communication
  - Kernel-provided memory buffers
    - Maximum number (4096)
    - Maximum segment size (8 MB)
    - Maximum total size (8 GB)
  - Operations
    - shmget(key): create/resolve shared segm
    - shmat(id, [address]): attach segment
    - shmdt(id): detach segment from process
  - Implementation
    - Via virtual memory subsystem (upcoming lecture)



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Communication in Multi-Server Systems

Communication in Multi-Server Systems

- Kernel split into
  - Multiple kernel subsystems (servers) at user-level
    - Pager, Fileserver, Network, Drivers, ...
  - Small, privileged µ-kernel
- Vertical communication
  - User/µ-kernel
  - Server/µ-kernel
  - Server/Device
- Horizontal communication
  - User/User
  - Server/User
  - Server/Server

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Communication in Multi-Server Systems

- Analysis
  - Complex safety and isolation requirements
    - Need safe communication facilities
    - µ-kernel approach: kernel-provided IPC
  - Modularization results in increased communication
    - Need flexible, low-overhead communication
    - E.g. L4 approach: synchronous IPC
  - Need abstraction for *safe* communication with devices
    - Driver subsystems are not implictly trusted anymore
    - Need safe transaction with drivers
    - Ultimately limited by hardware (e.g., DMA problems)

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Communication in Multi-Server Systems

- Case study: Mach
  - Kernel servers at user-level
    - Memory managers
    - Network Proxies
    - ...
  - Device drivers reside within the kernel
    - No user-level I/O subsystems
    - No I/O hardware abstractions
  - Asynchronous, unidirectional port system
    - Port: mailbox with only one receiver
    - Like TCP port, but per-process (rather than per-node)
    - Associated rights to send receive
  - Used for user/user and user/µ-kernel communication
    - Kernel-provided ports for system calls/services
    - kernel-provided startup ports for bootstrapping

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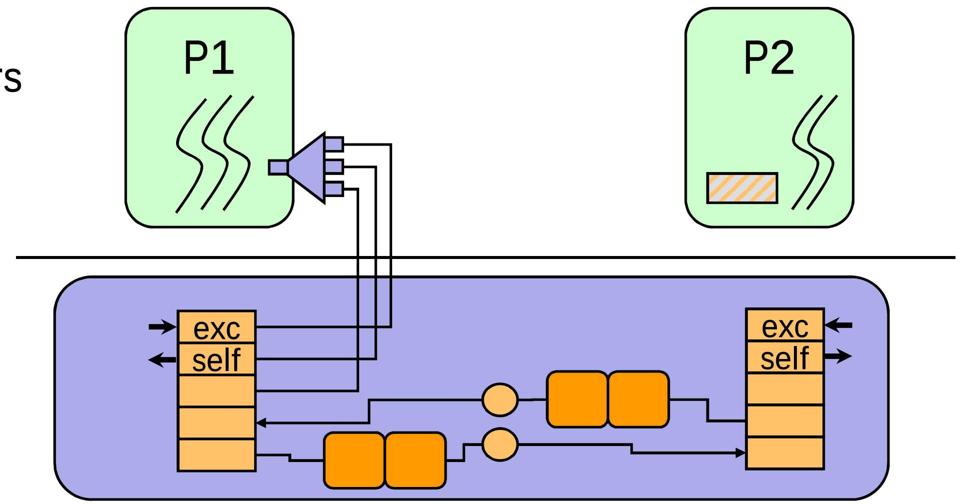
Communication in Multi-Server Systems

- Case study: Mach
  - Messages are buffered by the kernel
    - Enables asynchronous non-blocking send
    - Requires copying data to and from kernel
    - Blocks on full buffers
  - In-line data:
    - Copied indirectly between sender and receiver
    - Guaranteed in-order copy
  - Out-of-line data:
    - Copy-on-write mechanism
    - Avoid copying large buffers
  - Operations
    - port_allocate(self, &port)
    - port_insert_send()
    - port_receive()
  - Port sets
    - Groups of ports
    - UNIX select() semantics



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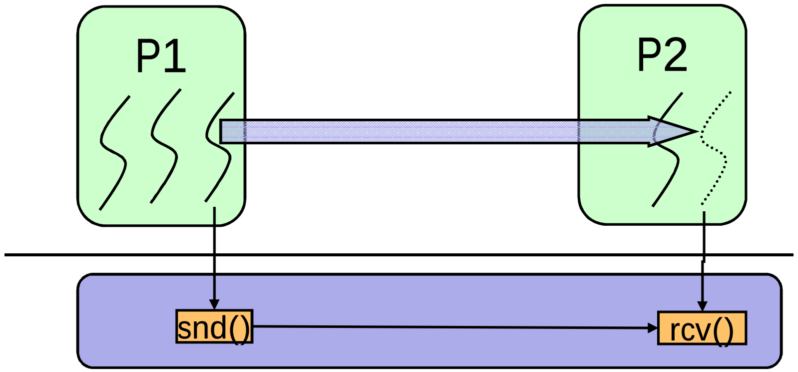
Communication in Multi-Server Systems

- Case study: L4
  - Kernel servers at user-level
    - Memory managers
    - User-level device drivers
  - Synchronous, rendezvous-based IPC
    - Communication endpoints: threads
    - Receiver can address multiple threads
    - Blocking and non-blocking variants (via timeouts)
  - IPC types
    - Register IPC
      - Fast register tansfer
      - Use, e.g., for synchronization
    - String IPC
      - Transfer memory content
      - Copied during IPC
    - Map IPC
      - Send pages (or ports) of own address space
      - Potentially restrict access rights
      - Kernel updates MMU hardware during IPC



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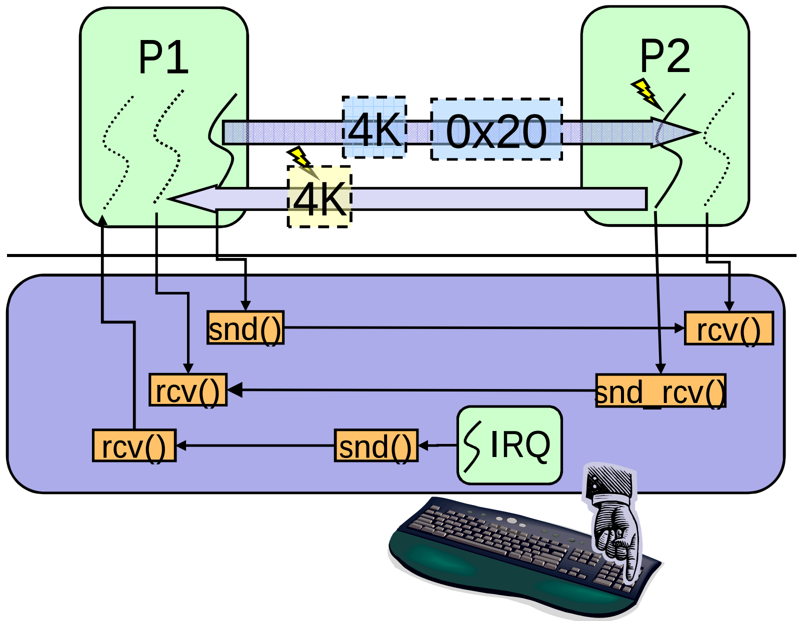
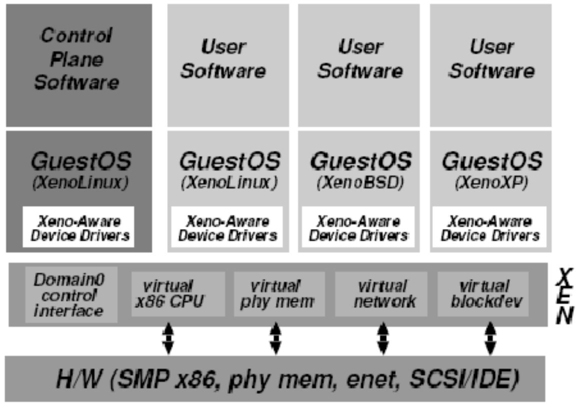
Communication in Multi-Server Systems

- Case study: L4
  - No buffering by the kernel
    - Pure synchronous send
    - Direct transfer from sender to receiver
  - Implement asynchronous IPC at user-level
    - Proxy threads
    - Buffer management at user level
  - Operations
    - send to
    - receive from
    - combinations
  - IPC abstracts hardware
    - Paging IPC
      - Can send page *fault* IPCs
      - Can send/receive memory/IO
    - Interrupts/Exceptions
      - Can send exception IPCs
      - Devices can send interrupt IPCs
      - Synchronous waiting for (actually asynchronous) interrupts



Communication in Multi-Server Systems

- Case study: Xen
  - Special case: virtual machine hypervisor
  - Multiple virtual machines at user-level
  - Client virtual machines
    - Concurrent workload
  - Control virtual machines
    - Management software
  - Hypervisor-aware client virtual machines (originally)



Source: Paul Barham et al. **Xen and the Art of Virtualization.** Proceedings of the nineteenth ACM symposium on Operating systems principles p.164-177

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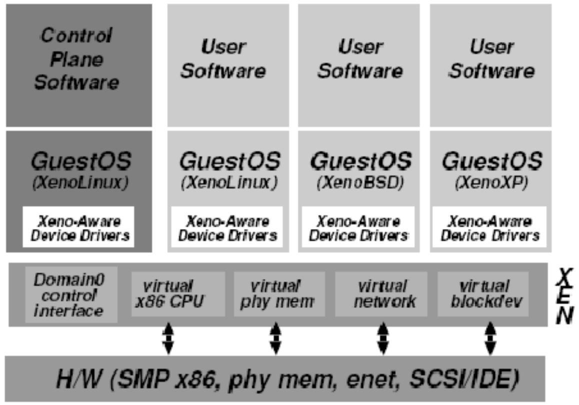
Communication in Multi-Server Systems



- Case study: Xen
  - Two types of VM/hypervisor communication:
  - Control transfer
    - Hypercall:
      VM requires privileged services
      - Same as system call in traditional OSes
      - Hardware-provided system call mechanisms (int, syscall, ...)
    - Asynchronous notification:
      VM receives virtual interrupt/events
      - User-specified callback handler
      - User flag temporarily disables events (virtual interrupt mask)

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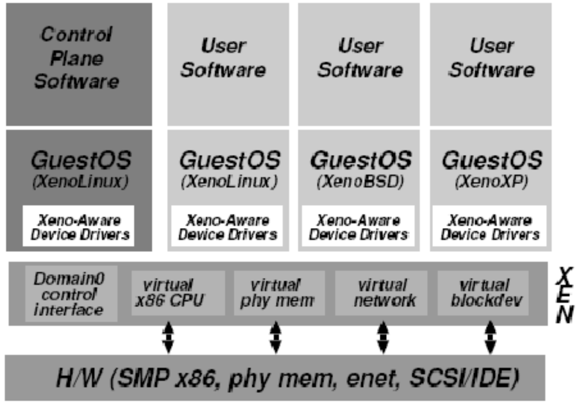
Communication in Multi-Server Systems

- Case study: Xen
  - Two types of VM/hypervisor
  - Data transfer
    - Used for transferring data blocks to/from devices
    - E.g., NIC packets, disk blocks,
    - Device virtualization requires hardware interpositioning
    - Extra data transfer layer between client VM and real device
    - Xen-aware device drivers
  - No explicit concept for inter-VM communication
    - Use virtual network abstraction



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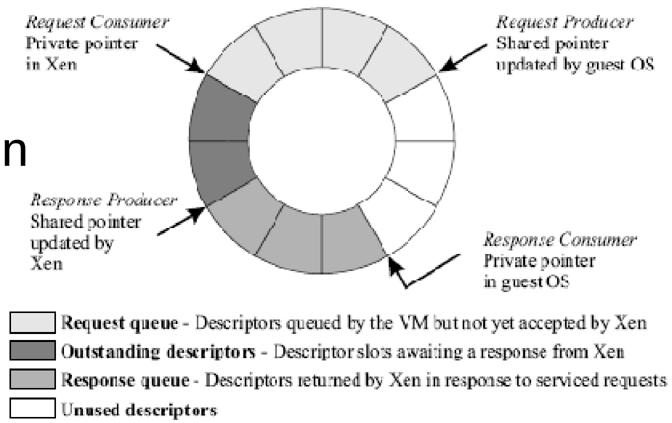
Communication in Multi-Server Systems

- Case study: Xen
  - Data transfer: I/O descriptor rings
    - Circular queue of requests and responses
      - Contains *descriptors,* not data
      - References I/O buffers within a client VM
    - Producer/consumer semantics
      - Client VM puts descriptor into ring
      - Xen removes descriptor
      - Use asynchronous event notification for responses
    - No in-order processing
      - Descriptors/Responses are tagged
    - No data copying
      - Reference physical memory
      - Sending: Use scatter-gather DMA
      - Receiving: Use memory mapping (exchange page frame)



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Thursday

- L4 API crash course – Part II

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