Managing Heavy Network Load: Eliminating Receive Livelock

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Engineering for Performance

- Much of the work in distributed systems concerns designing for
  - Consistency
  - Availability
  - Performance
- Performance is multi-faceted
  - Not just determined by design of distributed system itself (algorithms, protocols)
  - Low-level hardware, OS behavior play major role
- Achieving high performance requires deep understanding of **all layers:** hardware, OS, all the way through algorithms and protocols!

Engineering for Performance

Systems Thinking: the ability to reason about complex interactions among many layers, to find problems (and (re)design to avoid them)

- – Availability
- – Performance

- Performance is multi-faceted
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- Achieving high performance requires deep understanding of **all layers:** hardware, OS, all the way through algorithms and protocols!

Heavy Load Happens

- Servers have limited CPU, network link capacity, memory, disk bandwidth
- Demand often approaches or exceeds a server's capacity, e.g.,
  - Flash crowds at web server
  - Busy NFS server as client population grows
  - IP router or firewall carrying flash crowd traffic (or denial of service attack traffic!)
- But **software design** can limit performance at loads lighter than where these hardware limits kick in…

Example:
IP Packet Forwarding Performance

- Hardware: commodity workstation (DECstation 3000/300; PC-like), two 10 Mbps Ethernet interfaces
- Software: Digital UNIX 3.2 OS, screend firewall application in userspace
- Workload: forward IP packets from one Ethernet to another (UDP packets, 4 bytes of payload each)
- Packet-generating host has faster CPU than forwarder

Example: IP Packet Forwarding Performance

Question: How well does whole system scale as load increases?

Experiment: vary input packet rate to forwarder; observe output packet rate

firewall application in userspace

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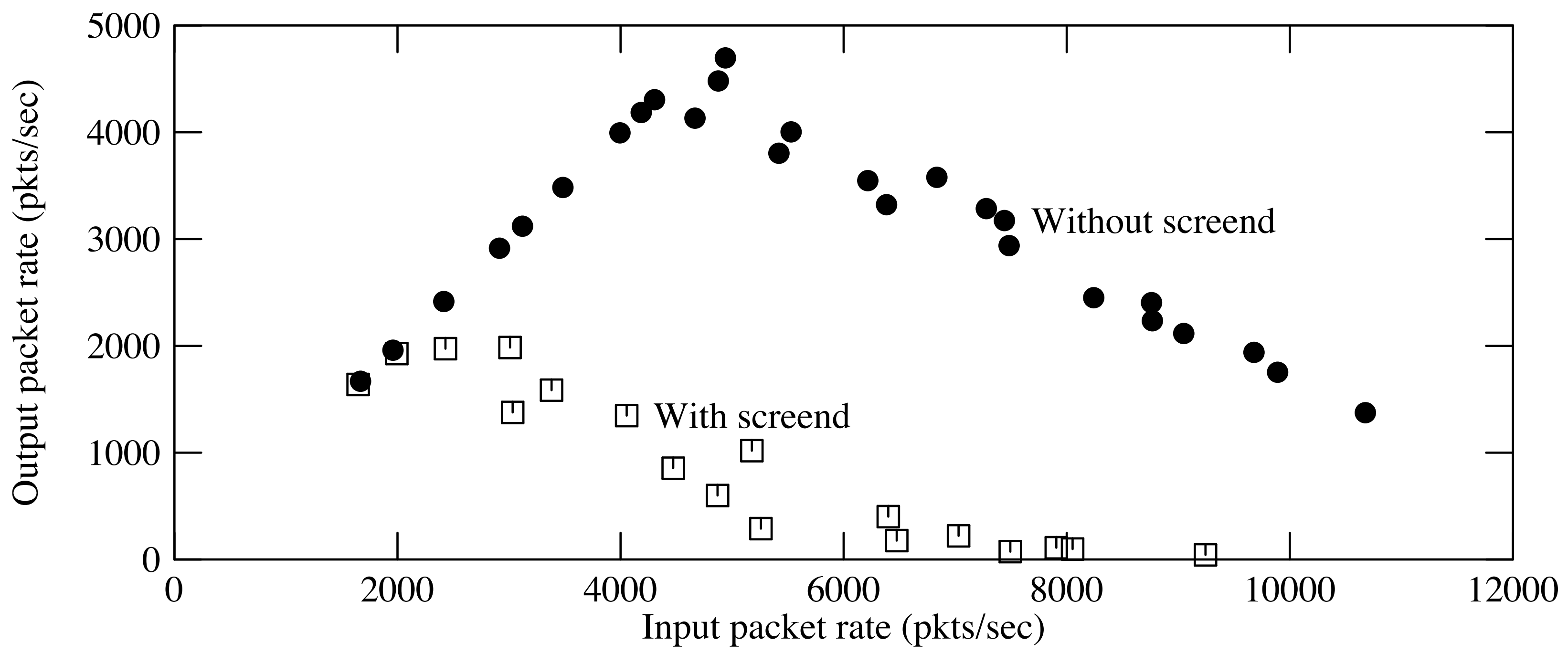
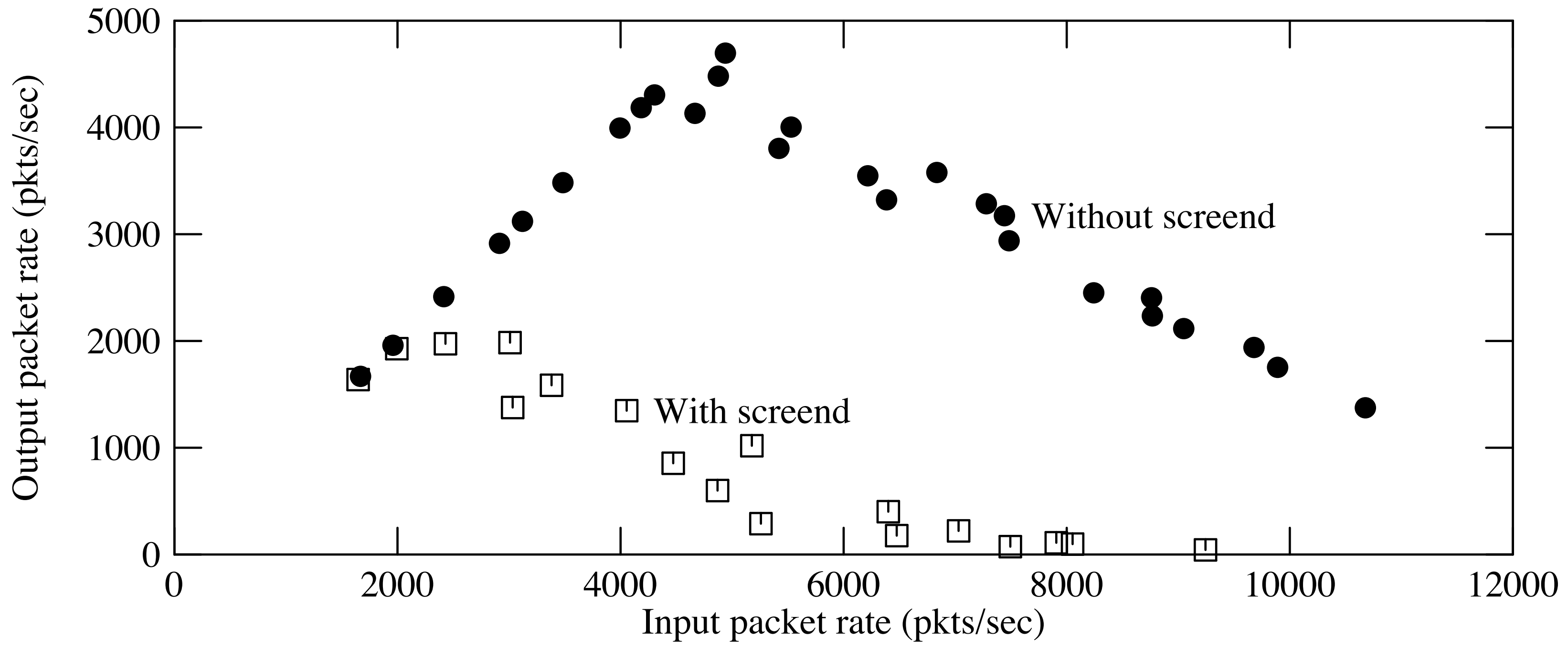
Example: IP Packet Forwarding Performance



- Peak output rate w/o firewall: ~4700 pkt/s
- Beyond ~4700 pkt/s, output rate decreases with further increasing load!

Example: IP Packet Forwarding Performance



Suppose **hardware's capacity** is 4700 pkt/s.

What would ideal system behavior be beyond that input rate?

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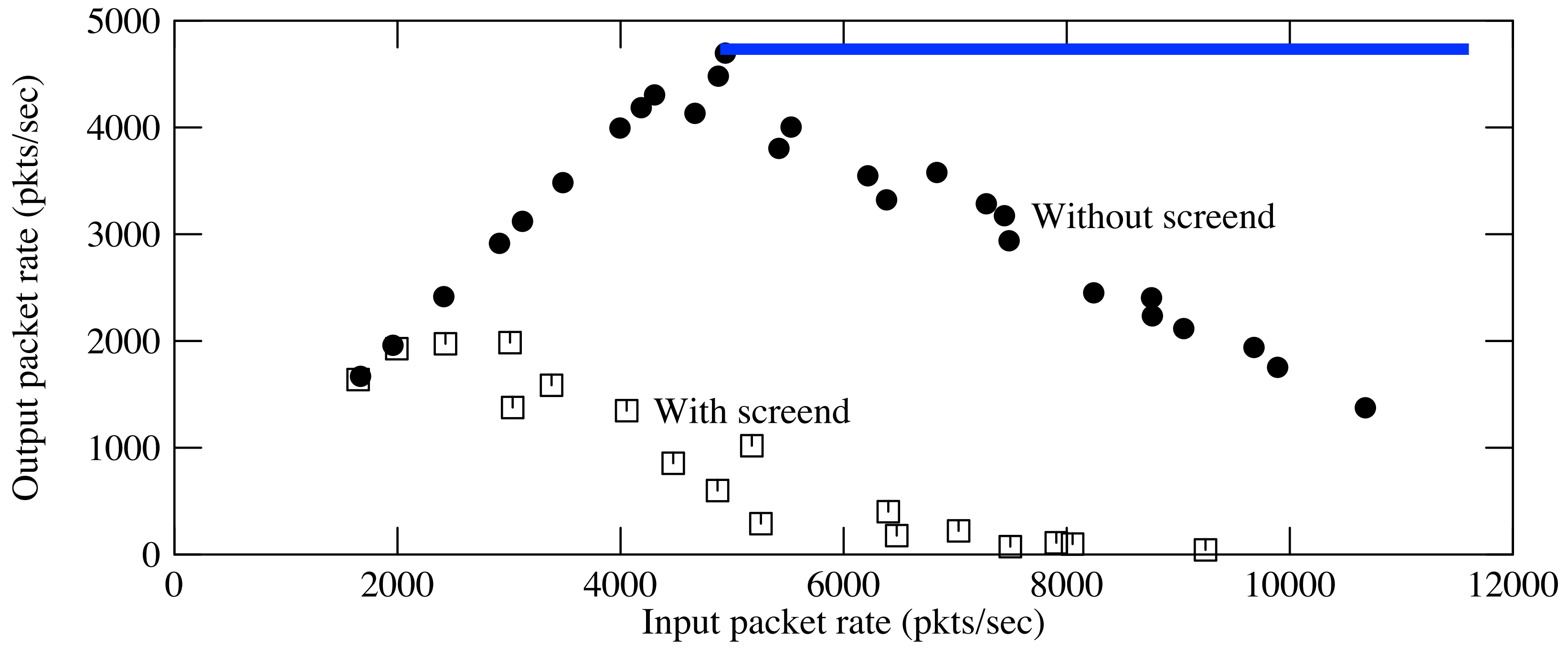
IP Packet Forwarding Performance



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Background: I/O Device Hardware

- I/O devices need to notify CPU of events
  - Packet arrival at network interface
  - Disk read complete
  - Key pressed on keyboard
- Two main ways CPU can learn of events:
  - Polling: CPU “asks” hardware device if any events have occurred (synchronous)
  - Interrupt: hardware device sends a signal to CPU saying “events have completed” (asynchronous)
- Key concerns: event latency and CPU load

Polling

- Requires programmed or memory-mapped I/O (relatively slow; over I/O bus)
- CPU "blindly" polls device explicitly in code
  - to guarantee low latency, must poll very often
  - high CPU overhead to poll very often
- For rare I/O events, CPU overhead of polling unattractive
- Disk I/Os complete only 100s of times per second; in 1980s-90s, only hundreds of network packets arrived per second
- OSes in that era eschewed polling

Interrupts

- I/O devices have dedicated wire(s) that they can use to signal interrupt(s) to CPU
- On interrupt, if interrupt priority level (IPL) > CPU priority level:
  - CPU saves state of currently running program
  - jumps to interrupt service routine (ISR) in kernel
  - invokes device driver, which asks device for events
  - returns to previously running program
- CPU priority level: kernel-set machine state specifying which interrupts allowed (others postponed by CPU)
- On modern x86_64, interrupt latency of ~3 us from device interrupt to start of ISR

Interrupts

Interrupts well-suited to **rare I/O events:** lower latency than rarely polling, lower CPU cost than constantly polling

Interrupts asynchronous—they **preempt other system activity**

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  - returns to previously running program

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Interrupts and Network I/O

- Disk I/O requests come from OS itself; completion interrupts inherently rate-controlled
- Network packets come from other hosts; no “local” rate control for received packet interrupts
- Remember: interrupts take priority over all other system processing (over other kernel execution, user-space applications)
- What will happen when received packet rate extremely high?
  - Answer depends on detailed software structure…

Interrupts and Network I/O

Receive Livelock:

When event rate (pkt arrival rate) so high, system spends all its time servicing interrupts, gets no other work done!

interrupts

- Remember: interrupts take priority over all other system processing (over other kernel execution, user-space applications)
- What will happen when received packet rate extremely high?
  - Answer depends on detailed software structure…

Design Goals for Network I/O System

- Goals:
  - Low latency for responding to I/O events
  - Low jitter (variance in latency)
  - Fairness: resources allocated evenly among tasks
  - High throughput for I/O (e.g., achievable packet receive rate, transmit rate)
- What are the tasks for a network server?
  - Packet reception
  - Packet transmission
  - Protocol processing (often in kernel)
  - Other I/O processing
  - Application processing

Background: OS Architecture for Interrupt-Driven Networking

- Packet arrives
- Network card interrupts at “high” IPL
- ISR looks at Ethernet header, enqueues packet for further processing, returns
- “Low” IPL software interrupt dequeues packets from queue, does IP/UDP/TCP processing, enqueues data for dst process
- Process reads data with read() system call
- Queues denote scheduling and priority level boundaries

Background: OS Architecture for Interrupt-Driven Networking

Queues are **scheduling** and **priority level** boundaries

Minimizing work in ISR **reduces service latency** for other device I/O interrupts

- "Low" IPL software interrupt dequeues packets from queue, does IP/UDP/TCP processing, enqueues data for dst process
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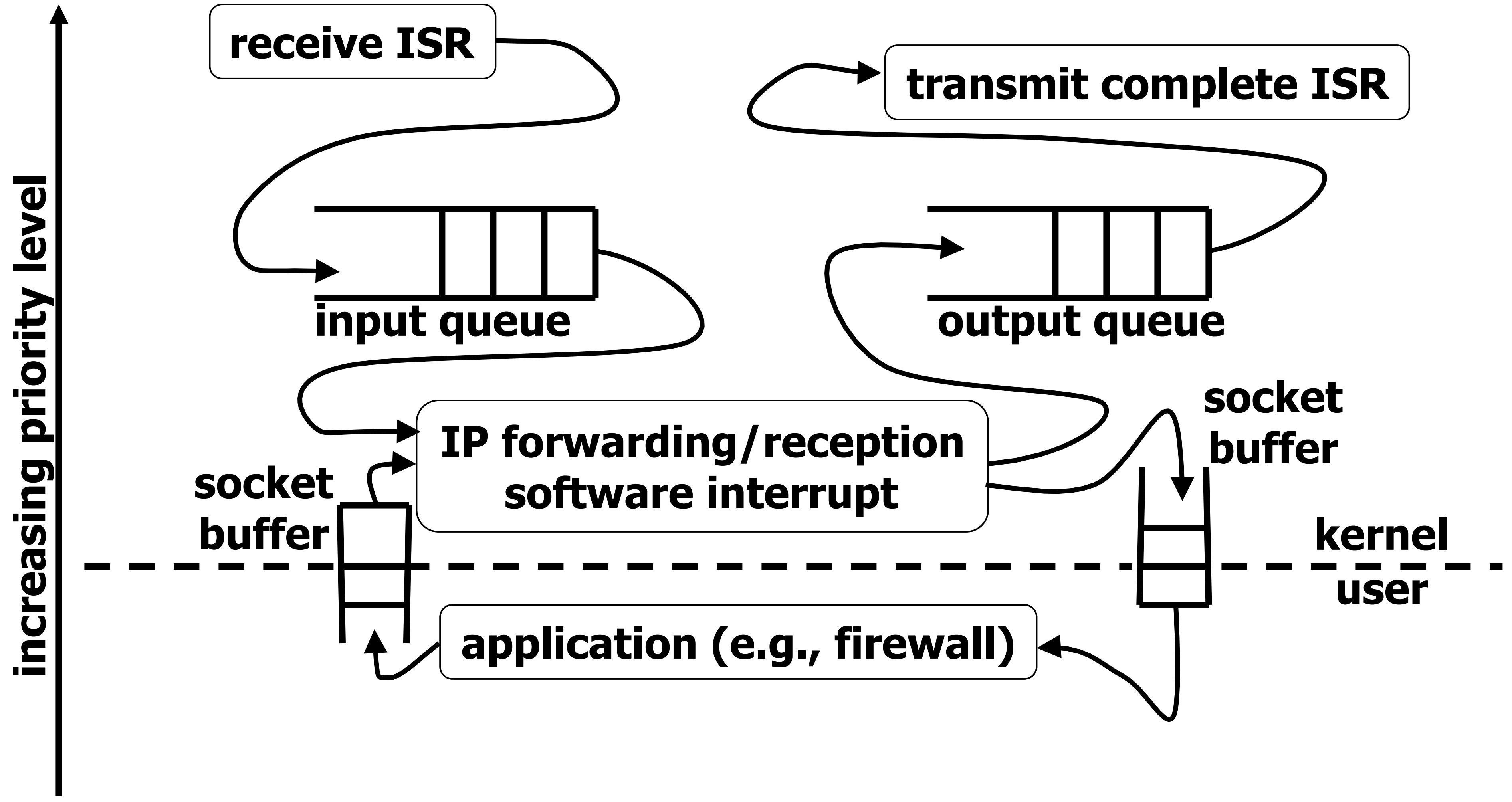
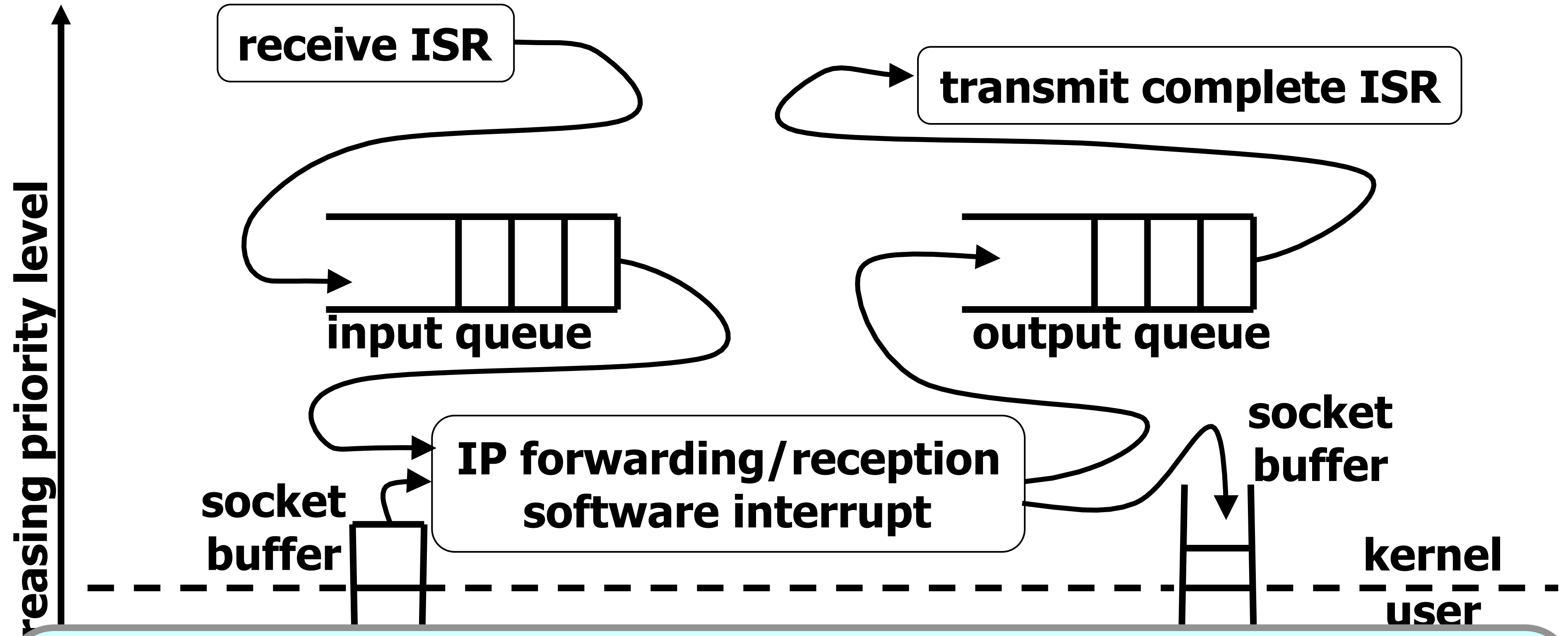
Interrupt-Driven Networking, UNIX Style



increasing priority level
receive ISR
transmit complete ISR
input queue
output queue
IP forwarding/reception software interrupt
socket buffer
socket buffer
kernel
user
application (e.g., firewall)

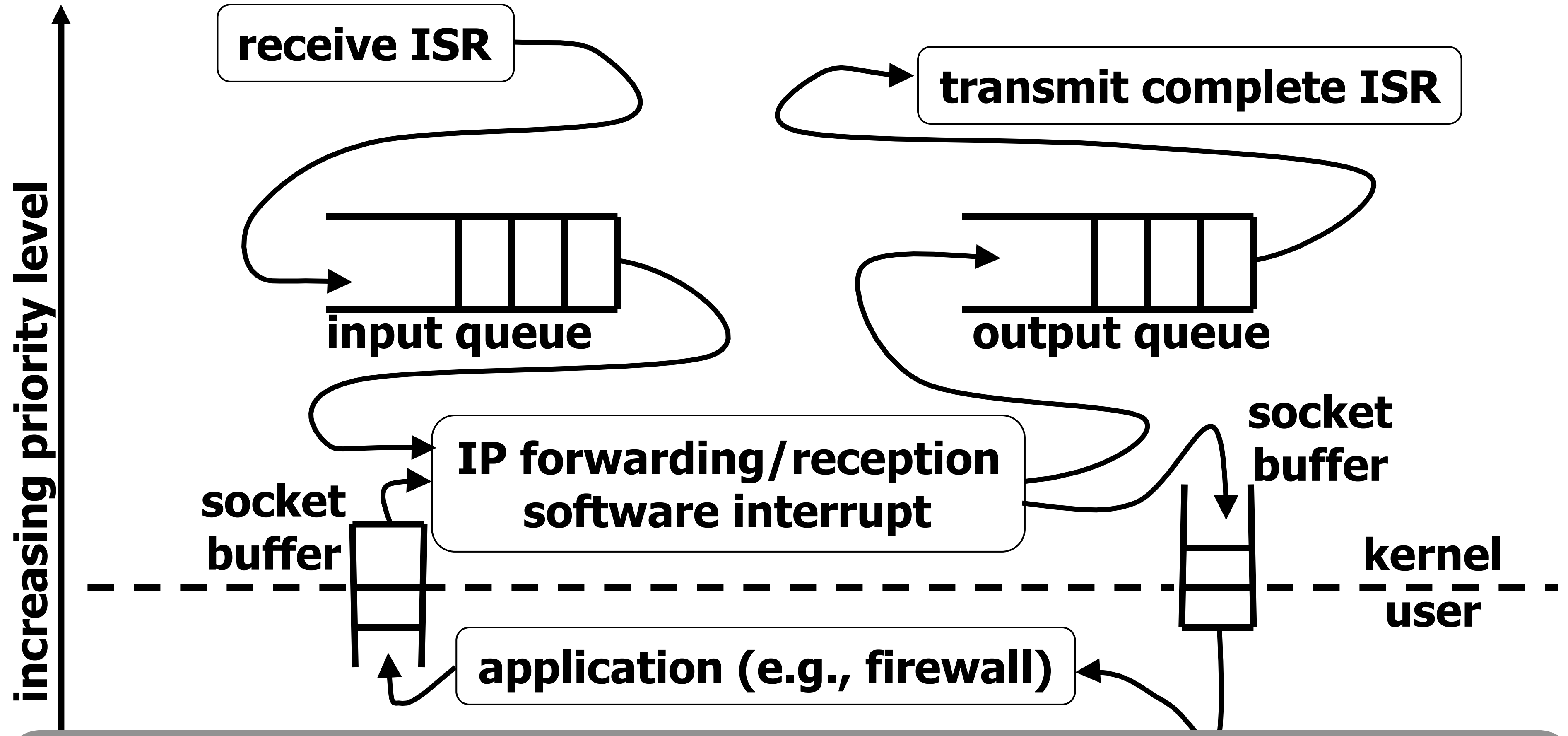
Interrupt-Driven Networking, UNIX Style



Design prioritizes **packet reception** above all else

Original motivation: small buffers on network interfaces (no longer a concern)

Interrupt-Driven Networking, UNIX Style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How will this system behave as packet receive rate increases—what will output packet rate do?

Receive Livelock Pathologies

- As input rate increases beyond maximum loss-free receive rate, output rate decreases
- System wastes CPU preparing arriving packets for queue, all of which dropped
- For input burst of packets, first packet not delivered to user level until whole burst put on queue (e.g., leaves NFS server disk idle!)
- In systems where transmit lower-priority than receive, transmit starves

Livelock Avoidance Technique 1: Minimize Receive Interrupts

- Goal: limit the receive interrupt rate
- Receive ISR:
  - sets flag indicating this network interface has received one or more packets
  - schedules kernel thread that polls network interfaces for received packets
  - does not re-enable receive interrupts
- That’s it! Set flag, schedule kernel thread, and return, leaving receive interrupts disabled.

Livelock Avoidance Technique 2: Kernel Polling Thread

- When scheduled, checks all network interfaces' "packets received" flags
- For such interfaces:
  - process packet all the way through kernel protocol stack (IP/forwarding/UDP/TCP), ending with interface output queue or socket buffer to application
  - maximum quota on packets processed for same interface on one invocation for fairness
  - round-robins among interfaces and between transmit and receive
  - Re-enable interface's receive interrupts only when no pending packets at that interface

Livelock Avoidance Technique 2: Kernel Polling Thread

Under overload, where do packets go?

Dropped by network interface card when buffering exhausted (either in card, or in host RAM), **at no CPU cost!**

protocol stack (IP forwarding/UDP/TCP), ending with interface output queue or socket buffer to application

– maximum quota on packets processed for same interface on one invocation for fairness

– round-robins among interfaces and between transmit and receive

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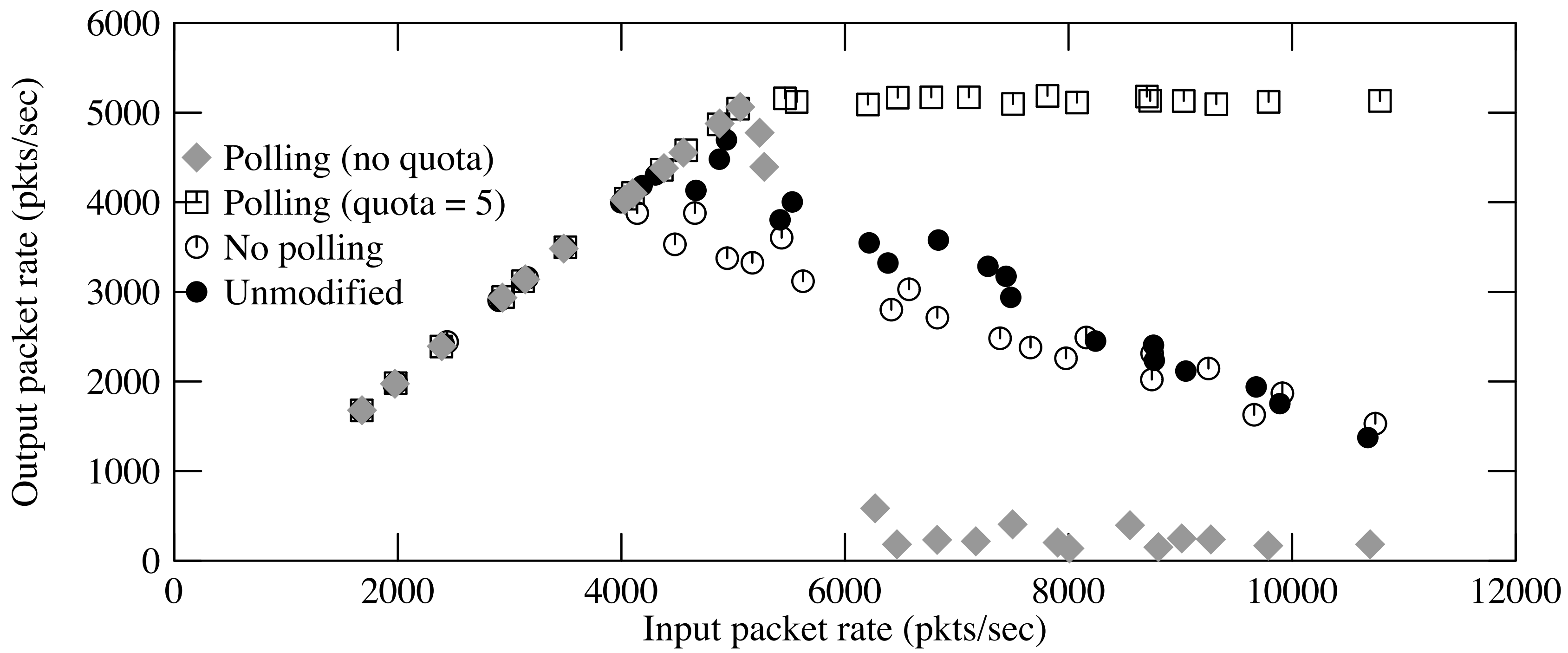
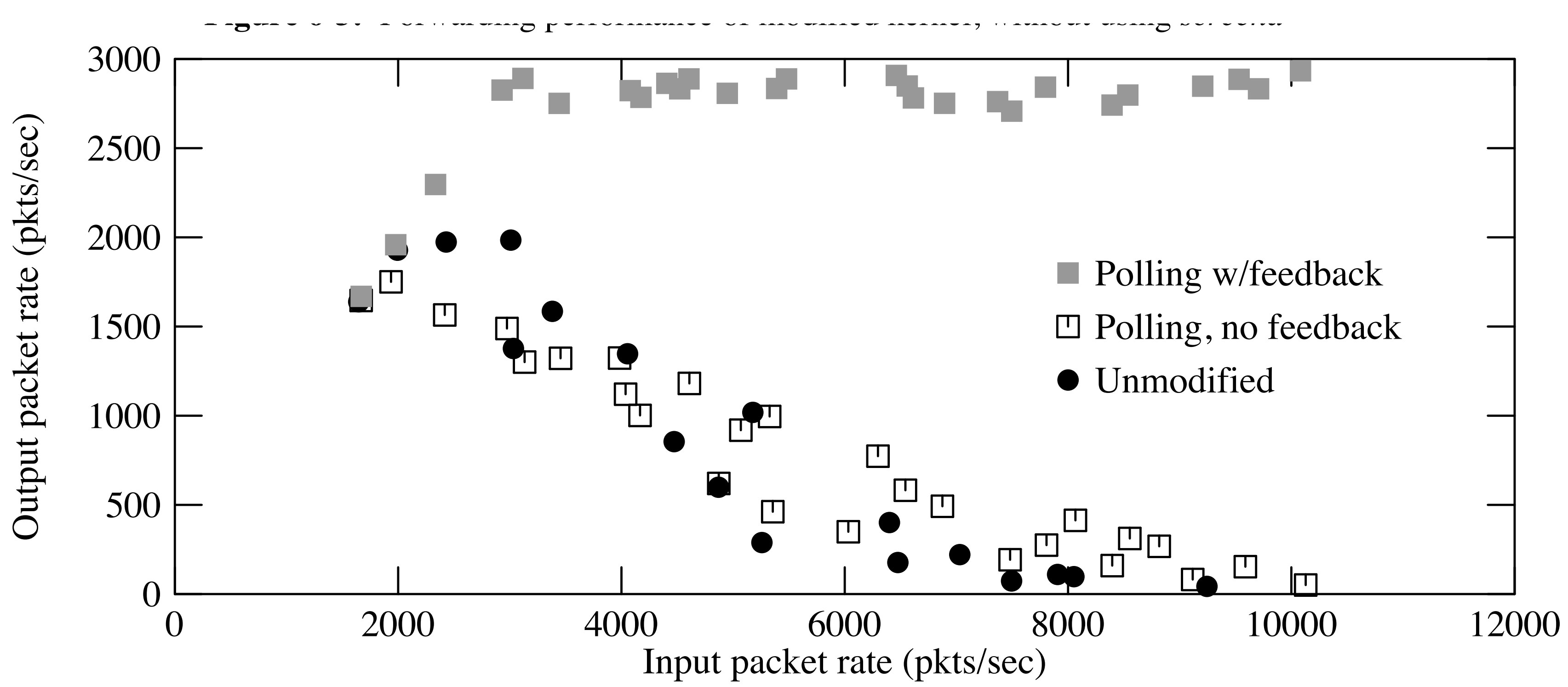
Performance Evaluation: Techniques 1 and 2



- No screend firewall
- Without quotas for input processing, big trouble! (Why?)

What about screend?



- User-level application still cannot run under heavy receive load!
- Technique 3: disable receive interrupts when queue to user application fills

Receive Livelock: Summary

- Scheduling vital to performance of a busy server
  - may be implicit (e.g., interrupts), not explicit (e.g., OS scheduler)
- Understanding cross-layer behavior vital to finding performance limitations and designing for high performance
- General lessons:
  - Don’t discard data after doing work on it
  - Poll while busy, interrupt while lightly loaded