Networking

Advanced Operating Systems
(263-3800-00)

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Outline

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- Introduction
  - Motivation
  - What the problem is
- Networking in BSD
- Multiplexing
- Lazy Receiver Processing
- Receive Livelock
- Demultiplexing techniques
  - Software demultiplexing
  - Hardware demultiplexing
- Structural approaches

Why does networking matter?

- Almost all interesting apps are now networked
  – Single-machine systems are now rare
- Only new h/w development to impact the OS since Unix
  – Focus of much OS research for 20 years
- Increasingly, network i/f is the only peripheral that matters
  – Disks increasingly appear to be the other side of a network
  – GPU increasingly less of a periphera

Too big a topic for one lecture!

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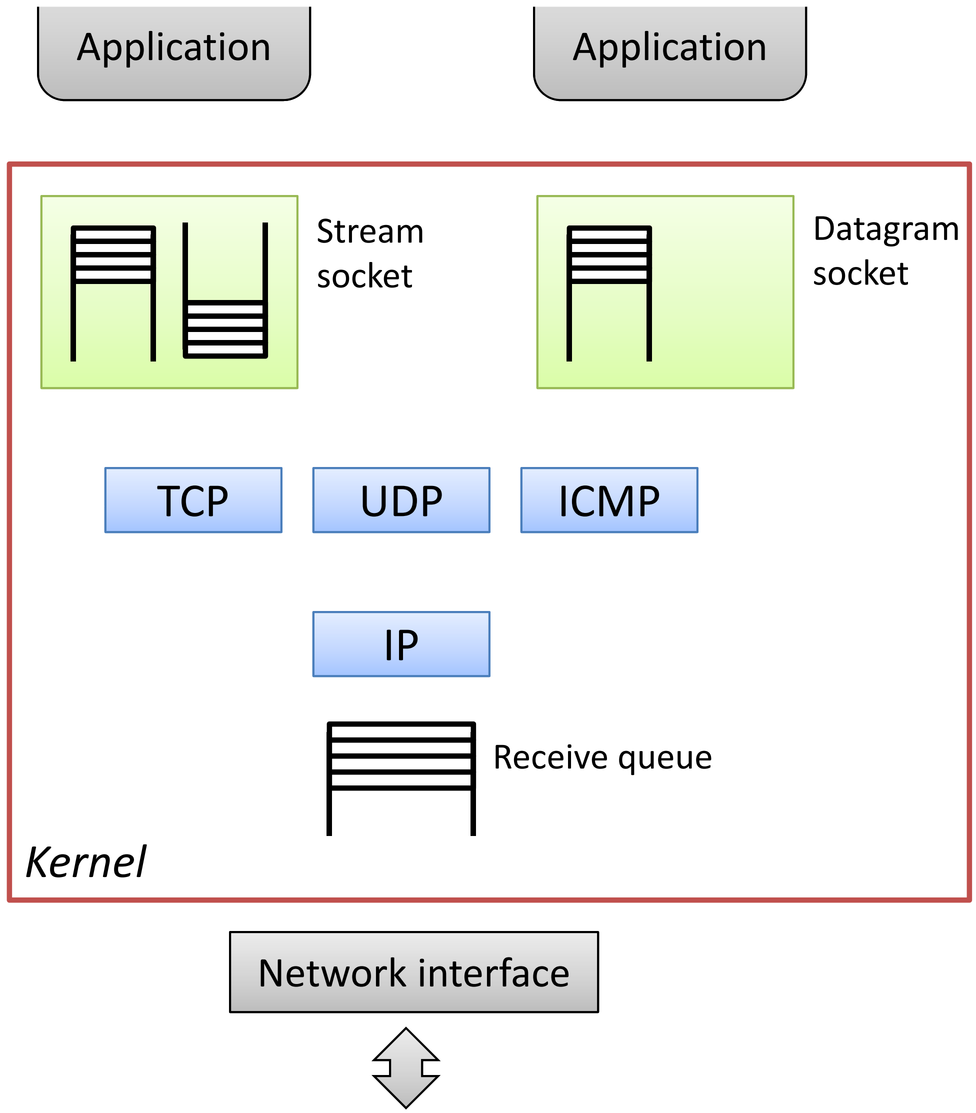
- Assume general familiarity with Unix-style networking
  - BSD sockets
  - Network interfaces, routing tables, etc.
- Will also assume you know about networks
  - Packet-oriented protocols
  - TCP end-system processing requirements
- Focus on:
  - General concepts
  - Specific techniques

What is the problem?

- Multiplexing / demultiplexing
  - When? Where? How many times?
- Packet scheduling
  - Prioritizing flows, throughput vs. latency
- Buffering
  - Where is the memory coming from?
- Protocol processing
  - E.g. TCP
- Interaction with the rest of the OS
  - Scheduling, memory allocation

Receiving a packet in BSD



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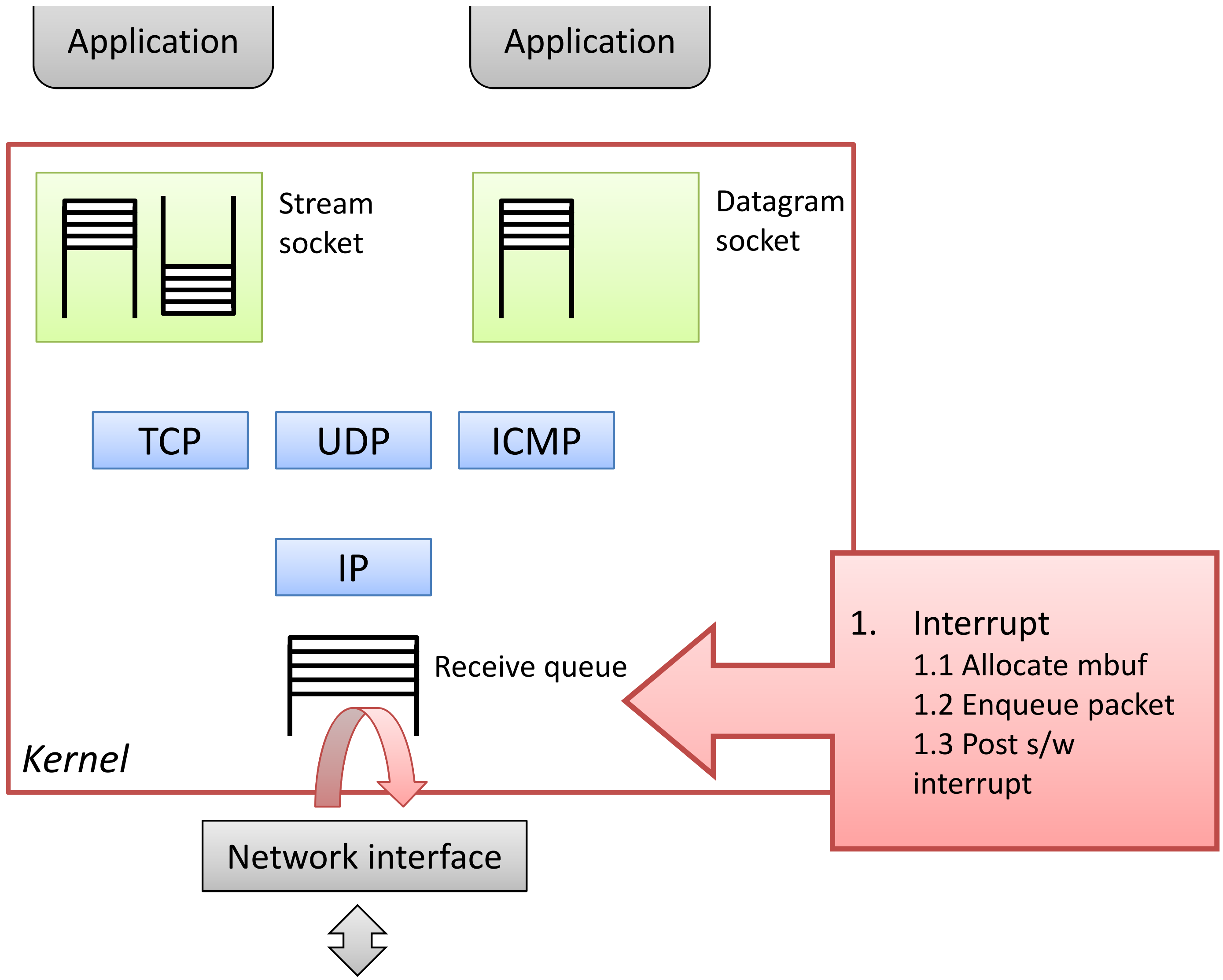

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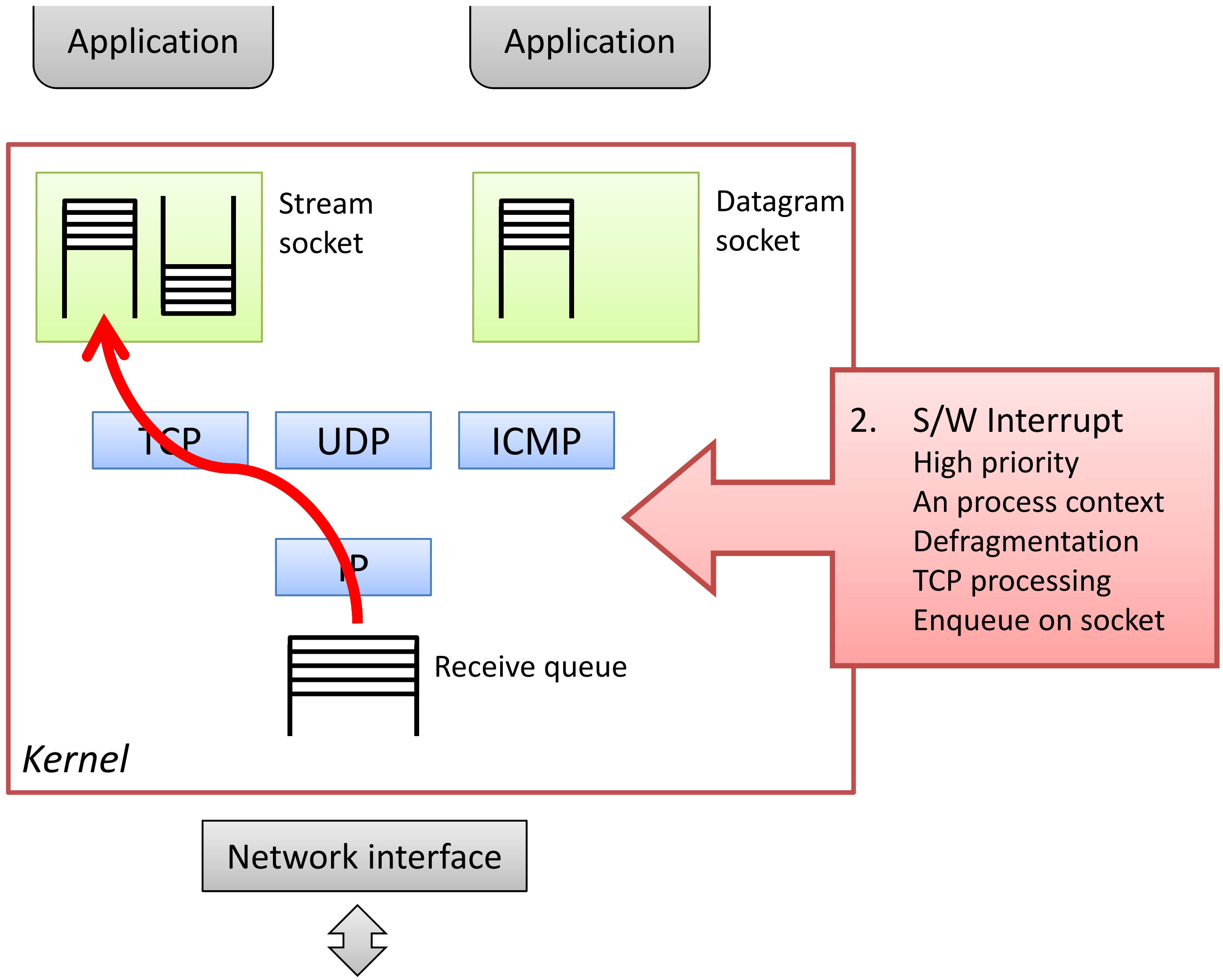

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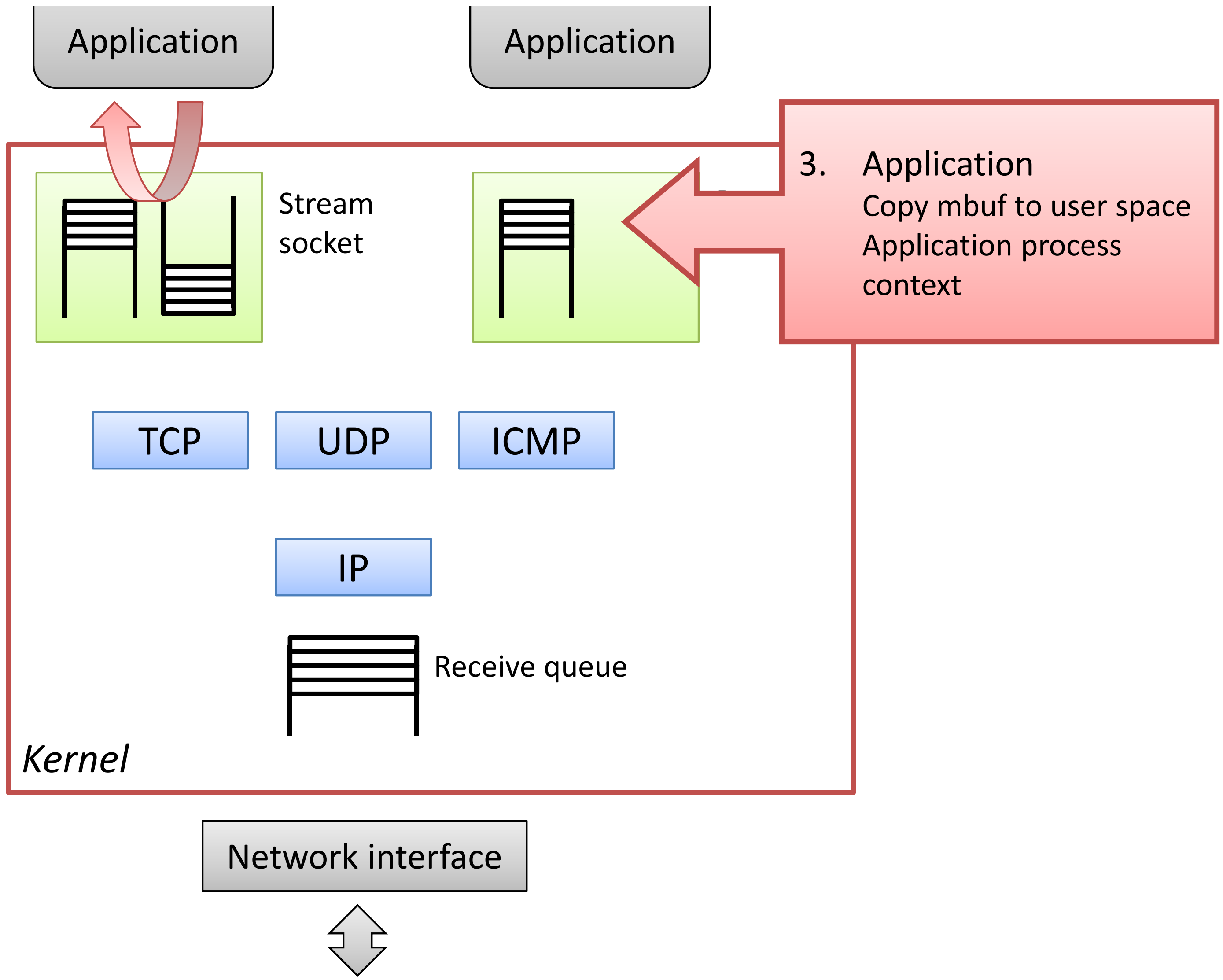
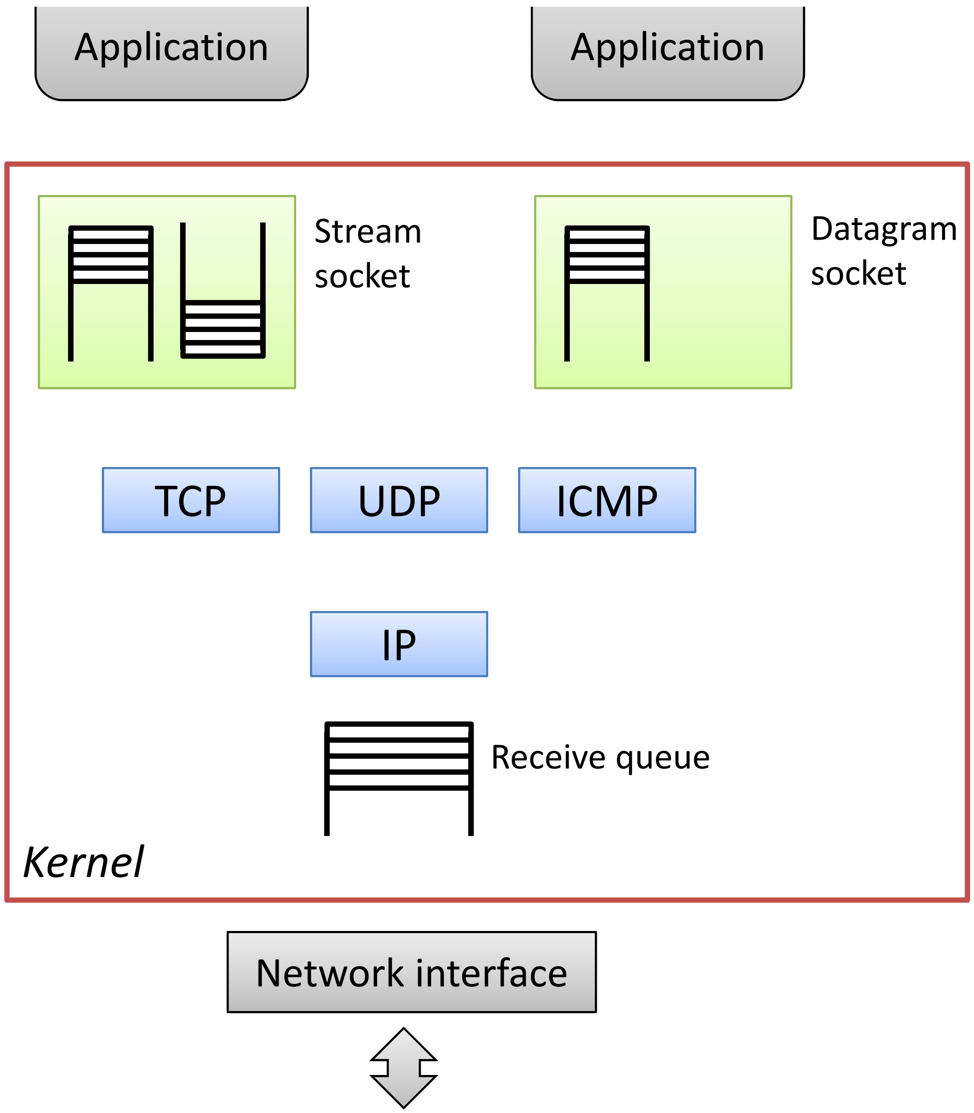


Sending a packet in BSD



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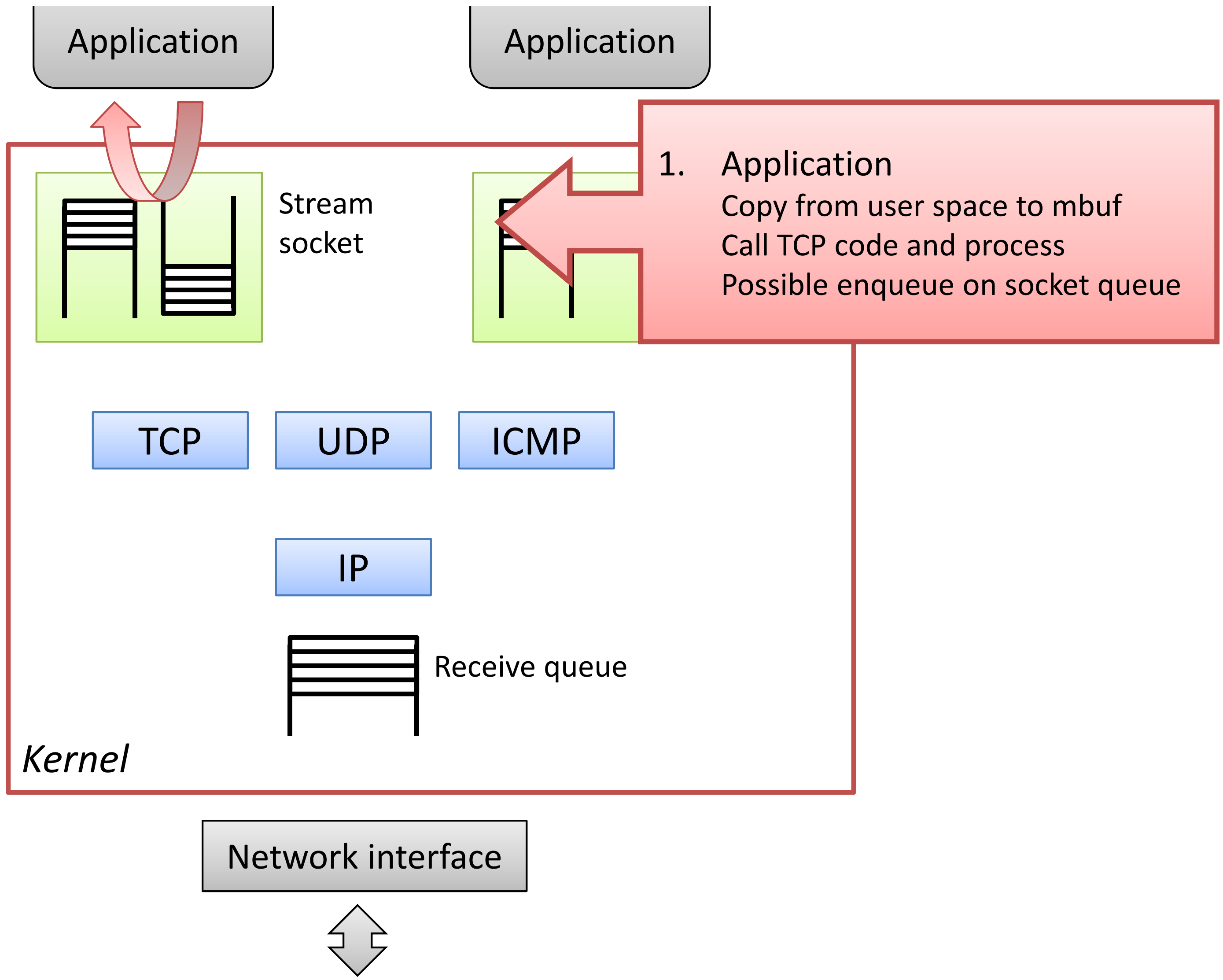

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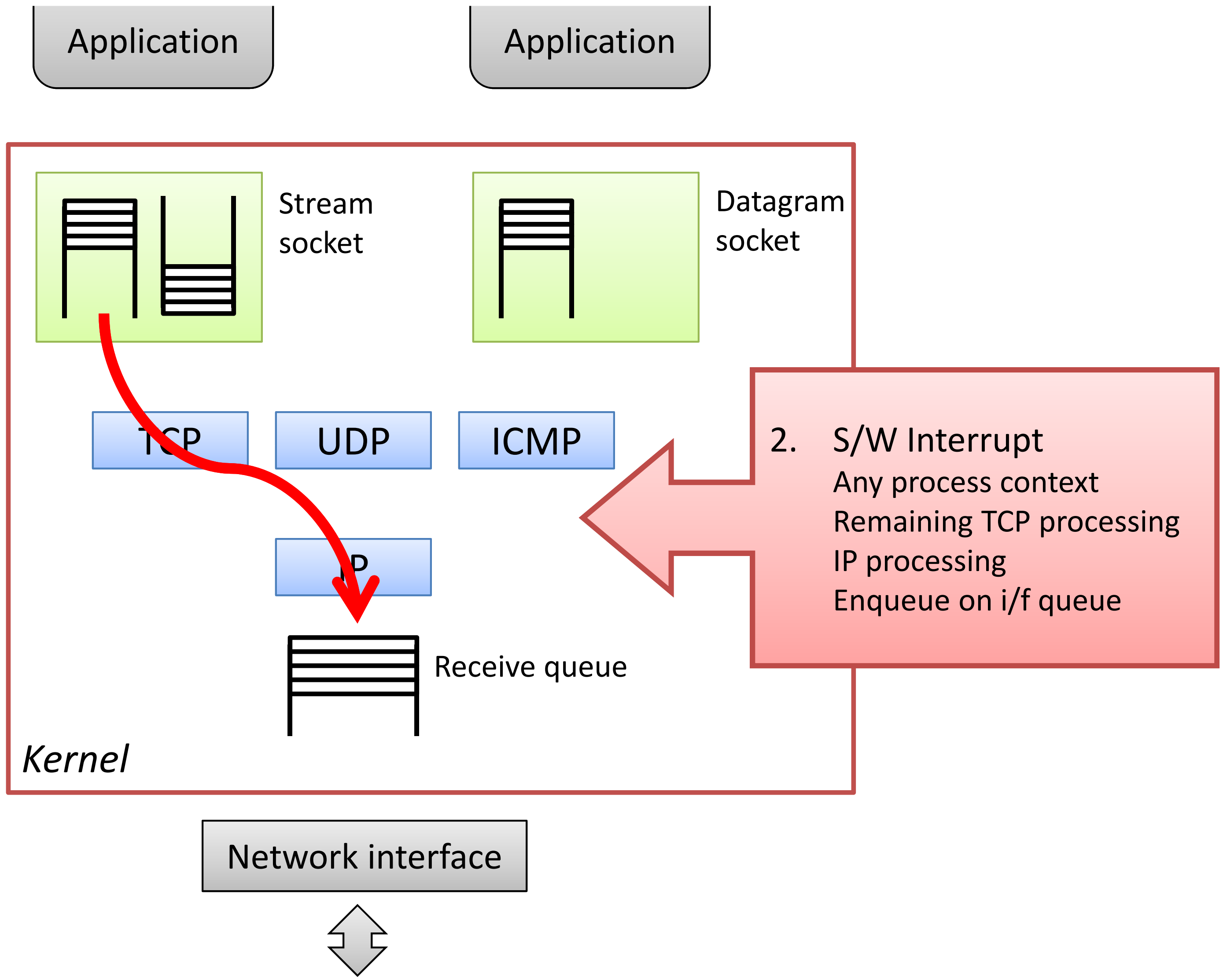

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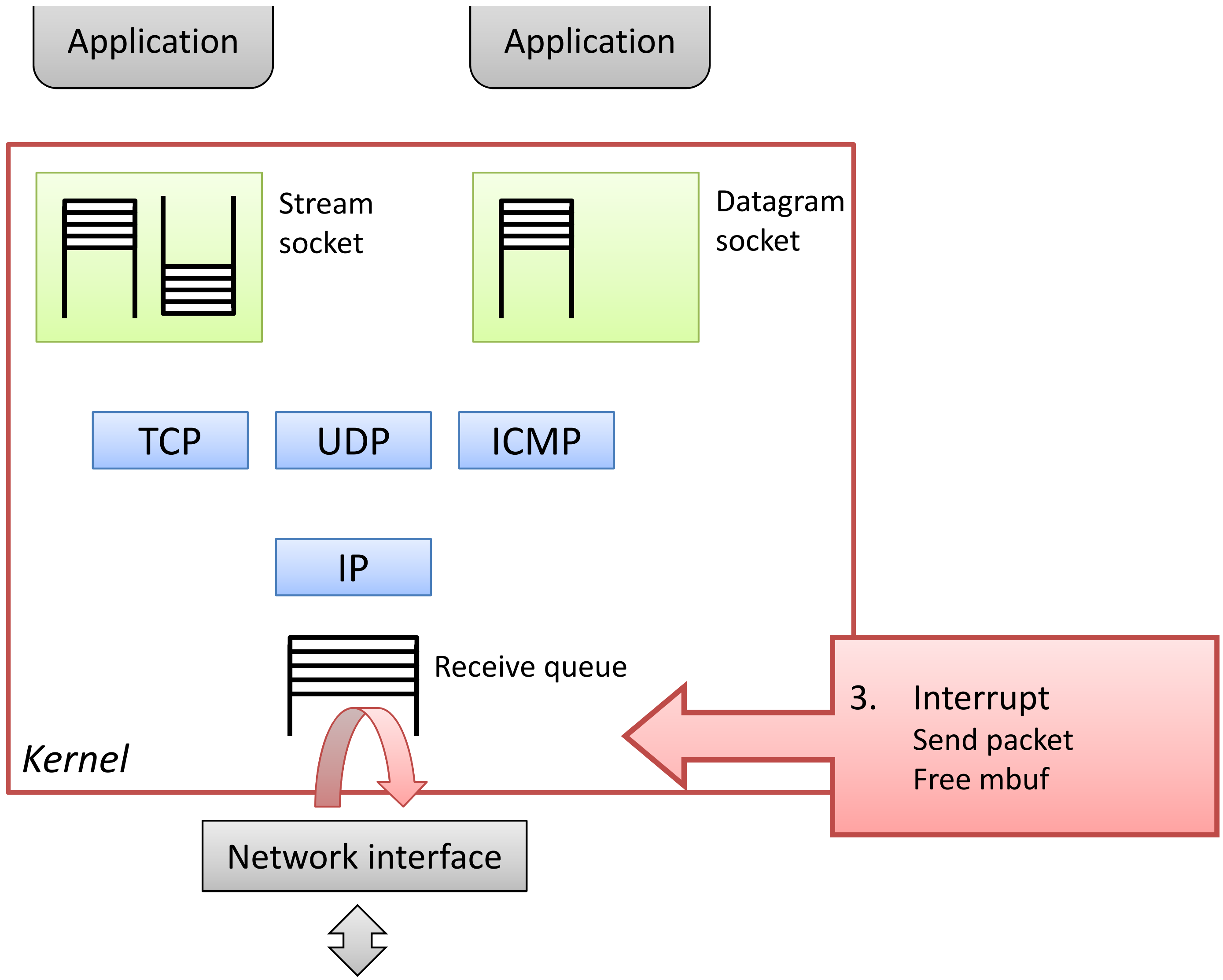

A note on terminology

- In Unix (and most systems):
  - Top half: called from user space (syscalls, etc.)
    - Per-process stack, synchronous traps, etc.
  - Bottom half: hardware and software interrupts
    - Dedicated stack, asynchronous w.r.t. top half, etc.

A note on terminology

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- In Linux ☹
  - Top half: hardware interrupts
  - Bottom half: software interrupts

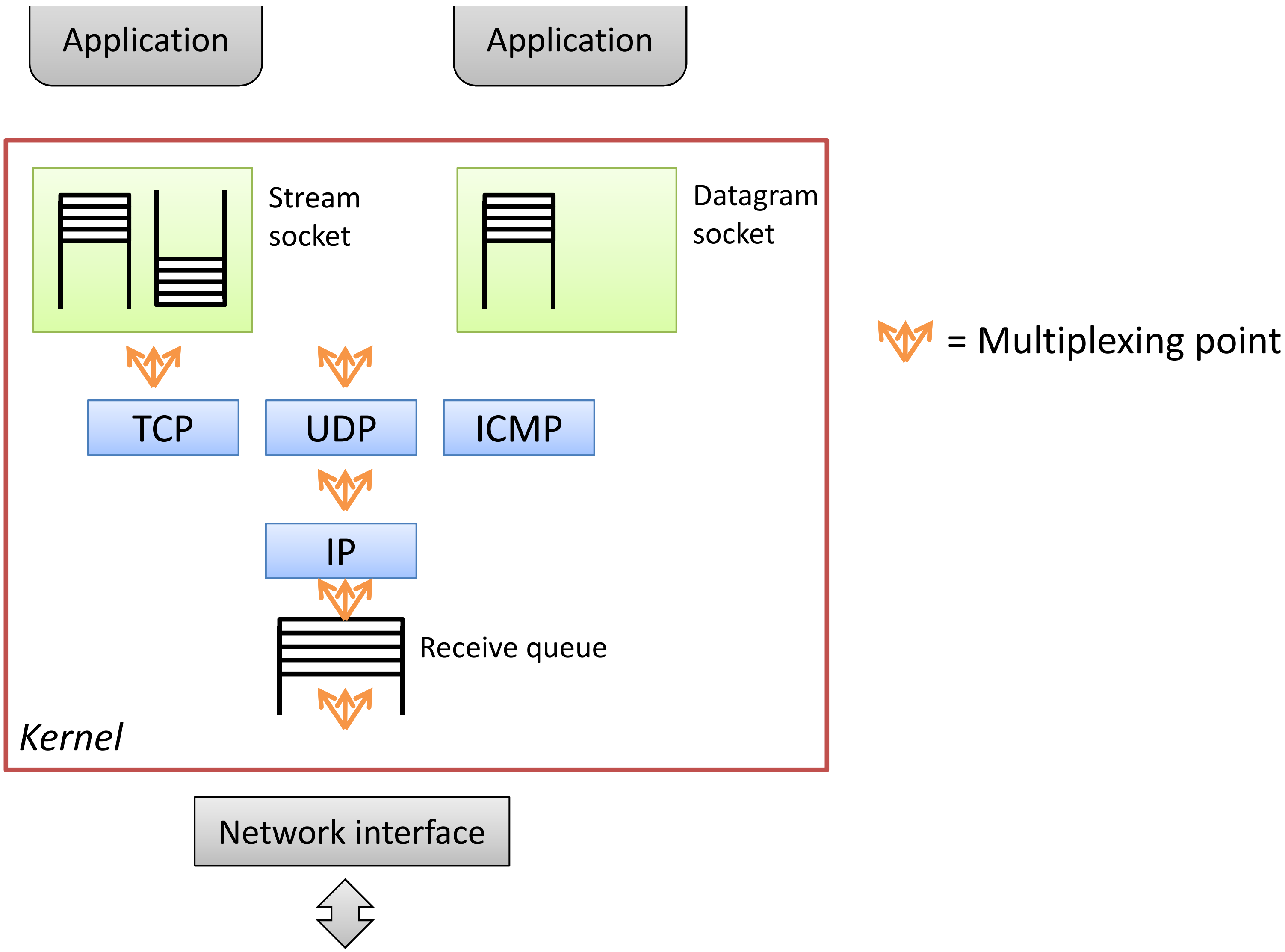
Multiplexing

- Fit traffic streams on a single channel
- Occurs at most levels of IP stack
- *Protocols* specify with headers/encapsulation
- Operating Systems also have to *schedule* messages
  - Which waiting packet do I send now?
- Examples:
  - IP, IPX, AppleTalk, etc. over Ethernet
  - TCP, UDP, ICMP, etc. over IP
  - Multiple TCP connections (ports)
  - ...

Demultiplexing

- Where to direct a packet from a lower layer
  - Lowest level: (physical!) network interface
  - Highest level: socket (for Unix/Windows...)
- Traditional approach: demux at multiple layers
  - IP, TCP, etc.
  - Extreme case: run each layer in own thread/process

Sending a packet in BSD



Layered vs. Early Multiplexing

[Tennenhouse, 1989]

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- "Layered Multiplexing Considered Harmful"
- Context: multimedia (soft realtime) networked applications
- Most multiplexing points have no knowledge of:
  - Application-level destination
  - Application-level flow
  - Application-level requirements for Quality of Service
- Result: QoS Crosstalk: applications interfere with each other
  - Easy to demonstrate with live audio/video, and big file transfer as cross traffic.

So why multiplex in layers?

- Advantages:
  - Modularity, simplicity
  - Efficiency: very simple demux functions
  - Low CPU overhead, high utilization
- Context: slow machines, fast networks
- Avoid crosstalk by scheduling at each mux point?
  - Impractical (complexity, slow)
  - Doesn’t work (still can’t distinguish flows)

Alternative: low-level multiplexing

- Multiplex ***low***, multiplex ***once***
- Receive path:
  - Identify application dest of packet as soon as possible
  - Schedule packet processing according to application
- Transmit path:
  - Queue all packet processing separately by application
  - Only multiplex at the point of transmission (NIC or driver)

Lazy Receiver Processing

[Druschel and Banga, 1996]

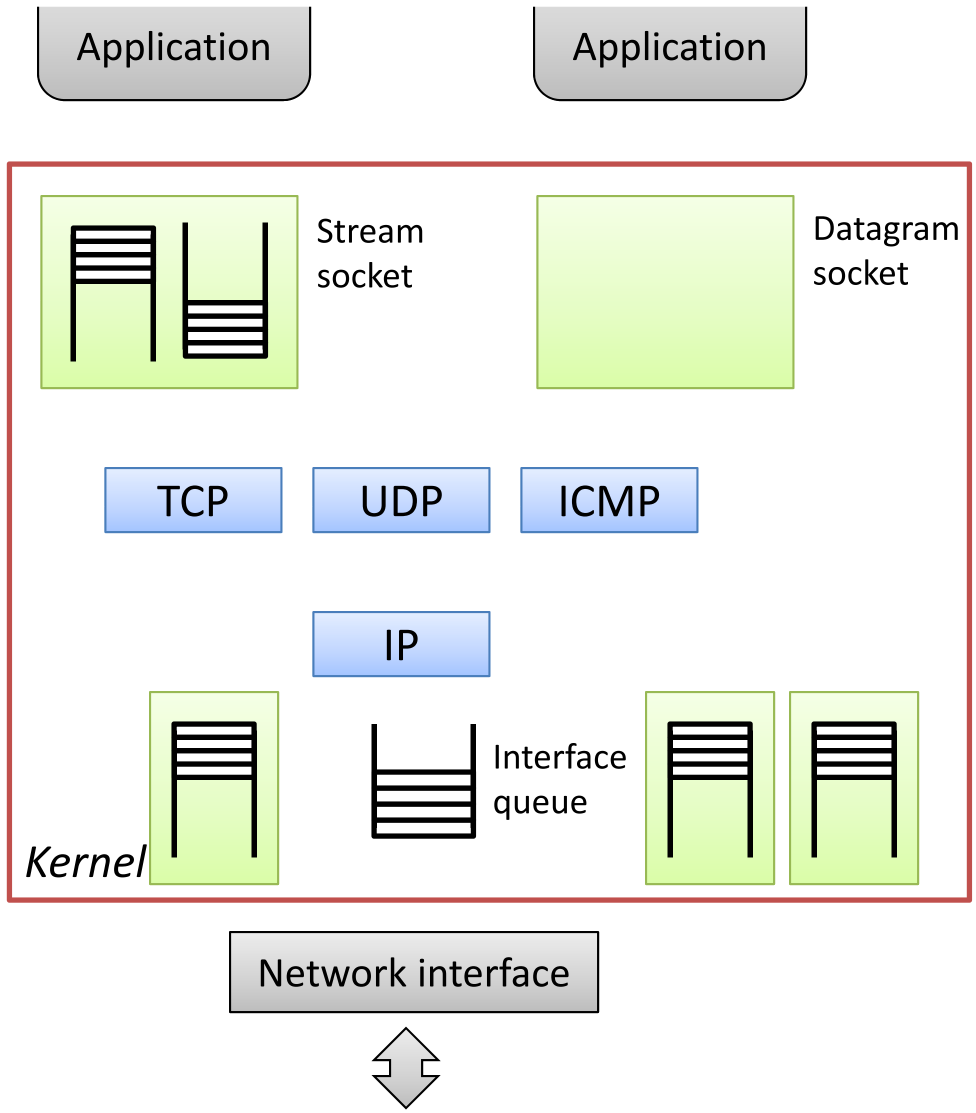
- BSD has "eager receiver processing": priorities are:
  1. capture and store packets in memory
  2. protocol processing of packets
  3. run the application
- No effective load shedding
  – Packet dropping can only happen late
- No traffic separation
  – Consequence of layered multiplexing ...
- Inappropriate resource accounting
  – Which application is doing the work in an interrupt?
  – The network is scheduling the computer!

Lazy Receiver Processing Ideas

[Druschel and Banga, 1996]

1. Use early demultiplexing
2. Queue incoming packets separately
3. Tail drop on per-socket queues
4. Schedule each packet along with its application
5. Account processing time to each application

LRP in practice



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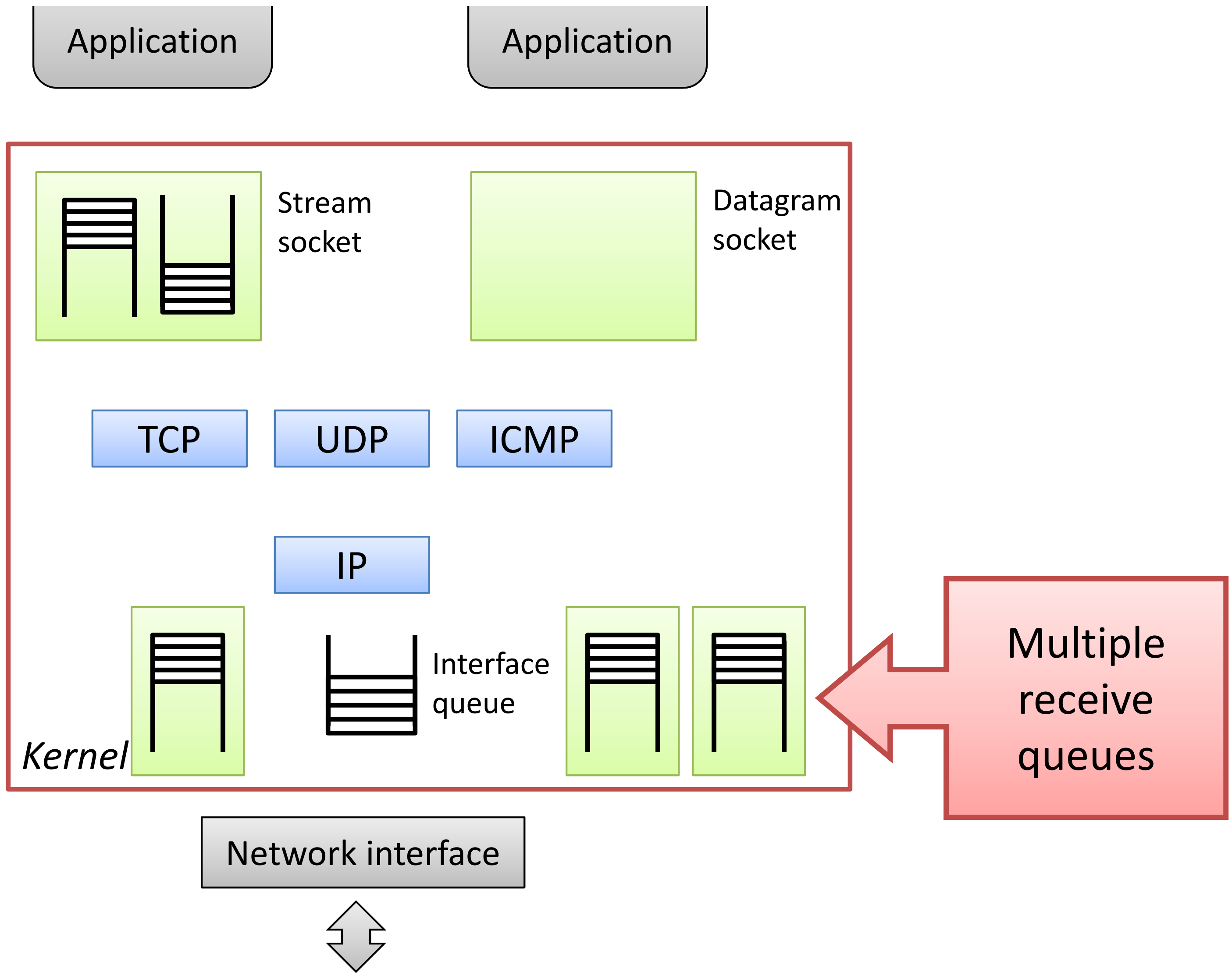

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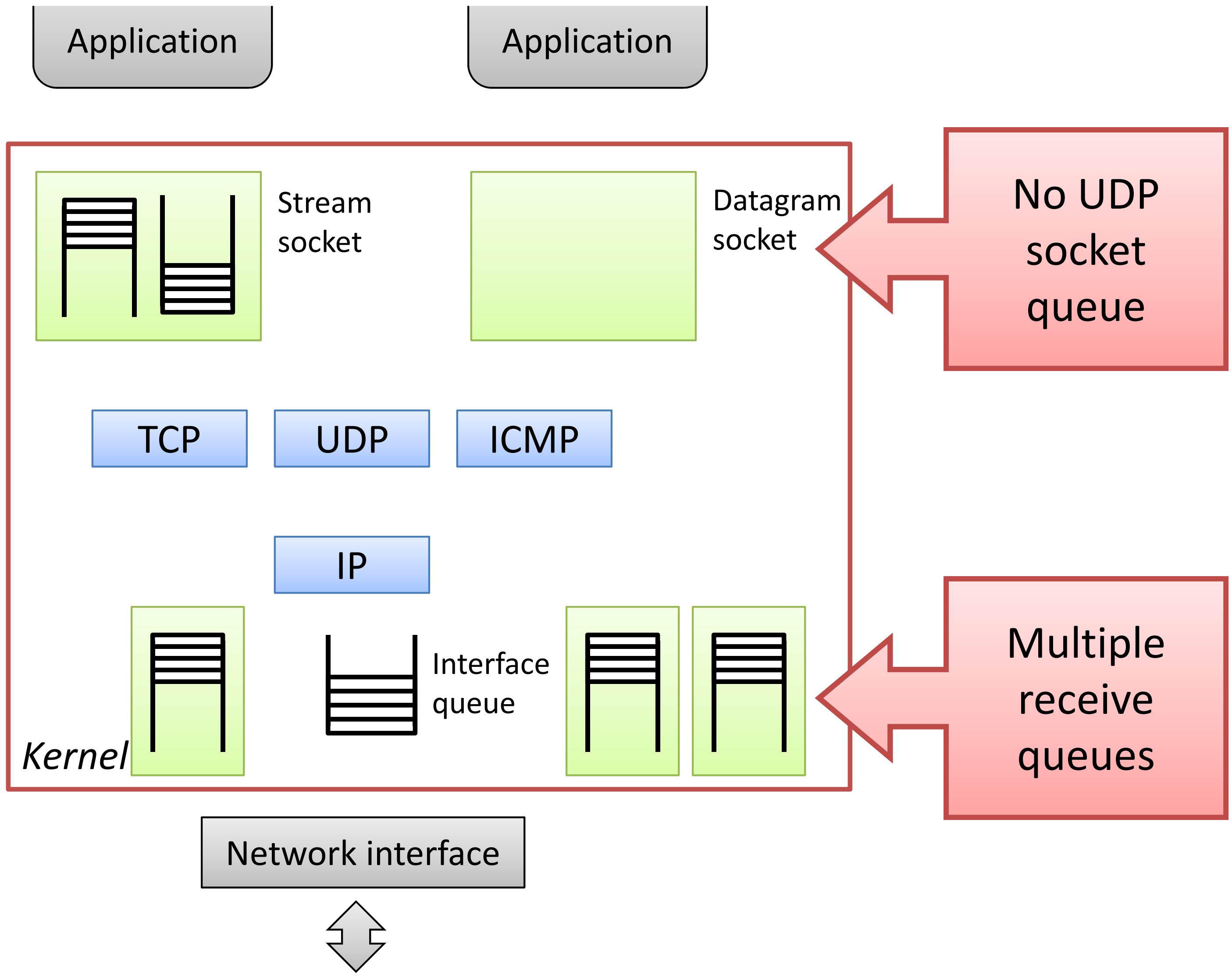

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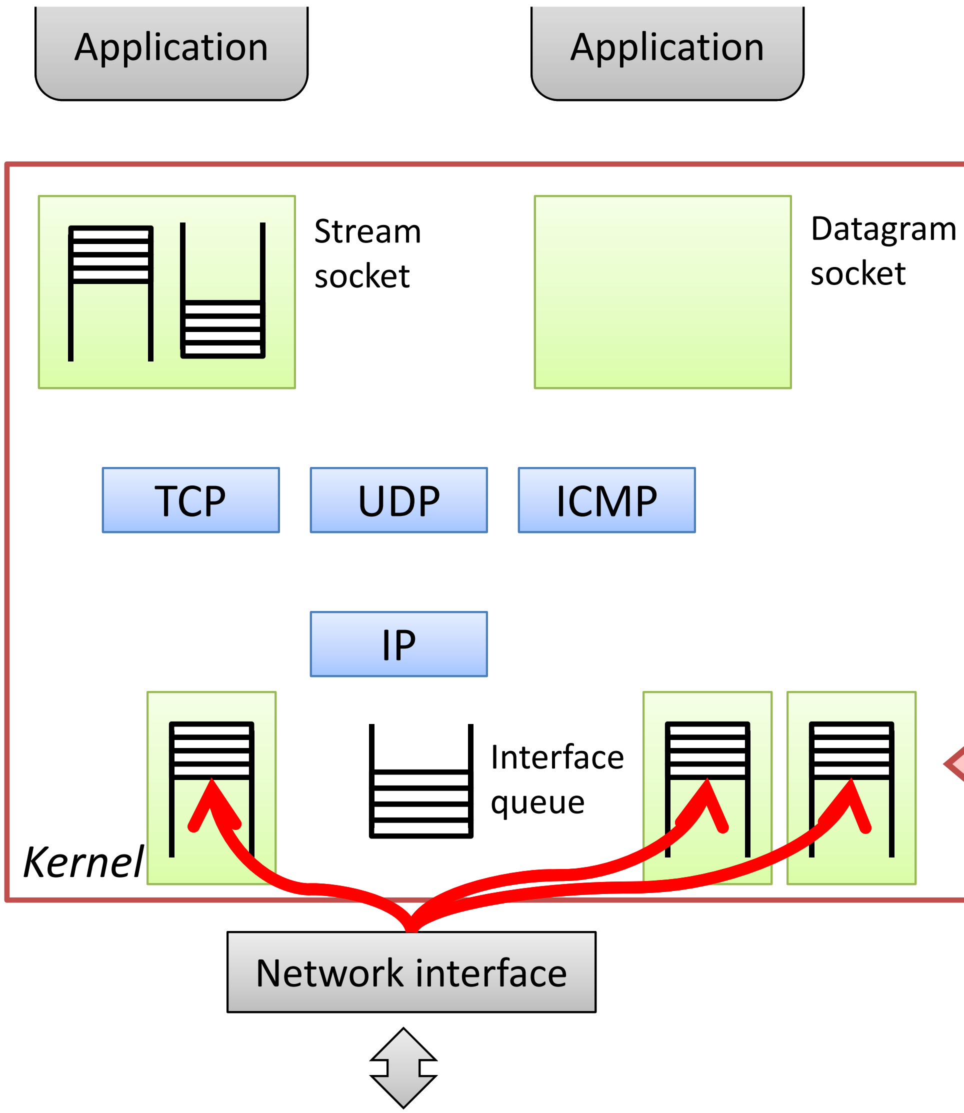
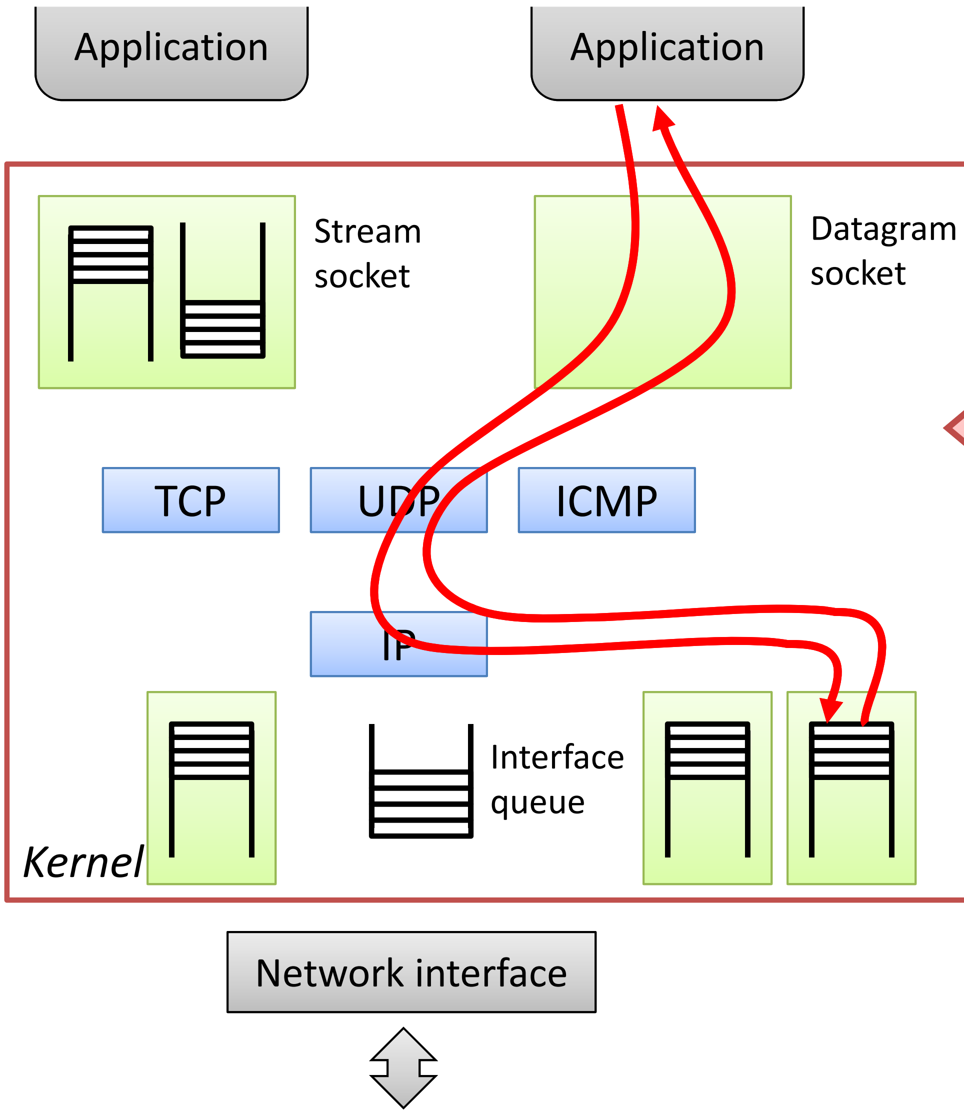


NIC demuxes
- Once (to a socket)
- Early (before processing)

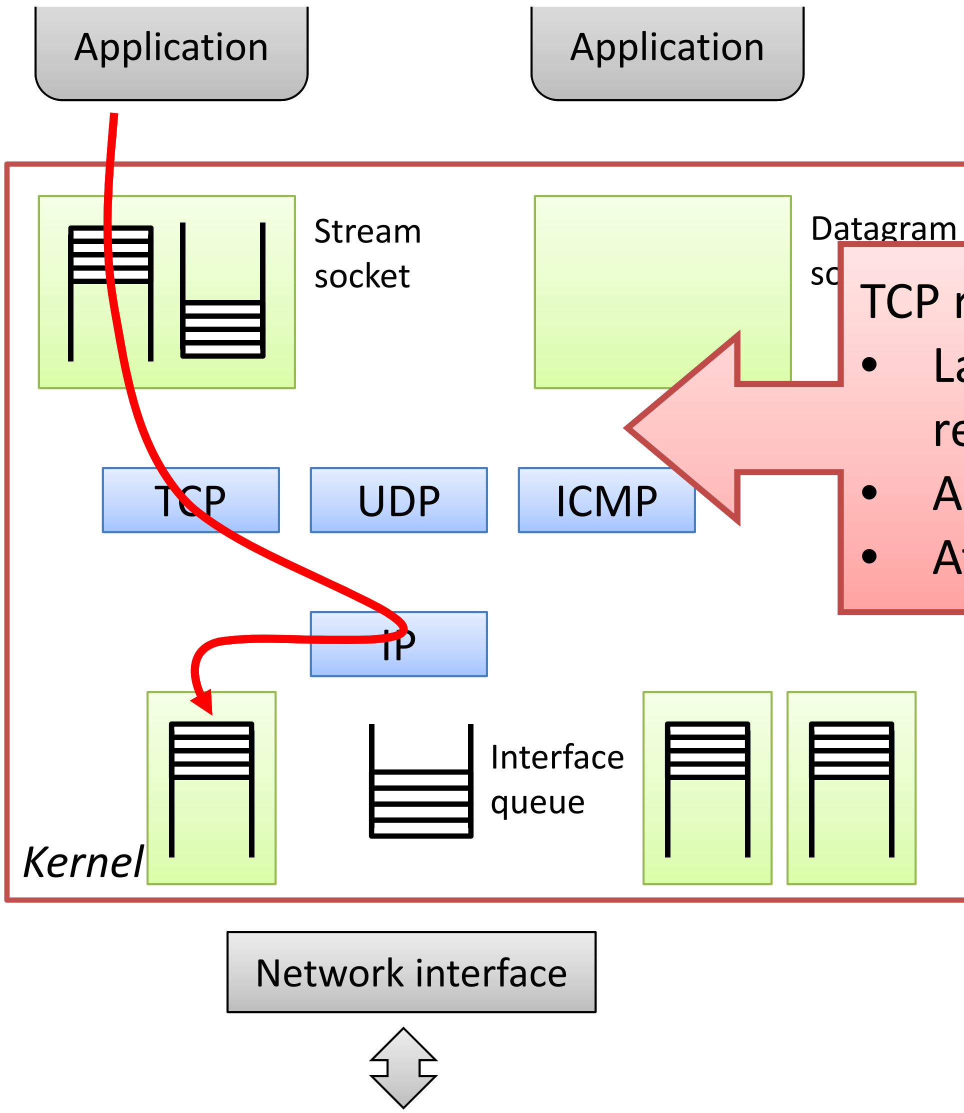
LRP in practice



UDP Processing

- Lazy (when application requests it)

LRP in practice



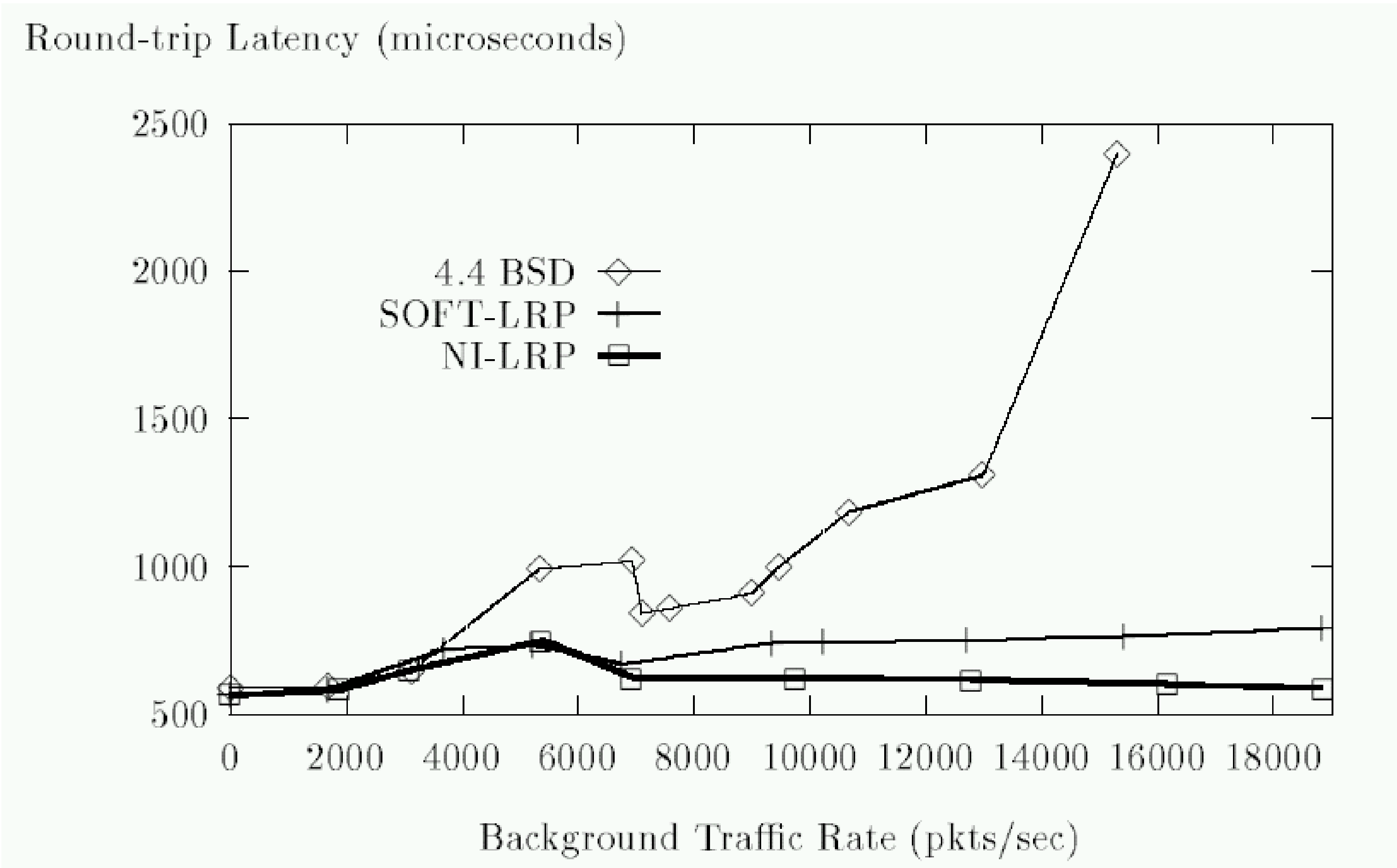
TCP receive

- Lazy (when application requests it)
- Accounted to dest. Process
- At dest. priority

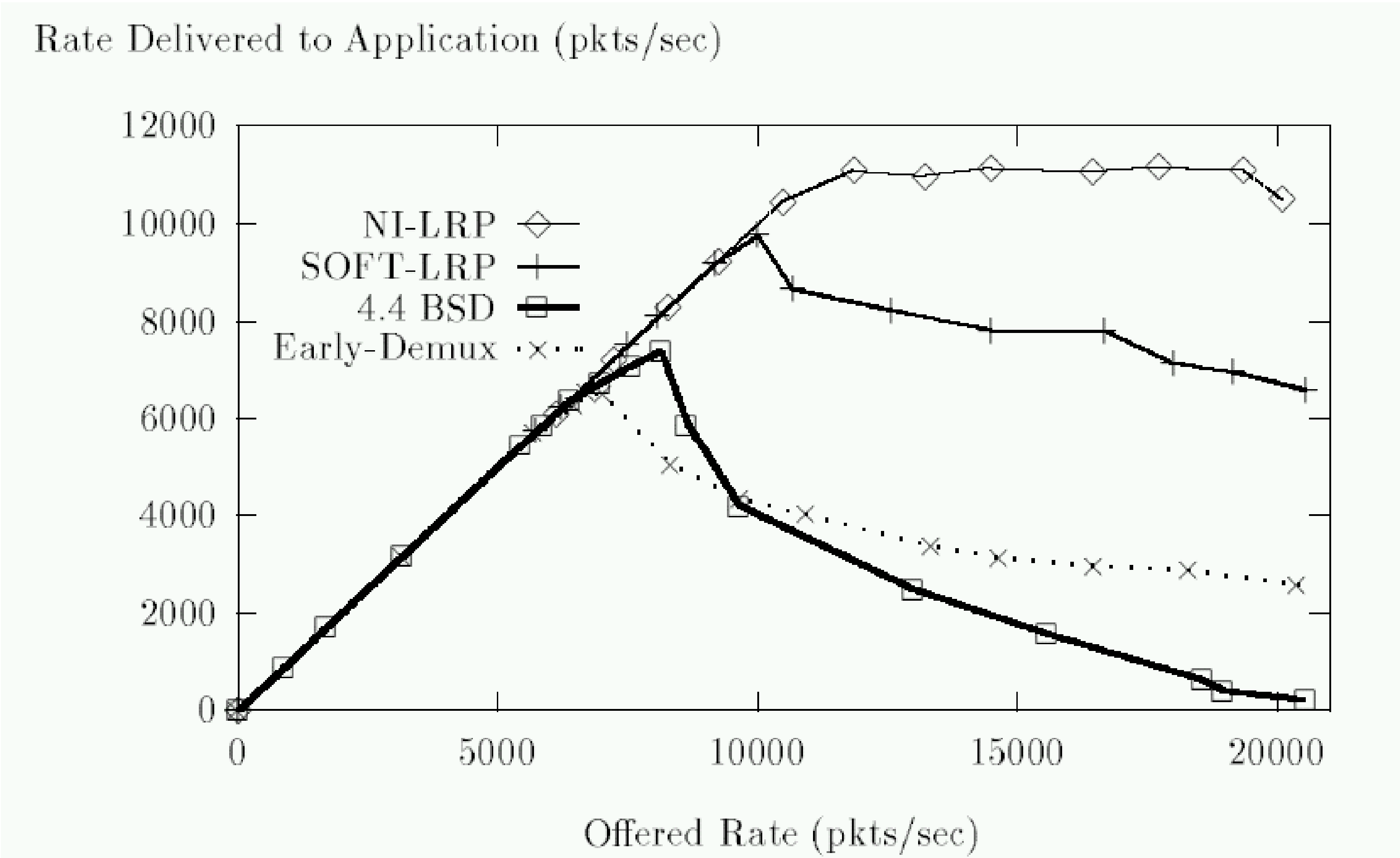
How to demux early?

- [G&B] used ATM: demux on Virtual Circuit Identifiers
  - Most ATMcards had per-VC queues, inc. the SBA-200
  - Requires one TCP connection per circuit
  - Also a good idea, but a story for another time...
- Ethernet cards (mostly) can’t do this...
  - “SOFT-LRP”: demux in interrupt handler
  - Adds latency, which is hard to account for
- See later ...

LRP Isolation



LRP stability



Livelock

- Graph shows ***livelock*** in action
  - As load increases, throughput **decreases**
  - Interrupts and processing overwhelm system
- Early demux alone is insufficient to prevent livelock
  - But helps somewhat under heavy load
- SOFT-LRP delays the onset
- NI-LRP (hardware) almost eliminates it

Eliminating livelock

[Mogul and Ramakrishnan, 1997]

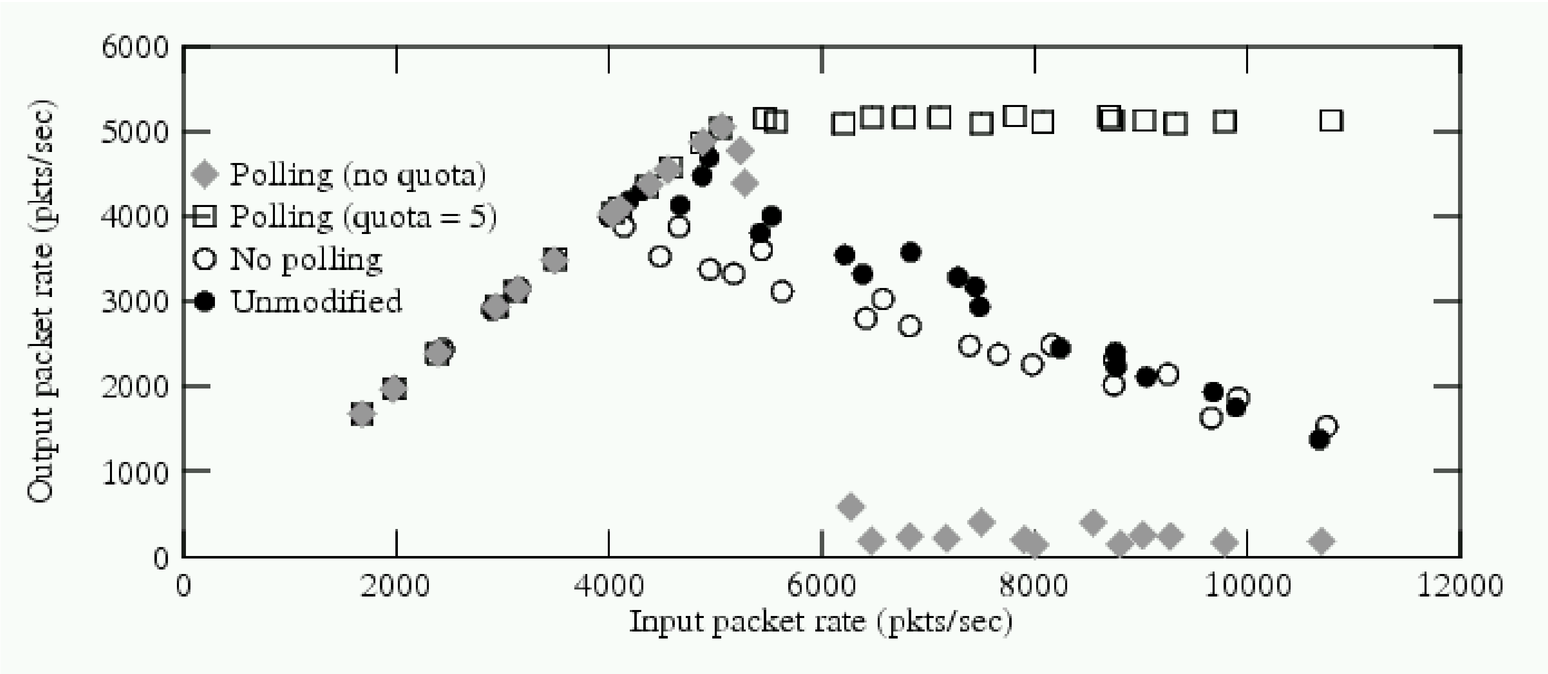
- Particular problem for:
  - Web servers, file servers, etc.
  - Network monitoring applications
  - Host-based routing
  - DoS resilience
- Throughput can drop to almost zero
  - E.g. no time for output processing
- Experience driven: NASDAQ, Election web servers

Approach:

[Mogul and Ramakrishnan, 1997]

- Avoid livelock:
  - Only use interrupts to initiate polling, then disable
  - Round-robin polling for input event sources
  - Schedule packet processing properly
  - Drop packets early
- Maintain performance:
  - Re-enable interrupts when no work pending to keep latency low
  - Buffer bursts in the receiving interface
  - Eliminate the IP input queue

Results



Output packet rate (pkts/sec)
Input packet rate (pkts/sec)
Polling (no quota)
Polling (quota = 5)
No polling
Unmodified
0
1000
2000
3000
4000
5000
6000
0
2000
4000
6000
8000
10000
12000

Software demux: basic idea

- **Packet filters**: old idea for inspecting the network
  - Each filter has an associated socket.
  - When a packet arrives, every filter is run on the packet
  - If the filter “passes” the packet, it’s delivered to the socket
- Not *quite* the same as a demultiplexer ...

Software demux: basic idea

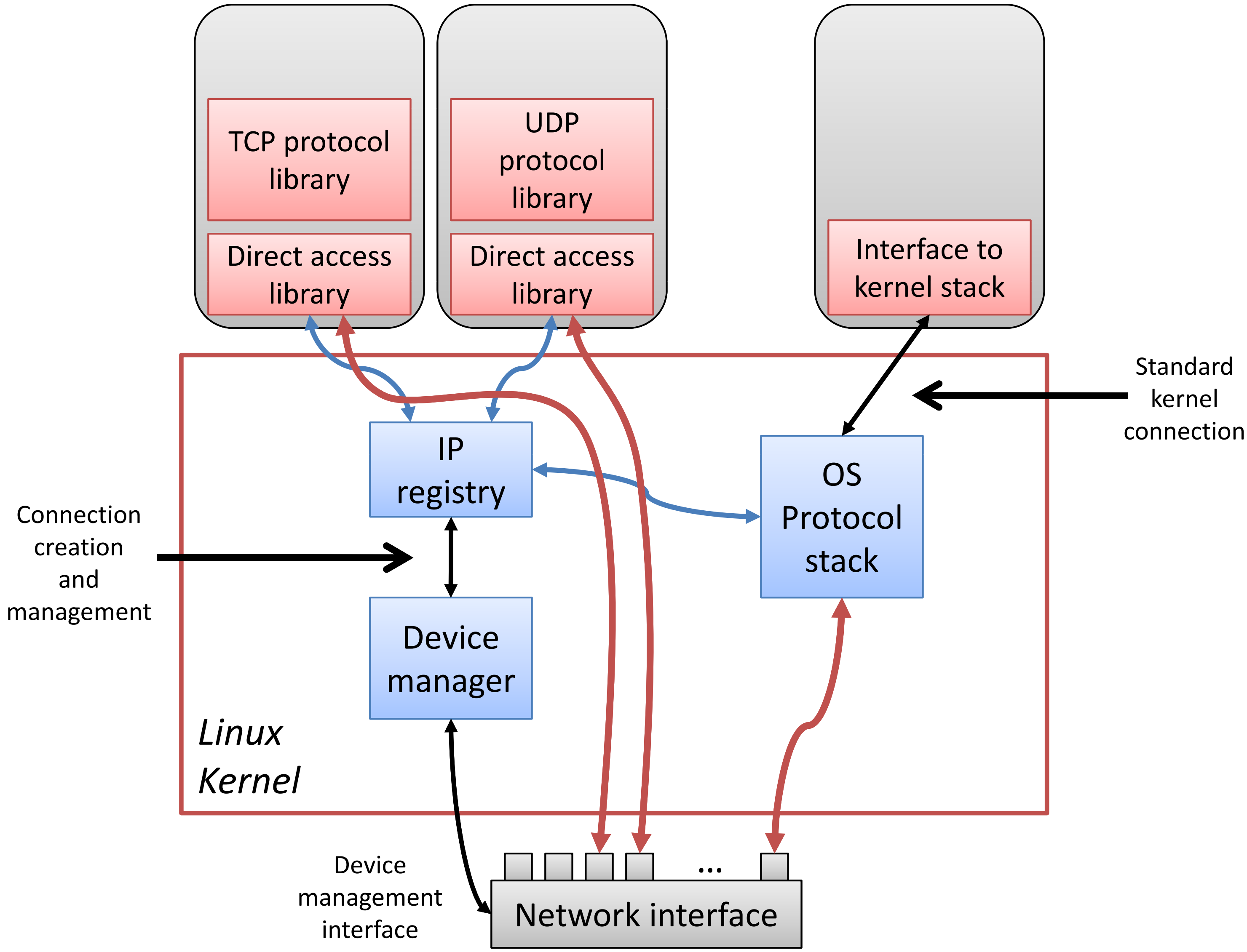
- Installation:
  - Write program in simple, high-level language
  - Compile to simple byte code (no jumps, etc.)
  - Hand to the kernel
  - Kernel installs
- Issues:
  - Slower than hard-coded demux (e.g. Linux main stack)
  - Or is it? c.f. DPF: efficient compilation of multiple filters

Hardware demux: Arsenic

[Pratt and Fraser, 2001]

- Early example of a User-Accessible network interface
  - for connectionless packet networks
  - c.f. UNet, VIA, RDMA, etc. (circuits are easy :-)
- Hardware can present as many devices
  - One per user process $\Rightarrow$ can map into userspace
  - “User-safe device”
- Kernel creates flows, installs filters
  - Run packet filters on the card
  - Compiled from HLL into MIPS machine code
  - Data DMAs direct into user-space buffers
- Original OS protocol stack used for “everything else”
  - Permanent default filter $\Rightarrow$ OS stack

Arsenic architecture



Direct access library

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- Direct Access Library
  - Creates “connections” by calling protocol registry
  - Registers *(virtual address, length) tuples with kernel*
  - Supples NIC with empty receive buffers & descriptors
  - Fills transmit buffers & descriptors
- Device Manager
  - Fields NIC interrupts, translates to user-space signals
  - Creates and tears down “connections”
  - Compiles and installs filters on the NIC

Critique: why sockets?

- Amost the only OS Network API in widespread use
- Despite this, many criticisms:
  - No data placement control: lots of copies, data can't be aligned
  - No queuing: only one outstanding read request at a time
  - Poor asynchronous communication (upcalls): see dispatch!
  - TCP is completely abstracted by the API: can't tweak or look inside
- Some of these can be worked around
  - e.g. **`setsockopt`** or **`ioctl`**
- Data placement / queueing remains problematic

Structural approaches: Nemesis

[Black et al., 1997]

- Observation: Considerable complexity introduced to a legacy kernel.
- Ground-up reimplementation considerably simpler.
  - Nemesis put all protocol processing in application
  - ATM hardware or BPF software for demultiplexing
  - Per-application outbound filters for sending packets (transmit multiplexing)
  - Out-of-band servers for connection setup/teardown
- Much better QoS isolation

Exokernel

[Ganger et al., 2002]

- Similar to Nemesis, but demonstrated benefits of collapsing application and network stack together
- “Cheetah” web server used its own TCP stack, avoiding sockets
  - Merged TCP and HTTP processing.
  - Merged TCP retransmission pool and file cache!
  - “Knowledge-Based Packet Merging”, e.g. setting FIN on last data packet, delayed ACK for HTTP requests.
  - Precomputing packet checksums on disk files

Exokernel

[Ganger et al., 2002]

- Other example: Webswamp (needed to benchmark Cheetah!)
- Web load generator using 3 specializations:
  - Count-Only Data Reception (don't bother looking at received data)
  - Skipping Checksum Verification (fine for testing)
  - Knowledge-Based Packet Merging, again: don't ACK the server's SYN, discard the final ACK/FIN bit.
- Throughput increased by 5 for small documents

Scout

[Mosberger and Peterson, 1996]

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- Very different attempt to deliver QoS & Isolation in the network stack
- **Paths** abstract data flow in the application
  - Across protection domains, processes, etc.
  - Comprised of processing with queues at each end
- Scheduler schedules **paths**, not **processes**
- Extends many ideas from classical networking into the OS
  - Queueing theory and techniques
  - Routing and circuits

What happened to this?

- Multiple queues for high-speed NICs are now commonplace
  - Though usually not enough yet for individual flows
- Receive-Side Scaling (RSS):
  - Multiple queues to exploit MP parallelism for scaling
- Interrupt coalescing is standard
- RDMA:
  - Circuit-based early demux
  - User-level signalling (bypasses kernel)
  - Surprising: setup overhead dominates
  - Niche market: HPC clusters

So what now?

- First, note:
  - L4 **completely ignores** networking!
  - Protocol stack is just another server process
- And Barrelfish?
  - Inside of the computer resembles a network, now, too
    $\Rightarrow$ NIC actually functions more as a **router/firewall**
  - But: must also parallelize flow processing!
  - Probably combination of:
    - Scout
    - RouteBricks [Dobrescu et al., 2009].

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