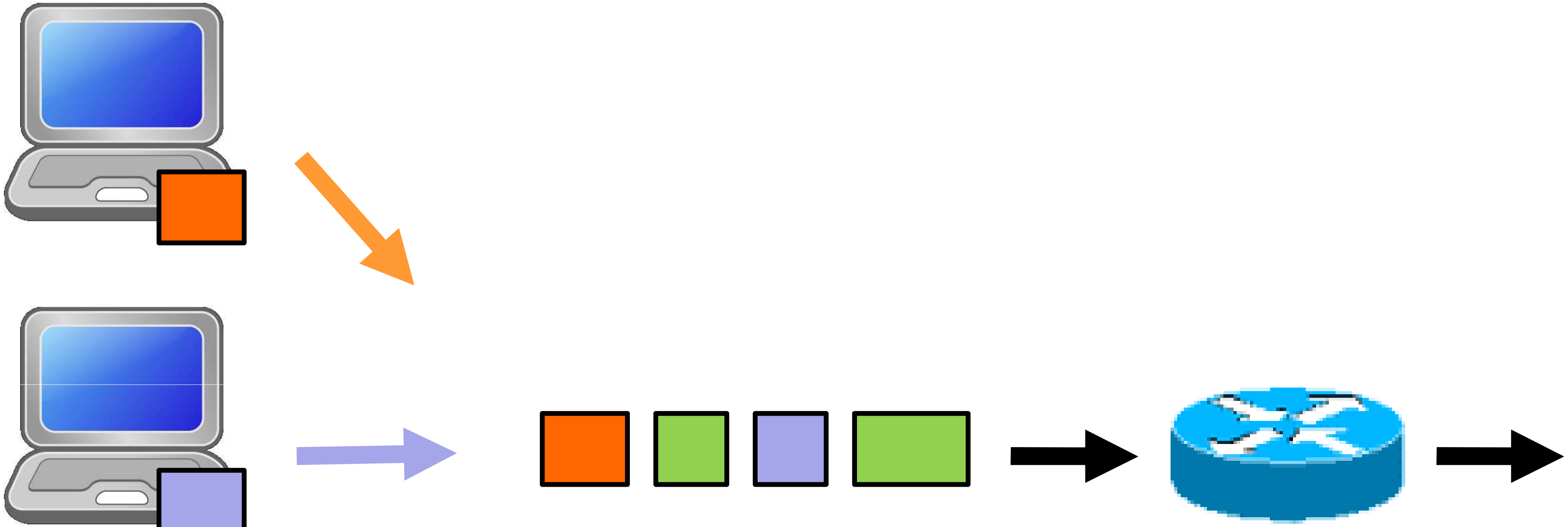
Lecture 7:
Packet Scheduling and Fair Queuing

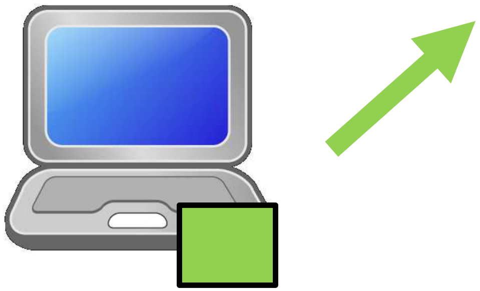
CS 598: Advanced Internetworking

Matthew Caesar

March 1, 2011

Packet Scheduling: Problem Overview



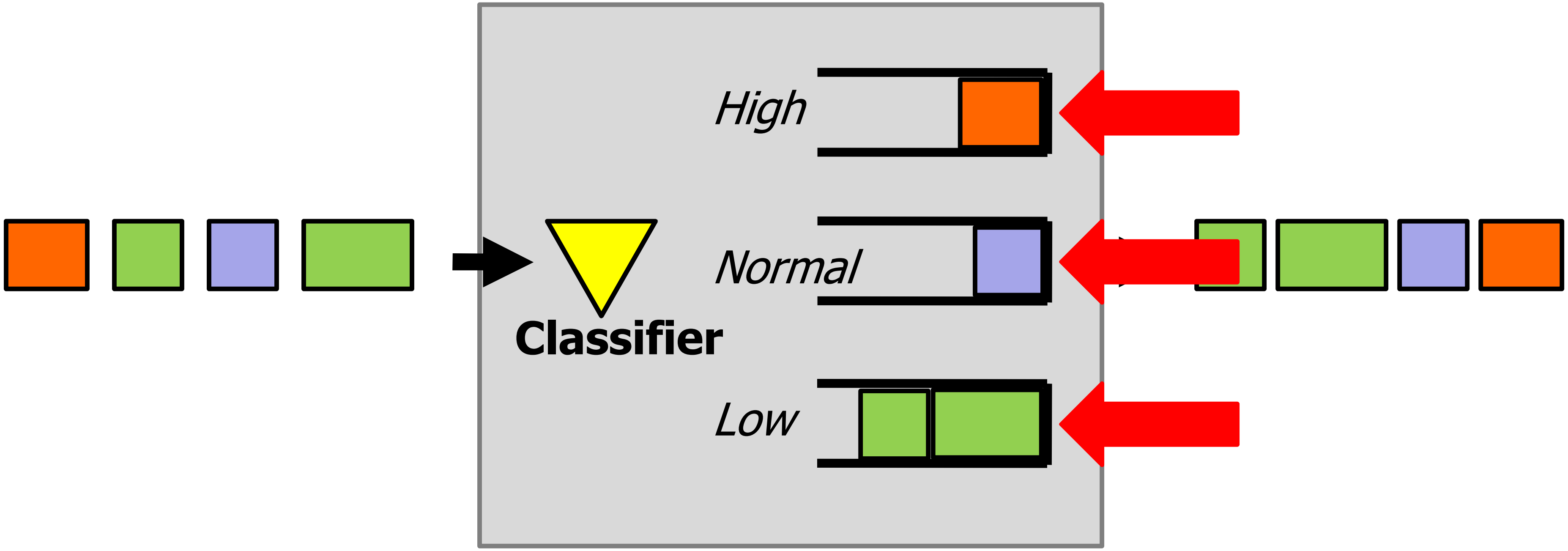


- When to send packets?
- What order to send them in?

Approach #1: First In First Out (FIFO)

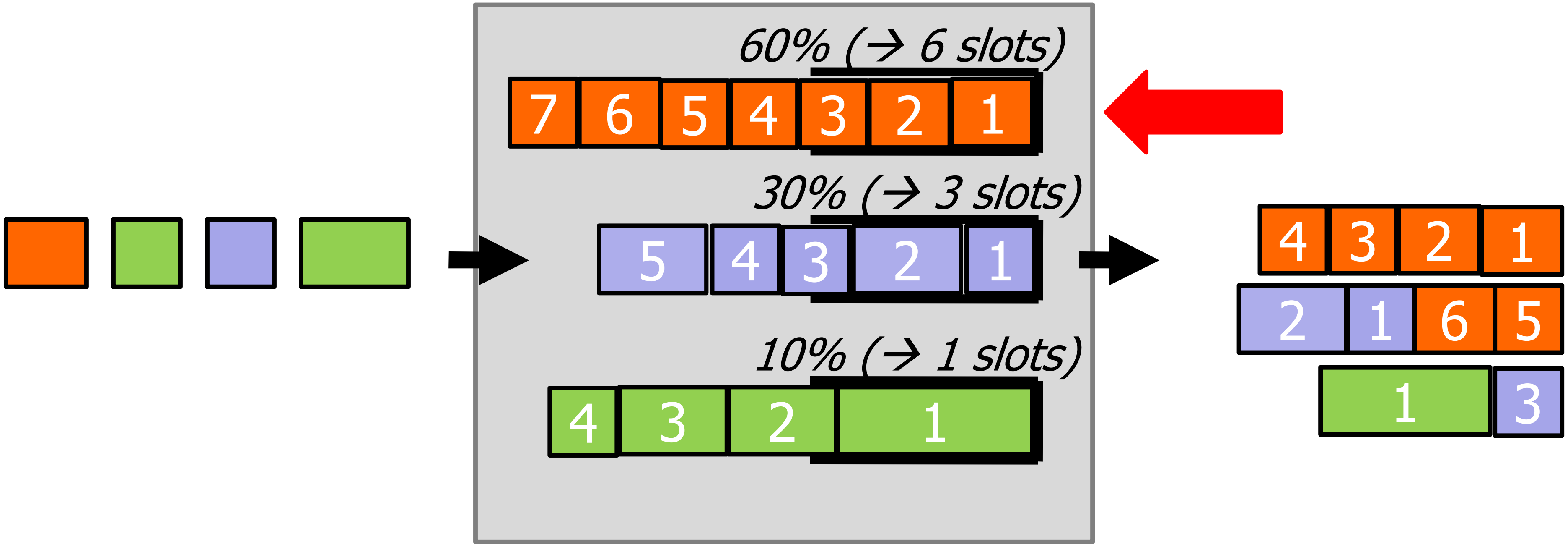
- Packets are sent out in the same order they are received
- Benefits: simple to design, analyze
- Downsides: not compatible with QoS
  - High priority packets can get stuck behind low priority packets

Approach #2: Priority Queuing



- Operator can configure policies to give certain kinds of packets higher priority
  - Associate packets with priority queues
  - Service higher-priority queue when packets are available to be sent
- Downside: can lead to starvation of lower-priority queues

Approach #3: Weighted Round Robin



- Round robin through queues, but visit higher-priority queues more often
- Benefit: Prevents starvation
- Downsides: a host sending long packets can steal bandwidth
  - Naïve implementation wastes bandwidth due to unused slots

Overview

- Fairness
- Fair-queuing
- Core-stateless FQ
- Other FQ variants

Fairness Goals

- Allocate resources fairly
- Isolate ill-behaved users
  - Router does not send explicit feedback to source
  - Still needs e2e congestion control
- Still achieve statistical muxing
  - One flow can fill entire pipe if no contenders
  - Work conserving → scheduler never idles link if it has a packet

What is Fairness?

- At what granularity?
  - Flows, connections, domains?
- What if users have different RTTs/links/etc.
  - Should it share a link fairly or be TCP fair?
- Maximize fairness index?
  - Fairness = $(\Sigma x_i)^2/n(\Sigma x_i^2)$ $0<\text{fairness}<1$
- Basically a tough question to answer – typically design mechanisms instead of policy
  - User = arbitrary granularity

Max-min Fairness

- Allocate user with “small” demand what it wants, evenly divide unused resources to “big” users
- Formally:
  - Resources allocated in terms of increasing demand
  - No source gets resource share larger than its demand
  - Sources with unsatisfied demands get equal share of resource

Max-min Fairness Example

- Assume sources 1..n, with resource demands X1..Xn in ascending order
- Assume channel capacity C.
  - Give C/n to X1; if this is more than X1 wants, divide excess (C/n - X1) to other sources: each gets C/n + (C/n - X1)/(n-1)
  - If this is larger than what X2 wants, repeat process

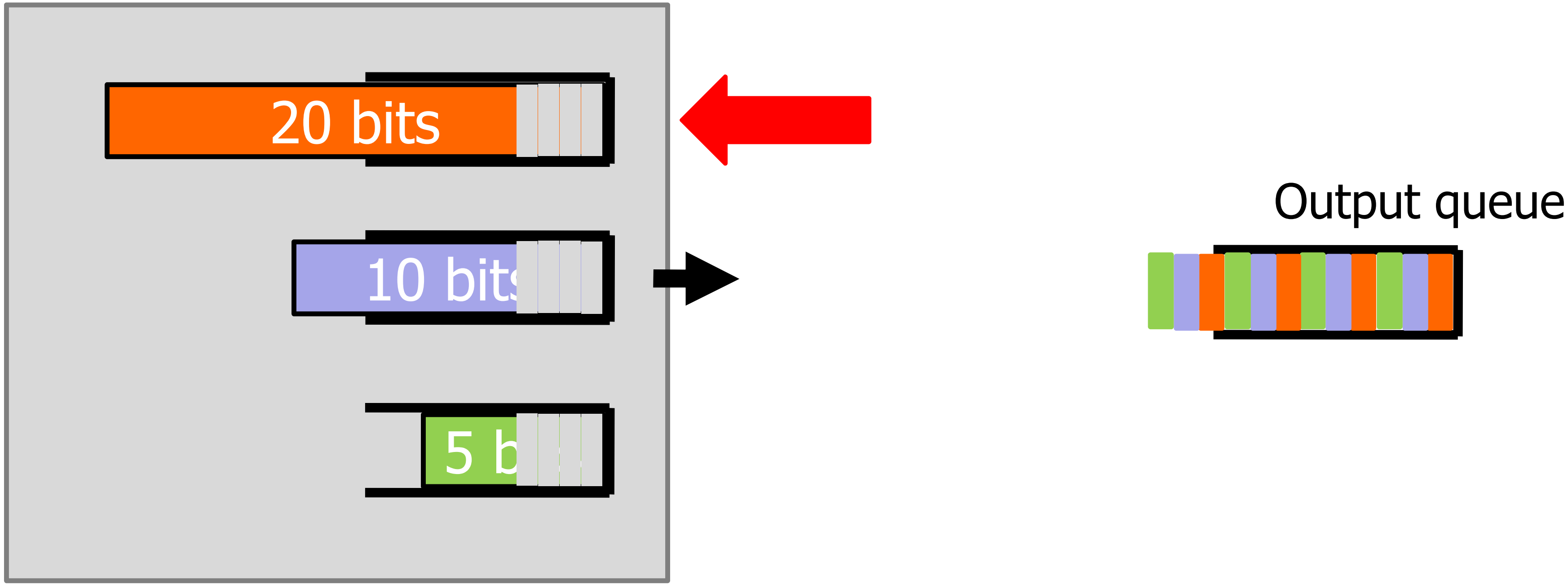
Implementing max-min Fairness

- Generalized processor sharing
  - Fluid fairness
  - Bitwise round robin among all queues
- Why not simple round robin?
  - Variable packet length → can get more service by sending bigger packets
  - Unfair instantaneous service rate
    - What if arrive just before/after packet departs?

Bit-by-bit RR

- Single flow: clock ticks when a bit is transmitted. For packet i:
  - P_i = length, A_i = arrival time, S_i = begin transmit time, F_i = finish transmit time
  - $F_i = S_i + P_i = \max(F_{i-1}, A_i) + P_i$
- Multiple flows: clock ticks when a bit from all active flows is transmitted → round number
  - Can calculate F_i for each packet if number of flows is know at all times
    - This can be complicated

Approach #4: Bit-by-bit Round Robin



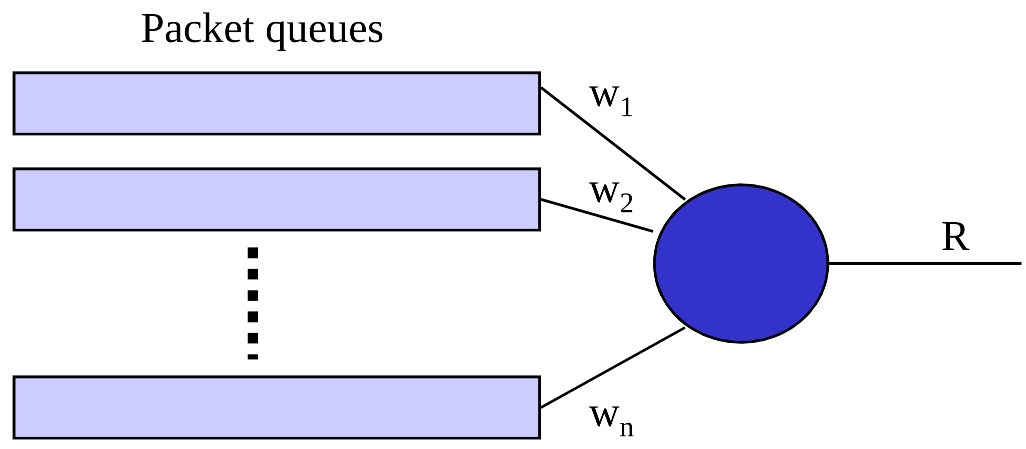
- Round robin through "backlogged" queues (queues with pkts to send)
  - However, only send one bit from each queue at a time
- Benefit: Achieves max-min fairness, even in presence of variable sized pkts
- Downsides: you can't really mix up bits like this on real networks!

The next-best thing: Fair Queuing

- Bit-by-bit round robin is fair, but you can't really do that in practice

- Idea: simulate bit-by-bit RR, compute the finish times of each packet
  - Then, send packets in order of finish times
  - This is known as Fair Queuing

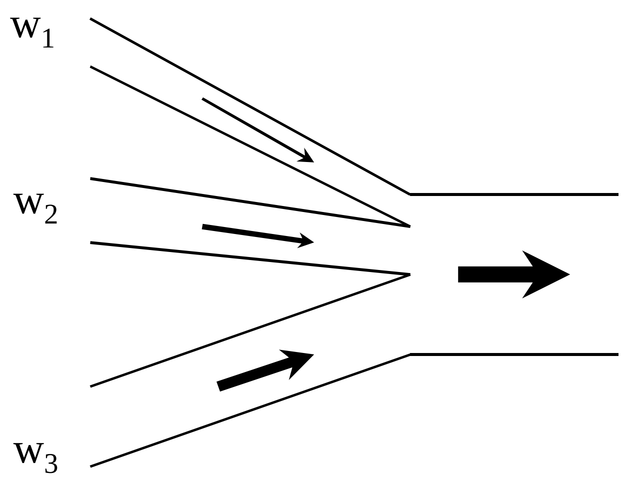
What is Weighted Fair Queuing?



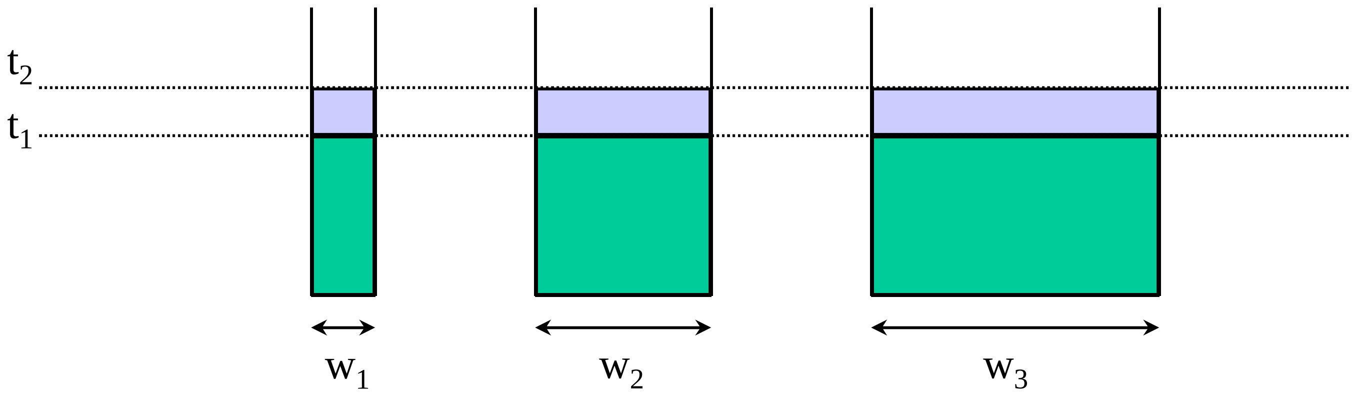
- Each flow i given a weight (importance) w_i
- WFQ guarantees a minimum service rate to flow i
  - $r_i = R * w_i / (w_1 + w_2 + ... + w_n)$
  - Implies isolation among flows (one cannot mess up another)

What is the Intuition? Fluid Flow

water pipes



water buckets

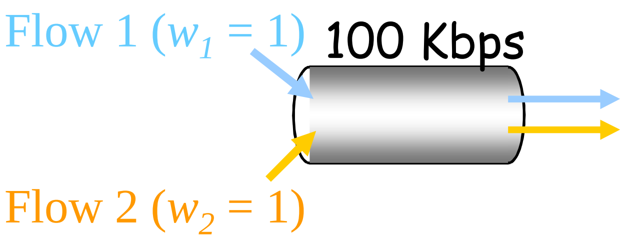


Fluid Flow System

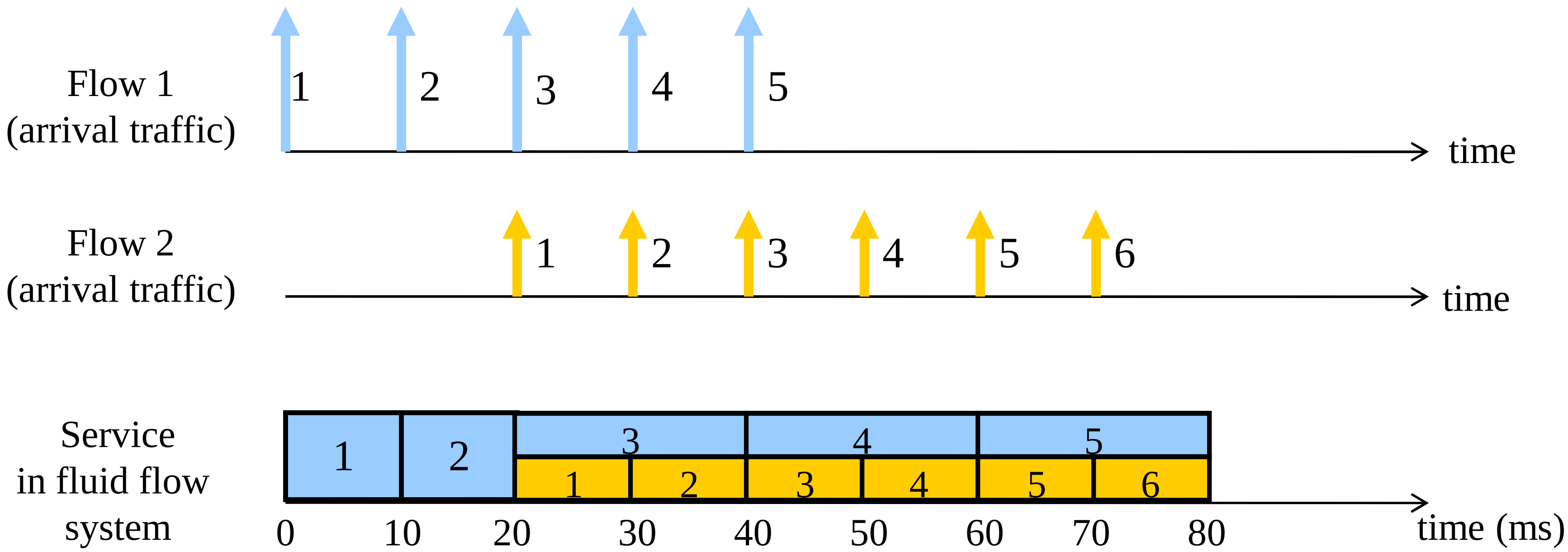
- If flows could be served one bit at a time:

- WFQ can be implemented using bit-by-bit weighted round robin
  - During each round from each flow that has data to send, send a number of bits equal to the flow’s weight

Fluid Flow System: Example 1

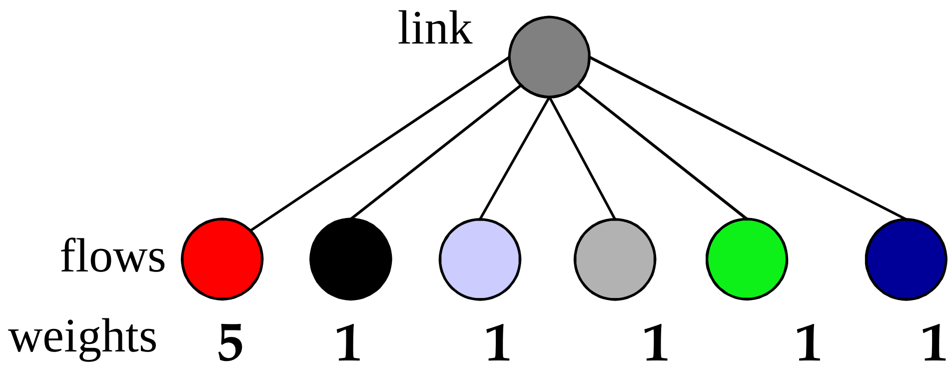


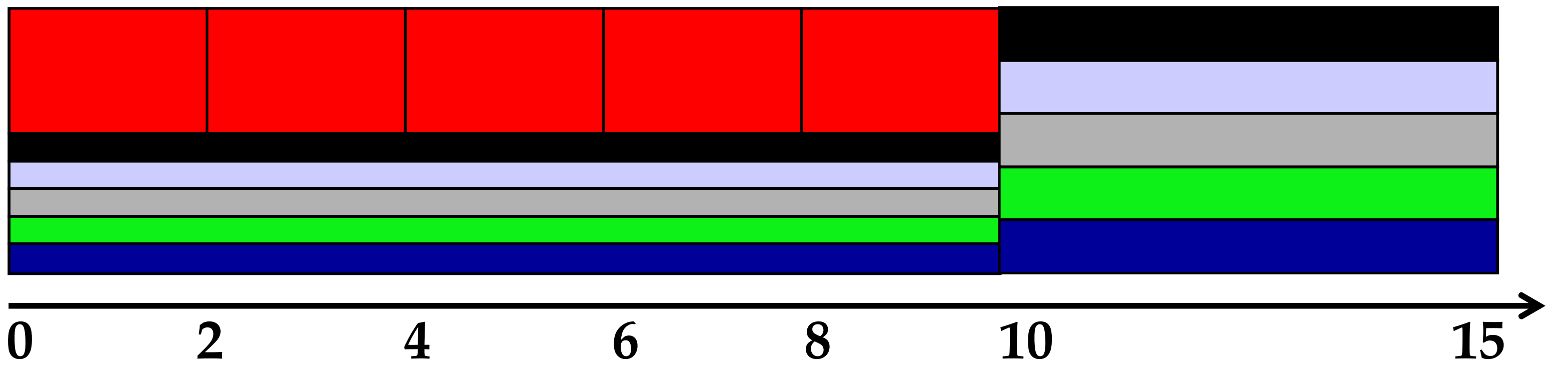
	Packet Size (bits)	Packet inter-arrival time (ms)	Arrival Rate (Kbps)
Flow 1	**1000**	**10**	**100**
Flow 2	**500**	**10**	**50**



Fluid Flow System: Example 2

- Red flow has packets backlogged between time 0 and 10
  - Backlogged flow → flow's queue not empty
- Other flows have packets continuously backlogged
- All packets have the same size



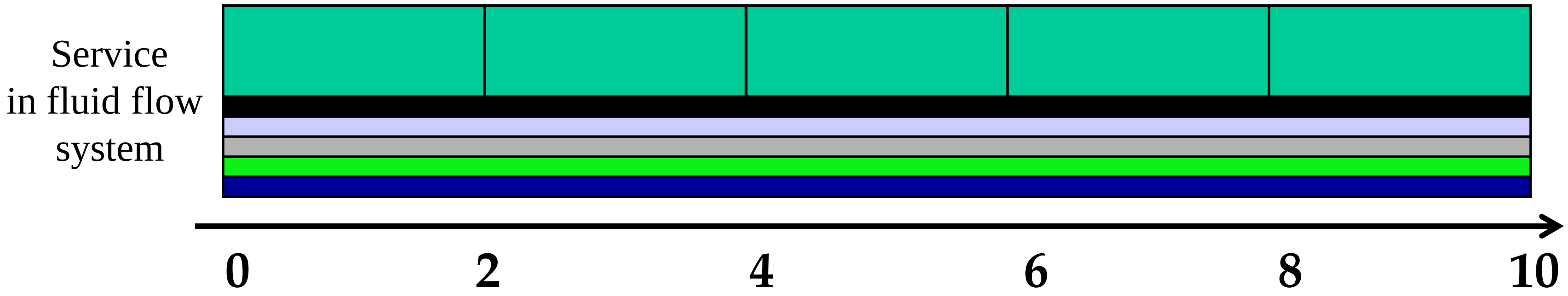


Implementation in Packet System

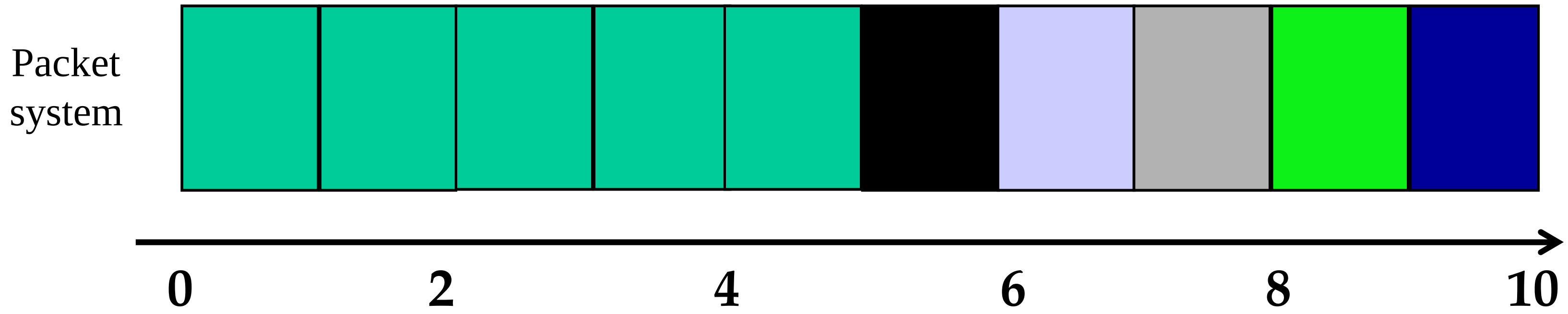
- Packet (Real) system: packet transmission cannot be preempted. Why?

- Solution: serve packets in the order in which they would have finished being transmitted in the fluid flow system

Packet System: Example 1

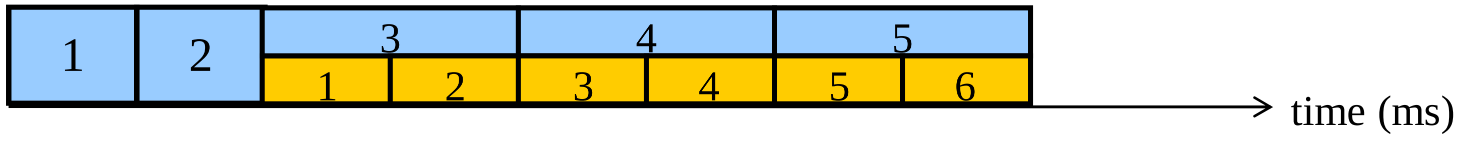


• Select the first packet that finishes in the fluid flow system



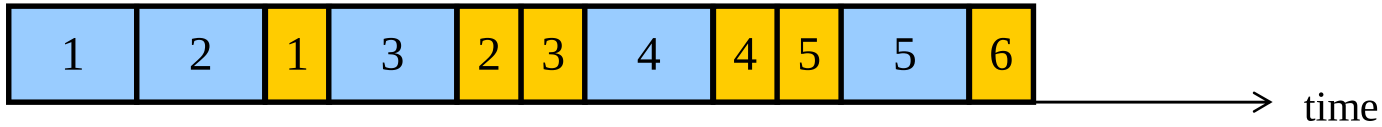
Packet System: Example 2

Service
in fluid flow
system



- Select the first packet that finishes in the fluid flow system

Packet
system

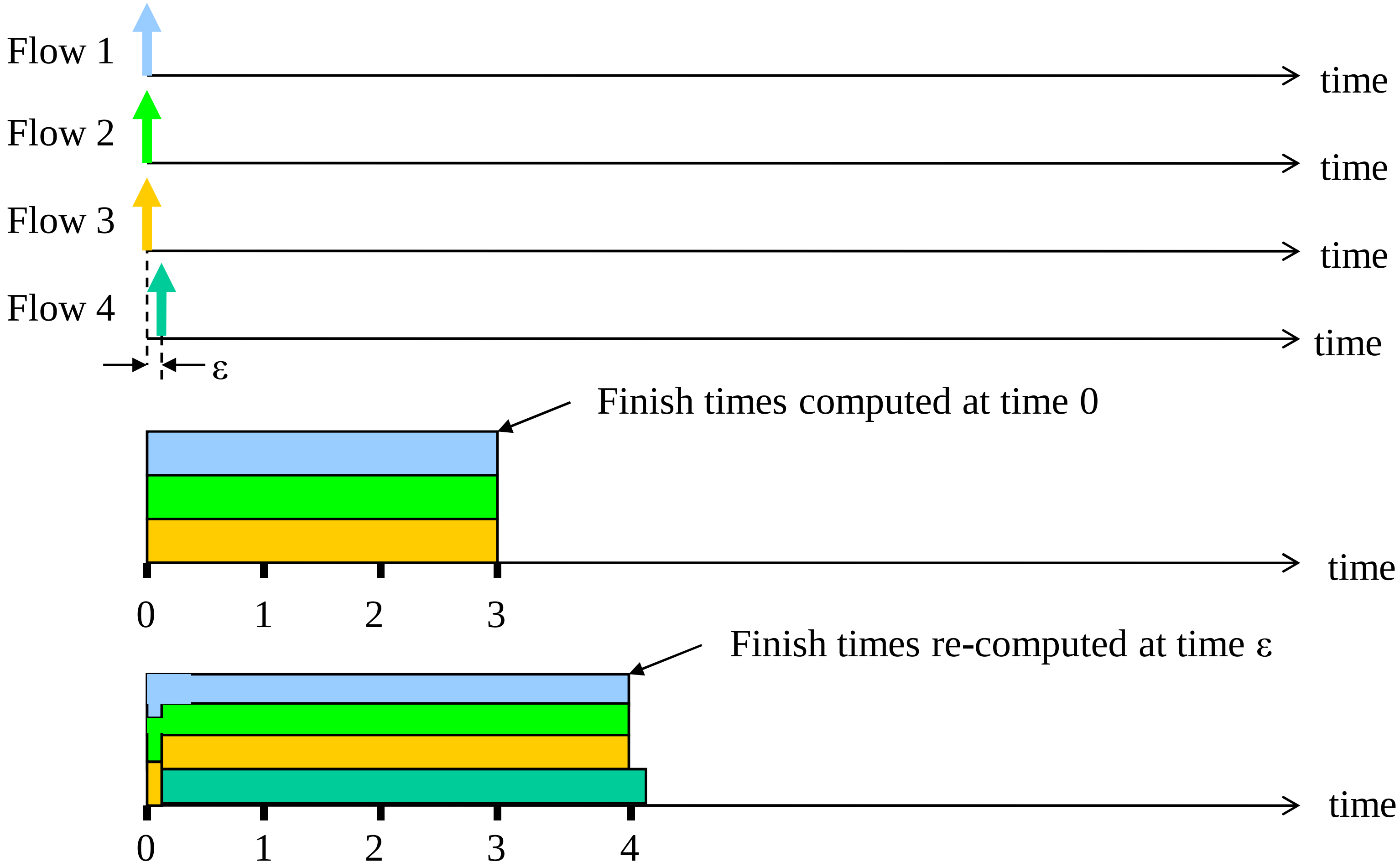


Implementation Challenge

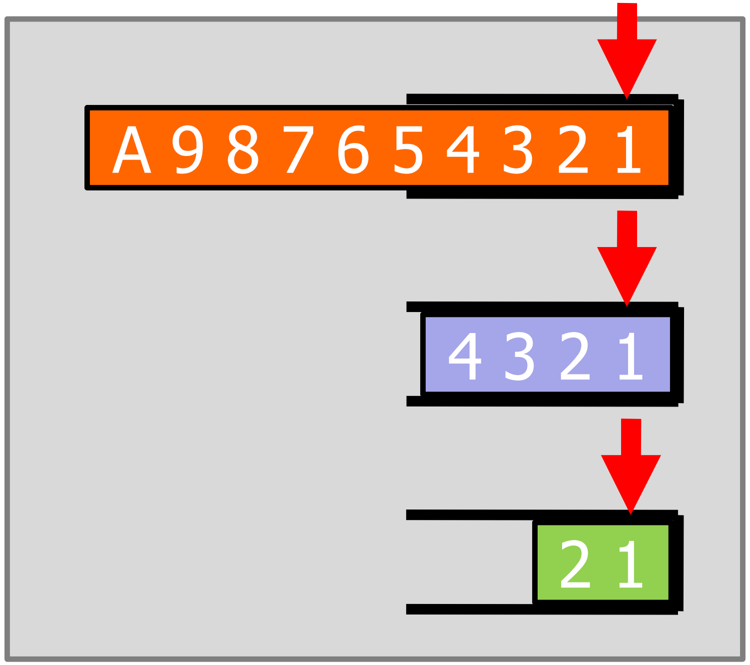
- Need to compute the finish time of a packet in the fluid flow system…
- … but the finish time may change as new packets arrive!
- Need to update the finish times of all packets that are in service in the fluid flow system when a new packet arrives
  - But this is very expensive; a high speed router may need to handle hundred of thousands of flows!

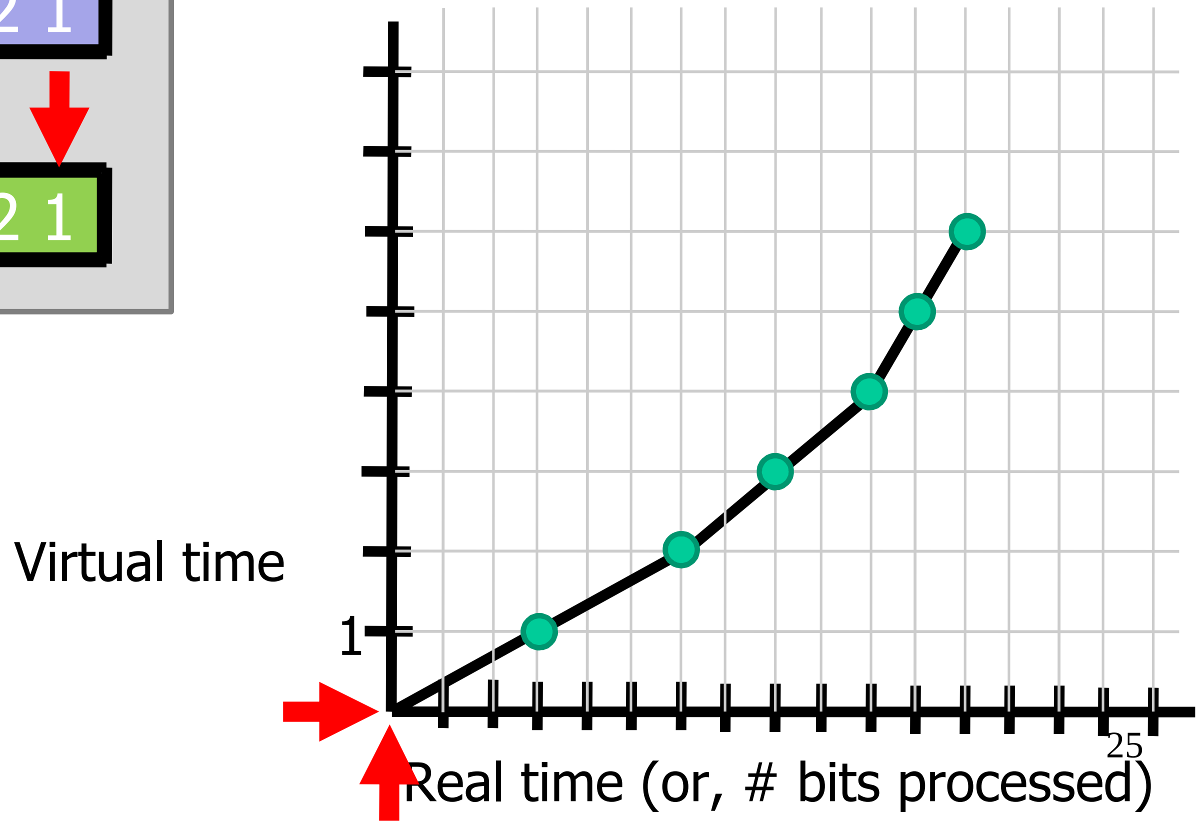
Example

- Four flows, each with weight 1



Approach #5: Self-Clocked Fair Queuing

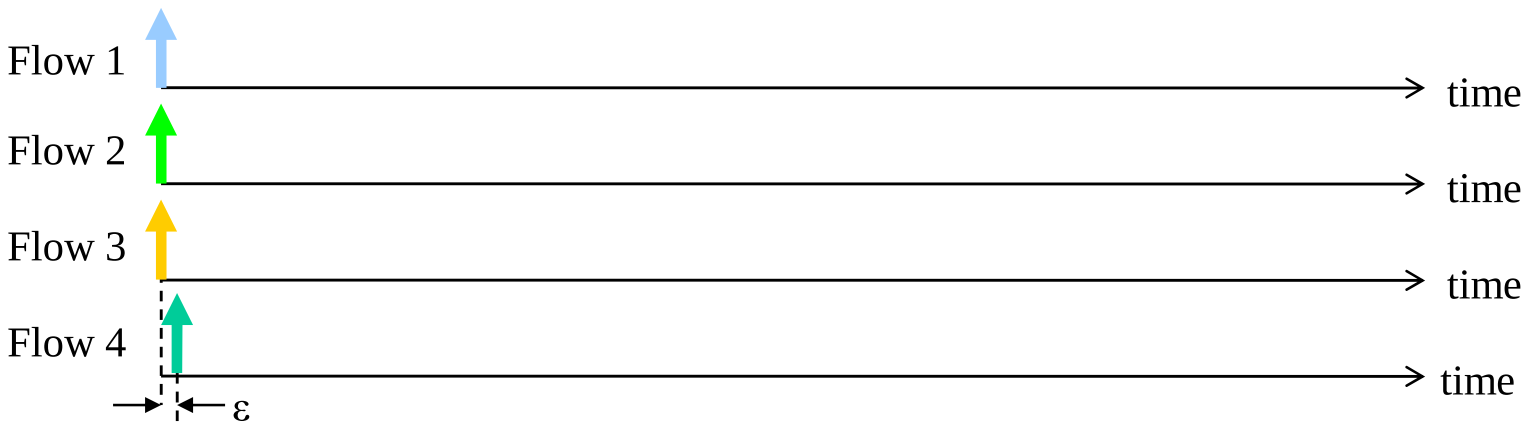




Solution: Virtual Time

- Key Observation: while the finish times of packets may change when a new packet arrives, the order in which packets finish doesn't!
  - Only the order is important for scheduling
- Solution: instead of the packet finish time maintain the round # when a packet finishes (virtual finishing time)
  - Virtual finishing time doesn't change when a packet arrives

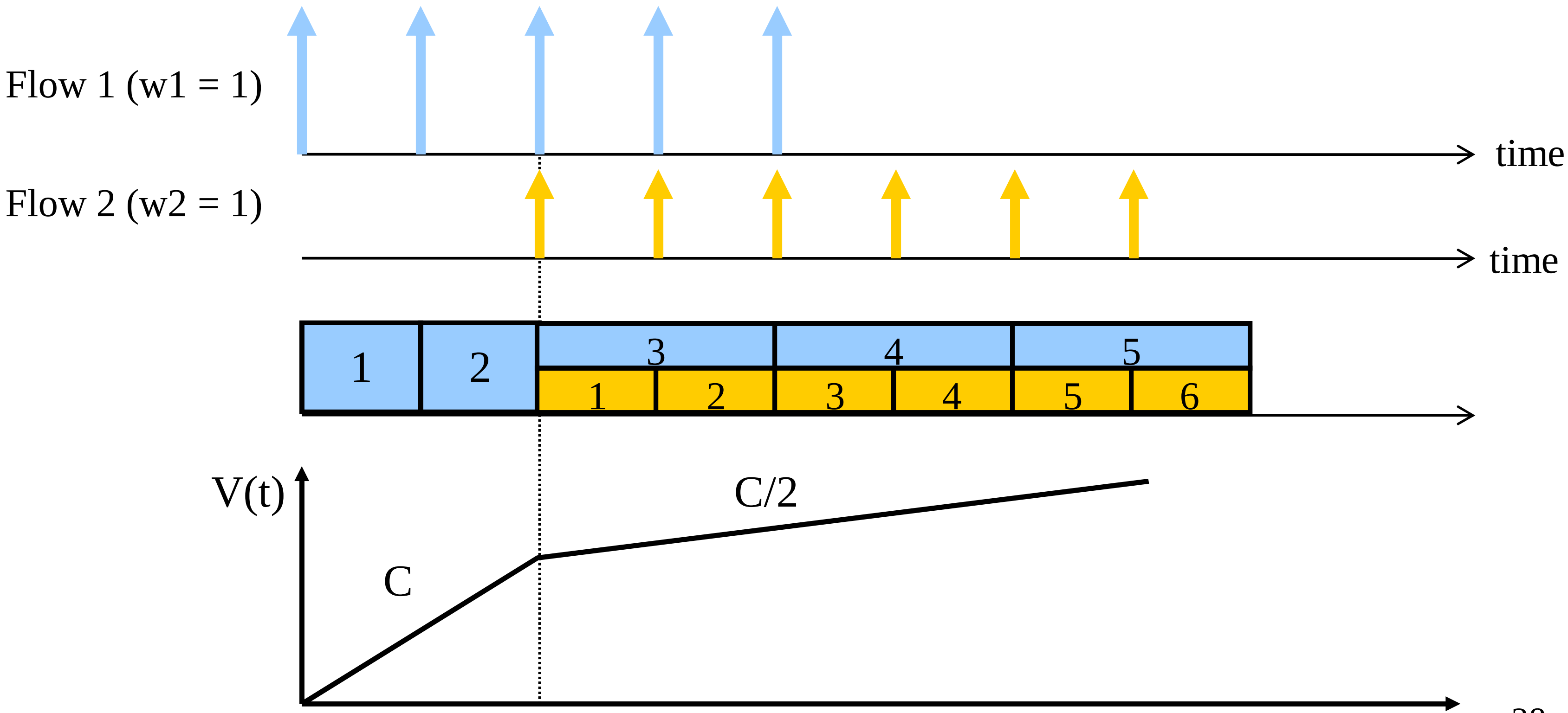
Example



- Suppose each packet is 1000 bits, so takes 1000 rounds to finish
- So, packets of F1, F2, F3 finishes at virtual time 1000
- When packet F4 arrives at virtual time 1 (after one round), the virtual finish time of packet F4 is 1001
- But the virtual finish time of packet F1,2,3 remains 1000
- Finishing order is preserved

System Virtual Time (Round #): V(t)

- V(t) increases inversely proportionally to the sum of the weights of the backlogged flows
  - During one tick of V(t), all backlogged flows can transmit one bit
- Since round # increases slower when there are more flows to visit each round.



Is Fair Queuing perfectly fair?

- No. Example: Once we begin transmission of a packet, it’s possible a new packet arrives that would have a smaller finishing time than the current packet
  - FQ is non-preemptive, so keep transmitting current packet

- However, if a packet is sitting in an output queue with its finish time calculated, and a new packet arrives with a sooner finish time, the new packet will be sent first

Fair Queueing Implementation

- Define
  - F_i^k - virtual finishing time of packet k of flow i
  - a_i^k - arrival time of packet k of flow i
  - L_i^k - length of packet k of flow i
  - w_i – weight of flow i

- The finishing time of packet $k+1$ of flow i is

$$F_i^{k+1} = \max(V(a_i^{k+1}), F_i^k) + L_i^{k+1} / w_i$$

- Smallest finishing time first scheduling policy

Properties of WFQ

- Guarantee that any packet is transmitted within *packet_length/link_capacity* of its transmission time in the fluid flow system
  - Can be used to provide guaranteed services
- Achieve fair allocation
  - Can be used to protect well-behaved flows against malicious flows

Fair Queuing Tradeoffs

- FQ can control congestion by monitoring flows
  - Non-adaptive flows can still be a problem – why?
- Complex state
  - Must keep queue per flow
    - Hard in routers with many flows (e.g., backbone routers)
    - Flow aggregation is a possibility (e.g. do fairness per domain)
- Complex computation
  - Classification into flows may be hard
  - Must keep queues sorted by finish times
  - Finish times change whenever the flow count changes

Overview

- Fairness
- Fair-queuing
- Core-stateless FQ
- Other FQ variants

Core-Stateless Fair Queuing

- Key problem with FQ is core routers
  – Must maintain state for 1000's of flows
  – Must update state at Gbps line speeds
- CSFQ (Core-Stateless FQ) objectives
  – Edge routers should do complex tasks since they have fewer flows
  – Core routers can do simple tasks
    - No per-flow state/processing → this means that core routers can only decide on dropping packets not on order of processing
    - Can only provide max-min bandwidth fairness not delay allocation

Core-Stateless Fair Queuing

- Edge routers keep state about flows and do computation when packet arrives
- DPS (Dynamic Packet State)
  - Edge routers label packets with the result of state lookup and computation
- Core routers use DPS and local measurements to control processing of packets

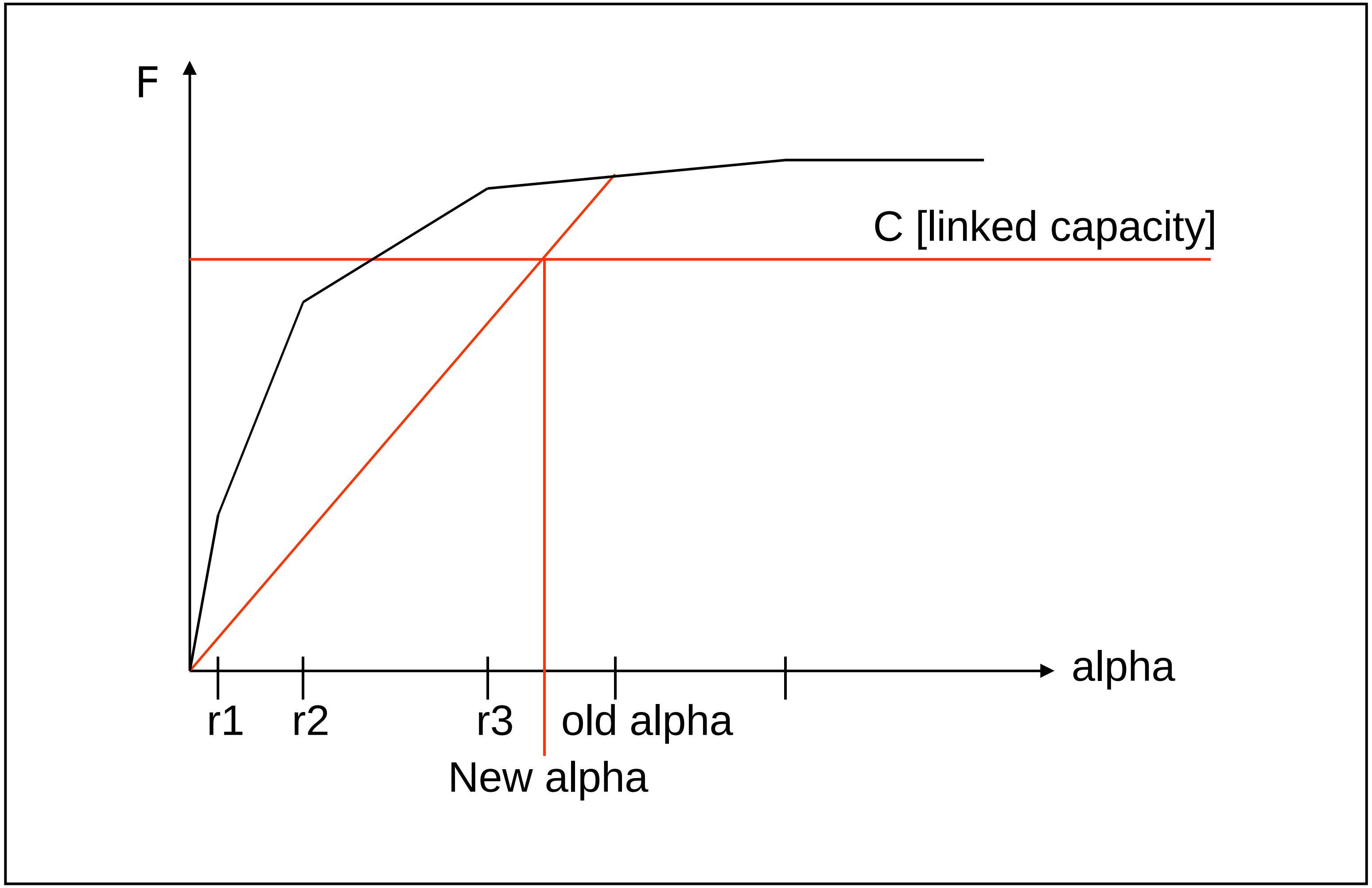
Edge Router Behavior

- Monitor each flow i to measure its arrival rate (r_i)
  - EWMA of rate
  - Non-constant EWMA constant
    - $e^{-T/K}$ where T = current interarrival, K = constant
    - Helps adapt to different packet sizes and arrival patterns
- Rate is attached to each packet

Core Router Behavior

- Keep track of fair share rate α
  - Increasing α does not increase load (F) by $N * \alpha$
  - $F(\alpha) = \Sigma_i \min(r_i, \alpha)$ → what does this look like?
  - Periodically update α
  - Keep track of current arrival rate
    - Only update α if entire period was congested or uncongested
- Drop probability for packet = $\max(1-\alpha/r, 0)$

F vs. Alpha



Estimating Fair Share

- Need $F(\alpha)$ = capacity = C
  - Can't keep map of $F(\alpha)$ values → would require per flow state
  - Since $F(\alpha)$ is concave, piecewise-linear
    - $F(0) = 0$ and $F(\alpha)$ = current accepted rate = F_c
    - $F(\alpha) = F_c / \alpha$
    - $F(\alpha_{new}) = C$ → $\alpha_{new} = \alpha_{old} * C/F_c$
- What if a mistake was made?
  - Forced into dropping packets due to buffer capacity
  - When queue overflows α is decreased slightly

Other Issues

- Punishing fire-hoses – why?
  - Easy to keep track of in a FQ scheme
- What are the real edges in such a scheme?
  - Must trust edges to mark traffic accurately
  - Could do some statistical sampling to see if edge was marking accurately

Overview

- Fairness
- Fair-queuing
- Core-stateless FQ
- Other FQ variants

Stochastic Fair Queuing

- Compute a hash on each packet
- Instead of per-flow queue have a queue per hash bin
- An aggressive flow steals traffic from other flows in the same hash
- Queues serviced in round-robin fashion
  - Has problems with packet size unfairness
- Memory allocation across all queues
  - When no free buffers, drop packet from longest queue

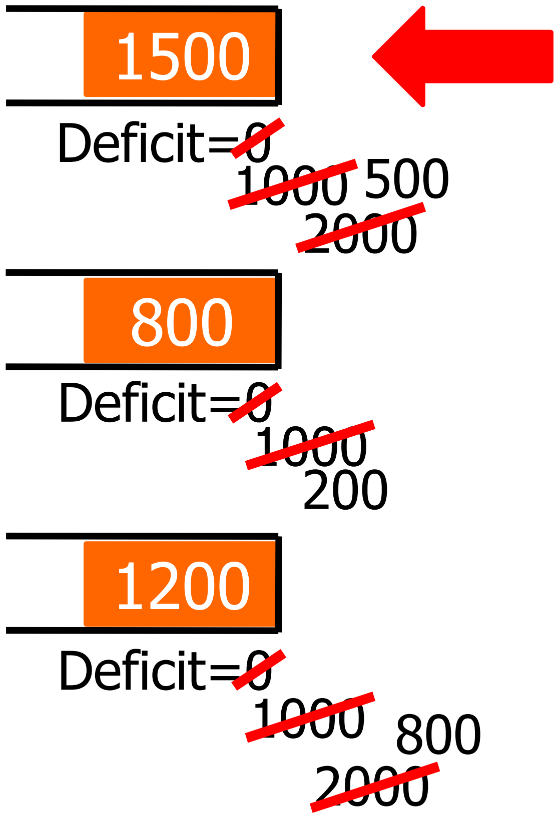
Deficit Round Robin

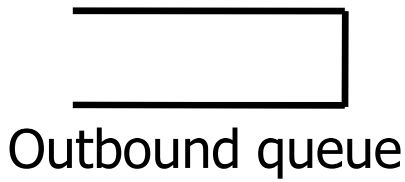
- Each queue is allowed to send Q bytes per round
- If Q bytes are not sent (because packet is too large) deficit counter of queue keeps track of unused portion
- If queue is empty, deficit counter is reset to 0
- Uses hash bins like Stochastic FQ
- Similar behavior as FQ but computationally simpler
  - Bandwidth guarantees, but no latency guarantees

Deficit Round Robin Example

Quantum Size = 1000

1. Increment deficit counter by Quantum Size
2. Send packet if size is greater than deficit
3. When you send a packet, subtract its size from the deficit





Self-clocked Fair Queuing

- Virtual time to make computation of finish time easier
- Problem with basic FQ
  - Need be able to know which flows are really backlogged
    - They may not have packet queued because they were serviced earlier in mapping of bit-by-bit to packet
    - This is necessary to know how bits sent map onto rounds
    - Mapping of real time to round is piecewise linear → however slope can change often

Self-clocked FQ

- Use the finish time of the packet being serviced as the virtual time
  - The difference in this virtual time and the real round number can be unbounded
- Amount of service to backlogged flows is bounded by factor of 2

Start-time Fair Queuing

- Packets are scheduled in order of their start not finish times
- Self-clocked → virtual time = start time of packet in service
- Main advantage → can handle variable rate service better than other schemes

Mobility models

CS 598: Advanced Internetworking

Matthew Caesar

March 3, 2011

Entity model: Random Walk

- A mobile node moves from its current location to a new location by randomly choosing a direction and speed in which to travel.

- Random Walk is a memoryless mobility pattern. This characteristic can generate unrealistic movements such as sudden stops and sharp turns

Random Walk Example

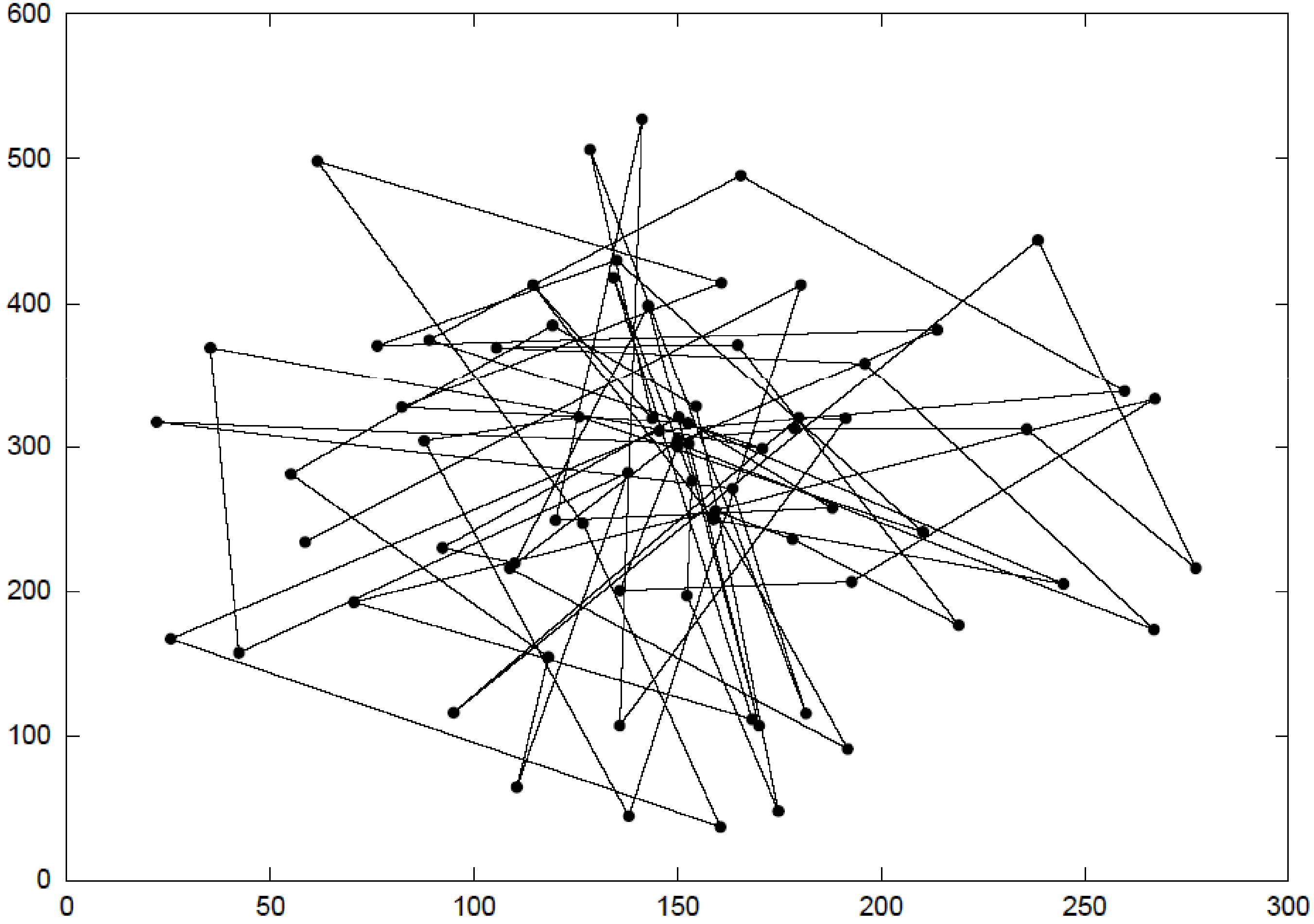


Figure 1: Traveling pattern of an MN using the 2-D Random Walk Mobility Model (time).

Entity model: Random Waypoint

- The Random Waypoint Mobility Model includes pause times between changes in direction and/or speed.
  - A mobile node stays in one location for a certain period of time (i.e., a pause time).
  - Once this time expires, the node chooses a random destination in the simulation area and a speed that is uniformly distributed between *[minspeed,maxspeed]*. The node then travels toward the newly chosen destination at the selected speed.
  - Repeat above two steps

- Often in the model, the nodes are initially distributed randomly around the simulation area. This initial random distribution of MNs is *not representative of the manner in which nodes distribute themselves when moving*.

Random Waypoint Example

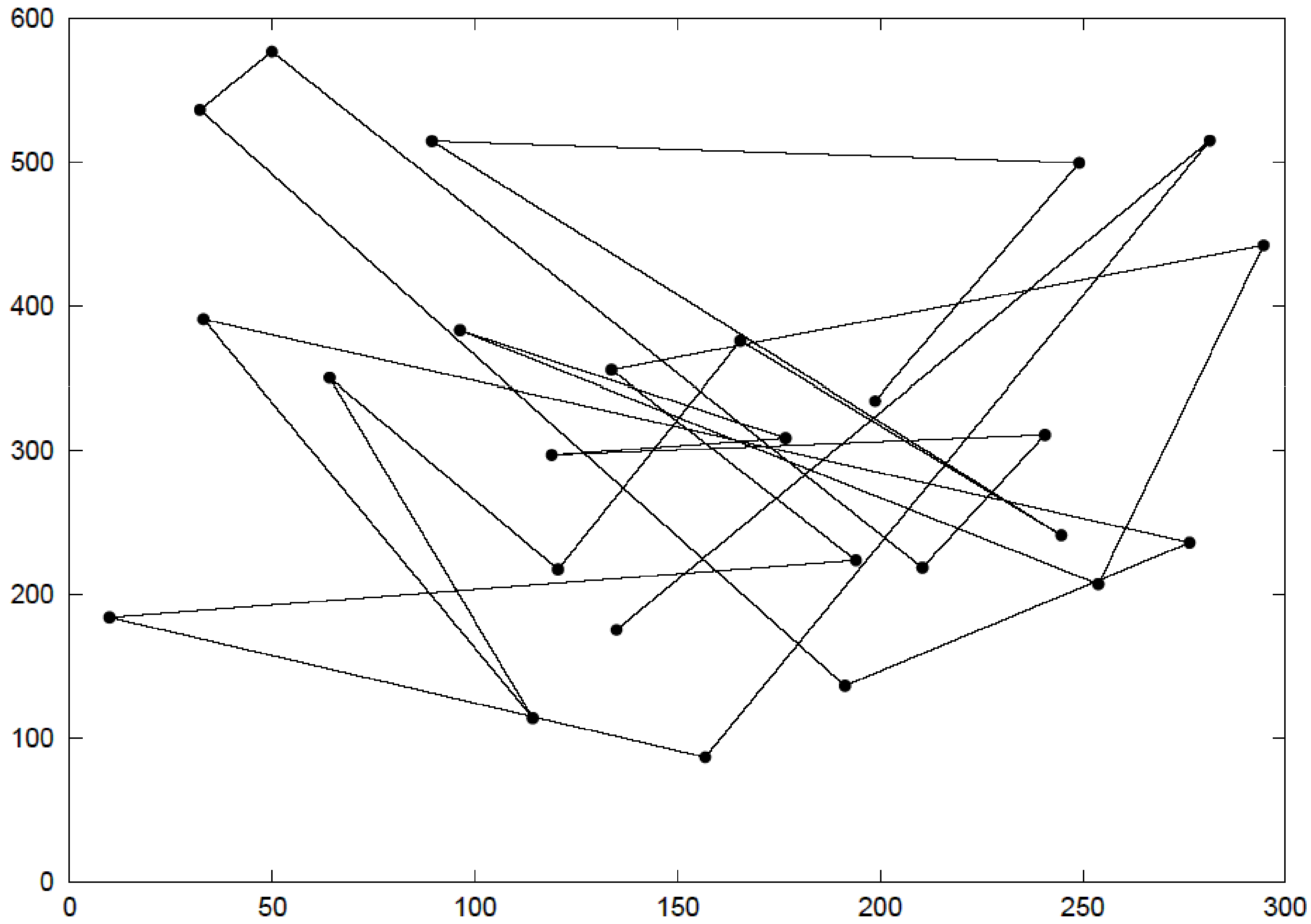


Figure 3: Traveling pattern of an MN using the Random Waypoint Mobility Model.

Other variants

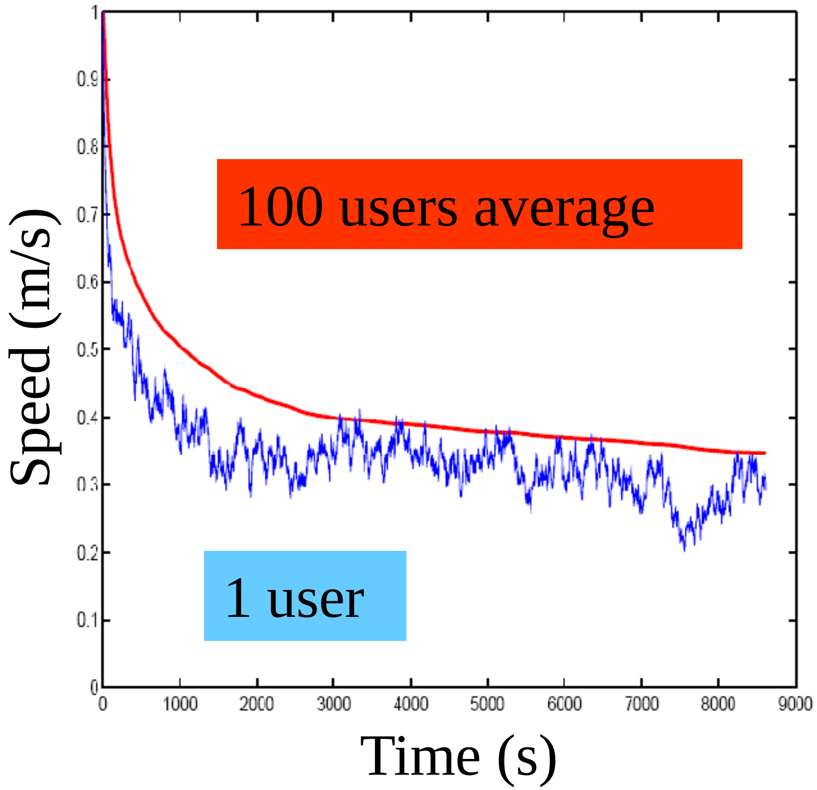
- Restricted Random Waypoint Model
  - Observation: on earth, there are obstacles to node movement
    - E.g., Buildings, trees
    - Nodes cannot walk through these obstacles
  - Place a set of obstacles
  - Choose waypoint direction randomly, but truncate length to avoid going through an obstacle

- The Reference Point Group Mobility (RPGM) model
  - Observation: in practice, nodes move as groups
    - E.g., cell phones on a train
  - Nodes associated into groups, groups move collectively
  - Individual nodes move around with small offsets to the group's movement

- City Section Mobility model
  - Observation: users on cars have very specific mobility pattern
    - Eg., can't go faster than car in front of you, cars collectively slow down/speed up, cars traverse grid-like pattern of streets
  - Nodes move in car-like patterns

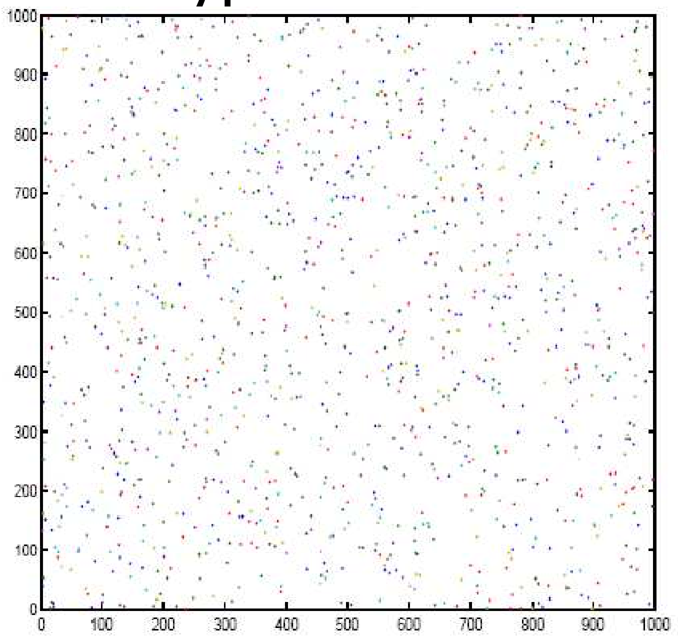
Challenges with mobility models

- Distributions of node speed, position, distances, etc change with time
- E.g., random waypoint:

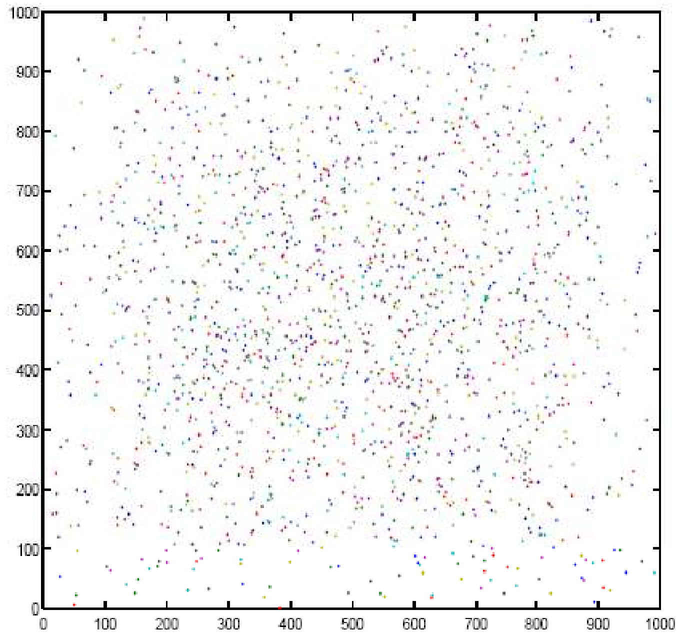


Challenges with mobility models

- Distributions of node speed, position, distances, etc change with time
  - E.g., distribution of node position under random waypoint:



Time = 0 sec



Time = 2000 sec

Finishing up DHTs

CS 598: Advanced Internetworking

Matthew Caesar

March 3, 2011

Security issues

- Sybil attacks
  - Malicious node pretends to be many nodes
  - Can take over large fraction of ID space, files
- Eclipse attacks
  - Malicious node intercepts join requests, replies with its cohorts as joining node's fingers
- Solutions:
  - Perform several joins over diverse paths, PKI, leverage social network relationships, audit by sharing records with neighbors

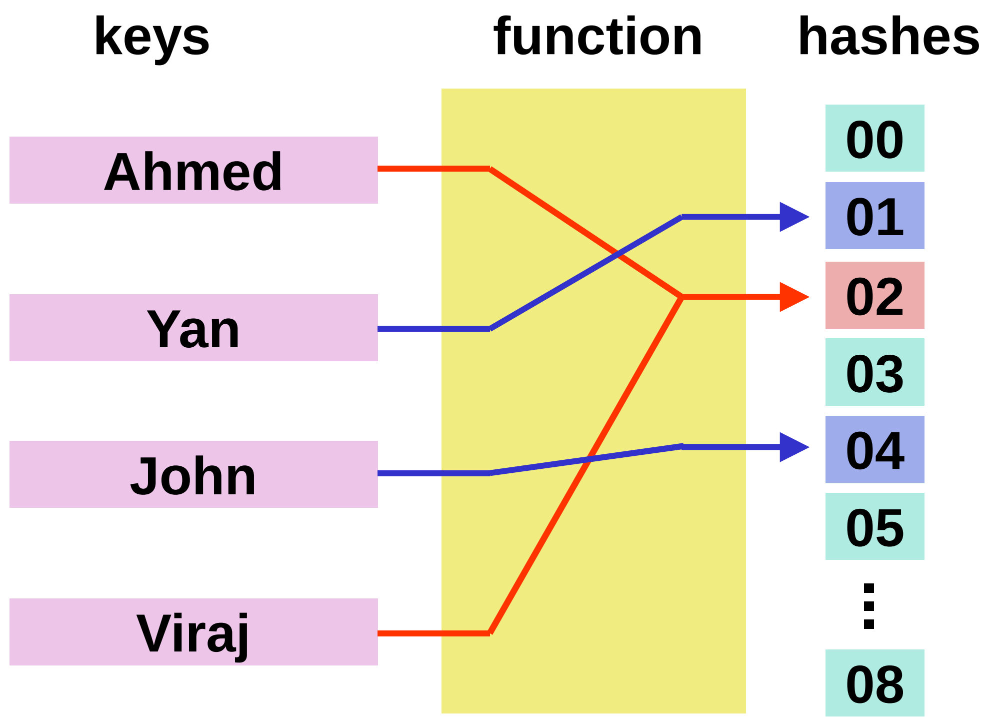
One-hop DHTs

- Idea: maintain global state of all nodes
  - Might get this for free (link state routing)
  - Hash over all visible nodes
- Benefits:
  - Reduces number of hops to reach a key
  - "Worth it" when node lifetimes weeks/months, when hundreds/thousands of lookups/second per node
  - Used in Amazon dynamo, cluster load balancing

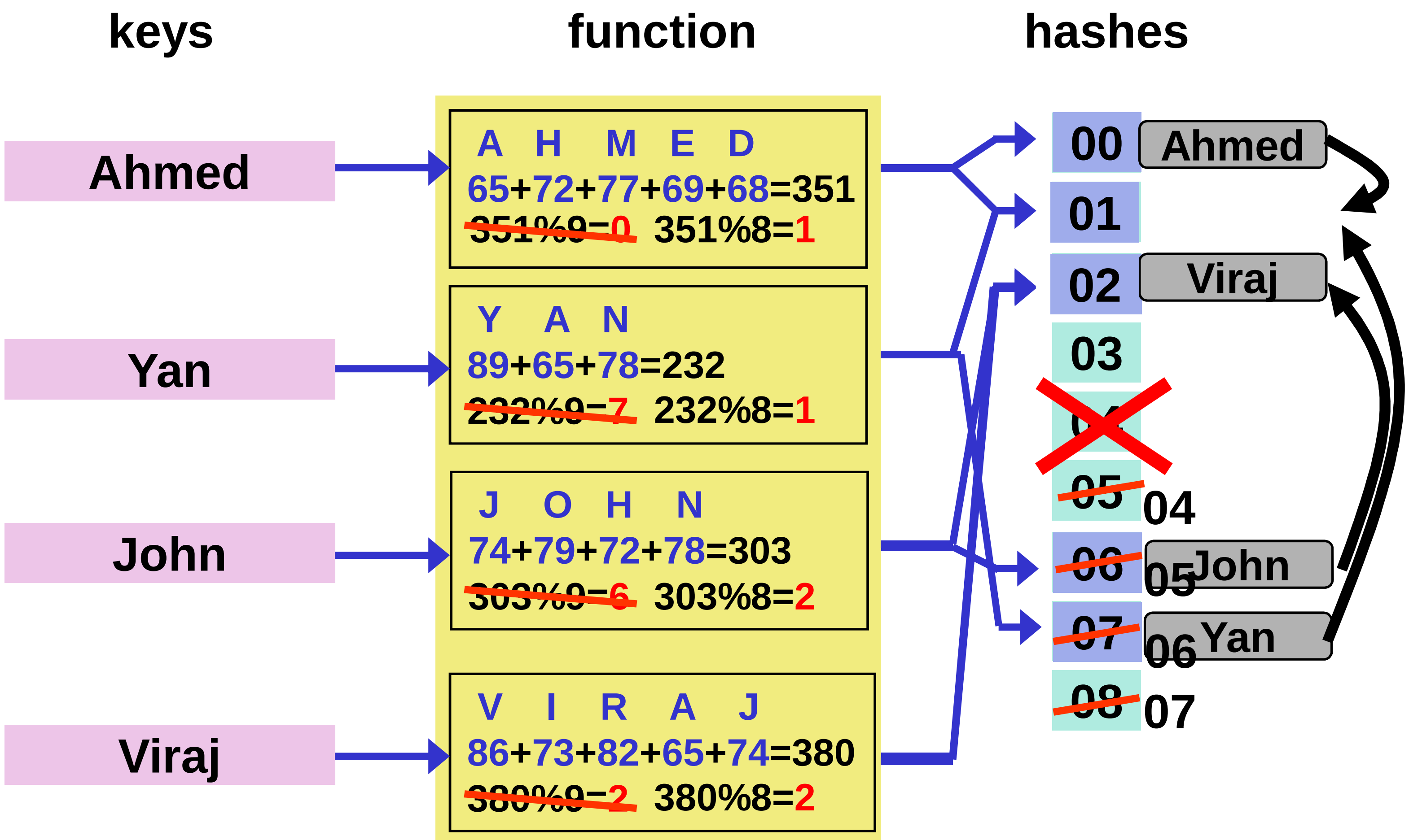
Consistent Hashing: Background

- Hash table: maps identifiers to keys
  - Hash function used to transform key to index (slot)
  - To balance load, should ideally map each key to different index
- Distributed hash tables
  - Stores values (e.g., by mapping keys and values to servers)
  - Used in distributed storage, load balancing, peer-to-peer, content distribution, multicast, anycast, botnets, BitTorrent’s tracker, etc.

Background: hashing



Example

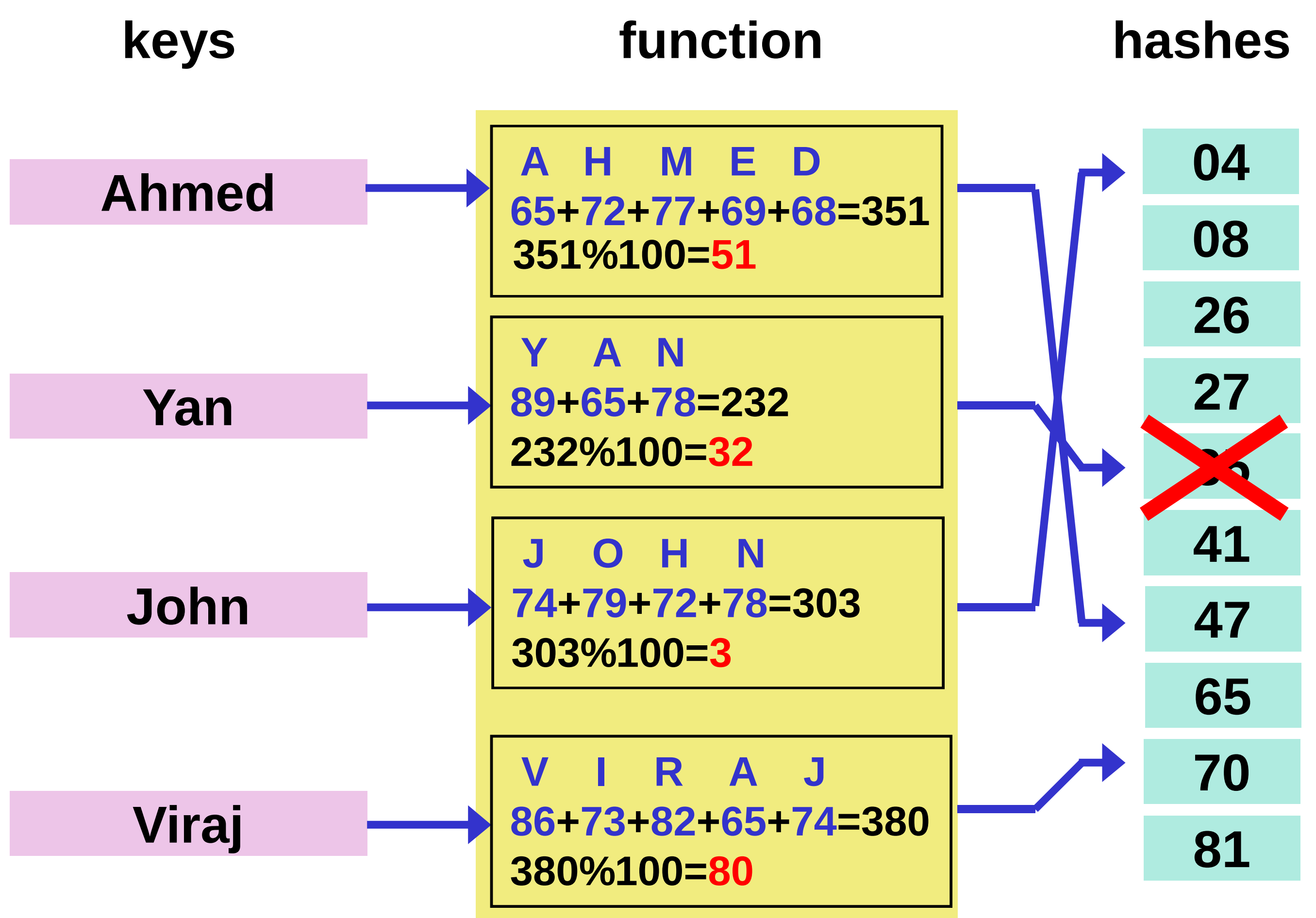


- Example: Sum ASCII digits, mod number of bins
- Problem: ______________________

Solution: Consistent Hashing

- Hashing function that reduces churn
- Addition or removal of one slot does not significantly change mapping of keys to slots
- Good consistent hashing schemes change mapping of K/N entries on single slot addition
  - K: number of keys
  - N: number of slots
- E.g., map keys and slots to positions on circle
  - Assign keys to closest slot on circle

Solution: Consistent Hashing



- Slots have IDs selected randomly from [0,100]
- Hash keys onto same space, map key to closest bin
- Less churn on failure → more stable system