Weighted Fair Queuing

"A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks",

A. Parekh, R. Gallager, IEEE/ACM Trans. on Networking June 1993, April 1994

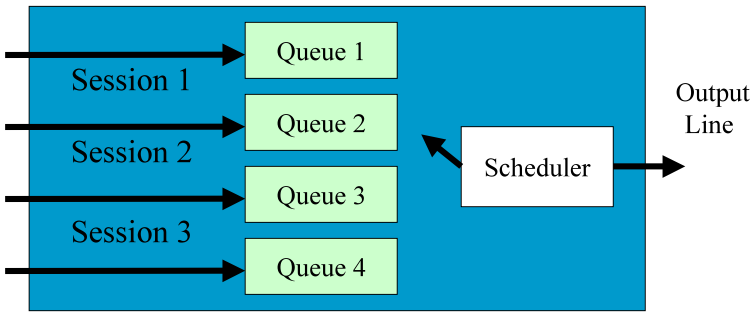
"WF^{2}Q: Worst Case Fair Weighted Fair Queuing",

Jon Bennett, Hui Zhang, IEEE INFOCOM 1996

Generic Switch Structure

- A Scheduling Discipline *resolves contention*. Decides who's next?
- Can differentiate users / classes of traffic.

Switch Output Module

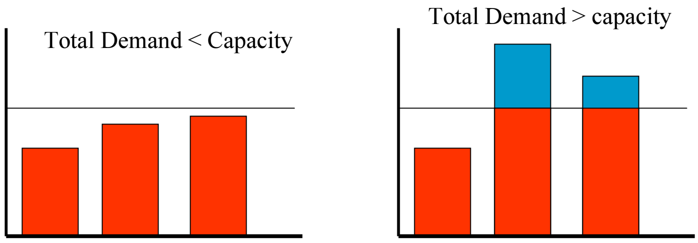


Scheduling

- Desired Properties
  - *Fair* resource sharing.
  - Performance guarantees.
  - Offer different users different quality of services
- Where?
  - Wherever contention for resources occurs.
  - We will concentrate on the output of a network layer switch.

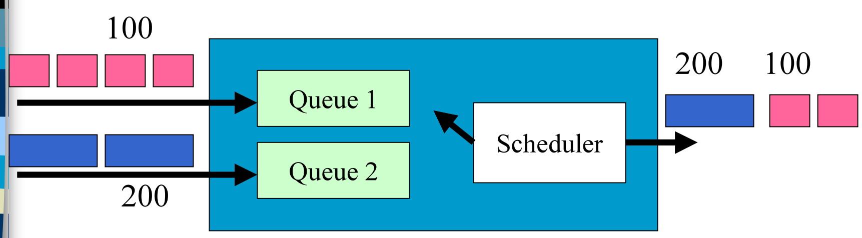
Max-Min Fairness

- Assume all users have equal *rights* (priority) to a resource:
  - Each connection gets no more than what it wants.
  - Excess is distributed evenly across connections.
- Possible to generalize for the *weighted* case: Some connections are more important than others.



Fairness

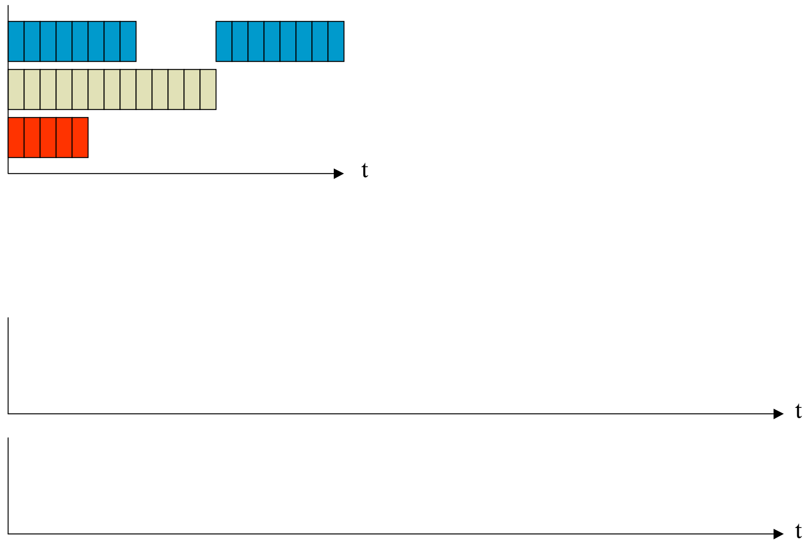
- Fairness is *intuitively* a good idea.
- But it also provides *protection*
  - traffic hogs cannot overrun others
  - No need to be aggressive to get what you want.



Outline

- Introduction to Link Scheduling
- Generalized Processor Sharing (GPS)
- Weighted Fair Queuing
- Worst Case Fair WFQ (WF^{2}Q)
- GPS Performance Guarantees
- Real World Use

Bit Round Robin Scheduling



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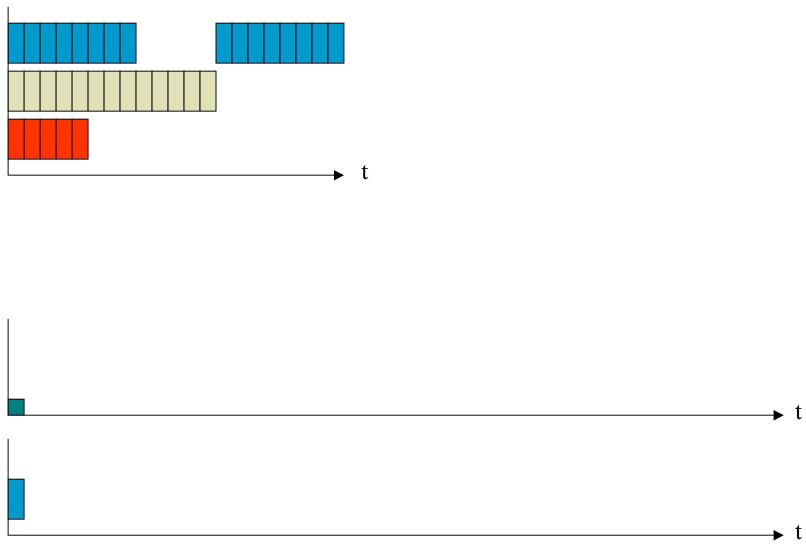

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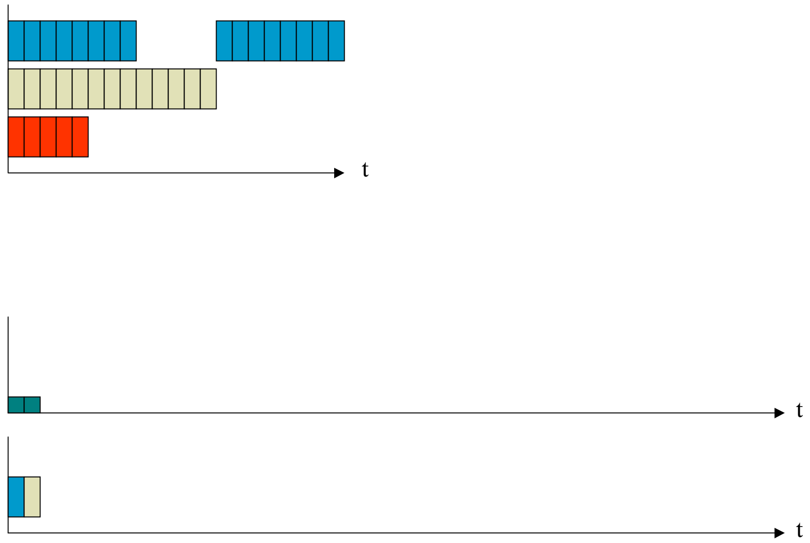

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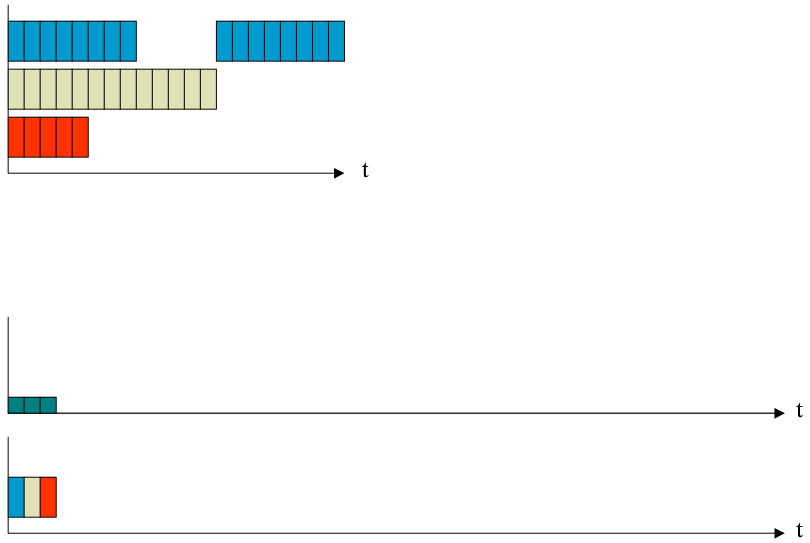

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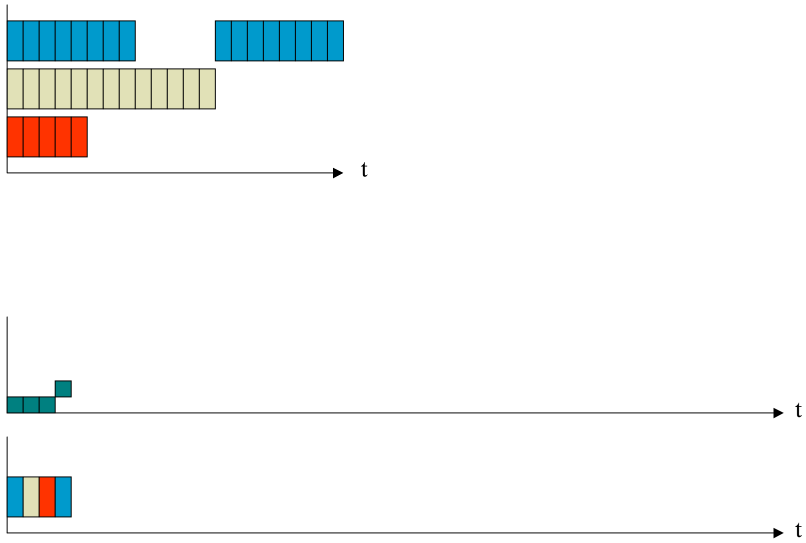

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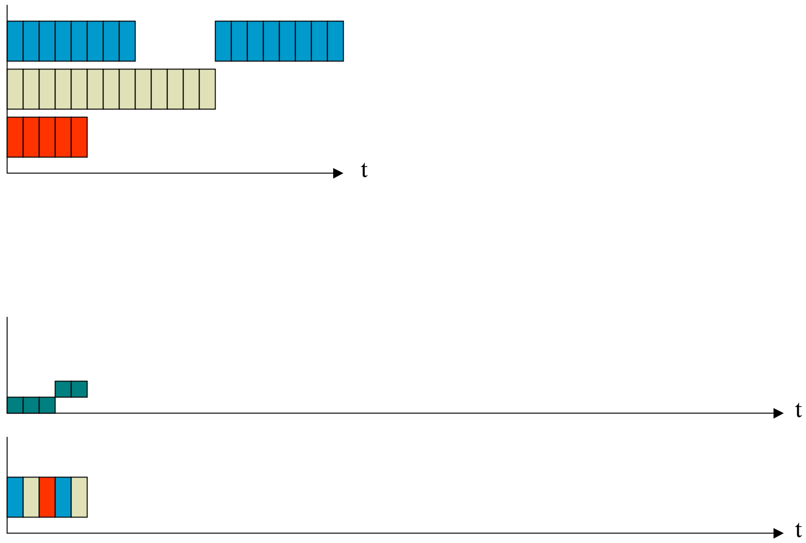

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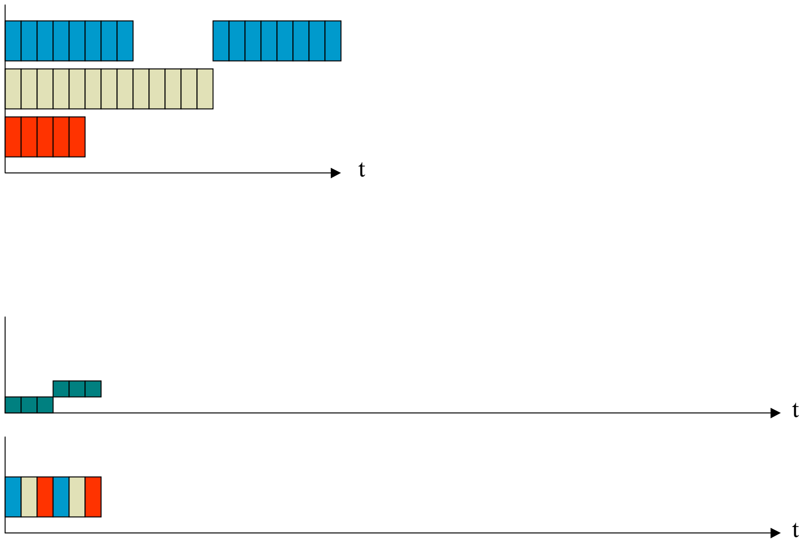

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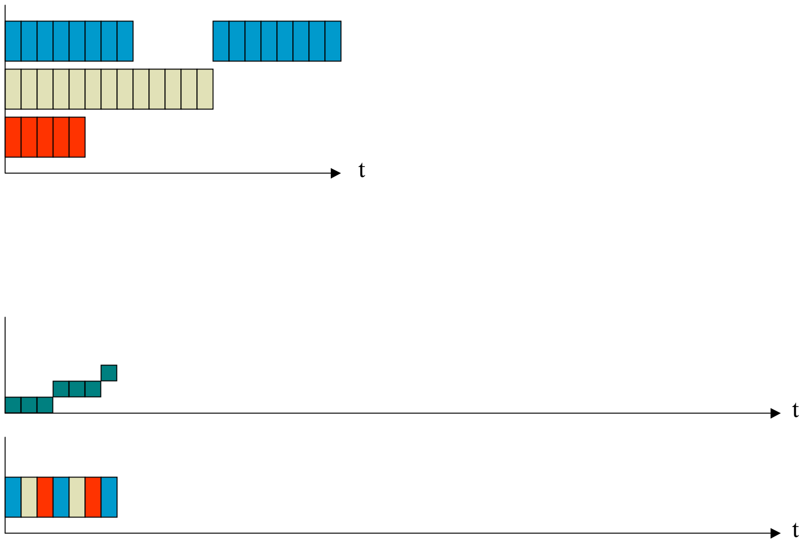

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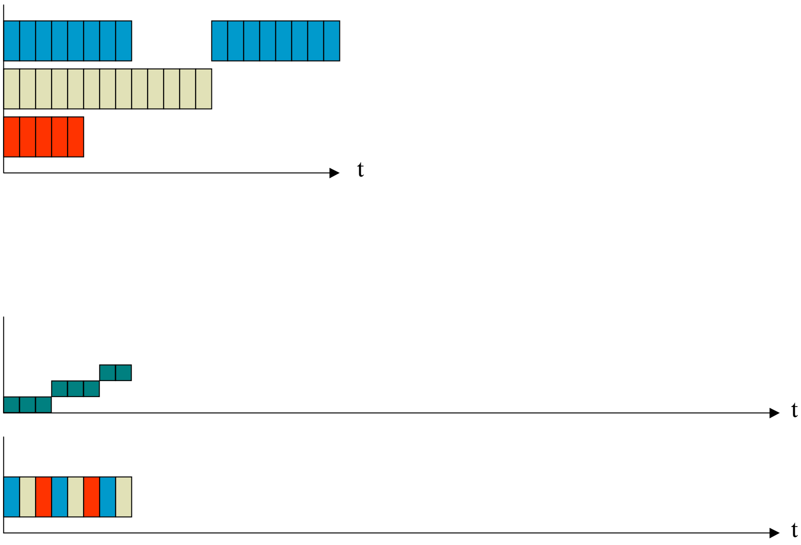

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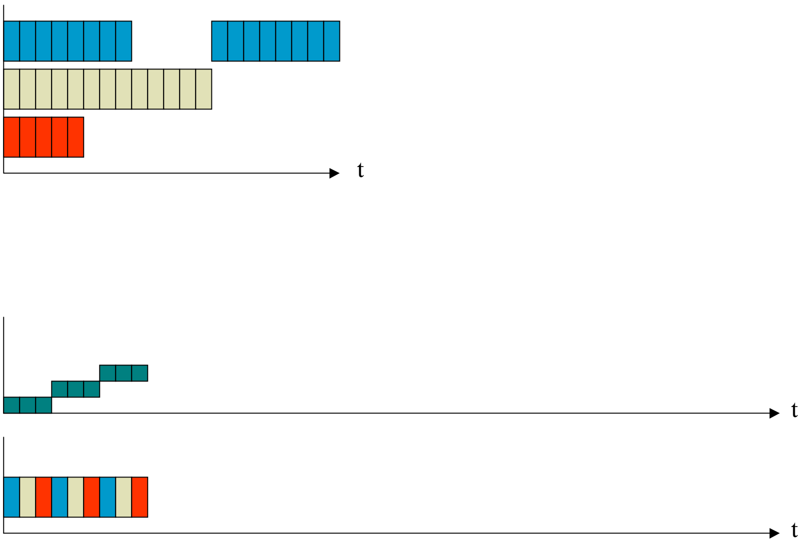

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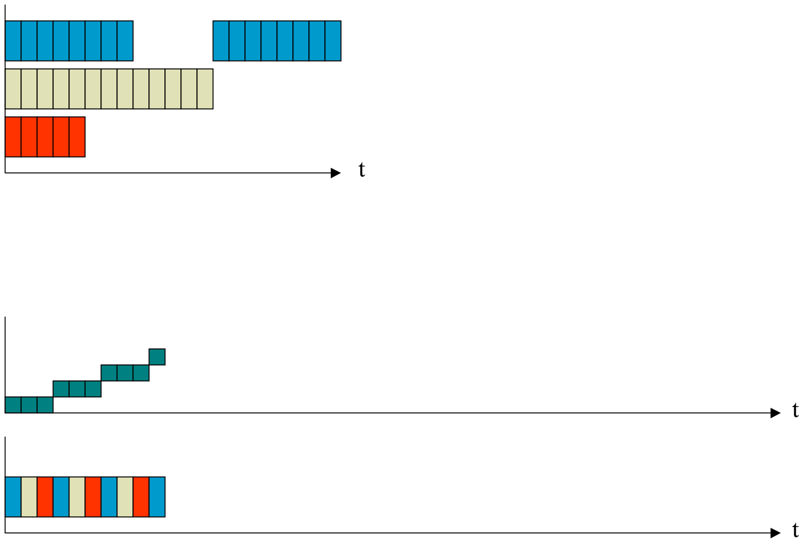

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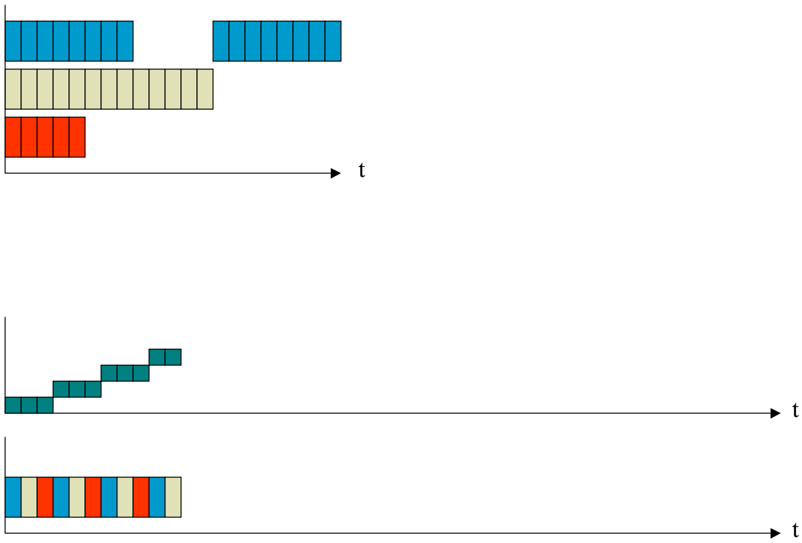

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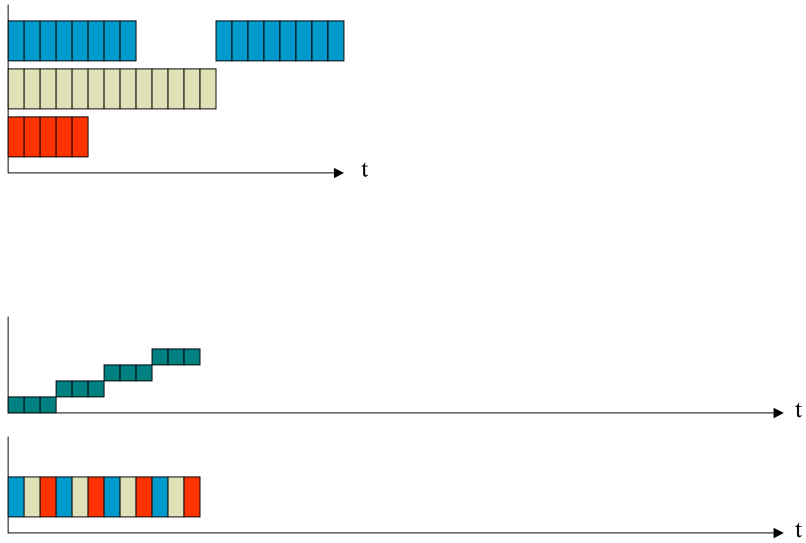

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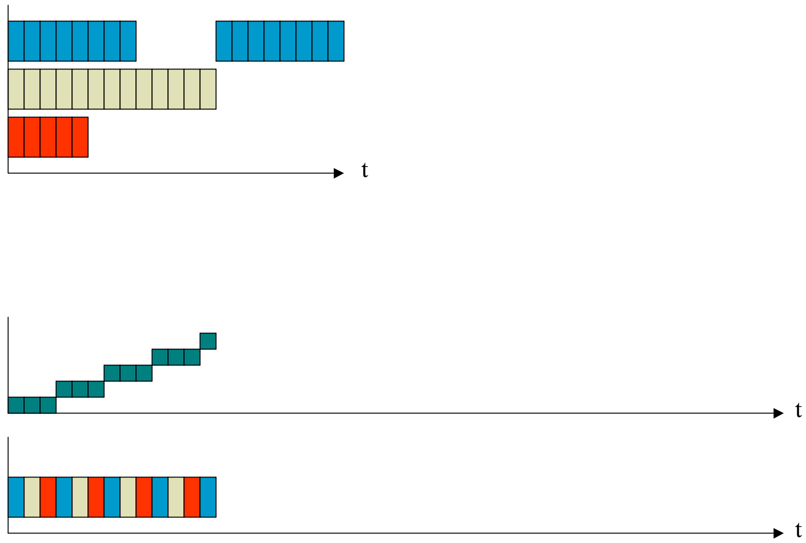

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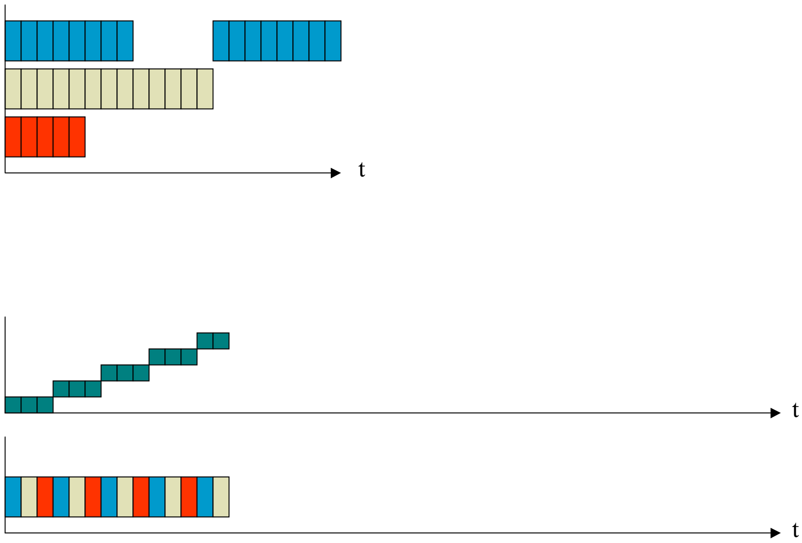

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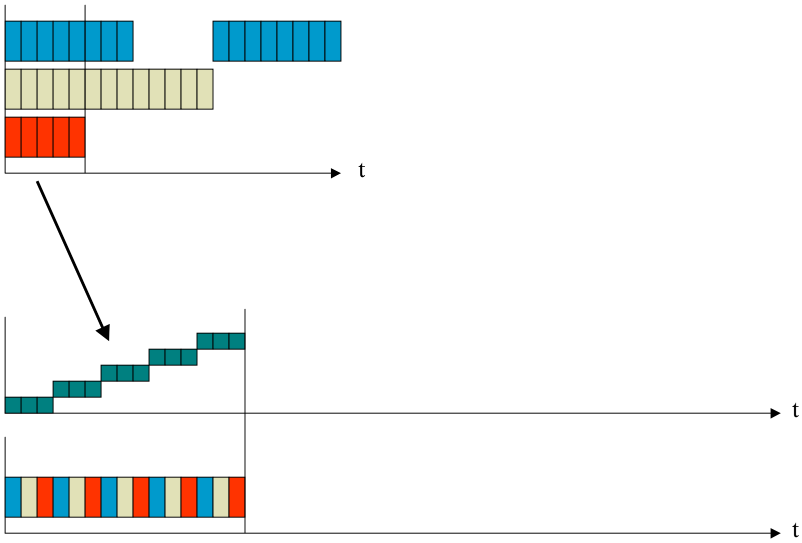

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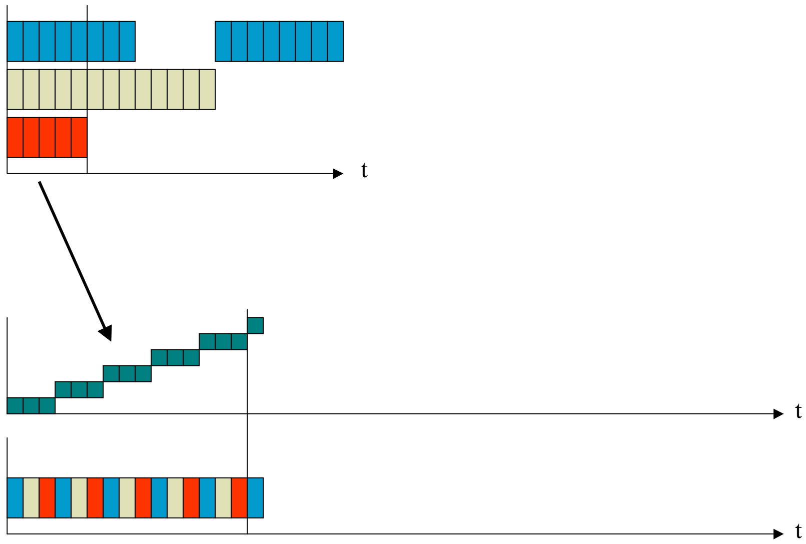

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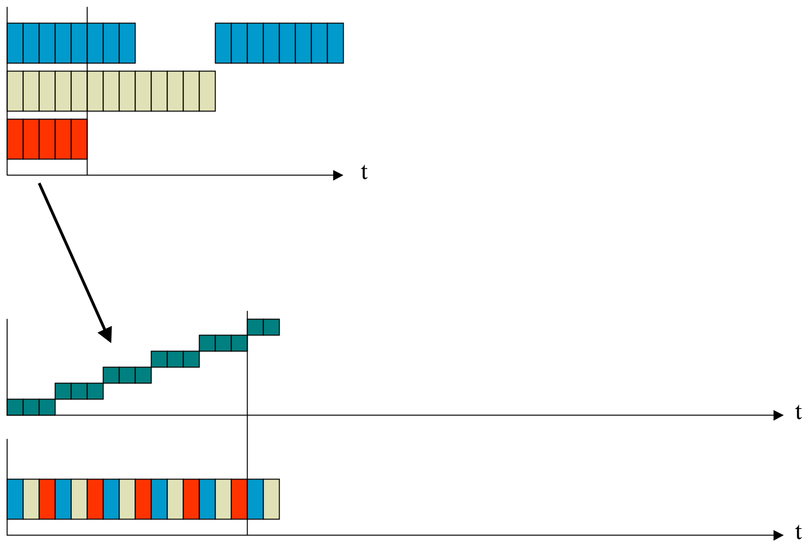

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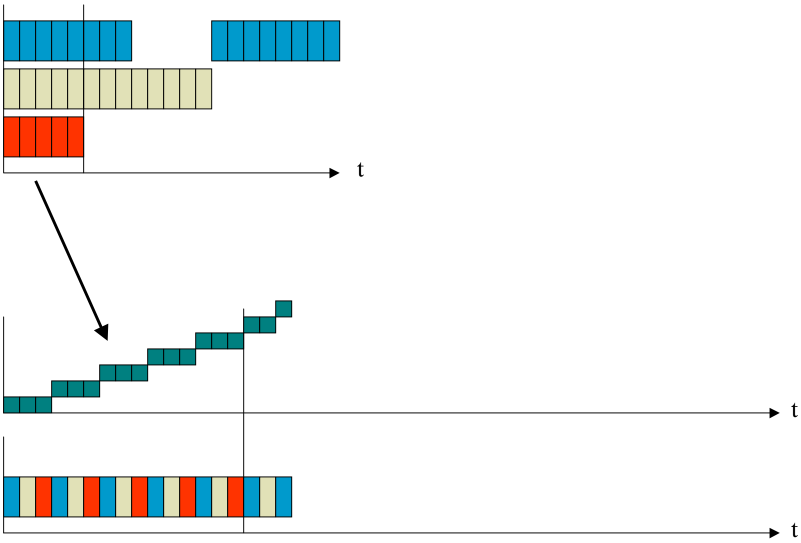

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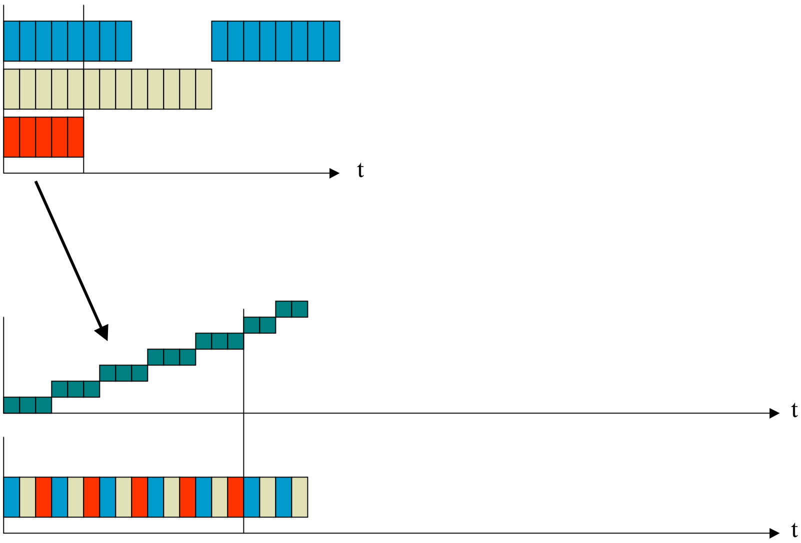

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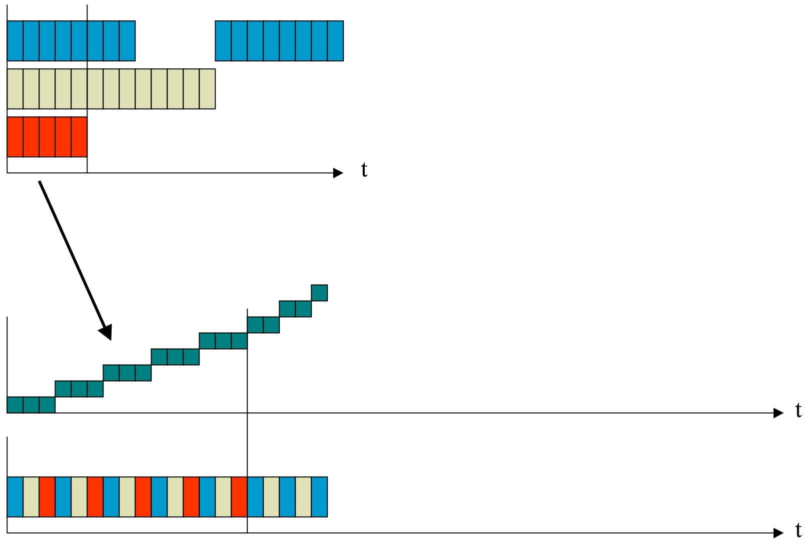

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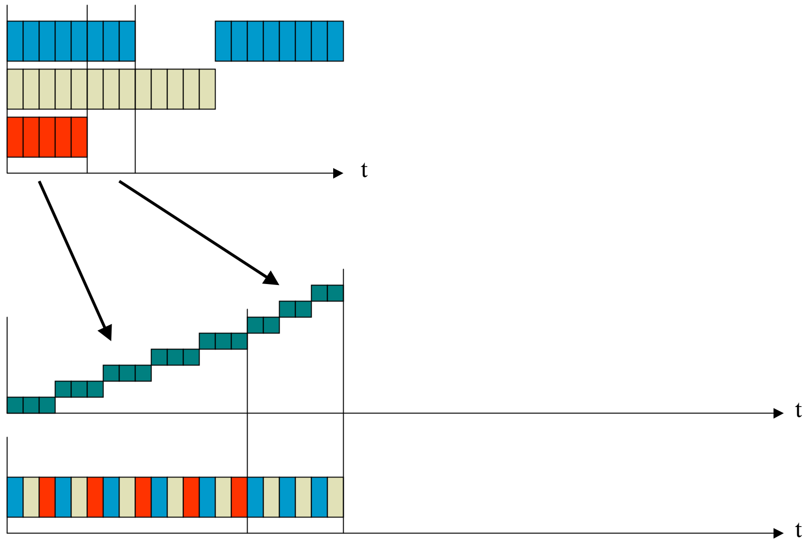

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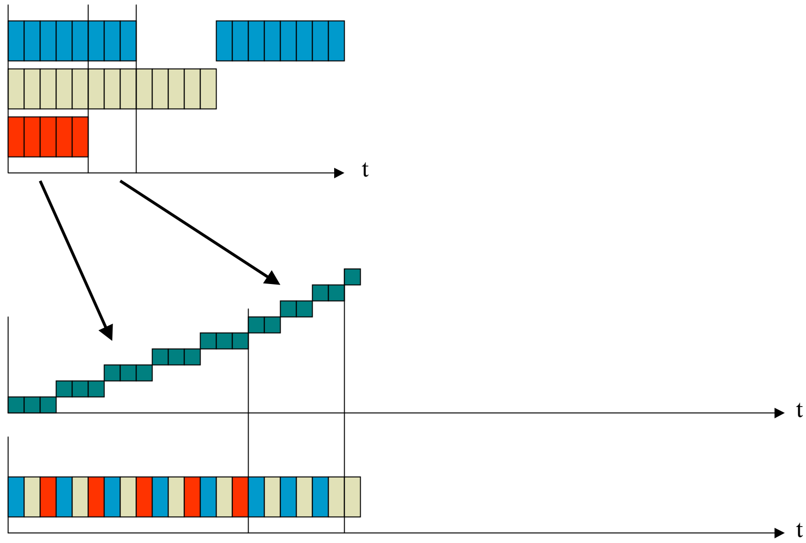

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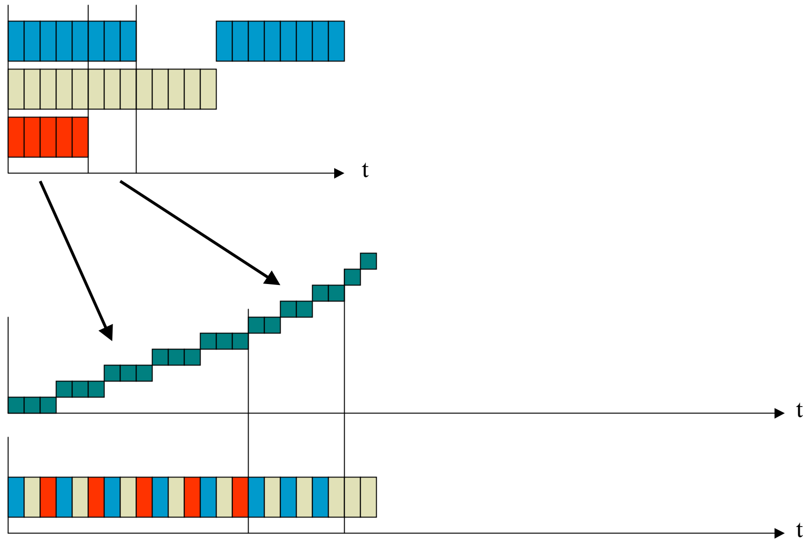

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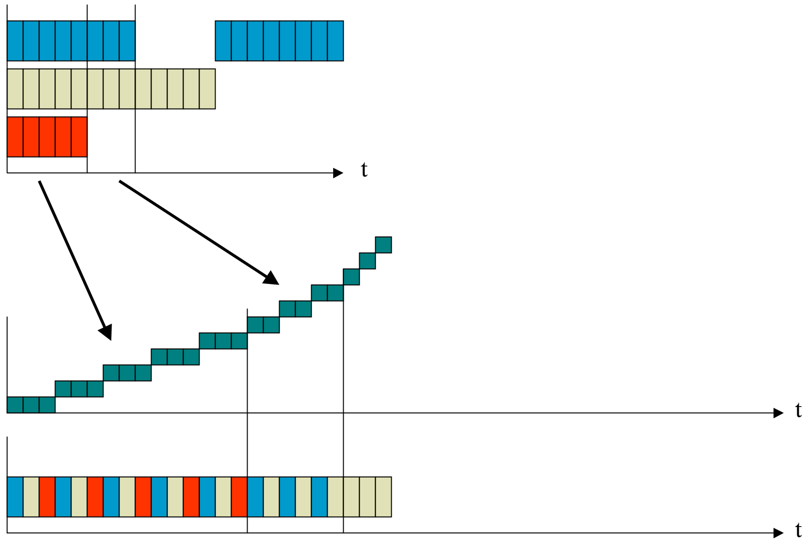

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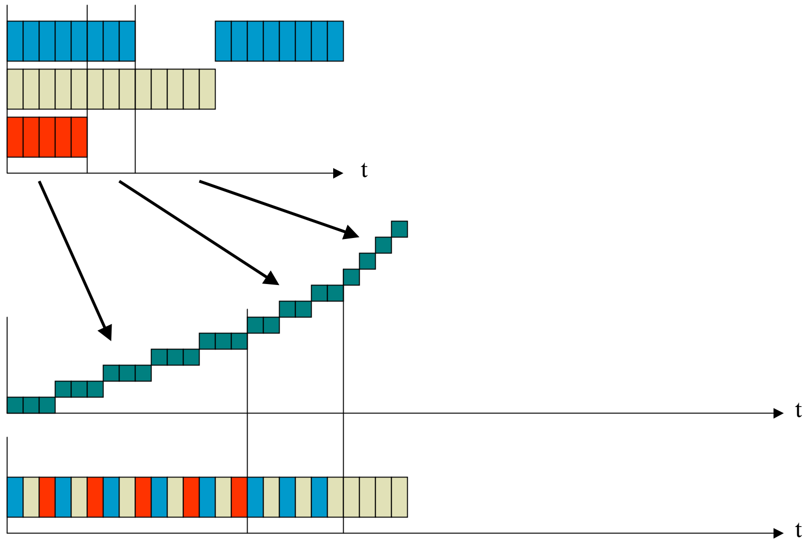

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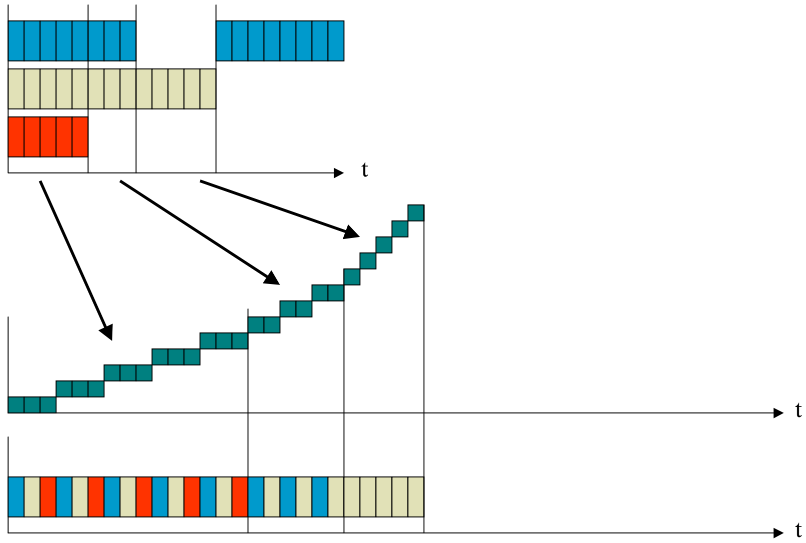

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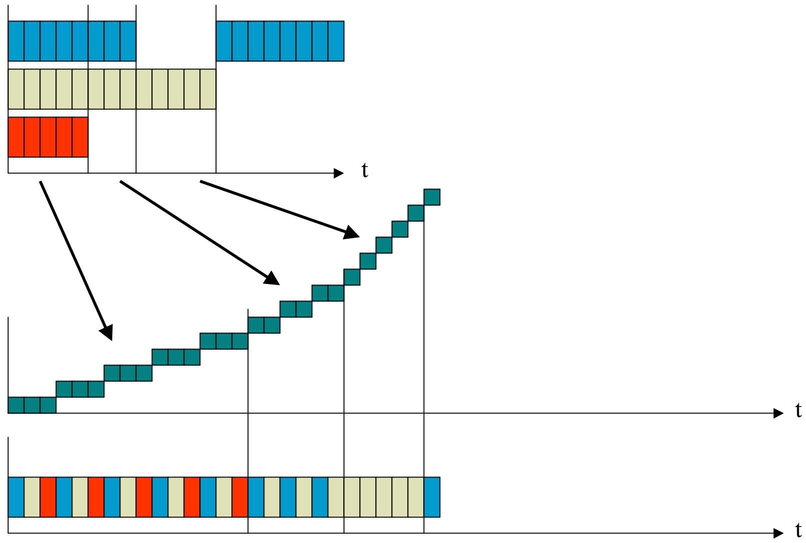

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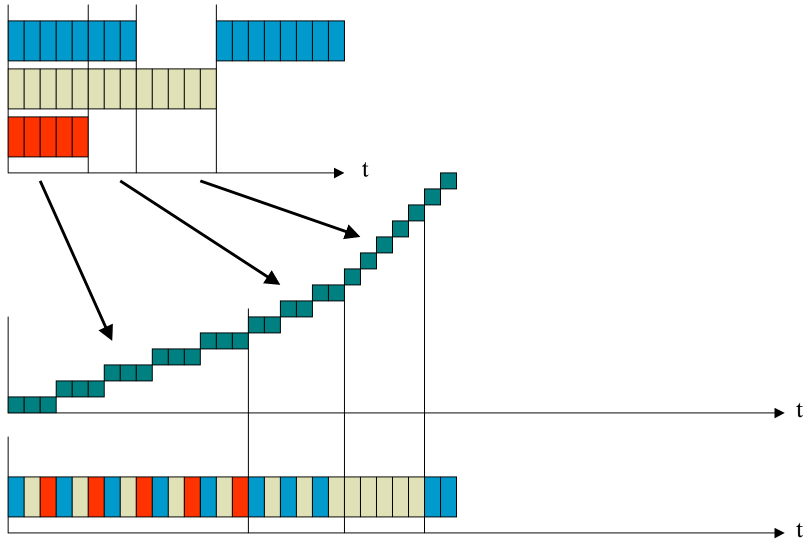

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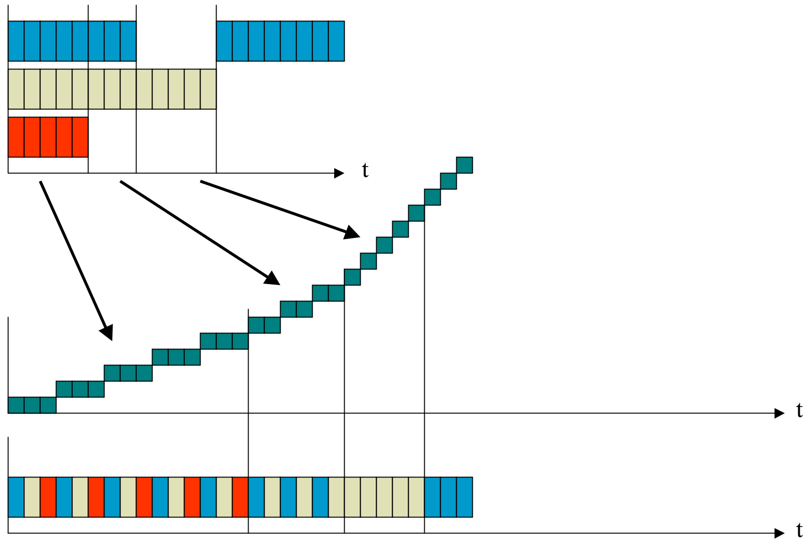

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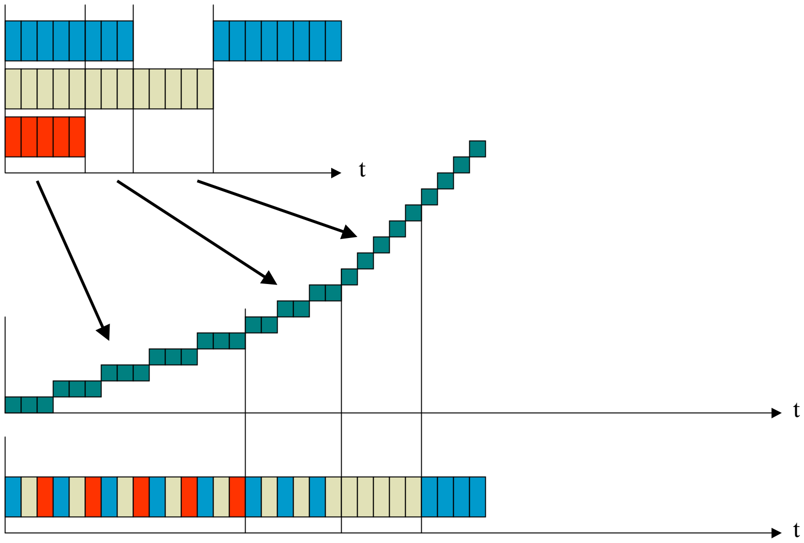

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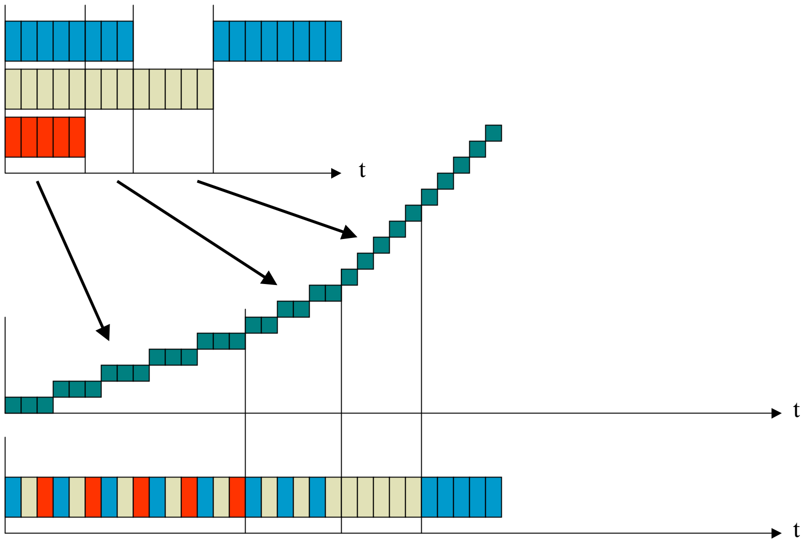

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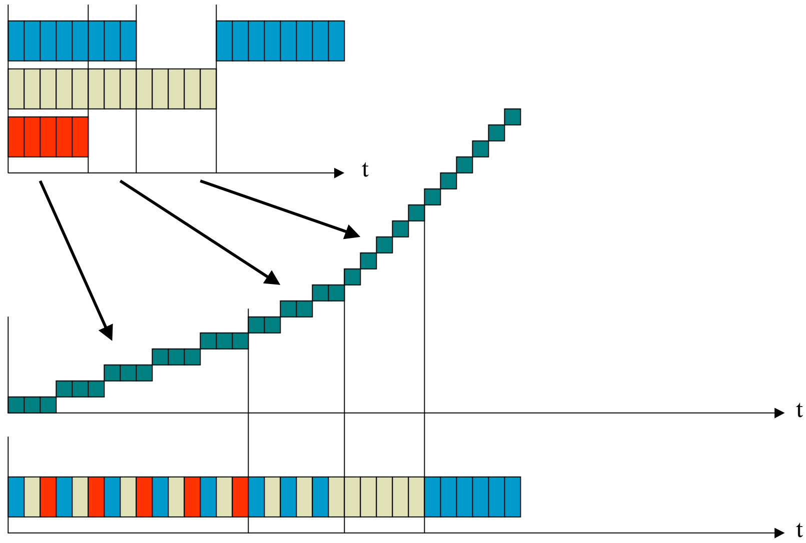

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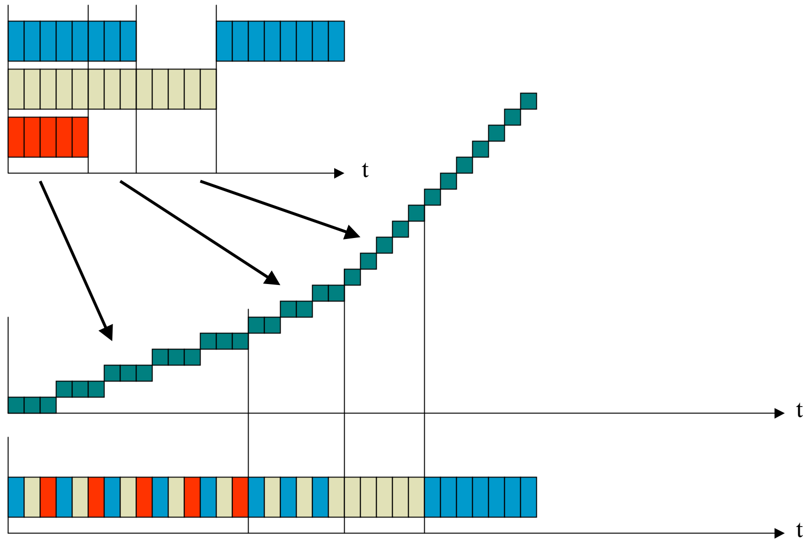

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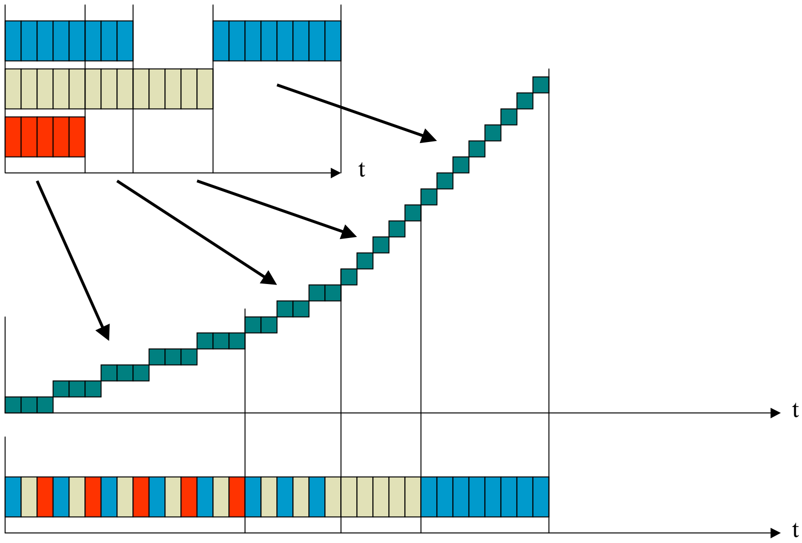

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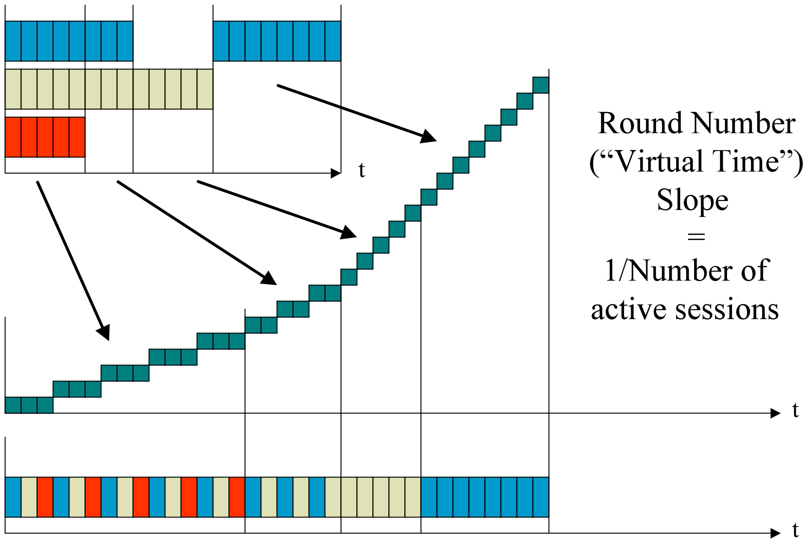
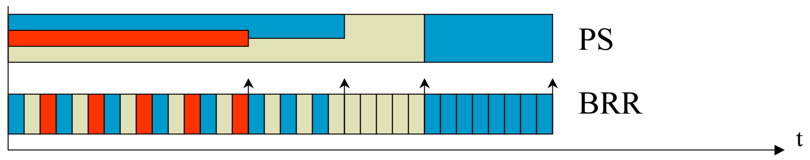


Generalized Processor Sharing

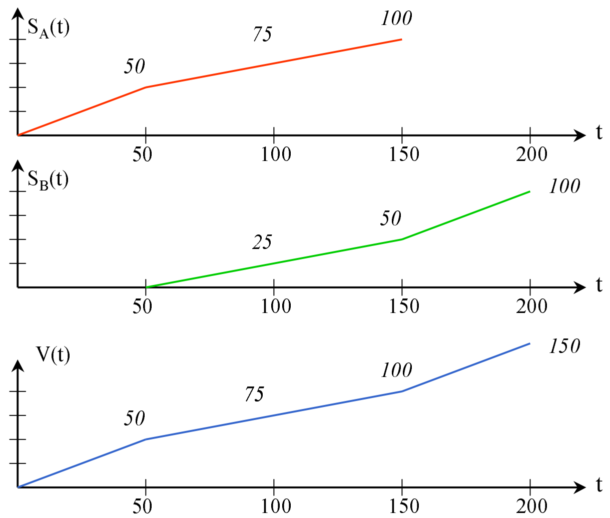
- Can add *weights* to each flow:
  - A flow with weight "2" gets to send two bits per round.
- Processor Sharing - send a small fraction of a bit each round
  - Like having multiple flows *sharing* the output line at the same time.
  - No flow has to wait for "its turn".
  - Is perfectly fair at all times.



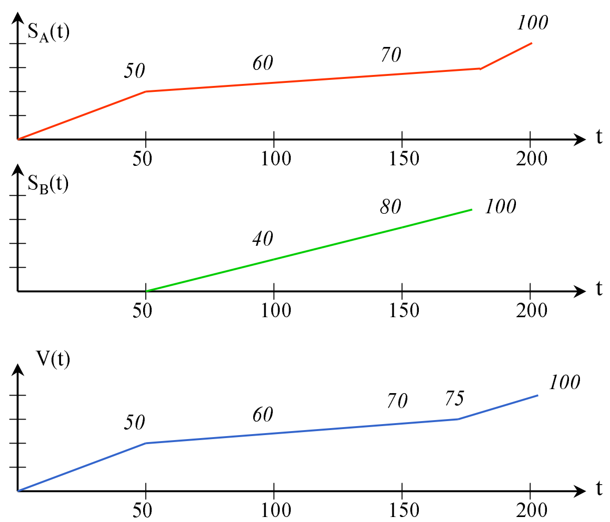
PS - Another Example

- Packet A arrives at time 0
- Packet B arrives at time 50
- Both packets are 100 bits long.
- Output line rate is 1 b/s.

PS - Another Example



GPS - A Weighted Example



$W_A = 1$

$F_A = V(0) + L / W_A$
$= 0 + 100 / 1$
$= 100$

$W_B = 4$

$F_B = V(50) + L / W_B$
$= 50 + 100 / 4$
$= 75$

Fair Queuing

- Cannot implement GPS
  - No way to serve more than one flow at a time.
  - Would rather not break packets to small pieces (overhead).
  - No real discipline can be as fair as GPS: when flow A is served we are unfair to all other flows.
- Can try to emulate GPS
  - Bounded approximation error.
  - Keep implementation cost low.
- "Weighted Fair Queuing", *S. Keshav 1989*.
  (Packet GPS in Parekh terminology)

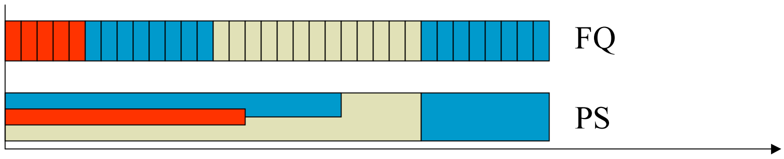
FQ - Basic issues

- Basic Idea
  - Serve packets in order of their *finish time* had we been doing GPS.
  - Cannot always do this unless we know the future.
- Implementation
  - Key idea: Round number (Virtual time) is an increasing function of time.
  - Can calculate finish number of packet when it arrives.
  - Send packets in order of their finish numbers.
  - Need to keep track of current round number V(*t*).

FQ - Example

- Note that FQ (unlike packet by packet round robin) handles variable packet sizes.

Packets are sent in order of departure in the corresponding PS system



FQ - Implementation

- When a packet of flow *f* arrives calculate its finish round number:
  - If flow *f* is active, $F(f, k) = F(f, k\text{-}1) + L(k)$
  - Otherwise, $F(f, k) = V(t) + L(k)$
- Need to keep track of virtual time $V(t)$
  - Slope of $1/N(t)*r$
  - Slope may change whenever a packet arrives (in GPS) or departs.
- Must keep track of active sessions in the simulated GPS systems
  - $Next(t) = t + [\ F_{min} - V(t)\ ]N(t)*r$
  - Computationally expensive.

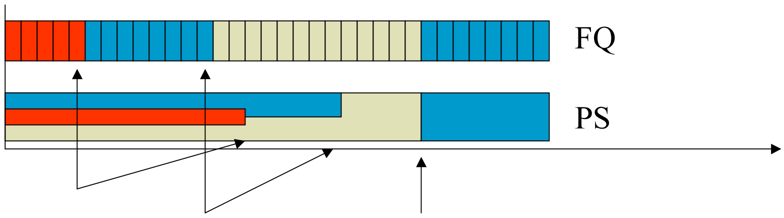
FQ - Implementation

- When the line becomes idle, transmit the packet with the *smallest* finish number.
  - V(t) is an increasing function of time.
  - If $F_A > F_B$, GPS will finish sending packet A *after* packet B.

WFQ and GPS

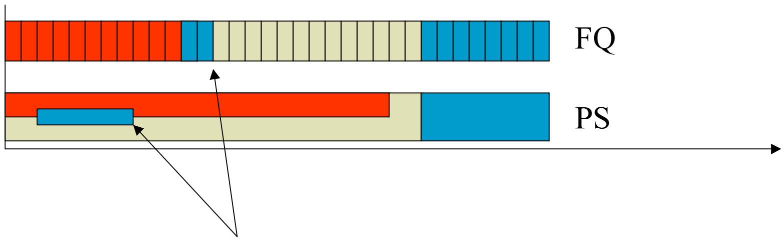
- GPS is not ahead of WFQ by more than one packet (in terms of transmitted bits up to time *t*).
- Packets in WFQ are not delayed more than one packet relative to GPS:
  - $S_{GPS}(f, t) - S_{WFQ}(f, t) \leq L_{max}$
  - $D_{WFQ}(f, k) - D_{GPS}(f, k) \leq L_{max} / r$

Delay Bound



When WFQ and GPS finish packets at the same order,
WFQ will never lag behind GPS.
(And may sometimes be ahead of GPS).

Delay Bound



When a packet arrives too late, it may have to wait for the current packet to finish transmission, hence L_{max}/r delay.

- Error term does *not* accumulate over time.
- May accumulate over multiple network hops.

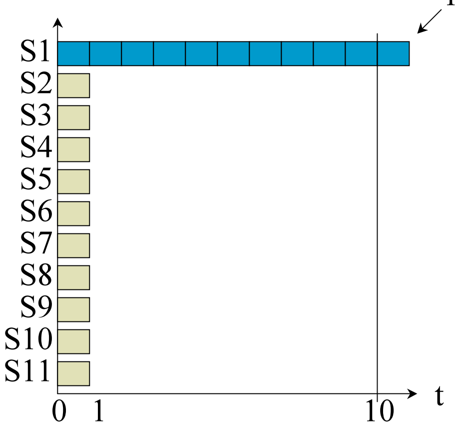
Worst Case WFQ (WF^2Q)

- Contrary to popular belief WFQ does *not* approximate GPS to within a difference of one packet.
  - No lower bound:
    $S_{WFQ}(f, k) - S_{GPS}(f, k) \leq L_{max}$
  - In fact WFQ might be well *ahead* of GPS!

- Less delay, but..
- More *jitter*,
- Difficult to estimate available bandwidth.
  - Necessary for best-effort traffic.

W^2FQ - Example

11th packet

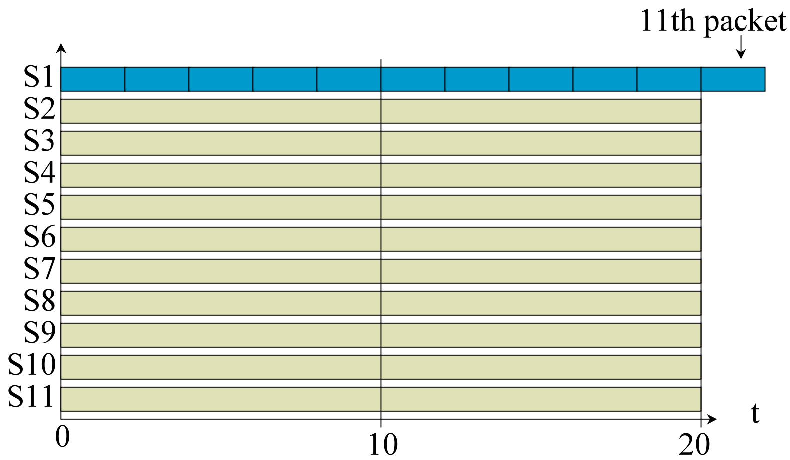


R1=0.5

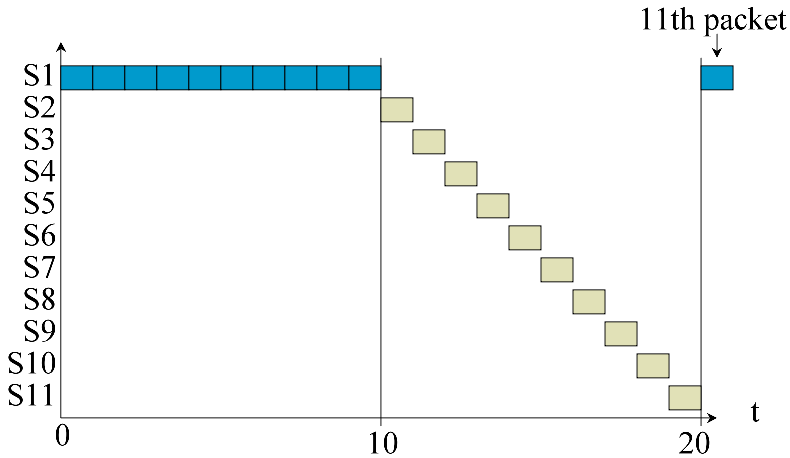
R2=R3=…=R11=0.05

Packet lengths: 1 sec

GPS Service Order



WFQ Service Order



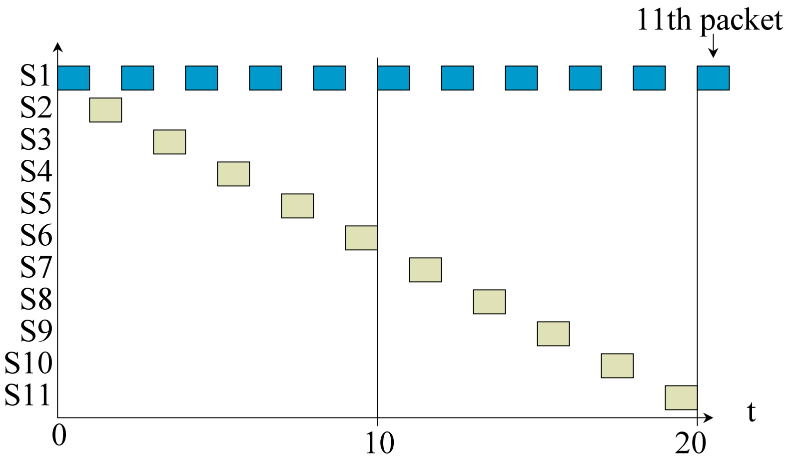
WF²Q Basics

- In WFQ the scheduler selects next packet with minimal finish number, *among all available packets*.
- To minimize difference between packet system and fluid-GPS, scheduler should consider *only packets that have started* in the emulated GPS system.

$$S_{i,GPS}(0,\tau) - S_{i,WF^2Q}(0,\tau) \le L_{\max}$$

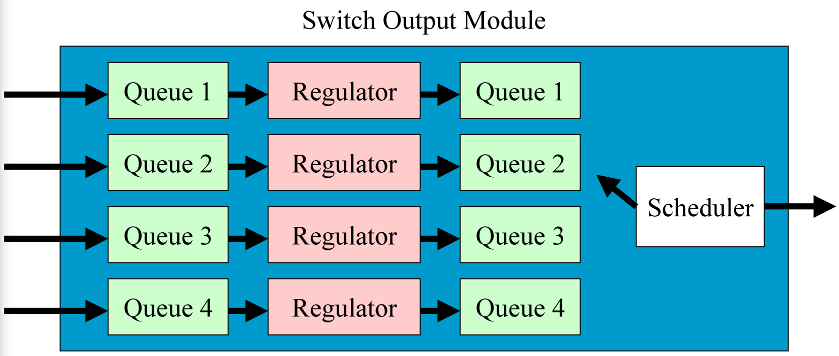
$$S_{i,WF^2Q}(0,\tau) - S_{i,GPS}(0,\tau) \le \left(1 - \frac{g_i}{r}\right) L_{i,\max}$$

W²FQ Service Order



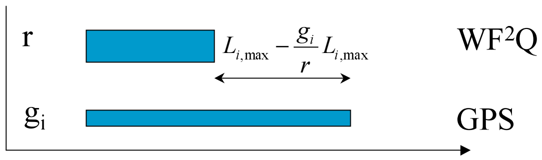
Implementation: Rate Controlled Scheduling

- Regulator holds packets until they are *eligible* for transmission.
- Scheduler decides which eligible packet should be transmitted next.



WF^{2}Q Properties

- Discipline is *work-conserving:*
  - Rate controller + GPS scheduler is the same as GPS alone.
  - Replace GPS with WFQ (both work conserving) to get WF^{2}Q.
- Lower bound
  - WF^{2}Q starts sending packet no earlier than GPS.
  - GPS may take more time to transmit the packet (depending on allocated and available bandwidth).



What next?

- WFQ (or WF^2Q) approximate GPS service to within a constant error term.
- GPS is much simpler to analyze (fluid model).
- Strategy
  - Determine performance bounds for networks of GPS schedulers.
  - Use our previously derived bounds to bound the performance of a corresponding WFQ network.

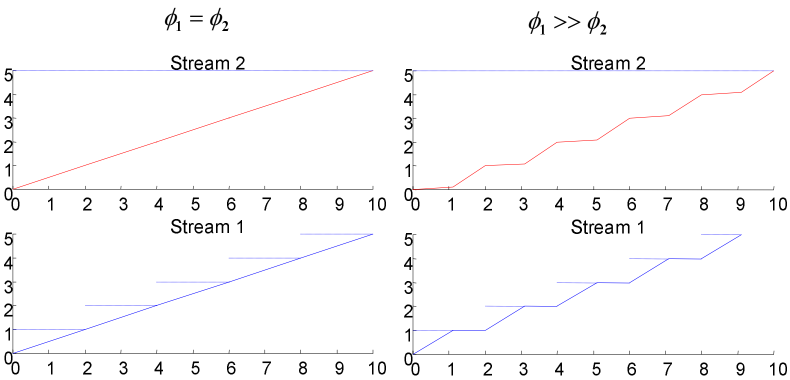
GPS Performance Analysis

Analyzing Networks of GPS schedulers.

GPS - Mathematical Model

- Generalized Processor Sharing is defined by $\frac{S_i(\tau,t)}{S_j(\tau,t)} \geq \frac{\phi_i}{\phi_j}$
  - Assuming session *i* is backlogged.
- Session 'i' is guaranteed a rate of $g_i \geq \frac{\phi_i}{\sum_j \phi_j} r$
- Protected from other sessions.
- Can reduce delays for a session by increasing its weight ϕ.
  - Corresponding increase in delay for other sessions.
  - Less impact on other sessions when the better treated session is *steady*.

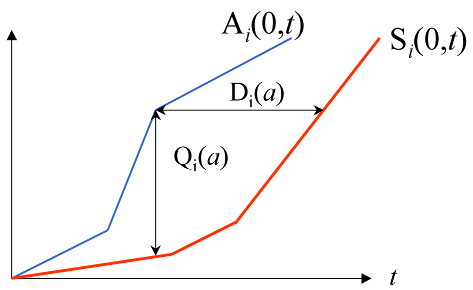
Weights Allocation



- Session 1 is a steady source (delay sensitive real time traffic).
- Session 2 is a bursty source (best effort traffic).

Guaranteed Performance

- Delay depends on arrival functions of *all* sessions.



- May also help bound the maximum queue length (I.e, size of buffers needed by the switch for every session).

Networks of GPS Servers

- Assume session '*i*' is leaky bucket constrained:
  - $A_i \sim (\sigma_i, \rho_i)$
  - Other sessions are not constrained.
  - Network may not even be stable.

- Assume g_i is the minimum guaranteed bandwidth allocated to session '*i*' along its path.
  - Session is *locally* stable: $g_i \geq \rho_i$

- Session '*i*' can be guaranteed maximum delay: $D_i \leq \frac{Q_i^{max}}{g_i} \leq \frac{\sigma_i}{g_i}$

WFQ End-to-End Delay

- When the servers are WFQ:

$$D_i^* \le \frac{\sigma_i}{g_i} + K\frac{L_{\max}}{g_i} + K\frac{L_{\max}}{r}$$

- First error term due to store & forward delay
  - Packets are processed by the scheduler when their last bit arrives.
- WFQ error term
  - Negligible when line rate is high.

A Simple Example

- Given:
  - A constrained connection A ~ (16 KByte, 150 Kbps)
  - 10 network hops (rate 45 Mbps)
  - Packet size are up to 8 KB
  - Total propagation delay: 30 ms.
- What is the required *guaranteed bandwidth* to get an end-to-end delay not more than 100 ms?
- Solution: 12.87 Mbps!
  - S&F delay contributes 46 ms to delay!
  - All other terms: 24 ms

Leaky Bucket Constrained Sources

- To reduce delays for a given session, we must increase its weight.
  - Increases guaranteed bandwidth for this session.
  - Reduces network capacity.
  - May overload the network turning it unstable.
- When is it possible to reduce delay while still maintaining stability?

Consistent Relative Session Treatment (CRST)

- Assume all sources are leaky bucket constrained $A_i \sim (\sigma_i, \rho_i)$
- **Definition:**
  - Session *j* is said to *impede* session *i* at node *m* if:

$$\frac{\phi_j^m}{\rho_j} > \frac{\phi_i^m}{\rho_i}$$

- **Definition:** Consistent Relative Session Treatment (CRST)
  - A GPS weight assignment for which:
  - If session *i* impedes session *j* at node *m*, then session *i* impedes session *j* at any other node where they contend for bandwidth.

Stability Condition

- **Theorem:**
  - A CRST GPS network is stable if the utilization at every node is less than one.

$$\sum_{i \in \{\text{sessions in node } m\}} \rho_i < r^m$$

- Finding D* and Q* for a general GPS network is a complex optimization problem.
- It turns out that it is easily bounded for CRST networks.
- In the following slides we will sketch an outline of the proof.

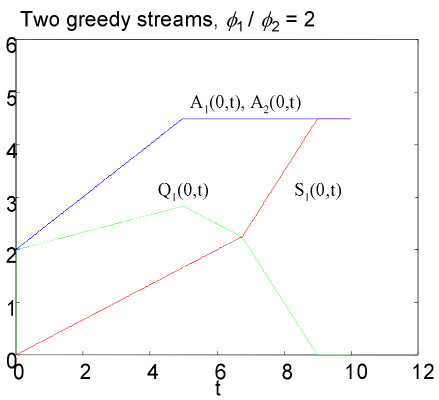
The Single Node Case

- Assume all sources are leaky bucket constrained $A_i \sim (\sigma_i, \rho_i)$
- **Definition**: Greedy Source
  - A leaky bucket constrained source is greedy starting at time t if its arrival function is maximal for all time $\tau > t$.
  - Uses all available tokens and maximum rate ρ_i
- **Theorem:**
  - For every session D^* and Q^* (worst delay and backlog) are achieved when *all* sessions are greedy starting at time 0, the beginning of a system busy period.

Greed...

- Intuitively simple:
  - When all sessions are greedy starting at time 0, *maximum* traffic is entering the network in (0,*t*).
  - All sessions are active, therefore each one is allocated *minimal* guaranteed bandwidth.
  - Result: maximum backlog and delay.
- No need to solve a difficult optimization problem to determine Q* and D*.

Single Node - Delay and Backlog



- Note that D* and Q* may not be achieved at the same time!
  - D depends on backlog size and clearing *rate*.

Feasible Ordering

- Assume all sessions are greedy starting at time 0.
- Server will finish serving all backlog at time:

$$t_B = \frac{\sum_{i=1}^{N} \sigma_i}{r - \sum_{i=1}^{N} \rho_i}$$

- Number the sessions according to the order in which their backlog is cleared.
- For the first session: $\rho_1 \le \frac{\phi_1}{\sum_{j=1}^{N} \phi_j} r$
- The second: $\rho_2 \le \frac{\phi_2}{\sum_{j=2}^{N} \phi_j} (r - \rho_1)$

- There may be more than one possible feasible ordering.
- The one that comes into play at time 0 depends on the σ_i's.

An Important Inequality

- **Theorem:**
  - Let 1,..,N be a feasible ordering, then for any time *t* and session *p*:

$$\sum_{k=1}^{p} \sigma_k^t \le \sum_{k=1}^{p} \sigma_k$$

  - I.e, burstiness is not increased by the GPS server.

Output Burstiness

- Maximum output burst (for session *i*) results when:
  - Backlog is maximal (Q^*)
  - Session *i* is the only active session (highest output rate).

$$\sigma_i^{out} \geq Q_i^*$$

- Other direction:

$$S_i(\tau,t) \leq Q_i(\tau,t) + \rho_i(t-\tau) \leq Q_i^* + \rho_i(t-\tau)$$

$$\sigma_i^{out} \leq Q_i^*$$

- Calculate Q* and determine output burstiness.

Network Internal Burstiness

- Following Cruz, we compute the burstiness at the output of every node on the session's path.
- If session *i* does not impede session *j* at node *m* then σ_j^{out} is independent of σ_i^{out}
- Iterative procedure computes σ^{out} for all sessions at all nodes
  - Characterizes traffic entering every network node.

Computing Bounds for Networks with Known Internal Burstiness

- Maximum delay is achieved when all sessions entering a node are greedy at the same time, *but*…
- Network topology may preclude certain arrival functions.
- Should compute maximum delay over all *possible* arrival functions of all sessions at all nodes.
  - Difficult optimization problem.

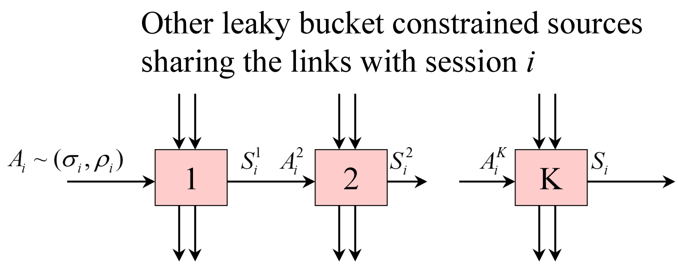
Independent Sessions Relaxation

- When computing session *i*'s delay and backlog assume all *others* sessions (*independent* sessions) can send traffic at (σ_j^m, ρ_j).
- Session *i* traffic is constrained to flow along its route so that:

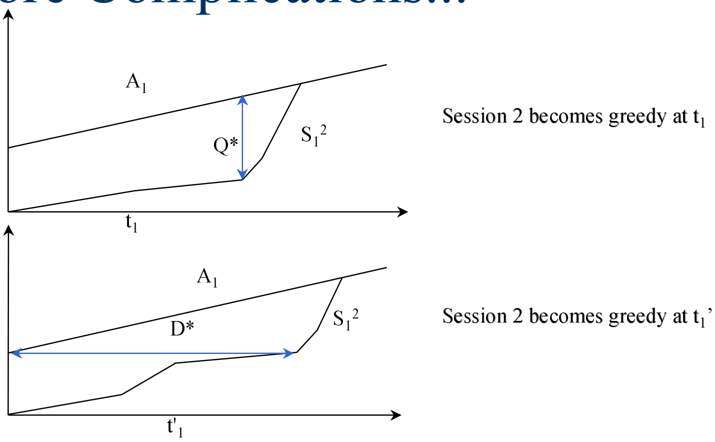
$$A_i^m = S_i^{m-1}$$

- Upper bounds the delay and backlog of session *i*.
  - Every arrival function allowable in the network is allowed under the relaxation too.

Independent Sessions



More Complications...

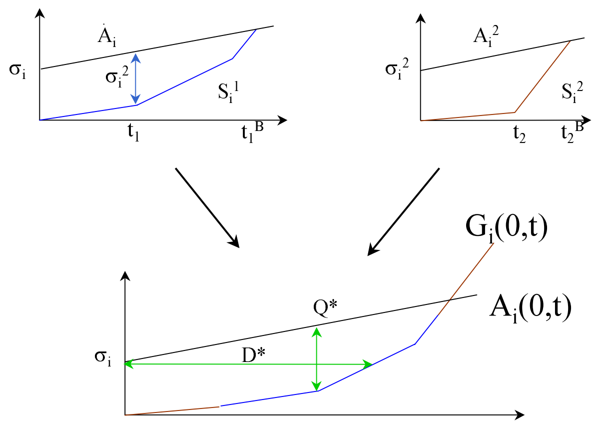


- Q* and D* are not necessarily achieved with the same arrival functions.

The Universal Service Curve

- We are looking for:
  - *End-to-end* delay (D*)
  - $Q^* = Q^1 + Q^2 + \ldots$ (total session *i* traffic in the network)
- Crucial insight:
  - Session *i* will always be limited by the *slowest* link on its path.
  - The set of all feasible rates for session *i* on link *m* is given by the slopes of $S_i^m(0,t)$ (assuming all sessions are greedy).
- Solution:
  - Construct the universal curve $G_i(0,t)$ by concatenating the segments of all $S_i^m(0,t)$ in increasing slope order.

Universal Curve - An Example



- The Universal Curve makes calculating D* and Q* easy!

Summary - GPS Networks

- If all sources are known to be leaky bucket constrained,
  - And we limit ourselves to CRST networks…
  - We can control each session's delay by adjusting the weights at each GPS node.
  - We can easily bound the delay and backlog.
- If only some sources are leaky bucket constrained,
  - Bandwidth and delay are coupled.
  - Can reduce delay for a session only by increasing its allocated bandwidth, thereby wasting network resources!
  - GPS protects sessions from bandwidth hogs.

Integrated Services in the Internet

Resource Reservation Protocol (RSVP)

Signaling

- Users need to communicate their bandwidth / delay requirements to the network.
  - Call setup.
  - Connection teardown.
  - Renegotiation.

- Switches communicate to select a path with enough resources.

Real World Use - RSVP

- Each router implements WFQ or other per-flow scheduling discipline.
- Resource Reservation Protocol used to request bandwidth allocation.

- Source specifies *Flowspec* (σ_i, ρ_i).
- Destination requests bandwidth (affects delay).

- Reservation request propagates from destination to source allocating bandwidth in each link (assigning *weights*).
- If bandwidth is not available, request is denied (*admission*).

Scaling

- Needs a QoS-capable routing protocol to select paths with available bandwidth.
  - More information to distribute through the network.
  - More changes as flows are started and destroyed.
- All routers must store per-flow information.
  - Less robust.
  - Difficult to implement at high speed (Internet backbones).

Aggregation

- More aggregation:
  - Less sessions to consider in backbone switches.
  - Less signaling.
  - BUT: less isolation!
- Solution:
  - Aggregate to a *class*.
  - Members of the same class have similar performance requirements.
  - Police traffic at the edge of the network (no protection inside network between sessions of the same class).

The End

Work Conserving vs. Non Work Conserving Service Disciplines

- Work conserving scheduler is *never* idle when there are packets in the queue.
- GPS, WFQ, WF^2Q are all work conserving disciplines.
- Non work conserving schedulers hold packets in queue until their eligibility time is reached (e.g., TDM).

Non Work Conserving Disciplines

- Reduce network internal burstiness.
  - Smaller buffers needed at switches.
- Increases mean delay.
  - Not a problem for *playback* applications.
  - Does not hurt worst-case performance.
- Wastes bandwidth.
  - Can serve best effort traffic when idle.
- High implementation costs at every switch (regulators).