Programmable Scheduling

Lecture 18, Computer Networks (198:552)

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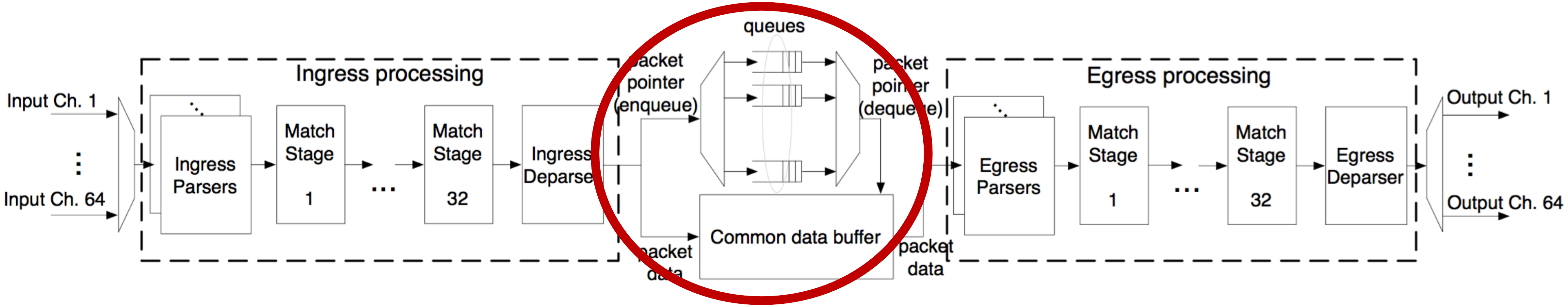
RUTGERS
UNIVERSITY | NEW BRUNSWICK

Scheduling in switch pipelines

- Packets wait in buffers/queues until serviced
- Two possibilities: Input-queued vs. output-queued
- Suppose there are pkts on port 1 to both 2 and 3
  - But suppose port 2 is clogged
  - Port 1's packets towards port 3 should not be delayed (HOL block)
- Better to have queues represent output port contention



Why care about packet scheduling?

- Significantly influences how packets are treated regardless of the endpoint transport
  - Implementations of Quality of Service (QoS) within large networks
  - Implications for net neutrality debates

- Intellectually interesting and influential ("top 10") question
  - Classic Demers et al paper (WFQ) has ~ 1500 citations
  - Important connections to sched literature (e.g., job scheduling)

- Scheduling algorithms influence many daily life decisions ☺

Scheduling vs. Buffer Management

- How packets enter vs. how packets leave the switch buffer
  - Typical buffer management: Tail-drop
- How should buffer memory be partitioned across ports?
- Static partitioning?
  - Inefficient: even if port 1 has nothing to send, might drop port 2
- Also want fair sharing of buffer
  - If output port 1 is congested, why should port 2 traffic suffer?
- State of the art: dynamic buffer sharing algorithms

Fair Resource Allocation

Allocate *how?* among *who*?

Fair and efficient use of a resource

- Suppose *n* users share a single resource
  - Like the bandwidth on a single link
  - E.g., 3 users sharing a 30 Gbit/s link

- What is a fair allocation of bandwidth?
  - Suppose user demand is “elastic” (i.e., unlimited)
  - Allocate each a *1/n* share (e.g., 10 Gbit/s each)

- But fairness is not enough
  - Which allocation is best: [5, 5, 5] or [18, 6, 6]?
  - [5, 5, 5] is fair but [18, 6, 6] is more efficient
  - What about [5, 5, 5] vs. [22, 4, 4]?

Fair use of a single resource

- What if some users have inelastic demand?
  - E.g., 3 users where 1 user only wants 6 Gbit/s
  - And the total link capacity is 30 Gbit/s
- Should we still do an “equal” allocation?
  - E.g., [6, 6, 6]
  - But that leaves 12 Gbps unused
- Should we allocate in proportion to demand?
  - E.g., 1 user wants 6 Gbps, and 2 each want 20 Gbit/s
  - Allocate [4, 13, 13]?
- Or, give the least demanding user all she wants?
  - E.g., allocate [6, 12, 12]?

Max-min fairness

- Protect the less fortunate
    - Any attempt to *increase* the allocation of one user necessarily *decreases* the allocation of another user with equal or lower allocation
- Fully utilize a bottleneck resource
    - If demand exceeds capacity, the link is fully used

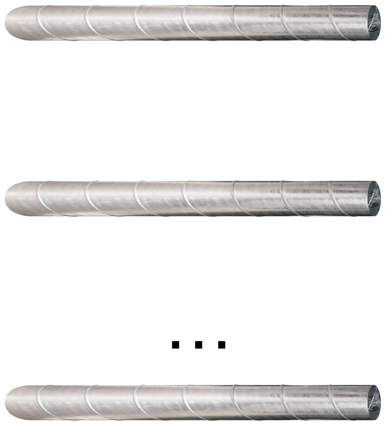
Max-min fairness for a single resource

- Progressive filling algorithm (also called waterfilling)
  - Grow all rates until some users stop having demand
  - Continue increasing all remaining rates until link is fully utilized

- If all users have elastic demands, single resource shared evenly

Link rate L

N elastic users



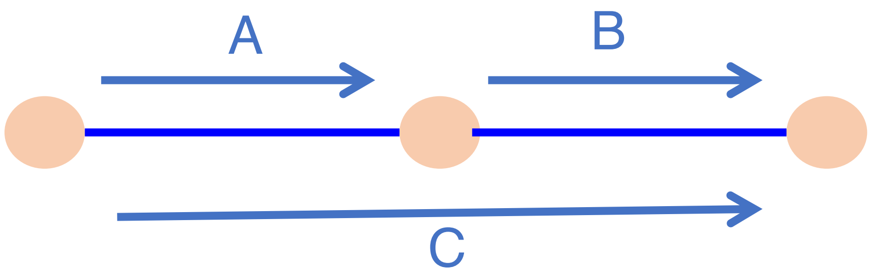
Link rate L/N

Link rate L/N

...

Link rate L/N

Allocation over multiple resources



Three users A, B, and C
Two 30 Gbit/s links

- Maximum throughput: [30, 30, 0]
  - Unfair: total throughput of 60, but user C starves
- Max-min fairness: [15, 15, 15]
  - Inefficient: everyone gets equal share, but throughput is just 45
- *Proportional fairness*: [20, 20, 10]
  - Allocate inversely proportional to resource use per bit
  - C is penalized for using two busy links, as opposed to one

Allocate fairly among *who?*

Abstract entity:
a *flow*

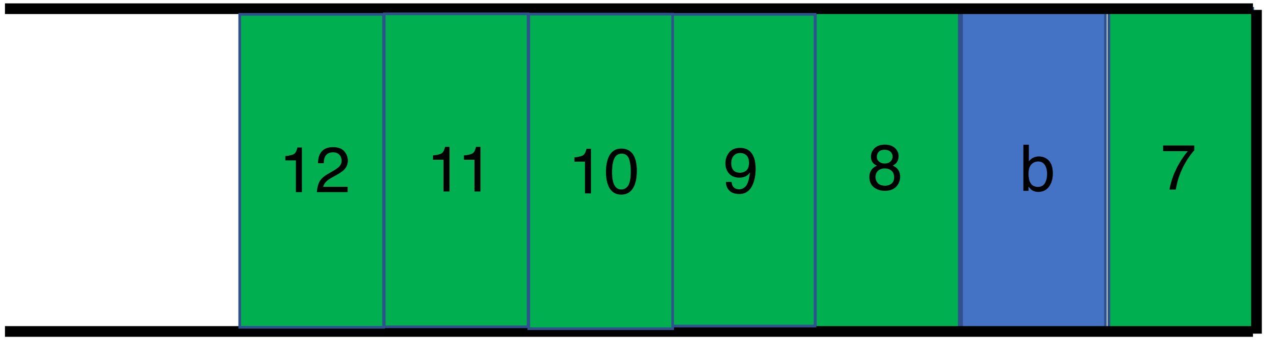
- Traffic sources?
  - Web servers, video servers, etc. need more than their fair share
- Traffic destinations?
  - Vulnerable to malicious sources denying service to receivers
- Source-destination pairs?
  - Can open up connections to many destinations
- Application flows? (i.e., src + dst + transport ports)
  - Malicious app can start up many such flows
- Administrative entities? (e.g., Rutgers NetID, ISP, …)
  - How should a router identify packets belonging to an entity?

Packet Scheduling Algorithms

Which packet to send next? (order)

When to send the next packet? (timing)

A taxonomy



- Granularity of allocation
  - Per-packet vs. per-flow vs bit-by-bit
- Pre-emptive vs. non-pre-emptive
  - Do you interrupt the current packet/flow if another shows up?
- Size-aware vs. unaware
  - Do you consider flow or packet sizes in scheduling?
- Class-based (strict priority) vs. shared
  - Are some flows strictly higher priority than others?
- Work-conserving vs. non-work-conserving
  - Do you always use spare link capacity when there is demand?

Examples of scheduling algorithms (1/3)

- FIFO over packets
- Round-robin over packets of different flows
- Shortest Remaining Processing Time (SRPT)
  - Flow-size-aware allocation which strictly prioritizes short flows
  - Also called shortest flow first in some contexts
  - Flow-size-unaware variant may predict demand using known flow size distribution

Examples of scheduling algorithms (2/3)

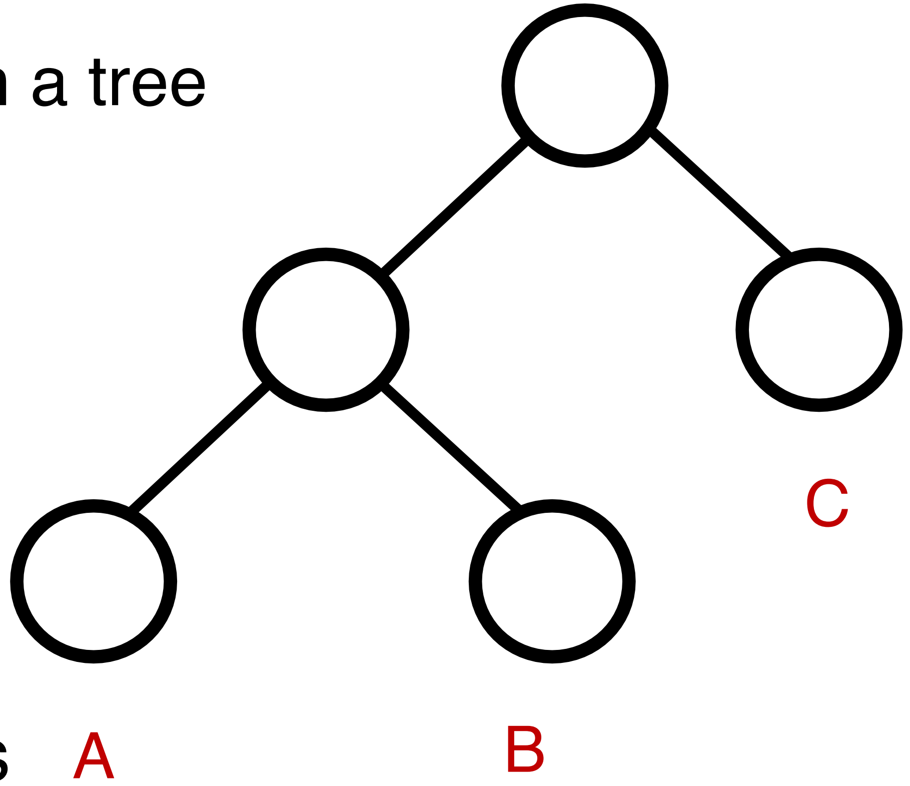
- Processor sharing
  - Assume each flow gets a fair share of the link every unit of time
  - Ideal: each flow starts receiving service immediately upon arrival

- Rate limiting
  - Non-work-conserving: flow can’t send even if more demand than limit

- Class-based strict prioritization
  - Pre-determined flow classes with strict priorities over each other
  - Starve low priority flows if higher priority flows are always sending

Examples of scheduling algorithms (3/3)

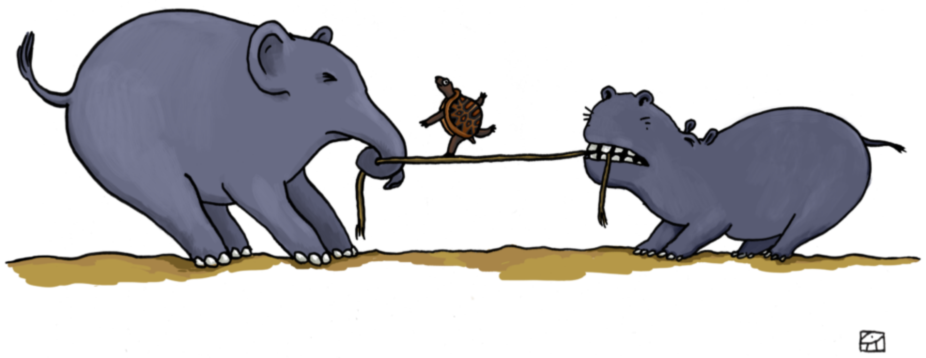
- Hierarchical policies
  - Arrange existing scheduling policies in a tree
- Example:
  - Rate-limit A + B
  - Fair-share among A and B within limit
  - Fair-share among A+B and C
- Complex multi-tenant isolation policies



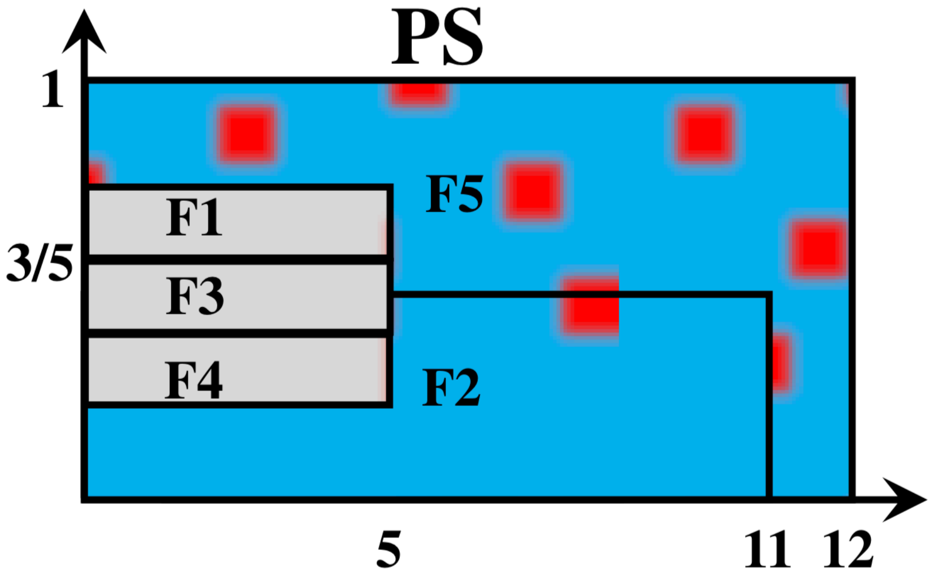
There’s not one optimal scheduling

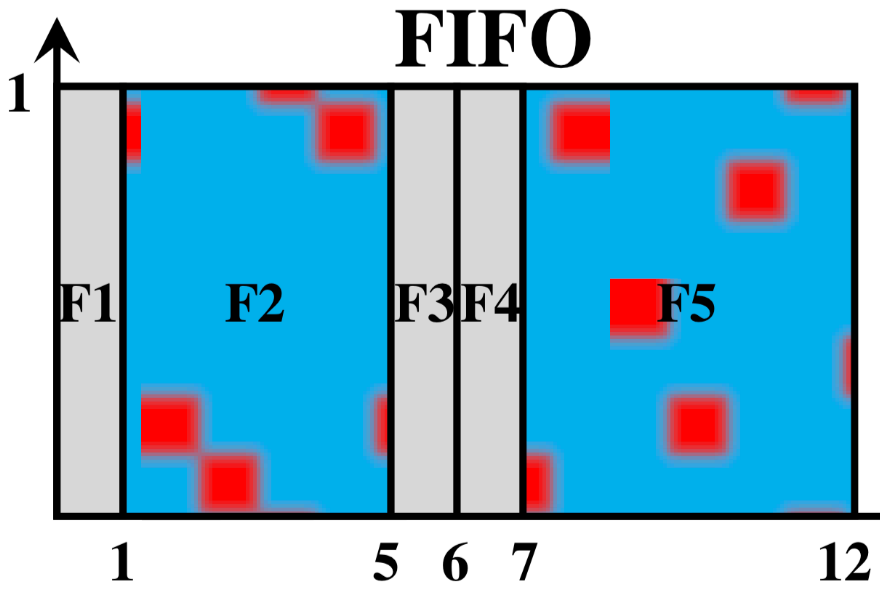
Flow ID	Size	Class
F1	1	1
F2	4	2
F3	1	1
F4	1	1
F5	5	2

Multiplexing
Avoids HOL blocking



Serialization
Reduces flow completion time





Source: Workload adaptive flow scheduling, by Faisal et al. CoNEXT 2018

Exercise: When does a flow finish?

- Consider a mix of “long” and “short” flows arriving at a Q
    - Ex: A flow may have as few as 2 packets or as many as 10^5
- Suppose a scheduling algorithm provides each flow:
    - An average per-packet delay d (e.g., 50 ms)
    - An average link bandwidth share t (e.g., 10 Mbit/s)
- Which among d & t determines
    - when a short flow finishes?
    - when a long flow finishes?

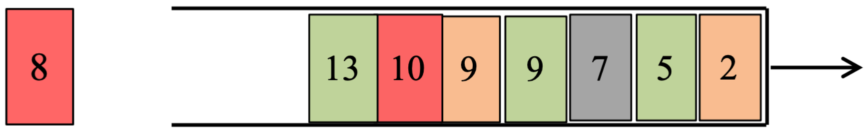
Push In First Out (PIFO)

A common primitive for many scheduling algorithms

Key ideas

- Scheduling algorithms determine order and timing of packet departures from a queue

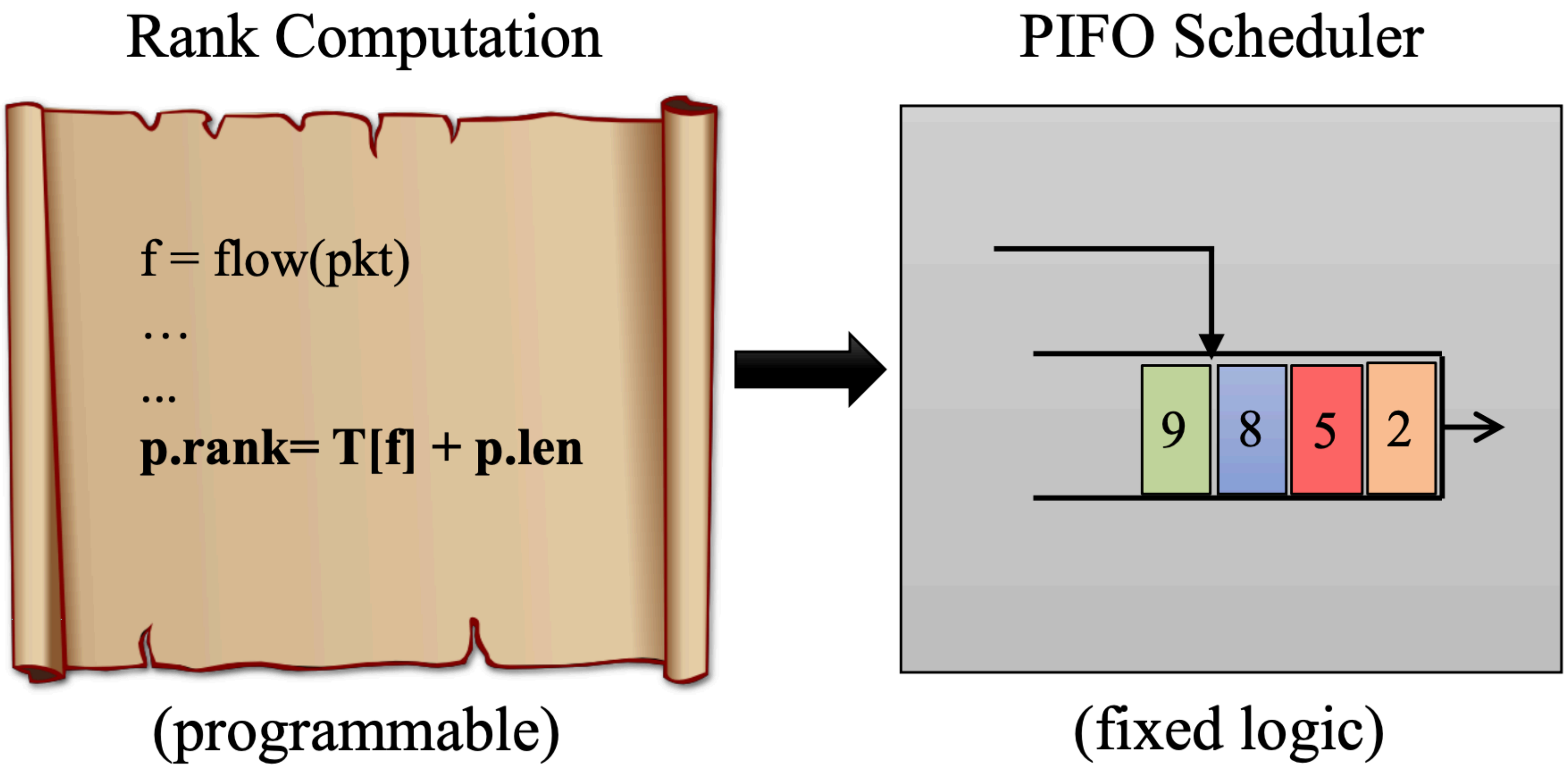
- Typically, relative order of buffered packets doesn't change upon new packet arrivals



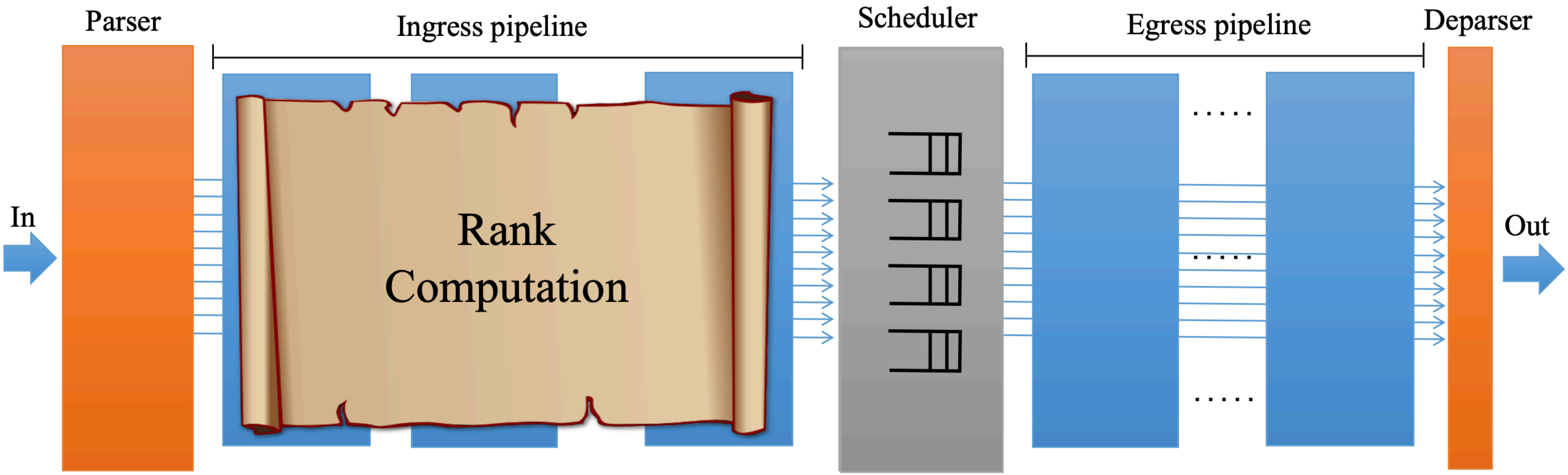
- Implement scheduling through a priority-queue-based data structure (PIFO)
  - Push-In: pkts have arbitrary ranks; push anywhere into queue
  - First-Out: always dequeue from the head of the queue

Programmable Scheduler

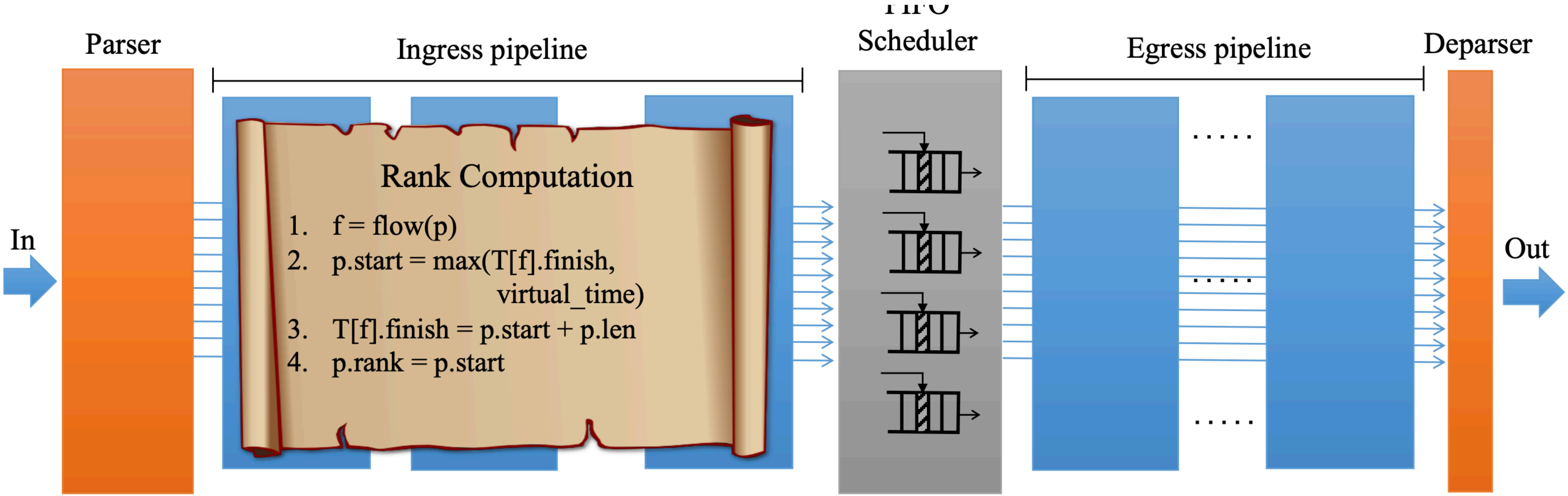
- To program the scheduler, program the rank computation



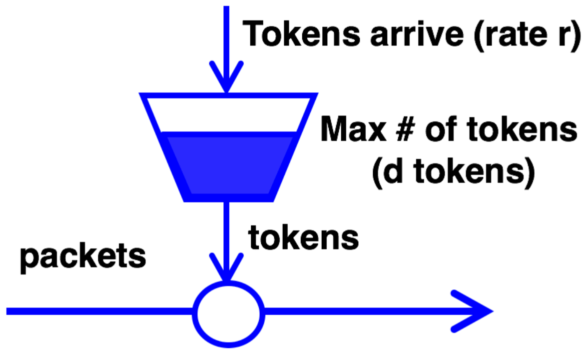
Programmable scheduling in the pipeline

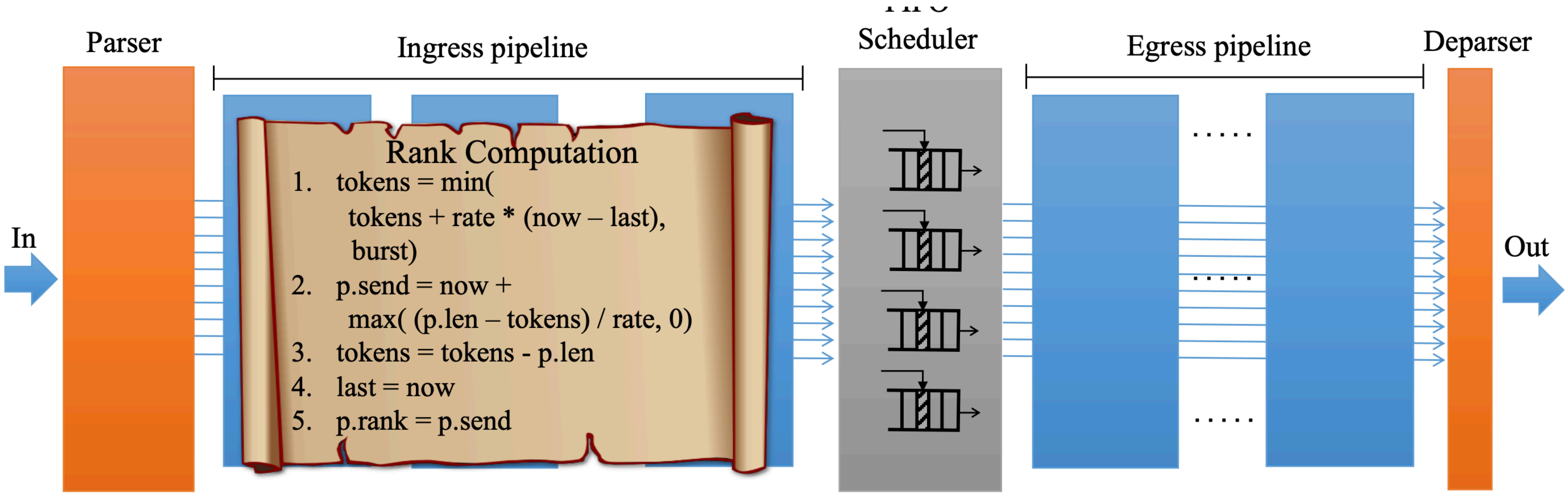


Fair queueing



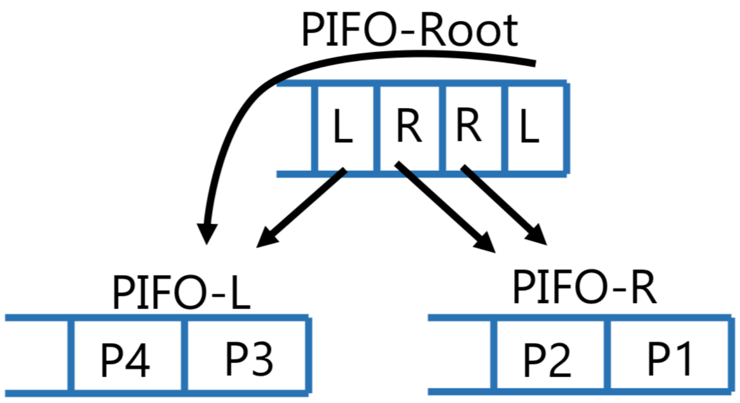
Token-bucket rate limiting



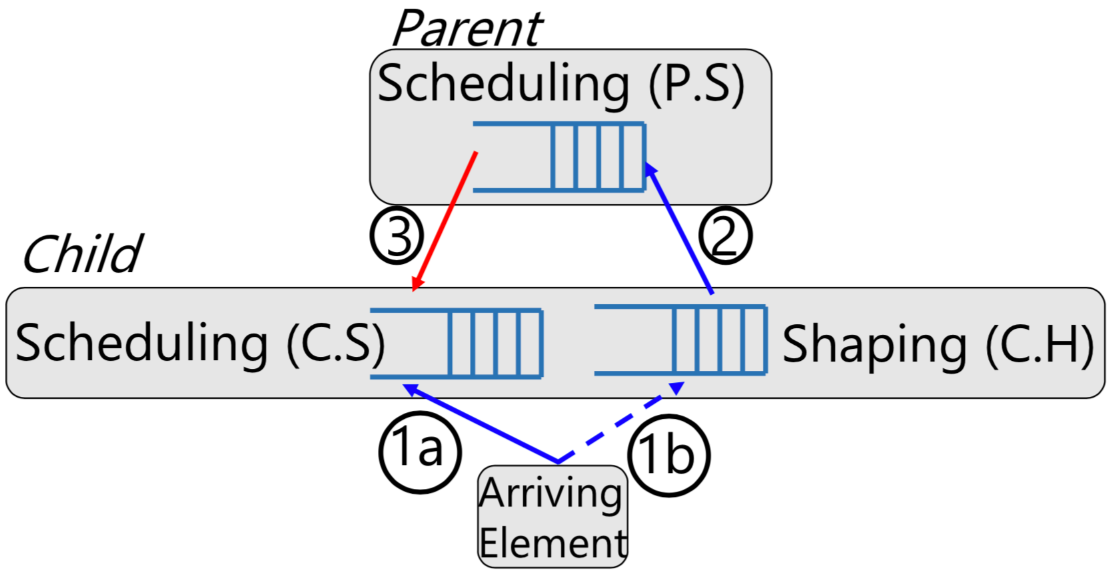


Generalizations

- Use a hierarchy of PIFOs to implement hierarchical policies
- Use a shaping PIFO to implement non-work-conserving scheduling policies



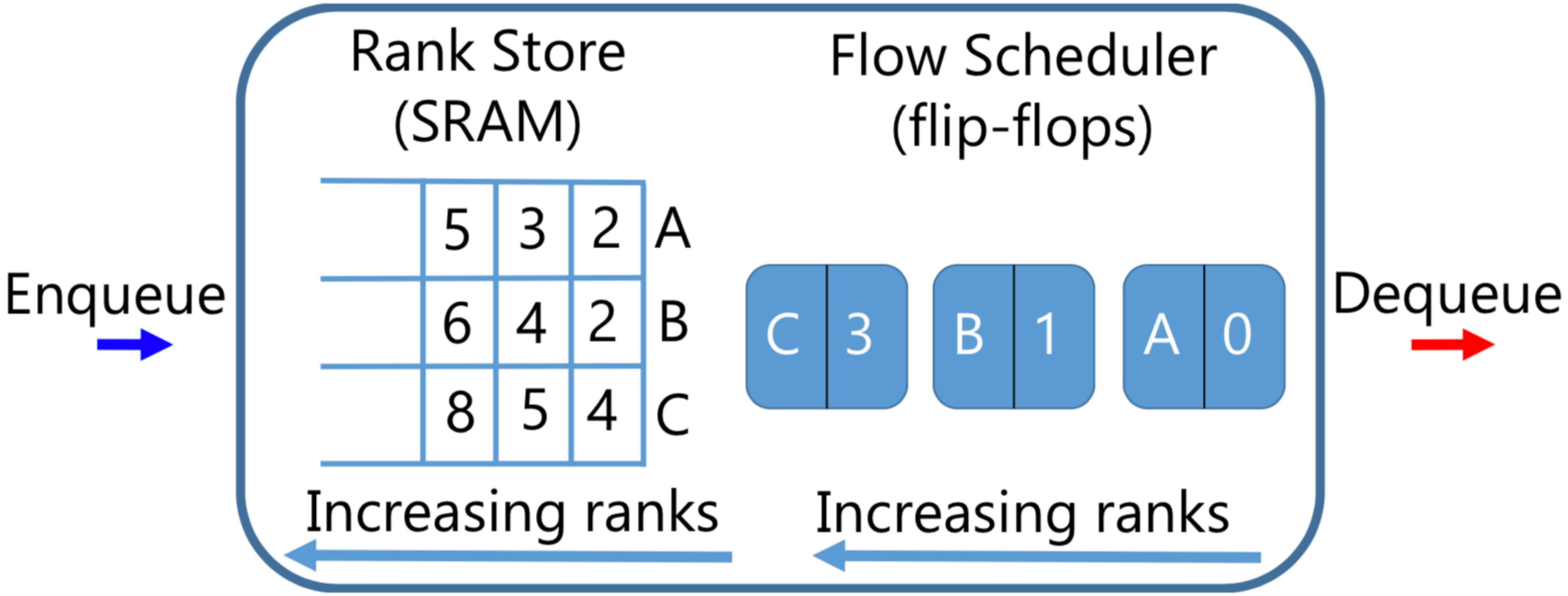
This tree encodes the order
L→ P3
R→ P1
R→ P2
L→P4
i.e., P3, P1, P2, P4



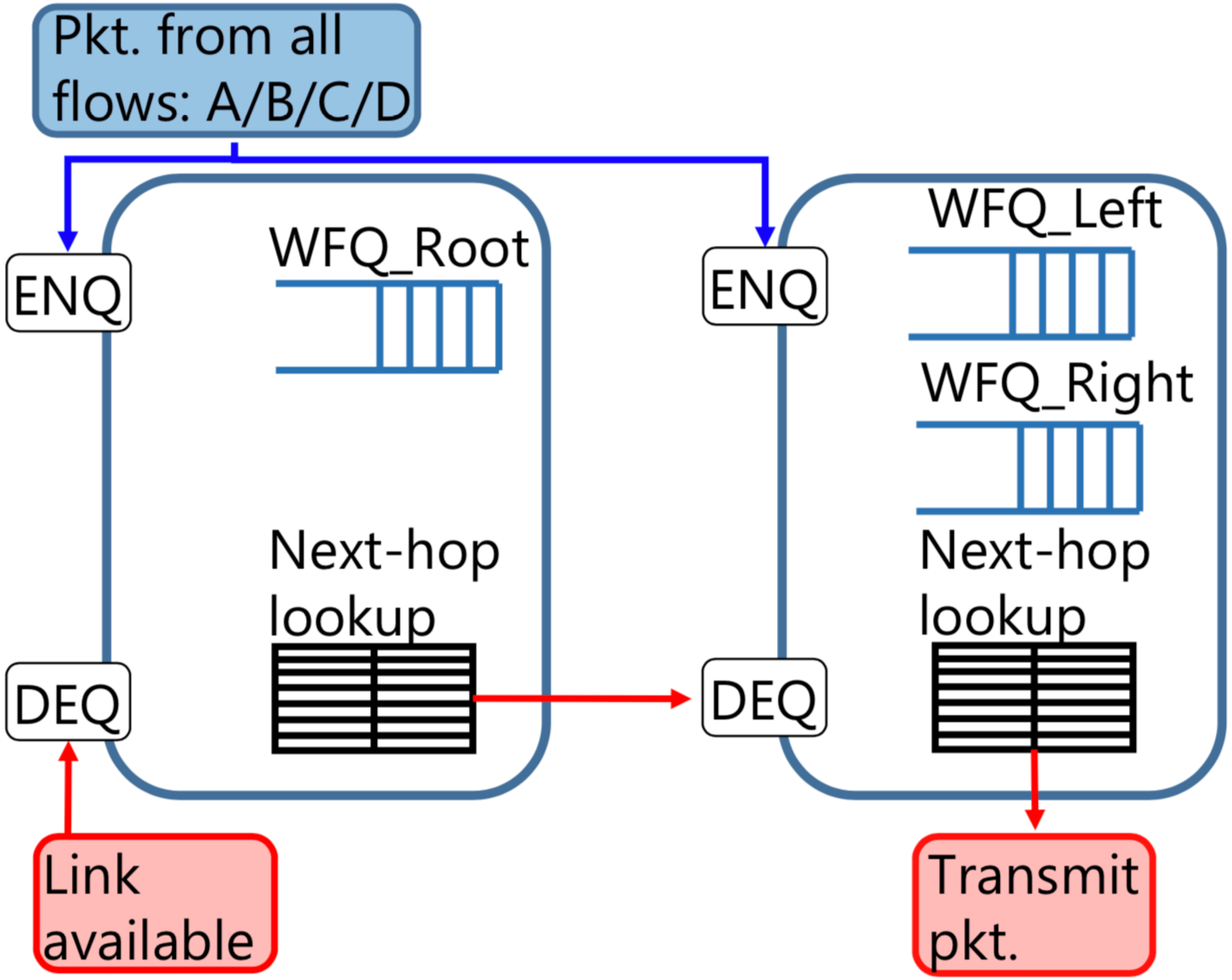
Implementation: Challenges

- Packet buffer is big! Schedule among all those packets?
  - Maintaining a sorted list of 64K packets?
  - Instead, make flow-level scheduling decisions
  - With FIFO order among packets of a given flow
- Sorting even just flows at line rate
  - Line-rate insertion and removal from hardware priority queue with 1000s of flow elements
  - Use fast flip-flops and pipelined logic

Implementation: Flow-level PIFOs



Encoding HPFQ in a PIFO mesh



Fair Queueing

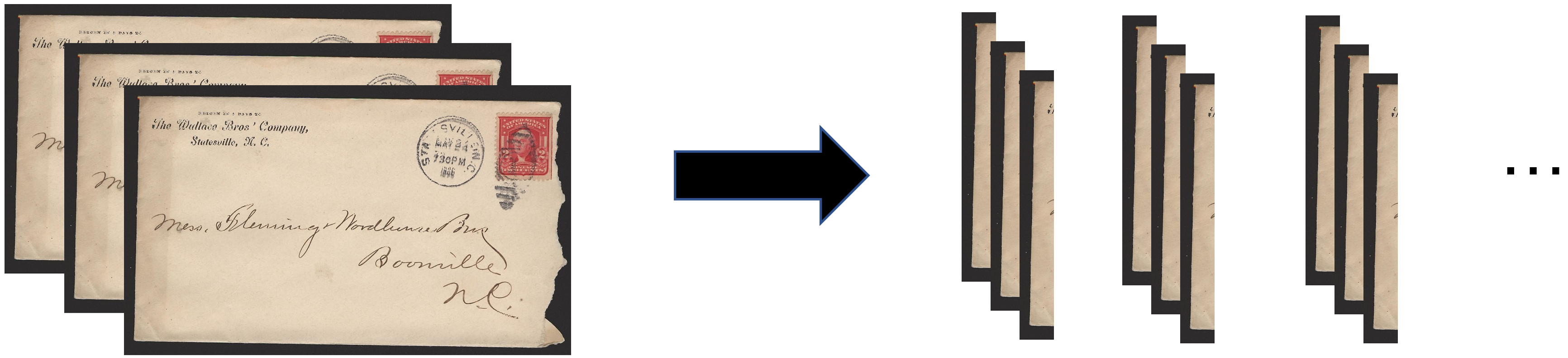
ACM SIGCOMM ’89

Alan Demers, Srinivasan Keshav, and Scott Shenker

An ideal to emulate: Processor sharing

- Fair-share bandwidth in the most fine-grained fashion possible
  - If there are N active flows, each flow gets 1/Nth of the link rate
  - “Bit by bit round robin” (BR)

- Implementing BR directly on routers is unrealistic. Why?
  - One reason: consider the processing of the bit downstream
  - E.g., where to route the bit?



Emulate bit-by-bit round robin (BR)?

- How about round robin over packets?
- Unfair! A flow can use larger packets and gain larger bandwidth
- Instead, determine when a packet would finish with BR
  - Depends only on packet arrival time & # of active flows
  - Let’s call this the “virtual finish time”
- FQ: Transmit packets in the order of the virtual finish times
  - Buffer management: drop pkt of the flow with the largest backlog

Deficit Round Robin

- Router-friendly implementation of a WFQ scheme