CS551
Router
Queue Management

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http://merlot.usc.edu/cs551-f12

Congestion Control vs. Resource Allocation

- Network's key role is to allocate its transmission resources to users or applications
- Two sides of the same coin
  - Let network do resource allocation (e.g., VCs)
    - difficult to do allocation of distributed resources
    - can be wasteful of resources
  - Let sources send as much data as they want
    - recover from congestion when it occurs
    - easier to implement, may lose packets

Connectionless Flows

- How can a connectionless network allocate anything to a user?
  - It doesn’t know about users or applications
- Flow:
  - A sequence of packets between same source - destination pair, following the same route
- Flow is visible to routers - it is not a channel, which is an end-to-end abstraction
- Routers may maintain soft-state for a flow
- Flow can be implicitly defined or explicitly established (similar to VC)
  - Different from VC in that routing is not fixed

Goals

- Fairness
  - Fair Queueing [Demers89a]
- Efficiency
  - RED [Floyd93a]
- Stability
  - XCP [Katabi02a]
- Service Differentiation
  - RIO [Clark98a]

Design Dimensions

- How quickly do you provide feedback
- What kind of fairness do you provide
  - Fair to whom (flows, users, etc.)
  - How fair (probabilistic, guarantee, etc.)
  - Definition of fair (equal size, max-min)
- How efficient you are (router go idle?)
- How much state you must keep
  - constant amount, for some flows, for each flow
- How do you signal congestion
  - dropping packets vs. explicit feedback (DECbit, ECN)

Queueing Policies

- Many policies have been considered
  - FIFO ("drop tail")
    - also drop head
  - Round robin (per flow)
  - Weighted round robin
  - Fair queueing
  - Token bucket
  - Vitrual clock
  - Class-based queueing (per class of traffic)
  - Stochastic fair queueing (statistical)

Taxonomy

- Router-centric v.s. Host-centric
  - *Router-centric:* address problem from inside network - routers decide what to forward and what to drop
    - variant: only at edge-routers
  - *Host centric:* address problem at the edges - hosts observe network conditions and adjust behavior
  - Not always a clear separation: hosts and routers may collaborate, e.g., routers advise hosts

Taxonomy (Cont...)

- Reservation-based v.s. Feedback-based
  - *Reservations:* hosts ask for resources, network responds yes/no
    - implies router-centric allocation
  - *Feedback:* hosts send with no reservation, adjust according to feedback
    - either router or host centric: explicit (e.g., ICMP source quench) or implicit (e.g., loss) feedback

Taxonomy (Cont...)

- Window-based v.s. Rate-based
- Both tell sender how much data to transmit
- *Window:* TCP flow/congestion control
  - Flow control: advertised window
  - Congestion control: cwnd
- *Rate:* still an open area of research
  - May be logical choice for reservation-based system

Service Models

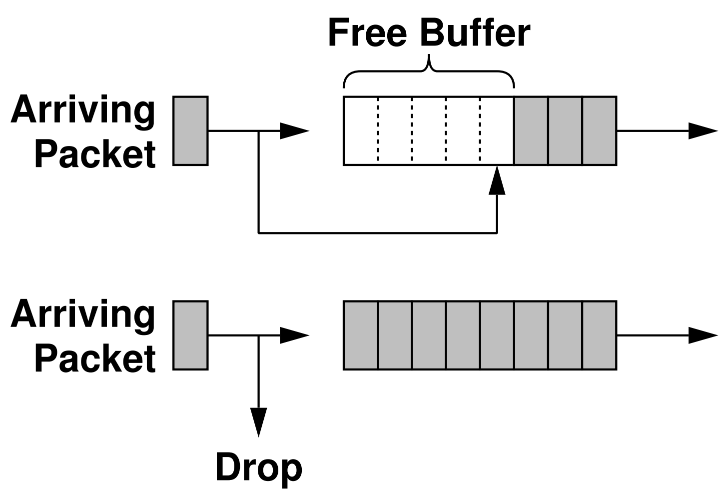
- In practice, fewer than eight choices
- Best-effort networks
  - Mostly host-centric, feedback, window based
  - TCP as an example
- Networks with flexible Quality of Service
  - Router-centric, reservation, rate-based

Queueing Disciplines

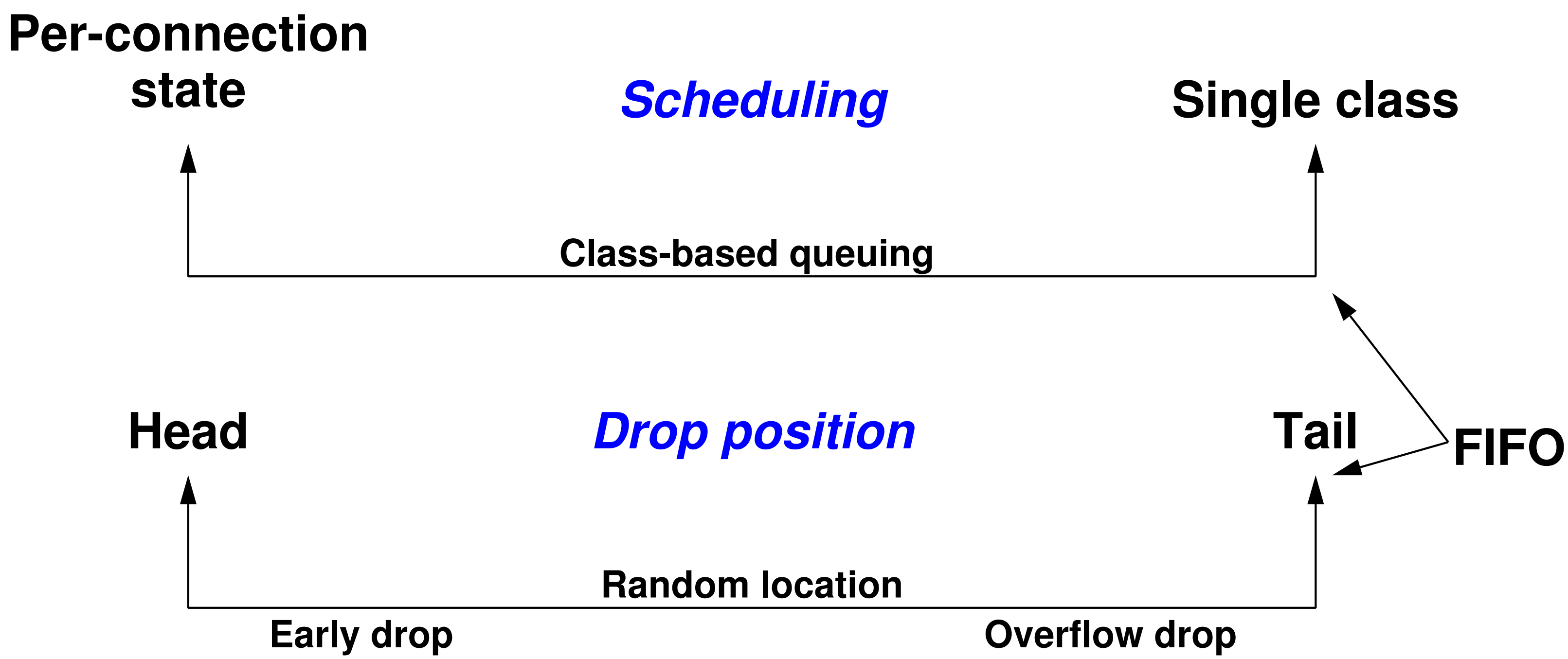
- Each router *must* implement some queuing discipline regardless of what the resource allocation mechanism is
- Queueing discipline allocates:
  - *bandwidth:* which packets get transmitted
  - *buffer space:* which packets get dropped
  - *promptness:* when packets get transmitted

FIFO Queuing

- FIFO:first-in-first-out (or FCFS: first-come-first-served)
- Arriving packets get dropped when queue is full regardless of flow or importance - implies *droptail*
- Important distinction:
  - *FIFO:* scheduling discipline (which packet to serve next)
  - *Drop-tail:* drop policy (which packet to drop next)



Dimensions


Per-connection state
Scheduling
Single class
Class-based queuing
Head
Drop position
Tail
FIFO
Random location
Early drop
Overflow drop

FIFO

- FIFO + drop-tail is the simplest queuing algorithm
  - Used widely in the Internet
- Leaves responsibility of congestion control to edges (e.g., TCP)
- FIFO lets large user get more data through but shares congestion with others
  - Does not provide *isolation* between different flows
  - No policing

Fair Queueing [Demers89a]

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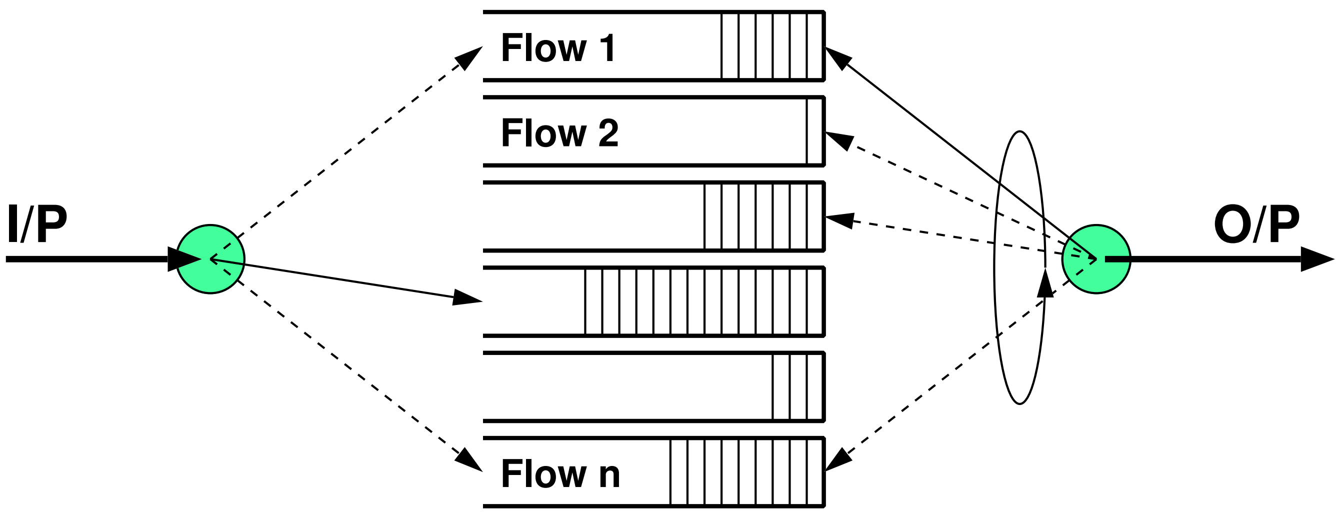
Fair Queuing

- Fair Queueing (FQ) [Nagle85,Nagle87]
- Main idea:
  - Maintain a separate queue for each flow currently flowing through router
  - Router services queues in *Round-Robin* fashion
- Changes interaction between packets from different flows
  - Provides isolation between flows
  - Ill-behaved flows cannot starve well-behaved flows
  - Allocates buffer space and bandwidth fairly

Fair Queueing Illustration



- Variation: Weighted Fair Queueing (WFQ)

Some Issues

- What constitutes a user?
  - Several granularities at which one can express flows
  - For now, assume at the granularity of source-destination pair, but this assumption is not critical
- Packets are of different length
  - Source sending longer packets can still grab more than their share of resources
  - We really need ***bit-by-bit round-robin***
  - Fair Queuing ***simulates*** bit-by-bit round-robin
    - not feasible to interleave bits!

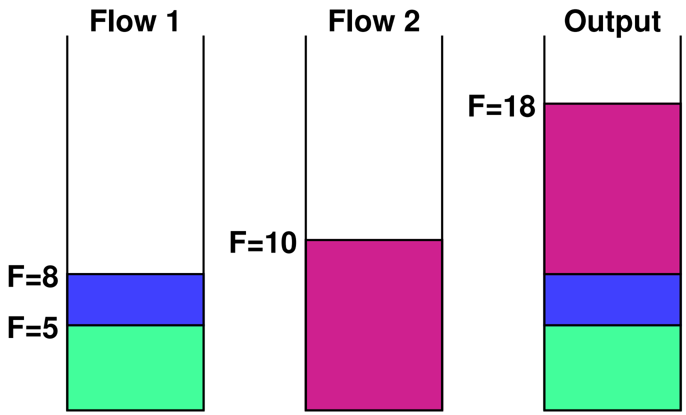
Bit-by-bit Round-robin

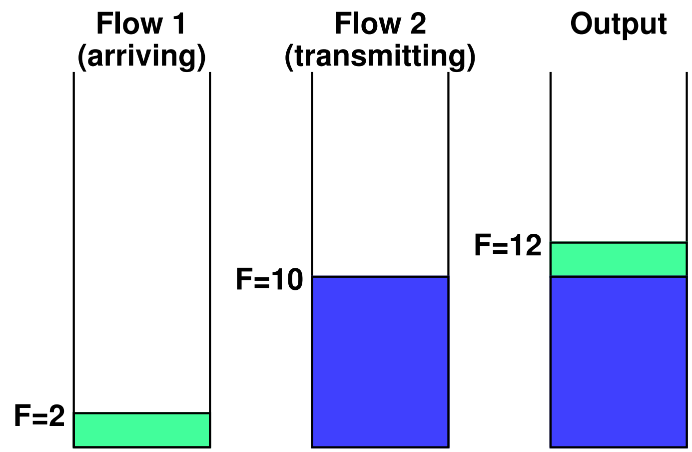
- Router maintains a logical clock
- Single flow: suppose clock ticks when a bit is transmitted. For packet i:
  - P_i: length, A_i = arrival time, S_i: begin transmit (start time) F_i: finish time
  - $S_i = \max(F_{i-1}, A_i)$
  - $F_i = S_i + P_i$
    - $F_i = \max(F_{i-1}, A_i) + P_i$
- Multiple flows: logical clock ticks when a bit from *all* active flows is transmitted
  - logical clock = number of *rounds* served
  - logical clock advances more slowly when there are more flows

Fair Queuing

- While we cannot actually perform bit-by-bit interleaving, can *compute* (for each packet) F_i. Then, use F_i to schedule packets
  - Transmit earliest F_i first
- Still not completely fair
  - But difference now bounded by the size of the largest packet
  - Compare with previous approach

Fair Queuing Example





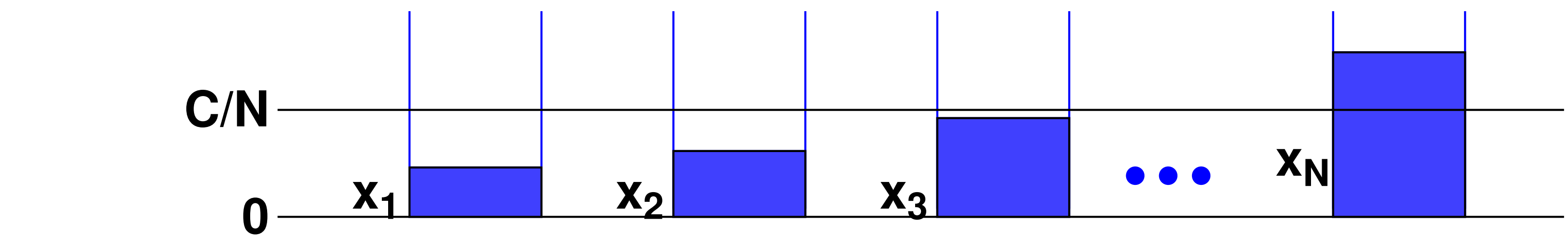
- Cannot preempt packet currently being transmitted

Max-min Fairness

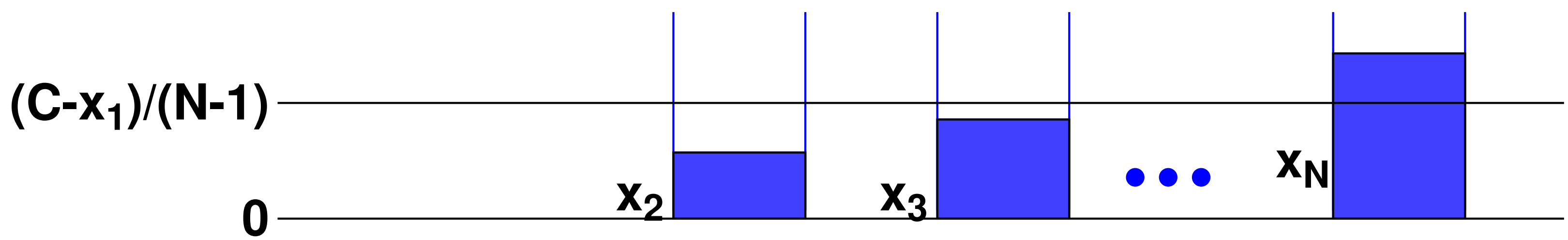
- ***Max-min Fairness:*** a fair service maximizes the service of the customer receiving the poorest service
- ***Max-min Fairness*** criterion:
  1) no user receives more than its *request*
  2) no other allocation scheme satisfying condition 1 has a high minimum allocation
  3) condition 2 remains recursively true as we remove the minimal user and reduce total resource accordingly

Max-min Fairness Example

- Total capacity C divided among N flows
  - x_i is the request of flow i
  - sort flows based on x_i
  - initially, assign C/N to each flow



  - satisfy x_1, redistribute remaining capacity evenly



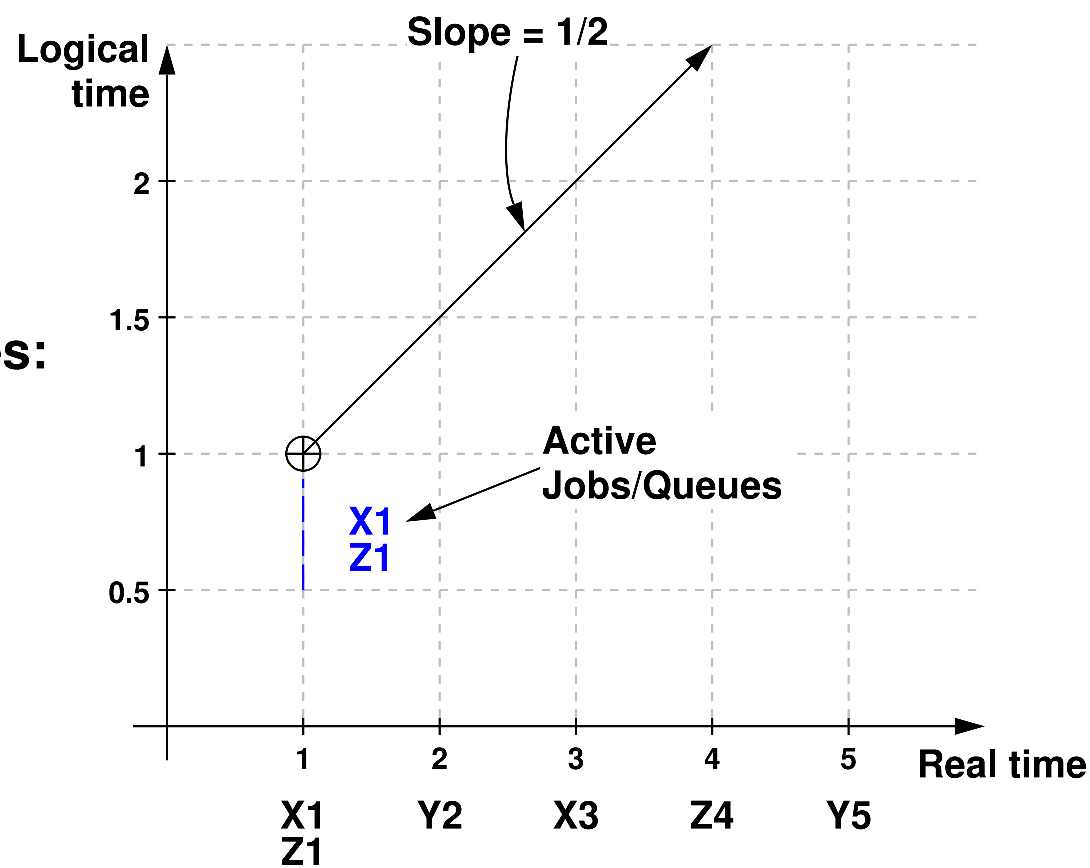
  - recursion

Fair Queuing Example

- All packets are of size 1 (P_i=1, $\forall$ i), real arrive times are in *real time*
  - e.g., three queues, X, Y, and Z, pack X1 arrive at queue X at real time 1, pack X3 arrive at queue X at real time 3, etc.
    - X1, X3
    - Y2, Y5
    - Z1, Z4
- $F_i = \max(F_{i-1}, A_i) + P_i$
  - $F_i = \max(F_{i-1}, A_i) + 1$
  - what are the logical arrival times for the 6 packets?
    - arrival times, finish times are all *logical times*
    - how do you map *real time* to *logical time*?
    - $A_{X1} = 1$
    - $A_{Z1} = 1$

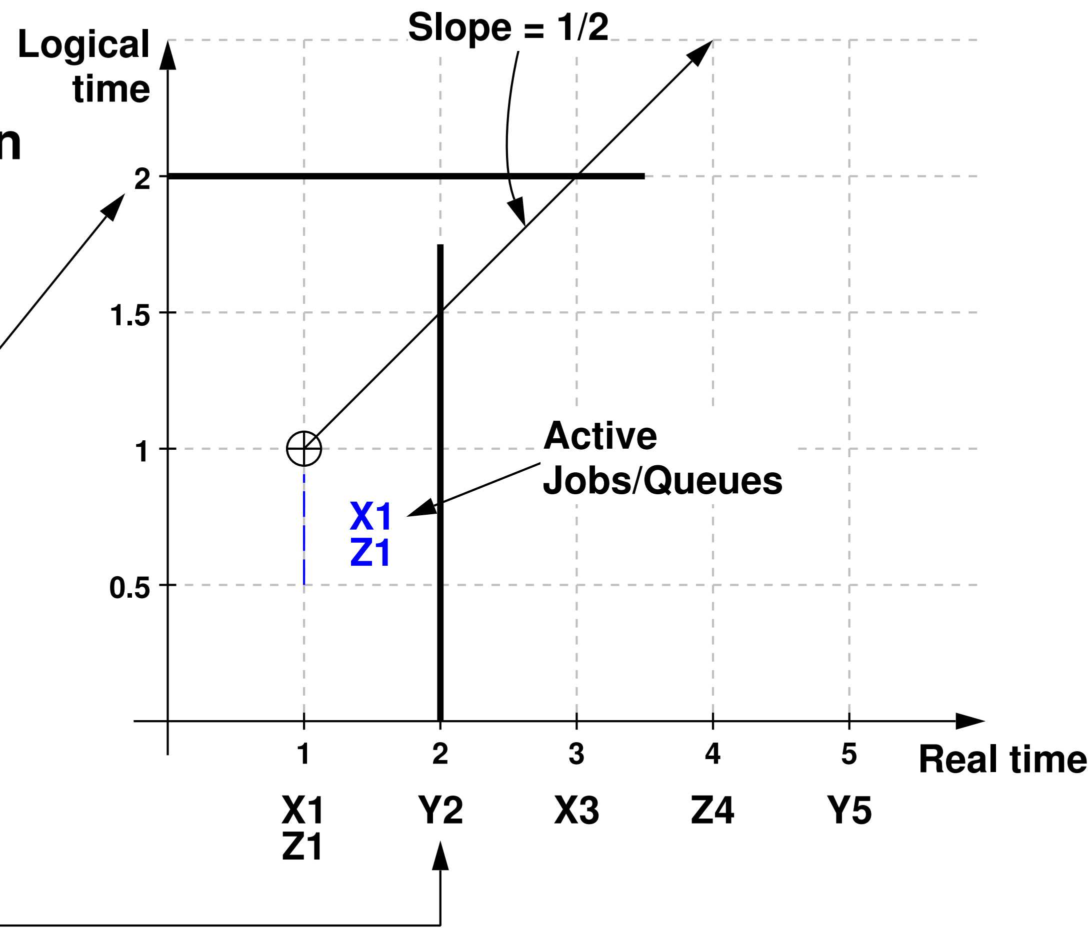
Fair Queuing Example (Cont...)

- Packets:
  - X1, X3
  - Y2, Y5
  - Z1, Z4
- Arrival/finish times:
  - $A_{X1} = 1$
  - $A_{Z1} = 1$
  - $F_{X1} = F_{Z1} = 2$
  - 2 flows, slope = 1/2
  - what's next?



Fair Queuing Example (Cont...)

- How to decide?
- Think event driven simulation...
  - $A_{X1} = 1$
  - $A_{Z1} = 1$
  - $F_{X1} = F_{Z1} = 2$
  - next arrival is Y2 (arrives at *real* time 2)
  - arrival wins here!



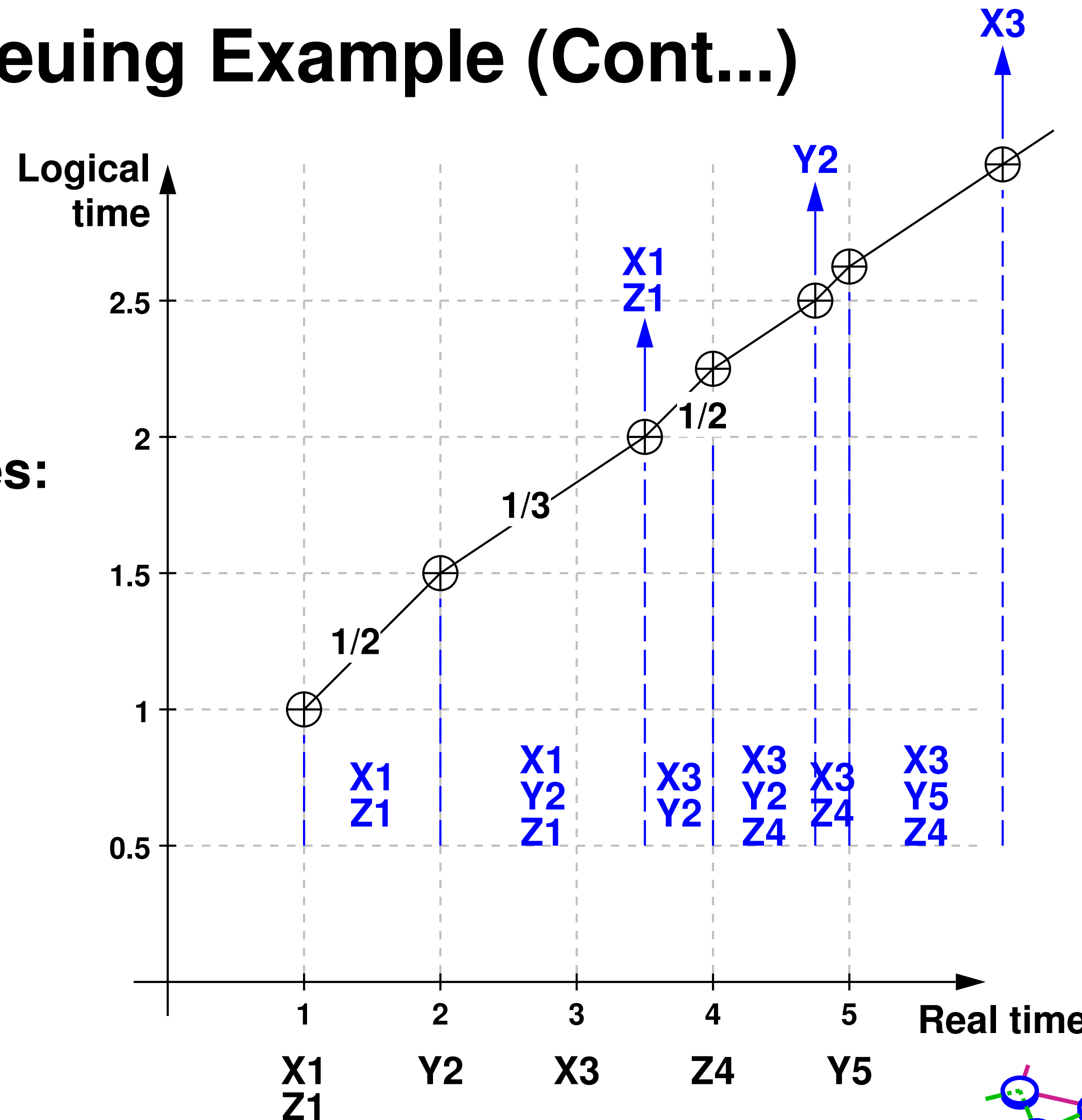
How To Calculate Next Event

- Current coordinate is (x0,y0) and slope is r
  - need to find the next event on the X-axis and the Y-axis
    - next event on the X-axis is the next pack arrival
    - next event on the Y-axis is the next packet departure

1) If next event will be an arrival event at *real* time x1
   - next event will occur at (x1,y1) where (y1-y0)/(x1-x0)=r
   - solve for y1, the *logical* arrival time of this arriving packet
     - from logical arrival time, you can easily calculate the *logical* finish time using the bit-by-bit RR equation
2) If next event will be a departure event at *logical* time y1
   - next event will occur at (x1,y1) where (y1-y0)/(x1-x0)=r
   - solve for x1, to make sure that there is no arrival between *real* time x0 and x1
     - verify that y1 is the *logical* finish time of the departing packet

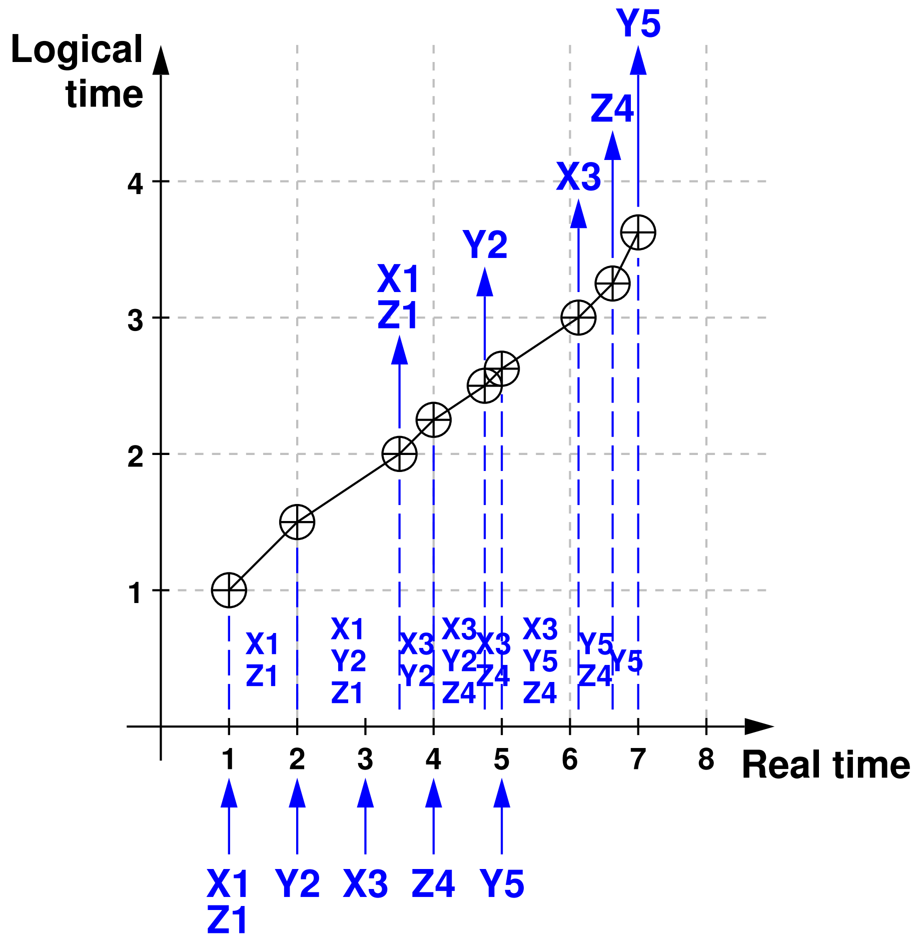
Fair Queuing Example (Cont...)

- **Packets:**
  - X1, X3
  - Y2, Y5
  - Z1, Z4
- **Arrival/finish times:**
  - $A_{X1} = 1$
  - $A_{Z1} = 1$
  - $F_{X1} = F_{Z1} = 2$
  - 2 flows, slope = 1/2
  - $A_{Y2} = 1.5$
  - $F_{Y2} = 2.5$
  - $A_{X3} = 1.833$
  - $F_{X3} = 3$



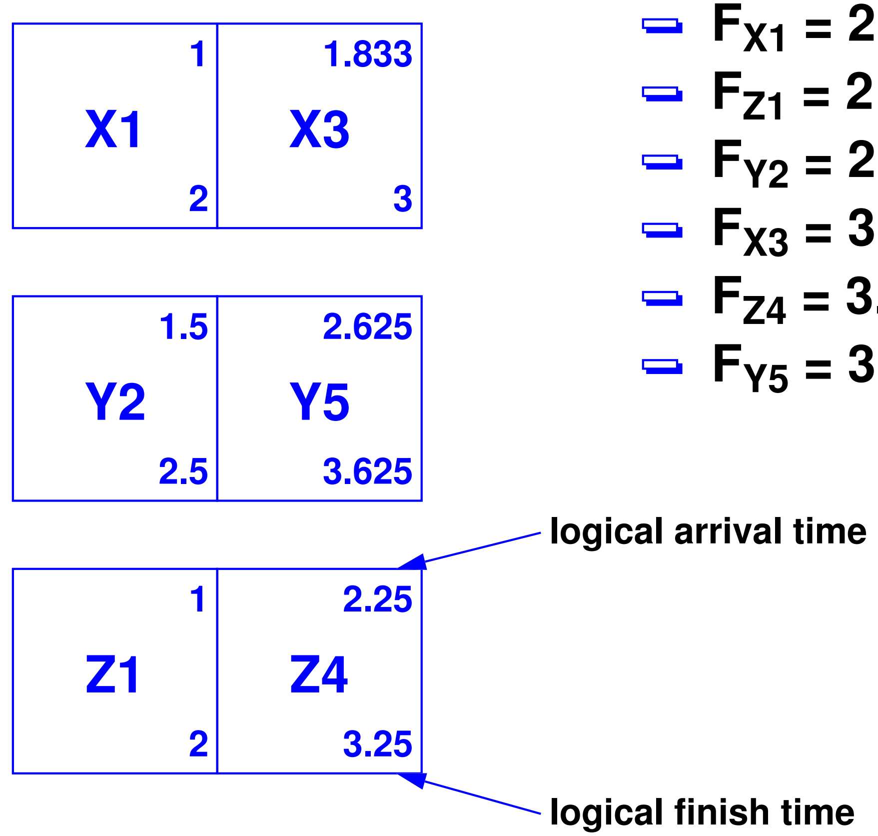
Fair Queuing Example (Cont...)

- Arrival/finish times:
  - $A_{X1} = 1$
  - $F_{X1} = 2$
  - $A_{Z1} = 1$
  - $F_{Z1} = 2$
  - $A_{Y2} = 1.5$
  - $F_{Y2} = 2.5$
  - $A_{X3} = 1.833$
  - $F_{X3} = 3$
  - $A_{Z4} = 2.25$
  - $F_{Z4} = 3.25$
  - $A_{Y5} = 2.625$
  - $F_{Y5} = 3.625$



Fair Queuing Example (Cont...)

- Arrival/finish times:
  - $A_{X1} = 1$
  - $F_{X1} = 2$
  - $A_{Z1} = 1$
  - $F_{Z1} = 2$
  - $A_{Y2} = 1.5$
  - $F_{Y2} = 2.5$
  - $A_{X3} = 1.833$
  - $F_{X3} = 3$
  - $A_{Z4} = 2.25$
  - $F_{Z4} = 3.25$
  - $A_{Y5} = 2.625$
  - $F_{Y5} = 3.625$



- Output:
  - $F_{X1} = 2$
  - $F_{Z1} = 2$
  - $F_{Y2} = 2.5$
  - $F_{X3} = 3$
  - $F_{Z4} = 3.25$
  - $F_{Y5} = 3.625$

Delay Allocation

- Aim: give less delay to those using less than their fair share
- Advance finish times for sources whose queues drain temporarily
- $B_i = P_i + \max(F_{i-1}, A_i - \delta)$
- Schedule earliest B_i first
- δ gives added promptness:
  - If $A_i < F_{i-1}$, conversation is active and δ does not affect it: $F_i = P_i + F_{i-1}$
  - If $A_i > F_{i-1}$, conversation is inactive and δ determines how much history to take into account

Notes on FQ

- FQ is a scheduling policy, not a drop policy
- Still achieves statistical multiplexing - one flow can fill entire pipe if no contenders - FQ is *work conserving*
- WFQ is a possible variation - need to learn about weights offline. Default is one bit per flow, but sending more bits is possible

Weighted Fair Queuing Example

- Weights for X, Y, and Z are 1, 2, and 1, respectively
  - X1, X3
  - Y2, Y5
  - Z1, Z4
- Shrink packet size of Y2 and Y5 by half
- Need to count Y twice when queue Y is not empty
- $F_i = \max(F_{i-1}, A_i) + P_i$
  - $A_{X1} = 1$
  - $A_{Z1} = 1$
  - ... (proceed as before)

More Notes on FQ

- Router does not send explicit feedback to source - still needs e2e congestion control
  - FQ isolates ill-behaved users by forcing users to share overload with themselves
  - User: flow, transport protocol, etc
- Optimal behavior at source is to keep one packet in the queue
- But, maintaining *per flow state* can be expensive
  - Flow aggregation is a possibility