Network Calculus: A worst-case theory for QoS guarantees in packet networks

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Outline

- Motivation
  - Performance analysis of real-time traffic
  - Why classical queueing theory is unfit
- Network Calculus
  - Basic modeling: arrival and service curves
  - Concatenation, bounds
  - "Pay burst only once" principle / IntServ
  - Advanced modeling: aggregate scheduling
  - Stochastic Network Calculus

Real-time traffic

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- Expected to represent the bulk of the traffic in the Internet soon
  - Skype users: 10^7-10^8
  - Cisco white paper: video traffic volume to surpass P2P in 2010
- Revenue-generating only if reliable
- Reliability boils down to "packets meeting deadlines"
  - End-to-end delay bounds are required

Performance analysis

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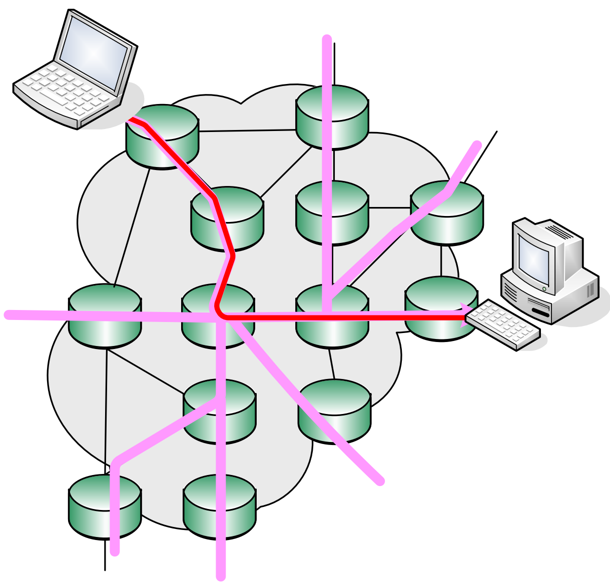
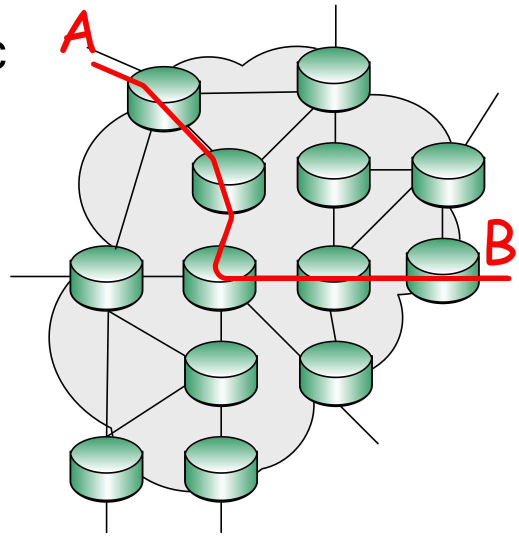
- Tagged flow (of packets) traversing a path
- Cross traffic
- Many queueing points (routers)
- How to compute a **bound on the e2e delay?**



Performance analysis (2)

- Service Level Agreement with upstream neighbor
- I will carry
  - up to X Mbps of your traffic
  - from A to B
  - within up to Y ms (!!)
  - for Z**$**



Network Calculus and Queueing Theory

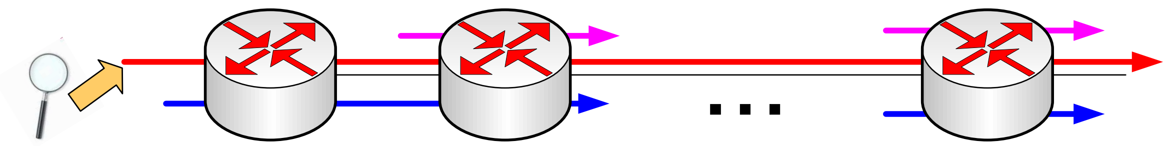
- 100 years of Queueing Theory
  - 1909. A. K. Erlang "*The Theory of Probabilities and Telephone Conversations*".
  - **Originated in the area of telecommunications**
  - Developed and applied in a variety of areas
  - Erlang Centennial held in Denmark, April 2009.

- ~20 years of Network Calculus
  - 1991. R. L. Cruz, "*A Calculus for Network Delay*".
  - **Recent development of queueing theory for computer networks**

NC and Queueing Theory (2)

- Queueing theory requires **models** for traffic
  - Simplistic models required for tractability
  - What if the traffic mix changes?
    - New applications (social networks, etc.)
    - Flash crowds (e.g., a football match)
    - Topology modifications (routing, link upgrades)
- Queueing theory mainly concerned with **average** performance metrics
  - Real-time traffic needs <u>bounds</u>

Modeling a network with NC (1)

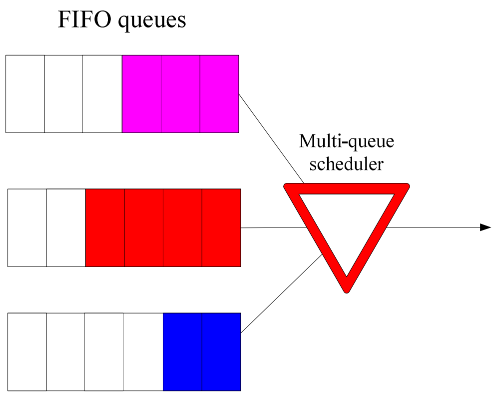


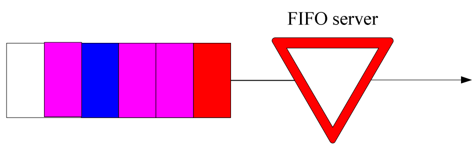
Fixed delays: propagation, …

Variable delay: queueing

Per-flow scheduling

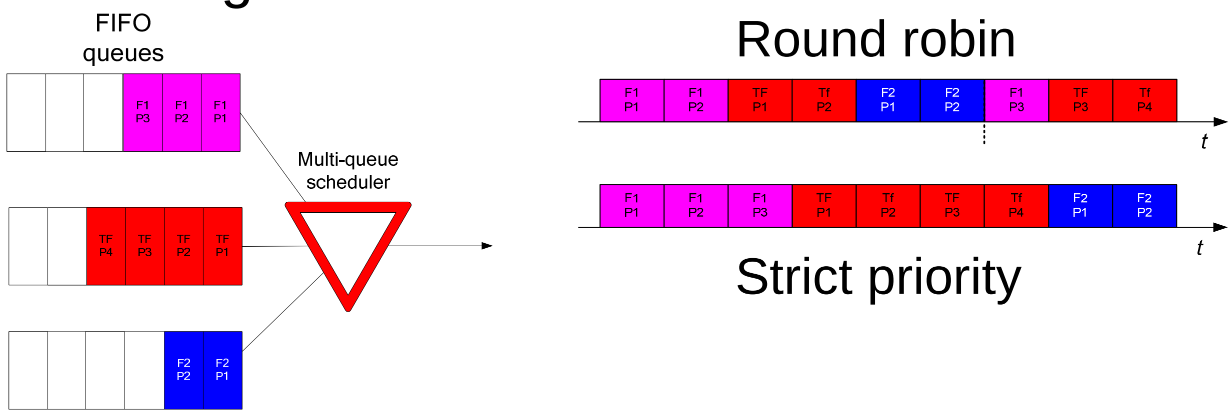
Aggregate scheduling





Modeling a queueing point with NC

- A scheduler serves its queues on a time sharing basis:



- Most guarantee that a queue is visited:
  - For a minimum amount of time
  - After a computable maximum vacation

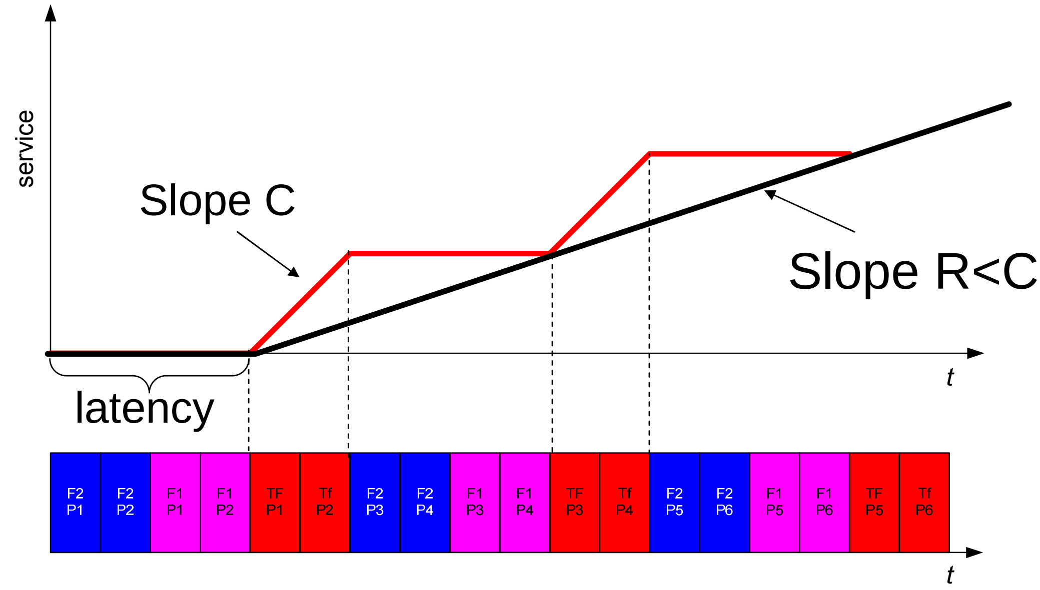
Modeling a queueing point with NC (2)

- <u>Minimum</u> service over a <u>maximum</u> interval
  - A **minimum guaranteed rate**
  - With a **latency** (when the server is away)
  - The latency is **upper bounded**

- Round robin schedulers (DRR, PDRR, …)
- Fair Queueing schedulers (PGPS, WFQ, WF2Q, STFQ, SCFQ, …)
- Strict priority (for the queue at highest prio)

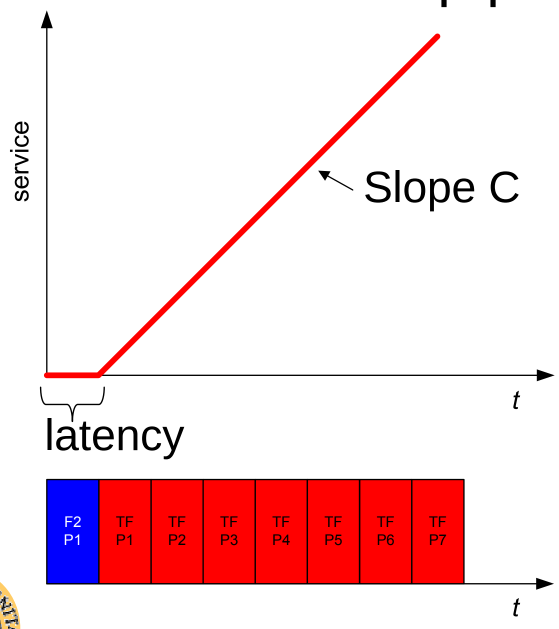
Example: a Round Robin scheduler

- Fixed length packets, 2 packets per queue



Example: a priority scheduler

- Strict non preemptive priority, queue scheduled at top priority



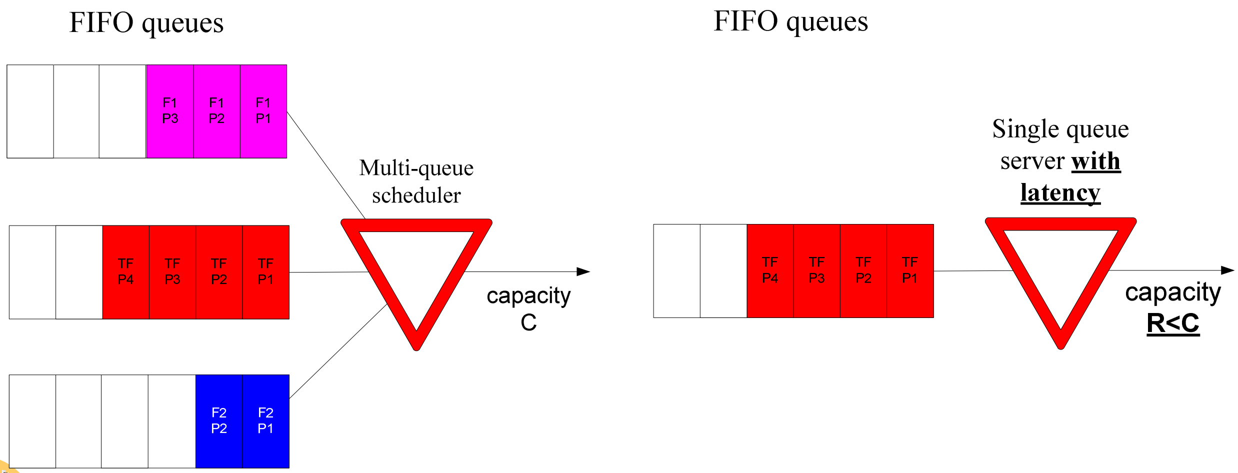
Service curve: summarizes the service received *in a worst case* by a backlogged tagged flow

Models the presence of other queues

Rate-latency service curves most common in practice

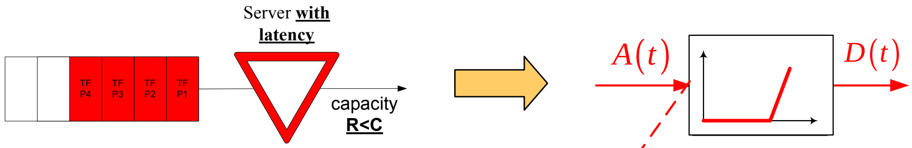
Modeling a queueing point with NC (3)

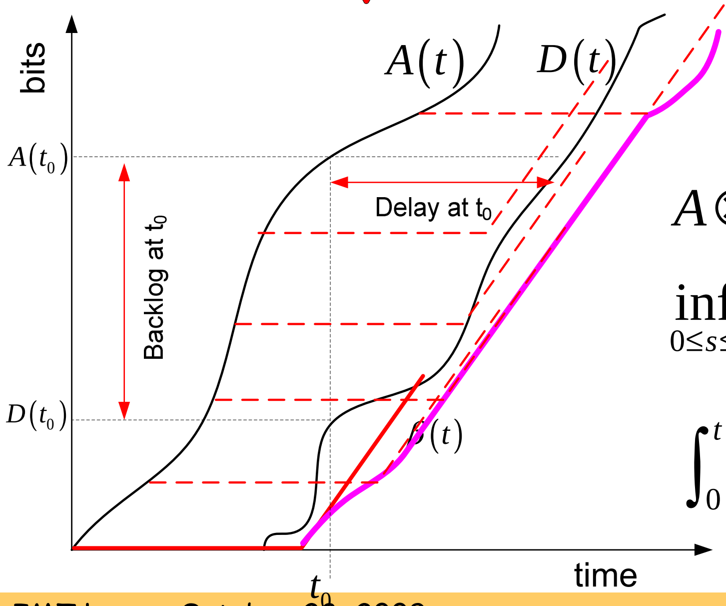
- Worst-case behavior for my queue:
  - served at **minimum** rate
  - with **maximum** latency



Modeling a queueing point with NC (4)

- **Nodes** transform functions of time





$$D(t) \geq A \otimes \beta(t)$$

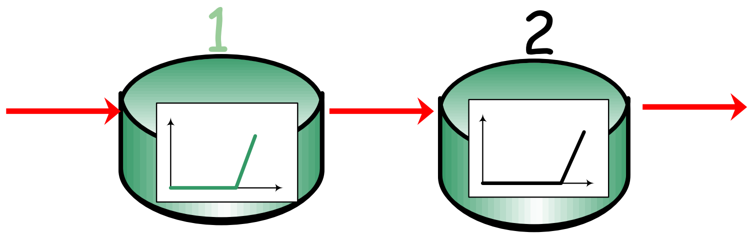
$$A \otimes \beta(t) =$$

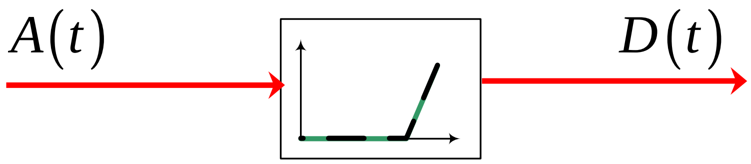
$$\inf_{0 \leq s \leq t} \{A(s) + \beta(t-s)\}$$

$$\int_0^t A(s) \cdot \beta(t-s)\, ds$$

Concatenation property

- Assume a flow traverses a tandem of nodes



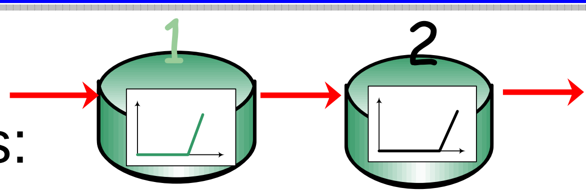


$$\beta_{1,2}(t) = \beta_1 \otimes \beta_2(t)$$

$$D(t) \geq A \otimes \beta_{1,2}(t)$$

It works for **<u>any</u>** # of nodes

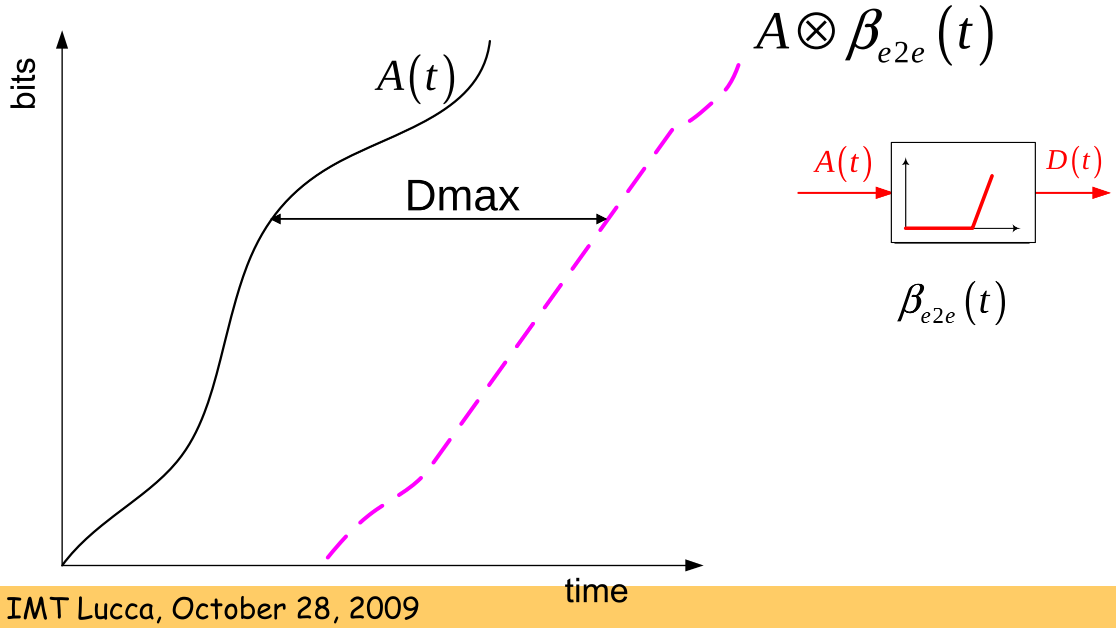
Concatenation property (2)



- At each of the *N* nodes:
  - Cross traffic could be anything
  - **Schedulers** need not be the same
- mid '90s: analyzing a tandem of **identical** schedulers
  - Took a whole PhD
  - Was enough for a top-level journal paper (Parekh '93, Saha '98,…, all on IEEE/ACM TNet)

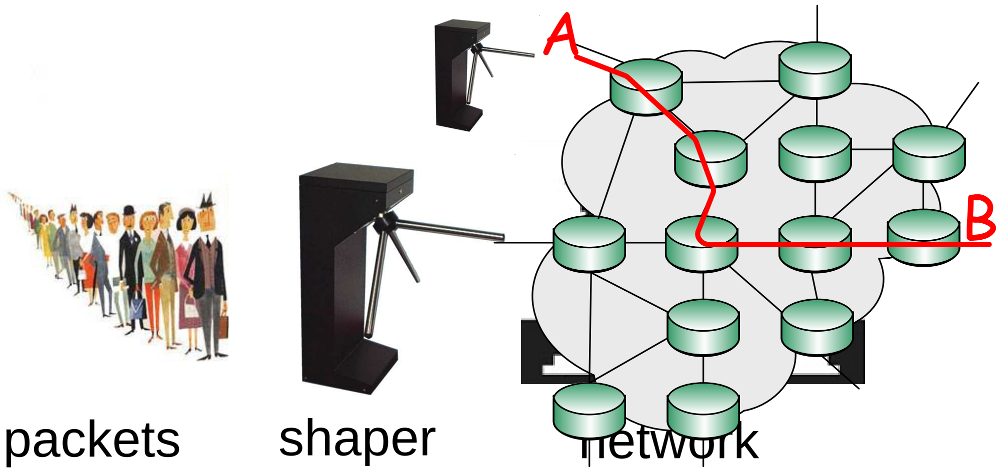
An end-to-end delay bound (1)

- A **bound on the delay** for a given arrival process can easily be computed



An end-to-end delay bound (2)

- Traffic shaping/policing
  - Check conformance with a pre-specified profile
  - Drop/delay out-of-profile traffic
  - Employed to verify SLA conformance



An end-to-end delay bound (3)

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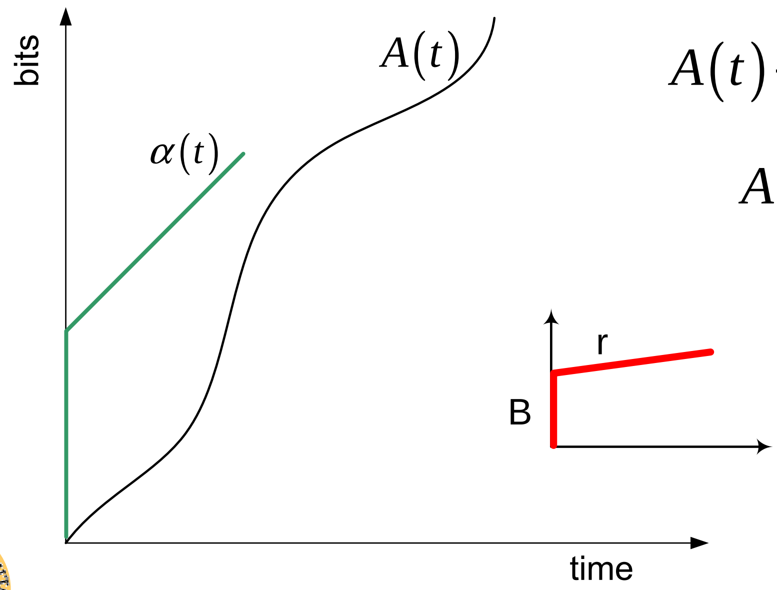
- Arrival curve: a **constraint** on the arrival process



$$A(t) - A(s) \le \alpha(t-s)$$

$$A(t) \le A \otimes \alpha(t)$$

example:
a token bucket
burst B, rate r

Backlog and delay bounds in NC

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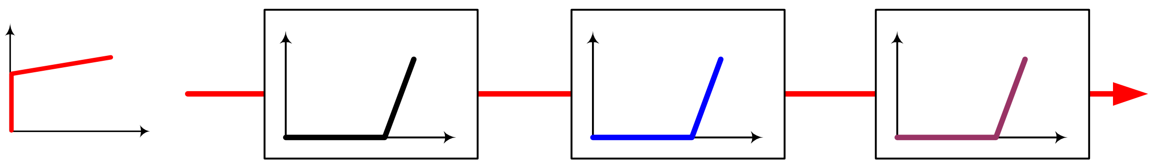
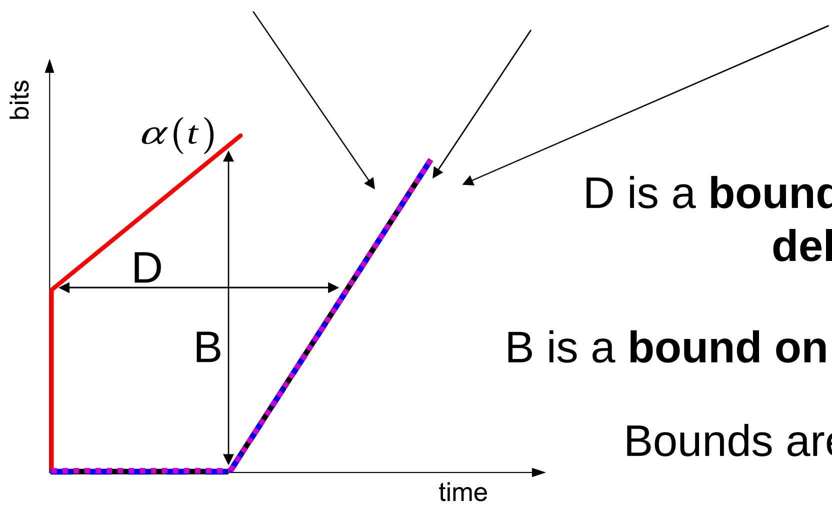
- **service curve** for a path + **arrival curve** for a flow





D is a **bound on the e2e delay**

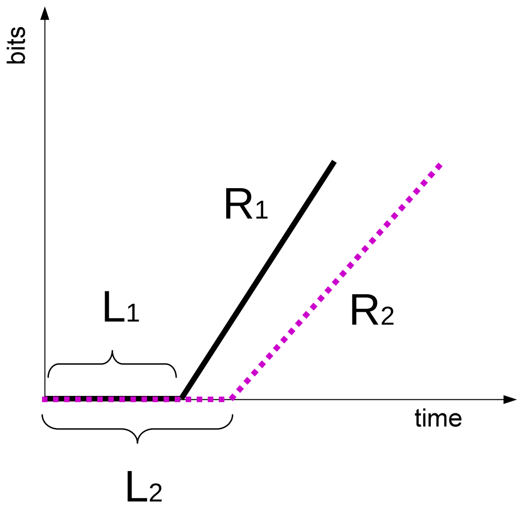
B is a **bound on the backlog**

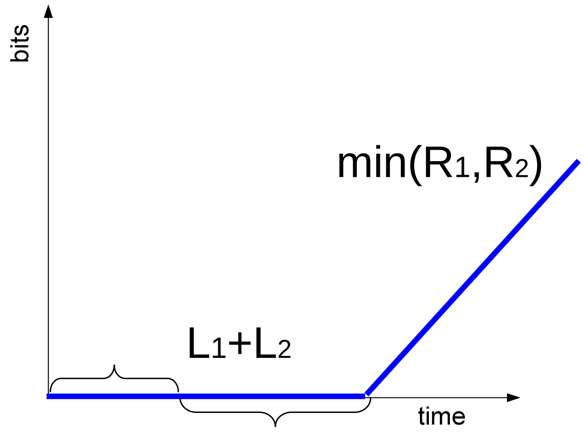
Bounds are **tight**

Convolution of rate-latency curves

$$\beta_i(t) = R_i \cdot (t - L_i)^+$$

$$\beta_{1,2}(t) = \beta_1 \otimes \beta_2(t) = \inf_{0 \le s \le t} \{\beta_1(s) + \beta_2(t-s)\}$$

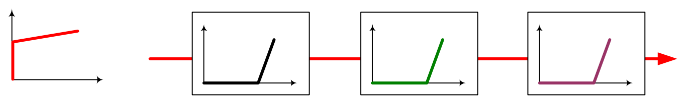


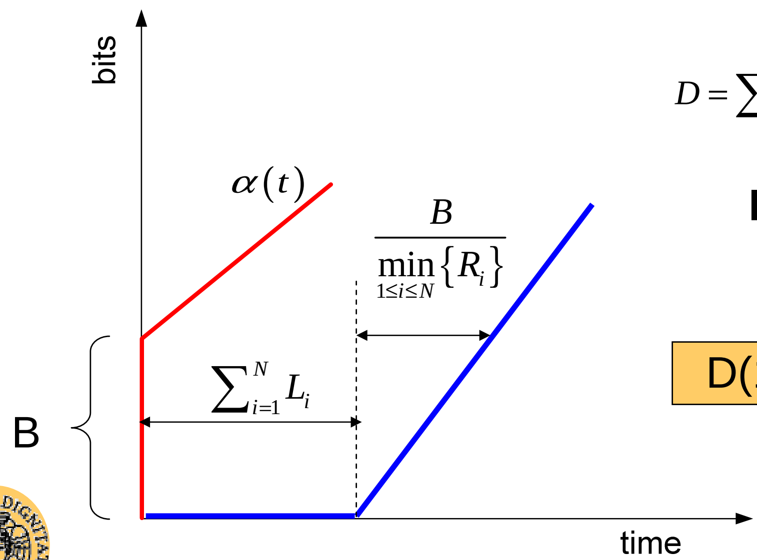


- **Sum** of the latencies, **min** of the rates

"Pay bursts only once" principle

- When traversing a tandem, your DB consists of
  - N latencies
  - <u>One</u> **burst delay**





$$D = \sum_{i=1}^{N} L_i + \frac{B}{\min_{1 \le i \le N}\{R_i\}} < \sum_{i=1}^{N} \left[L_i + \frac{B}{R_i} \right]$$

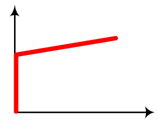
Pay burst only once

(at the min rate)

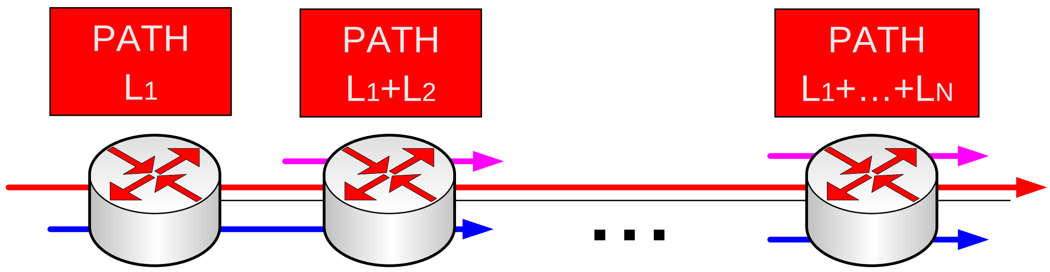
D(1…N) < D(1)+…+D(N)

IntServ architecture (1)

- RSVP protocol
- FlowSpec: burst and rate of the flow
  - i.e., its token bucket **arrival curve**

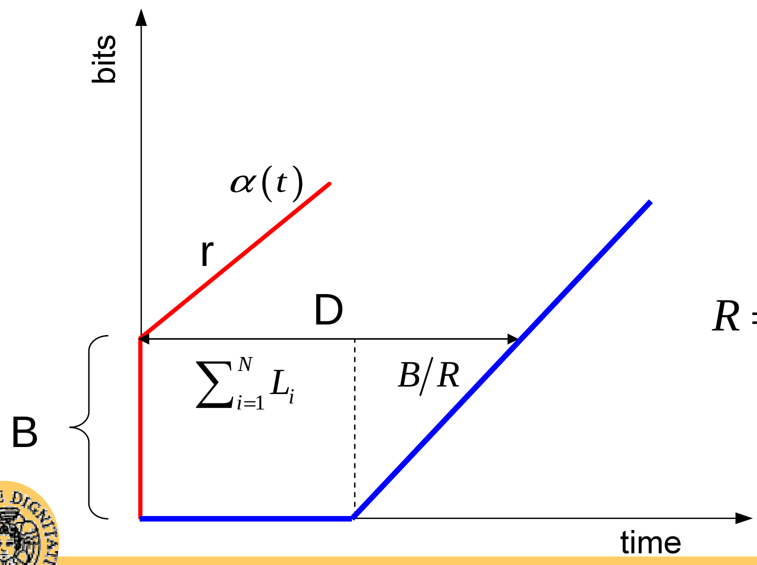


- **Path** message
  - Includes **FlowSpec** and **required delay bound**
  - Collects node latencies at each hop



IntServ architecture (2)

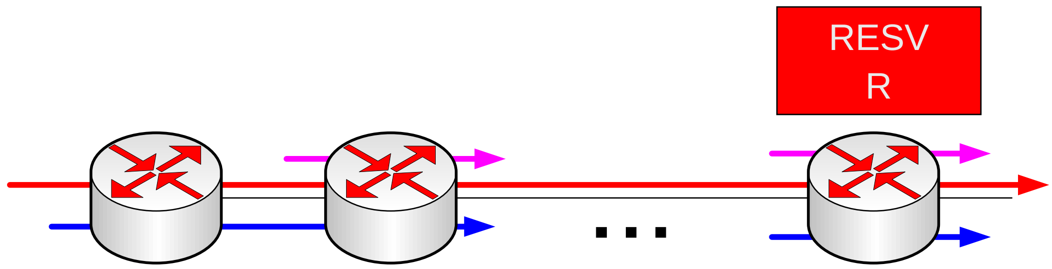
- At the destination
  - compute what **rate** you need to reserve
  - Based on your **required delay D**



$$R = \max\left\{ \frac{B}{D - \sum_{i=1}^{N} L_i}, r \right\}$$

IntServ architecture (3)

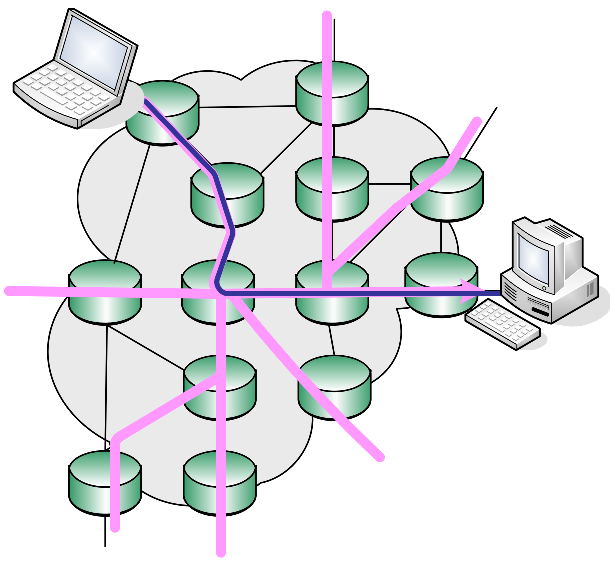
- RESV message travels back and **reserves** a rate R at each node
  - The delay bound is guaranteed from now on



Traffic aggregation

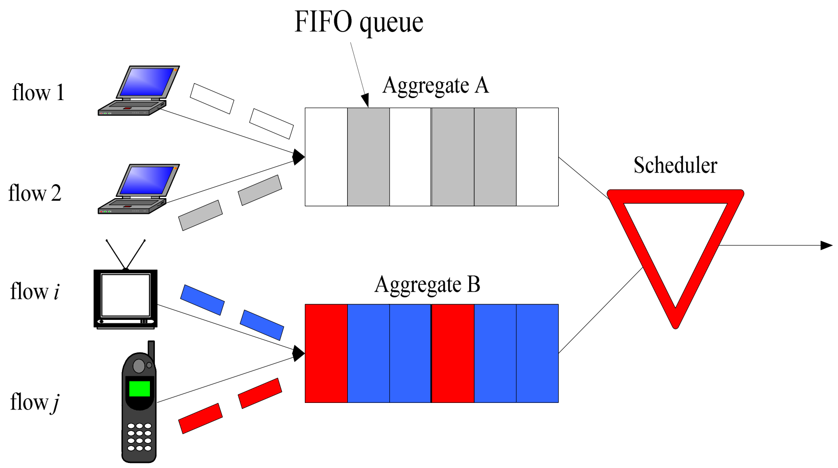
- Aggregation as "the" solution for <u>scalable</u> provisioning of QoS in core networks
- Internet:
  - **Differentiated Services**
  - **MPLS**

Per-flow resource management (e.g., packet scheduling) <u>just doesn't scale</u>



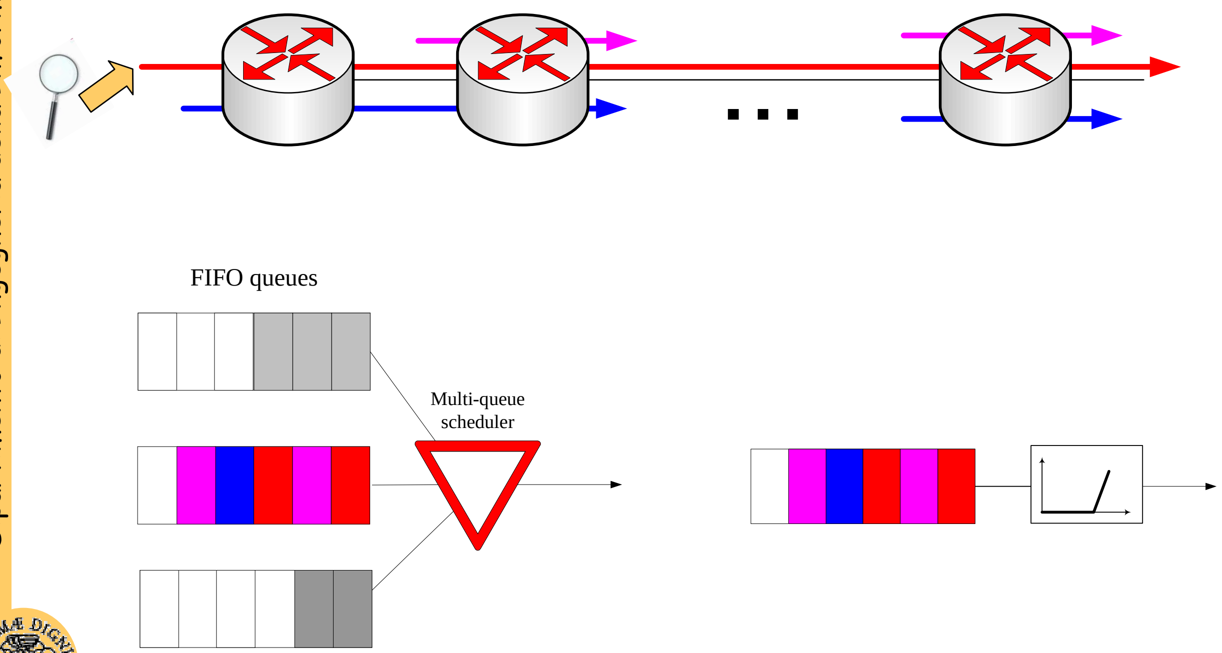
Per-aggregate scheduling

- Packets of an aggregate normally queued FIFO
- Arbitration (scheduling) **among** aggregates
  - Forwarding guarantees **for the aggregate**



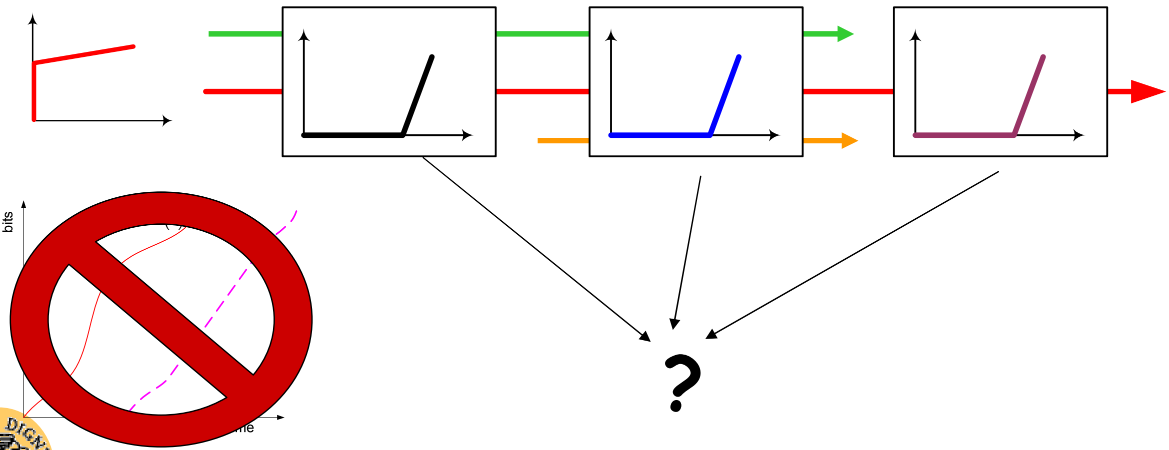
NC with aggregate scheduling

- Computations get more involved…



Traffic aggregation (cont.)

- Aggregates change along a path
  - Per-node guarantees for **different sets of flows** at each node
  - Cannot use concatenation of SCs



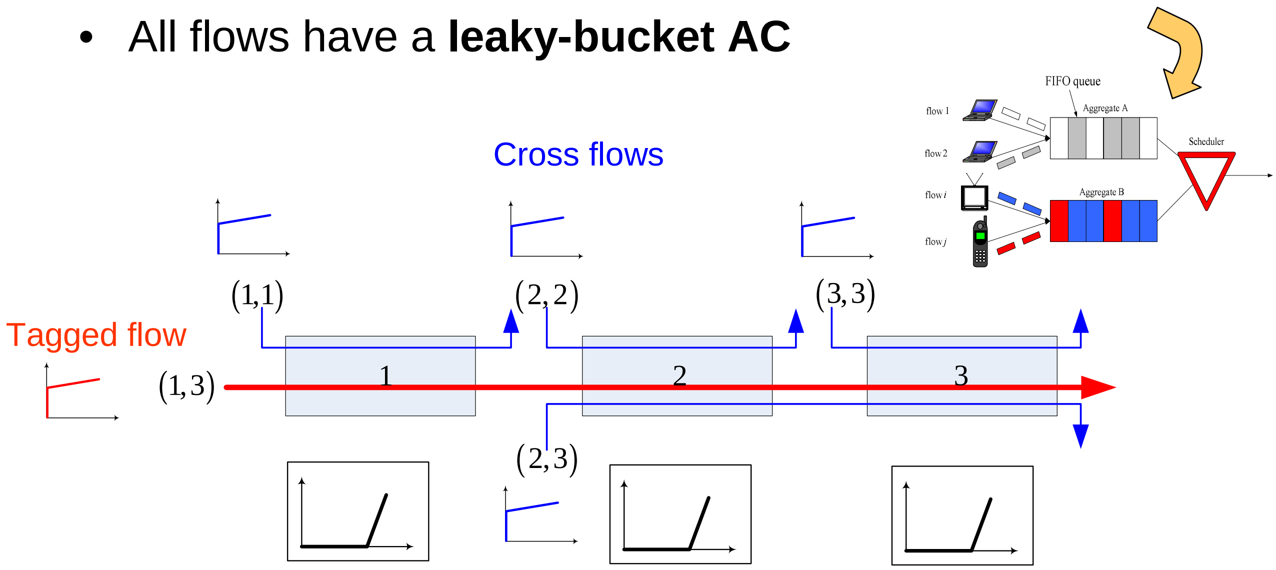
Performance evaluation problem

- Users care about <u>*their flows*</u>, not *aggregates*
- Users want <u>*e2e delay bounds*</u>, not *per-node forwarding guarantees*

How to compute
per-flow **end-to-end** delay bounds
from ***per-aggregate*** **per-node** guarantees?

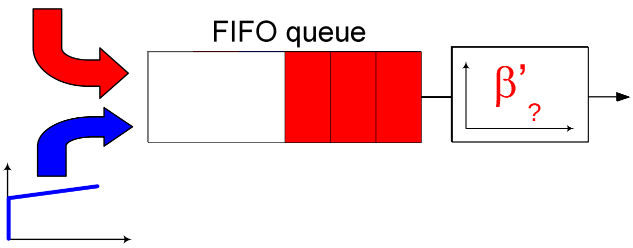
Performance Analysis

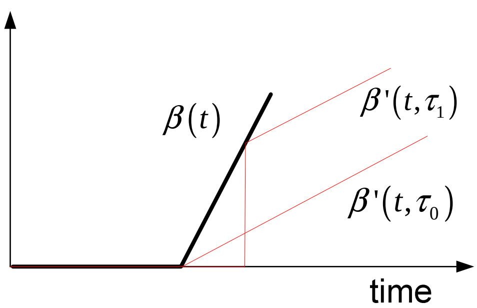
- **Tandem network** of FIFO rate-latency elements
- All nodes have a **rate-latency SC** for the aggregate
- All flows have a **leaky-bucket AC**



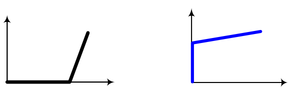
Leftover service curves

- Th. **FIFO Mux - Minimum Service Curves**
  - [Cruz *et al.*, '98]





$$\beta'(t,\tau) = \left[\beta(t) - \alpha_2(t-\tau)\right]^+ \cdot 1_{\{t>\tau\}}, \tau \geq 0$$



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The LUDB methodology

LUDB: Least Upper Delay Bound

Step 1:

Apply the FIFO Mux theorem iteratively so as to "remove" all cross-flows

Ref: L. Lenzini, E. Mingozzi, G. Stea, "A Methodology for Computing End-to-end Delay Bounds in FIFO-multiplexing Tandems" Elsevier Performance Evaluation, 65 (2008), pp. 922-943

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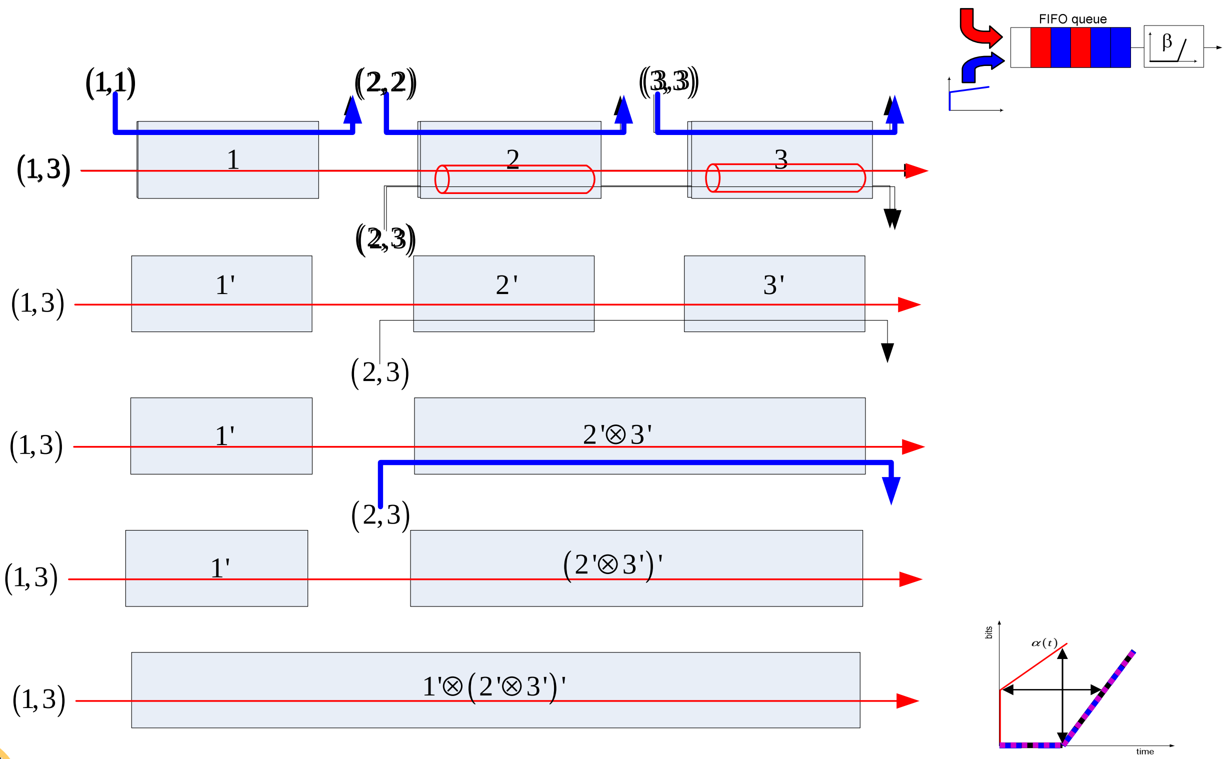
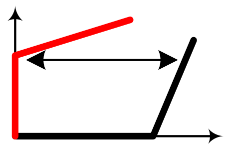
The LUDB methodology (2)



The LUDB methodology (3)

- An **n-dimensional infinity** of e2e SCs for the tagged flow
  - n = # of cross-flows
- Delay bound = fn. of n parameters



- <u>Step 2</u>
  - Solve an **optimization problem**

$$LUDB = \min_{\tau_i \geq 0} \left\{ D\left(\tau_1, \dots, \tau_n\right) \right\}$$

  - The minimum is the **best**, i.e. **tightest**, delay bound

Nested vs. non-nested tandems

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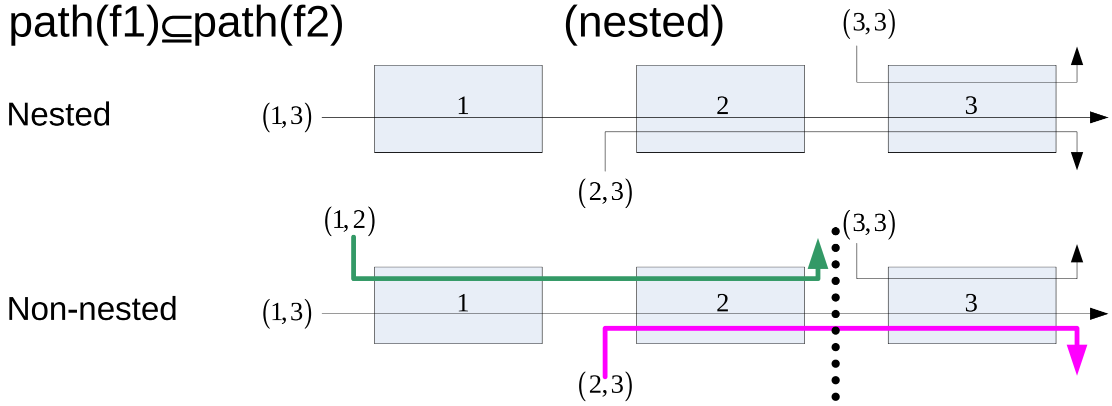
- **Nested iff**
  - path(f1)∩path(f2) =∅ (disjoint)
  - path(f1)⊆path(f2) (nested)



  - You can <u>**only**</u> compute an e2e SC for the tagged flow in a **nested tandem**

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Two important points

- The LUDB method:
  1. Is <u>scalable</u> enough
     - You can use it in paths of 30+ nodes
  2. Yields <u>accurate</u> bounds
     - Close to a flow’s **Worst-Case Delay**
     - (Sometimes)

Ref: L. Bisti, L. Lenzini, E. Mingozzi, G. Stea, "Estimating the Worst-case Delay in FIFO Tandems Using Network Calculus", Proc. VALUETOOLS'08, Athens, Greece, October 21-23, 2008

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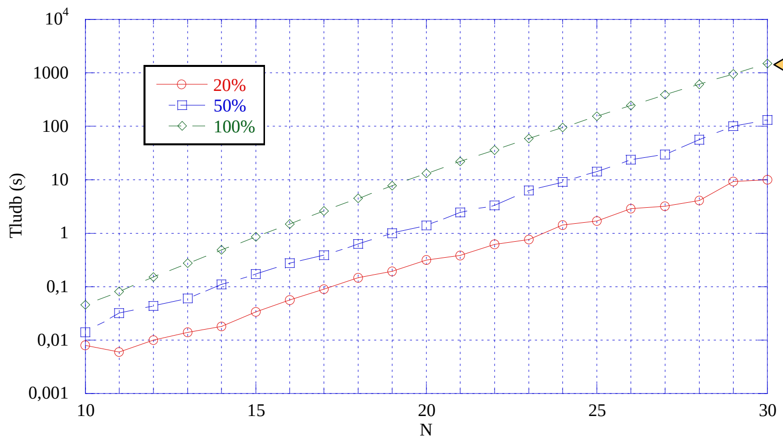
Scalability

- Computation times for **very nasty** non-nested tandems

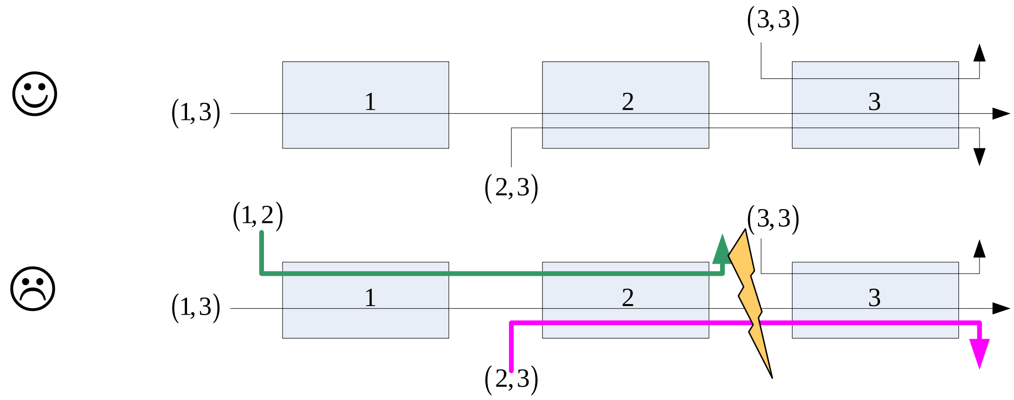


30 nodes, 465 flows, 20 mins

Ref: L. Bisti, L. Lenzini, E. Mingozzi, G. Stea, “Computation and Tightness Assessment of End-to-end Delay Bounds in FIFO Tandems Using Network Calculus", *submitted to journal*, 2008

Accuracy

- Delay bounds are as useful as they are **tight**, i.e. close to the Worst-Case Delay
  - WCD unknown (to date)
- End-to-end analysis is fundamental

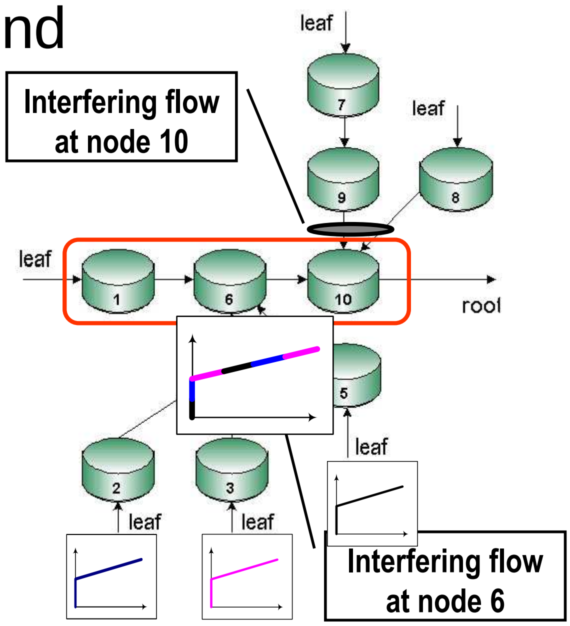


Sink-tree networks

- Closed-form delay bound

$$D = \sum_{i=1}^{N} \left[L_i + \frac{B_i}{CR_i} \right]$$

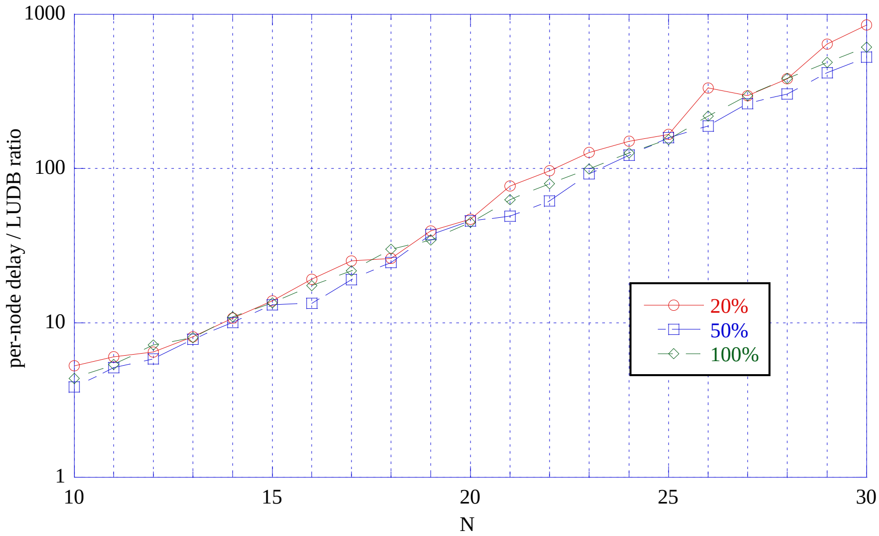
- = Worst-Case Delay
  - Proof by construction



Ref: L. Lenzini, L. Martorini, E. Mingozzi, G. Stea, "Tight End-to-end Per-flow Delay Bounds in FIFO Multiplexing Sink-tree Networks", Perf. Evaluation, 63/9-10, Oct. '06, pp. 956-987

Accuracy (2)

- Compared to (naïve) per-node analysis



500-1000
times smaller

Stochastic Network Calculus

- Brings in a probabilistic framework
  - Better captures statistical multiplexing
  - Concatenation results still hold

deterministic

$$D(t) \geq A \otimes \beta(t)$$

stochastic

$$\mathrm{P}\left\{A \otimes \beta(t) - D(t) > x\right\} \leq g(x)$$

- Currently active field of research
  - SIGMETRICS, VALUETOOLS

Conclusions

- Network Calculus allows one to compute e2e delay bounds
  - **Easy** and **tight** in a per-flow scheduling environment
  - **Complex** and **not always tight** in an aggregate-scheduling environment
- Only method known so far
- Stochastic extensions: promising research area
  - Better account for statistical multiplexing

References

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4. R.L. Cruz. “A calculus for network delay, part i: Network elements in isolation”. IEEE Transactions on Information Theory, Vol. 37, No. 1, March 1991, pp. 114-131.
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More references

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Thank you for listening

- Questions?
- Comments?