Reducing the complexity of WFQ

- reduce the number of queues by aggregating connections with similar characteristics & constraints
- simplify the algorithm by using an approximation of virtual time
    - need virtual arrival times to compute virtual finish times via

$$V(d_{k+1}^{(j)}) = \max\left\{ V(d_k^{(j)}), V(a_{k+1}^{(j)}) \right\} + \frac{L_{k+1}^{(j)}}{\phi_j}$$

    - instead of keeping the virtual time continuously updated, <u>self-clocked fair queueing</u> approximates $V(a_{k+1}^{(j)})$ by setting it to be the virtual finish time of the packet being served at the time packet k+1 arrived

Quality of service

- fine-grained:
  - provide QoS to individual applications / flows
  - eg. Integrated Services architecture
    ATM QoS
- Coarse-grained:
  - provide QoS to large classes of data / aggregated traffic
  - eg Differentiated Services architecture

Integrated Services (IETF 95-97)

- specifications of service classes
  - guaranteed service: network guarantees some maximum packet delay
  - controlled load: network uses a queueing mechanism such as WFQ to isolate the controlled load traffic from other traffic, & admission control to limit the total amount of controlled load traffic on a link
- required mechanisms
  - each flow gives the network a flowspec describing the flow's traffic characteristics (TSpec) & the requested service (RSpec)

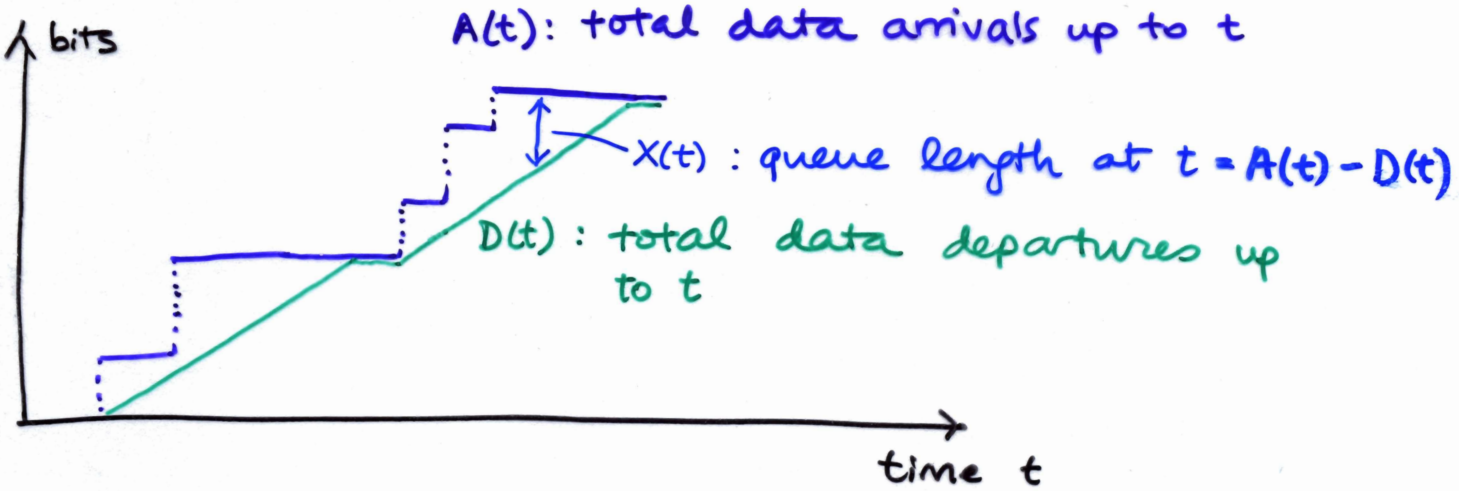
- admission control & policing
- resource reservation protocol
- packet classification & scheduling

Differentiated Services (IETF 98)

- DiffServ-aware routers implement Per-Hop Behaviors (PHBs) which specify how packets of each class are forwarded, eg.
  - Expedited Forwarding (EF): packets forwarded with low delay & low loss, either using PQ or WFQ; admission control & policing to limit total EF traffic
  - Assured Forwarding (AF): WFQ among classes; within each class there are subclasses with different drop profiles (weighted RED)

Deterministic network analysis

- packets arrive & are buffered at an output link – each arrival increases the buffer queue length by the length of the arrived packet
- non-idling / work-conserving link: whenever the queue is nonempty, the queue length decreases at the link rate c
- fluid assumption: work with reals instead of integer nos of bits
- infinite buffer



- Assume $A(t) = 0$ for $t < 0$
- $D(t) = \inf_{0^- \leq s \leq t} \left(A(s) + c \cdot (t-s) \right)$

  ($D(s) \leq A(s) \ \forall s$, & D increases with slope c)

  $= \inf_{s \in \mathbb{R}} \left(A(s) + B(t-s) \right)$

  where $B(t) = c \cdot t^+$

Network calculus (Cruz 91)

Def^n: (min, +) convolution

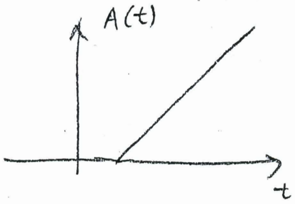
If $A(t)$ & $B(t)$, $t \in \mathbb{R}$ are nonnegative nondecreasing fxns, their (min, +) convolution is

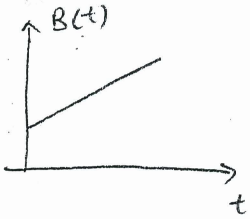
$$(A * B)(t) := \inf_{\tau \in \mathbb{R}} (A(\tau) + B(t-\tau))$$

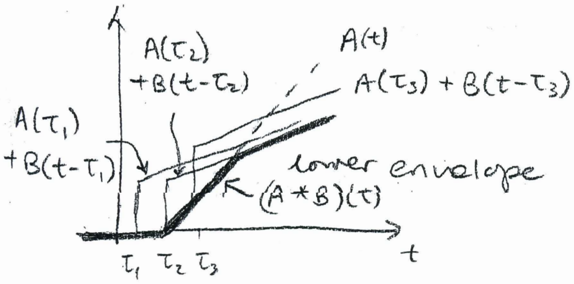
[cf usual (+, x) convolution

$$(A * B)(t) = \int A(\tau)\, B(t-\tau)\, d\tau \quad]$$

- Visualization:







- Properties:

$A * B = B * A$ (commutativity)

$(A * B) * C = A * (B * C)$ (associativity)

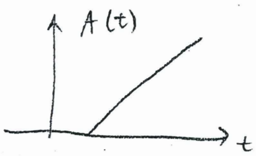
- **Def^n:**

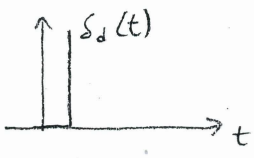
$$\delta(t) = \begin{cases} 0 & \text{for } t < 0 \\ \infty & \text{for } t \geq 0 \end{cases}$$

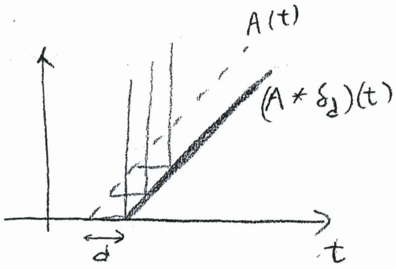
$\rightarrow A * \delta = A$

- delay element $\delta_d(t) = \delta(t-d)$

$\rightarrow (A * \delta_d)(t) = A(t-d)$







- **Def^n.** $B(t)$ is causal if $B(t) = 0$ for $t < 0$
  - for causal $B(t)$, $B \leq \delta$

  $\rightarrow A * B \leq A * \delta = A$

- Service curves for network elements

$A(t) \rightarrow$ [$S(t)$] $\rightarrow D(t)$

- let $S(t)$ be a nonnegative, nondecreasing causal function
- If $D \geq A * S$, S is a lower service curve
- If $D \leq A * S$, S is an upper service curve
- If $D = A * S$, S is the service curve

- latency rate server
  - lower service curve of the form $r(t-d)^+$ where r is the rate & d is the max delay for any data unit
  - examples:
    - constant rate fluid server : ct^+
    - GPS for flow i : $\frac{c\phi_i}{\sum_j \phi_j} t^+$
    - WFQ for flow i : $\frac{c\phi_i}{\sum \phi_j}\left(t - \frac{L_{max}}{c}\right)^+$