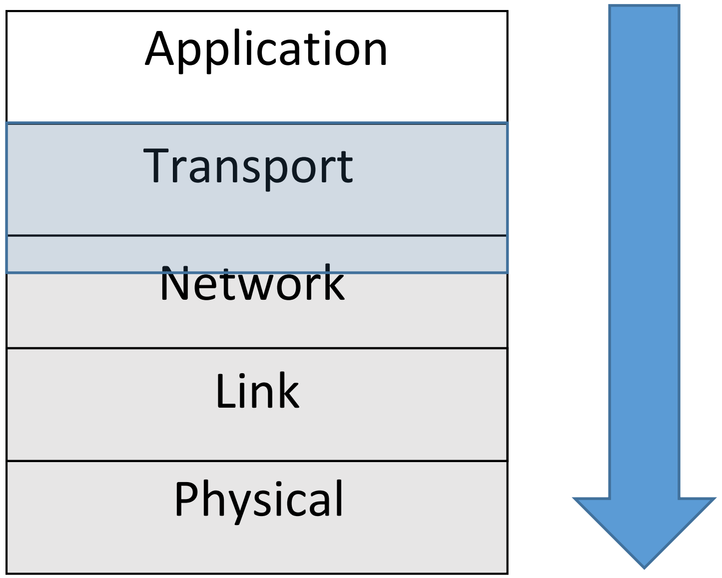
(Transport Layer)
Congestion Control

Where we are in the Course

- Still in Transport layer
- (Gently) moving down to include a bit of network layer



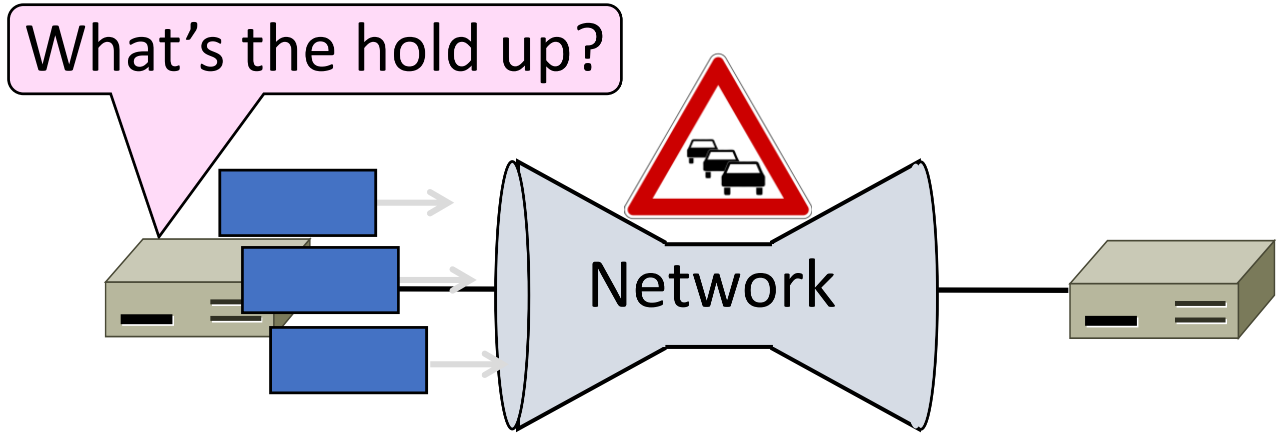
TCP to date:

- We can set up a connection (connection establishment)
- Tear down a connection (connection release)
- Keep the sending and receiving buffers from overflowing (flow control)

What's missing?

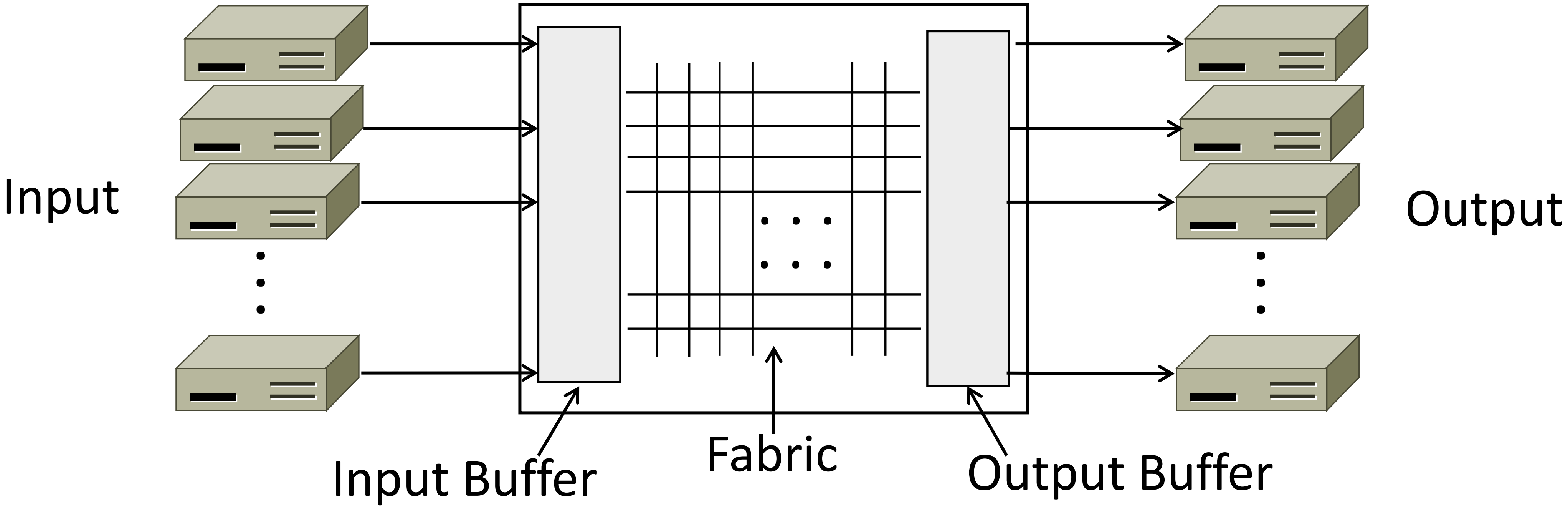
Network Congestion

- A "traffic jam" in the network
  - Later we will learn how to control it



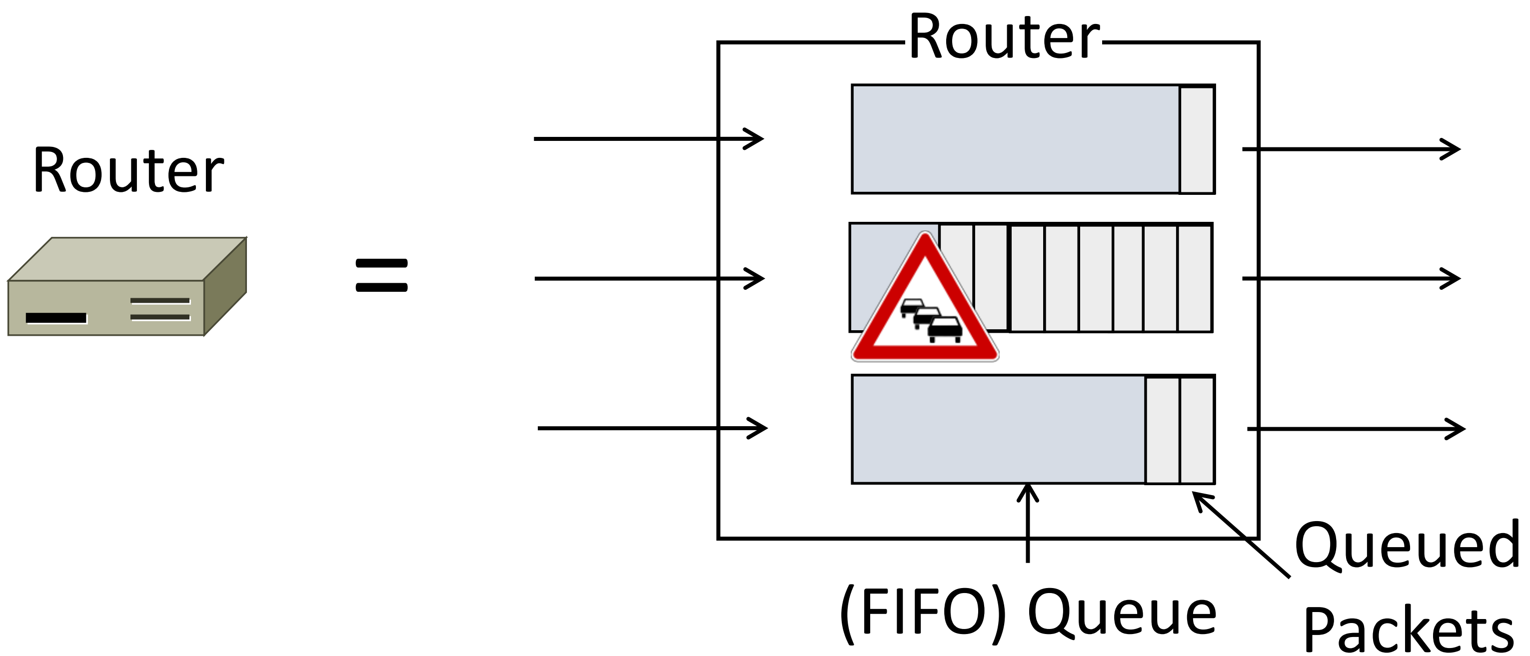
Nature of Congestion

- Routers/switches have internal buffering



Nature of Congestion (2)

- Simplified view of per port output queues
  - Typically FIFO (First In First Out), discard when full

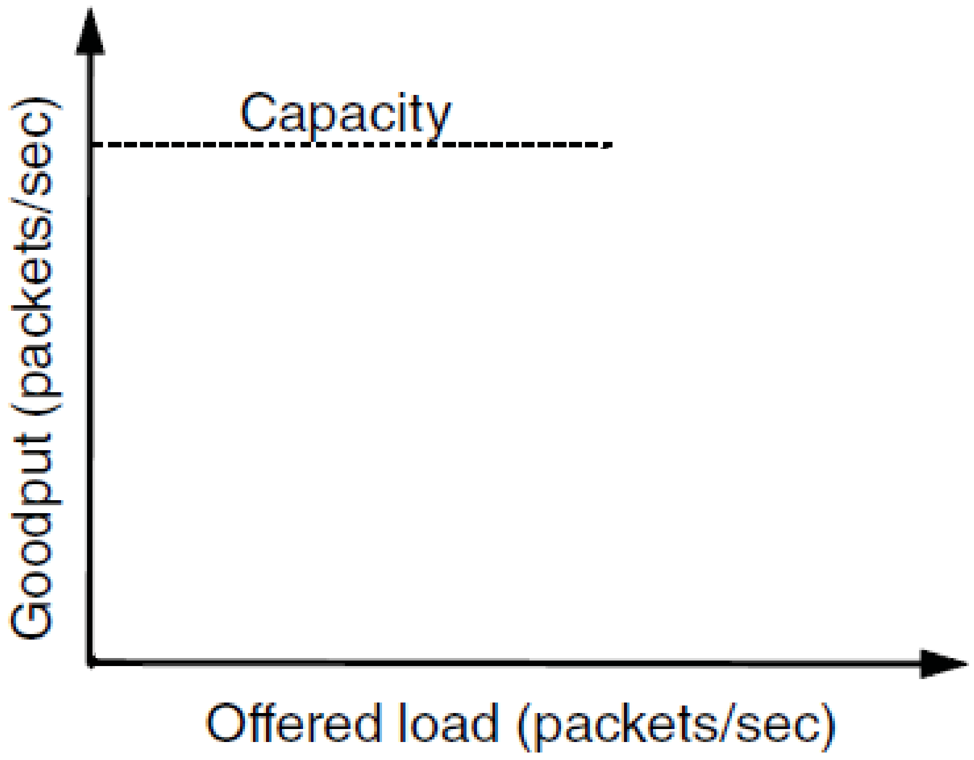


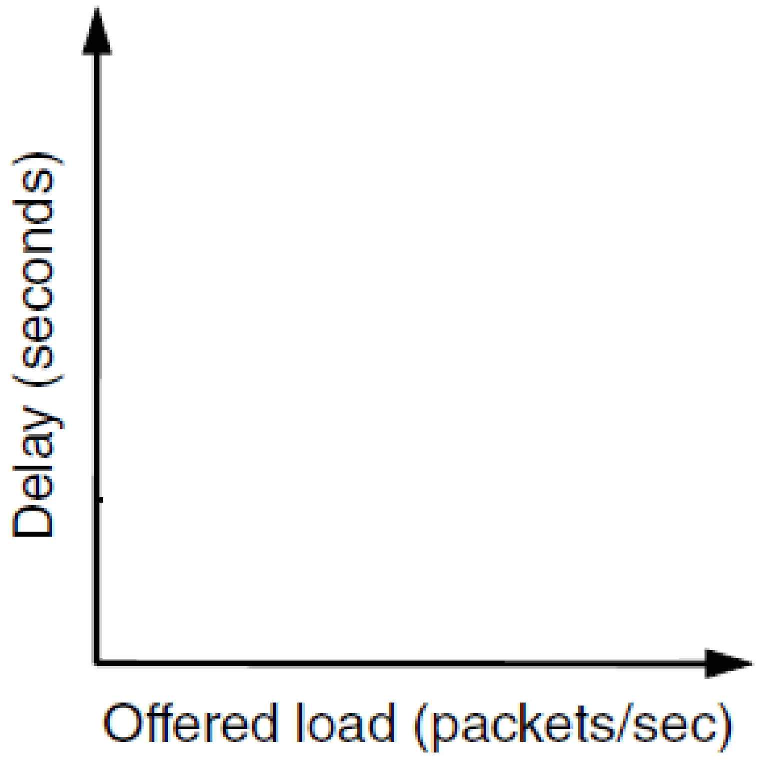
Nature of Congestion (3)

- Queues help by absorbing bursts when input > output rate
- But if input > output rate persistently, queue will overflow
  - This is congestion
- Congestion is a function of the traffic patterns – can occur even if every link have the same capacity

Effects of Congestion

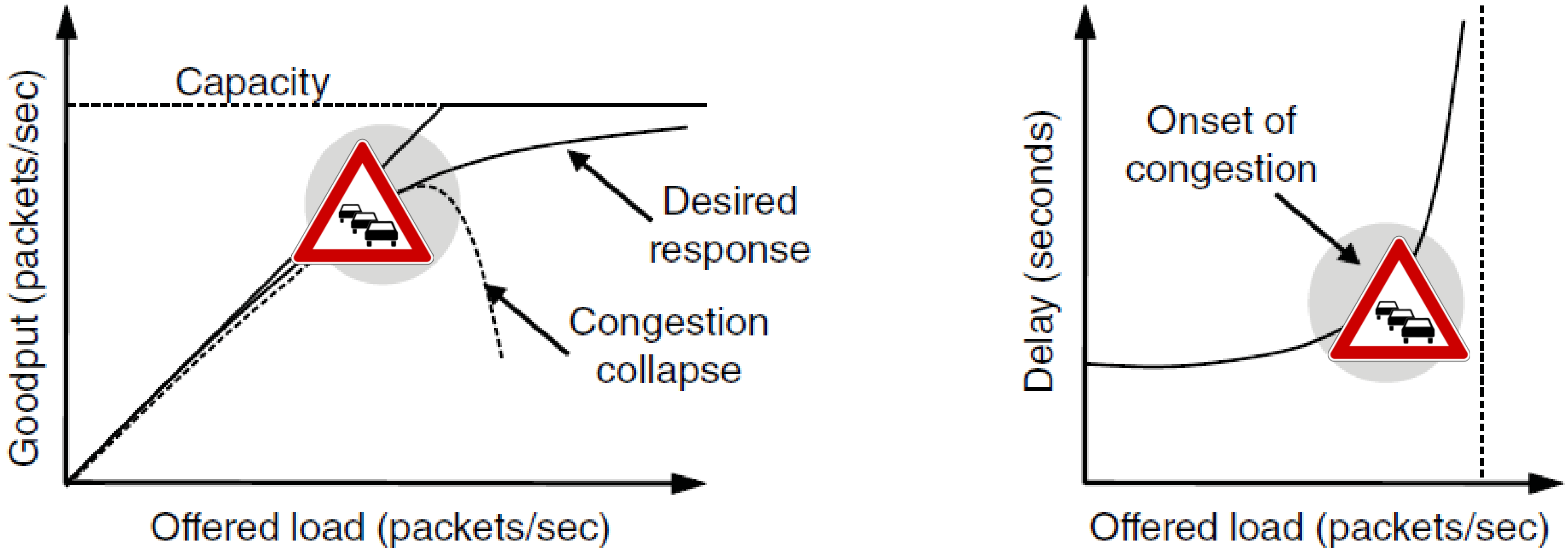
- What happens to performance as we increase load?





Effects of Congestion (2)

- What happens to performance as we increase load?



Effects of Congestion (3)

- As offered load rises, congestion occurs as queues begin to fill:
  - Delay and loss rise sharply with more load
  - Throughput falls below load (due to loss)
  - Goodput may fall below throughput (due to spurious retransmissions)
- None of the above is good!
  - Want network performance just before congestion

Bandwidth Allocation

- Important task for network is to allocate its capacity to senders
  - Good allocation is both efficient and fair
- Efficient means most capacity is used but there is no congestion
- Fair means every sender gets a reasonable share the network

Bandwidth Allocation (2)

- Key observation:
  - In an effective solution, the Transport (end-to-end) and Network (routers) layers must work together
- Network layer witnesses congestion
  - Only it can provide direct feedback
- Transport layer causes congestion
  - Only it can reduce offered load

Bandwidth Allocation (3)

- Why is it hard? (Just split equally among flows!)
  - Number of senders and their offered load changes
  - Senders may lack capacity in different parts of network
  - Network is distributed; no single party has an overall picture of its state

Bandwidth Allocation (4)

- Solution context:
  - Senders (TCP) adapt concurrently based on their own view of the network
  - Design this adaption so the network usage as a whole is efficient and fair
  - Adaption is continuous since offered loads continue to change over time

Fair Allocations

Fair Allocation

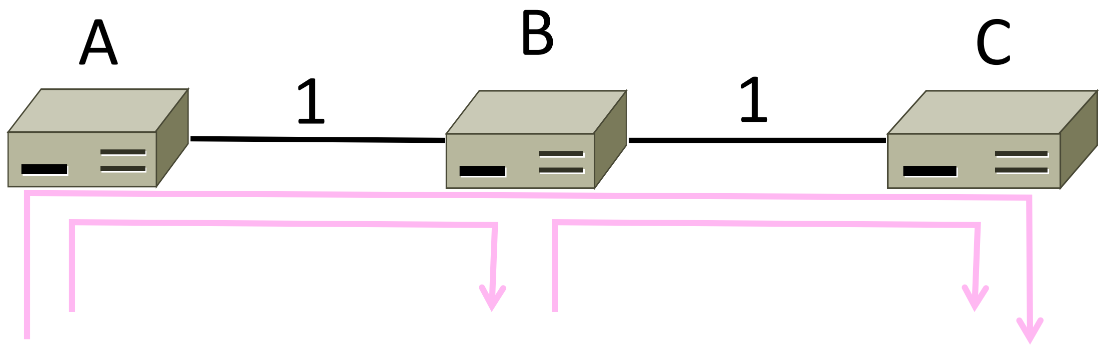
- What's a "fair" bandwidth allocation?
  - The max-min fair allocation

Recall

- We want a good bandwidth allocation to be both fair and efficient
  - Now we learn what fair means
- Caveat: in practice, efficiency is more important than fairness

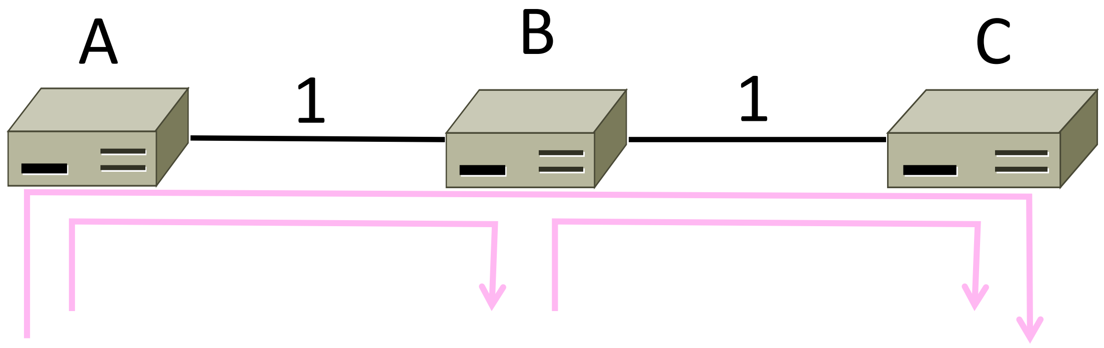
Efficiency vs. Fairness

- Cannot always have both!
  - Example network with traffic:
    - A→B, B→C and A→C
  - How much traffic can we carry?



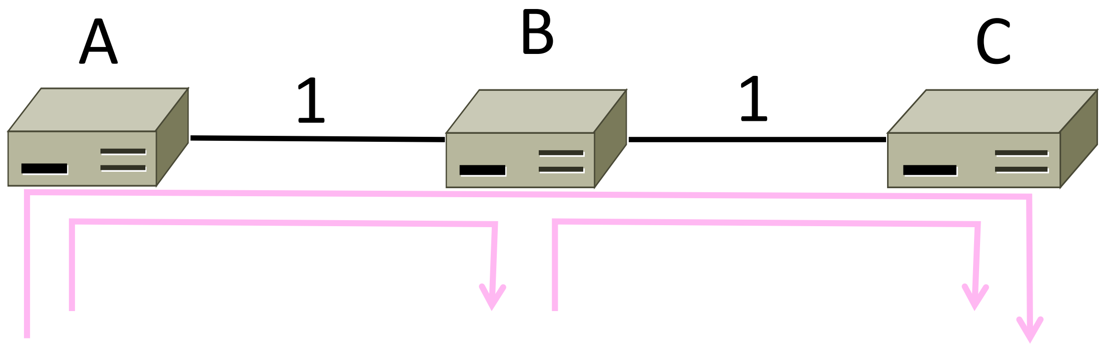
Efficiency vs. Fairness (2)

- If we care about fairness:
  - Give equal bandwidth to each flow
  - A→B: ½ unit, B→C: ½, and A→C, ½
  - Total traffic carried is 1 ½ units



Efficiency vs. Fairness (3)

- If we care about efficiency:
  - Maximize total traffic in network
  - A→B: 1 unit, B→C: 1, and A→C, 0
  - Total traffic rises to 2 units!

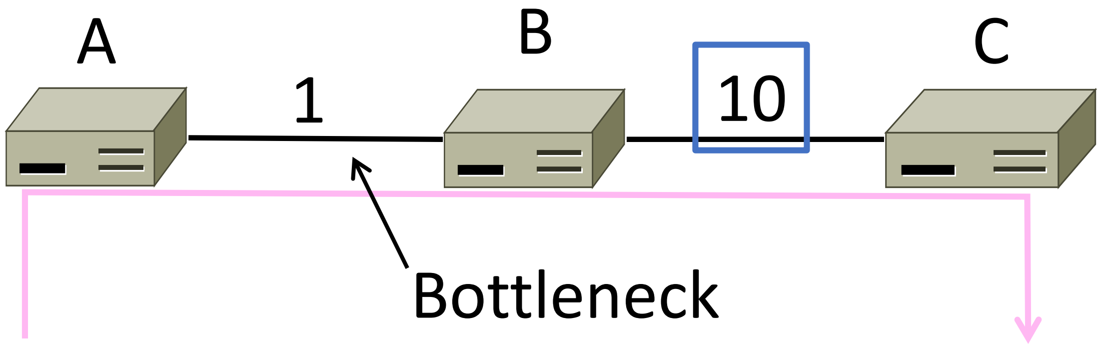


The Slippery Notion of Fairness

- Why is "equal per flow" fair anyway?
  - A→C uses more network resources than A→B or B→C
  - Host A sends two flows, B sends one
- Not productive to seek exact fairness
  - More important to avoid starvation
    - A node that cannot use any bandwidth
  - "Equal per flow" is good enough

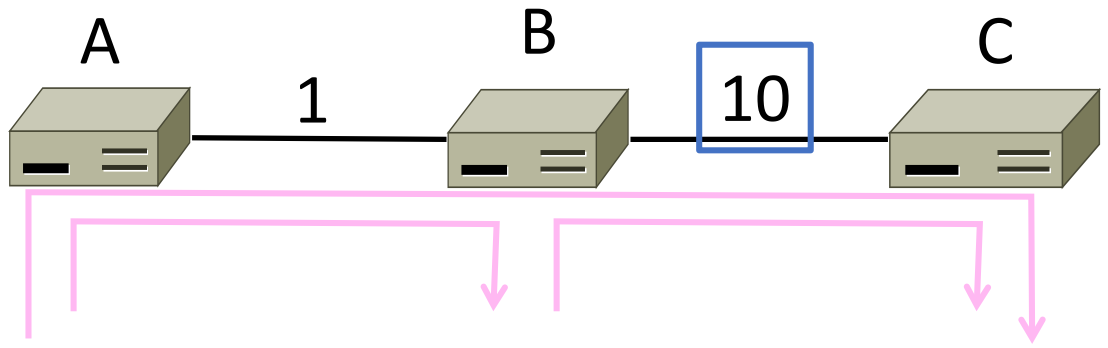
Generalizing "Equal per Flow"

- Bottleneck for a flow of traffic is the link that limits its bandwidth
  - Where congestion occurs for the flow
  - For A→C, link A–B is the bottleneck



Generalizing "Equal per Flow" (2)

- Flows may have different bottlenecks
  - For A→C, link A–B is the bottleneck
  - For B→C, link B–C is the bottleneck
  - Can no longer divide links equally among all flows in a sensible way…



Max-Min Fairness

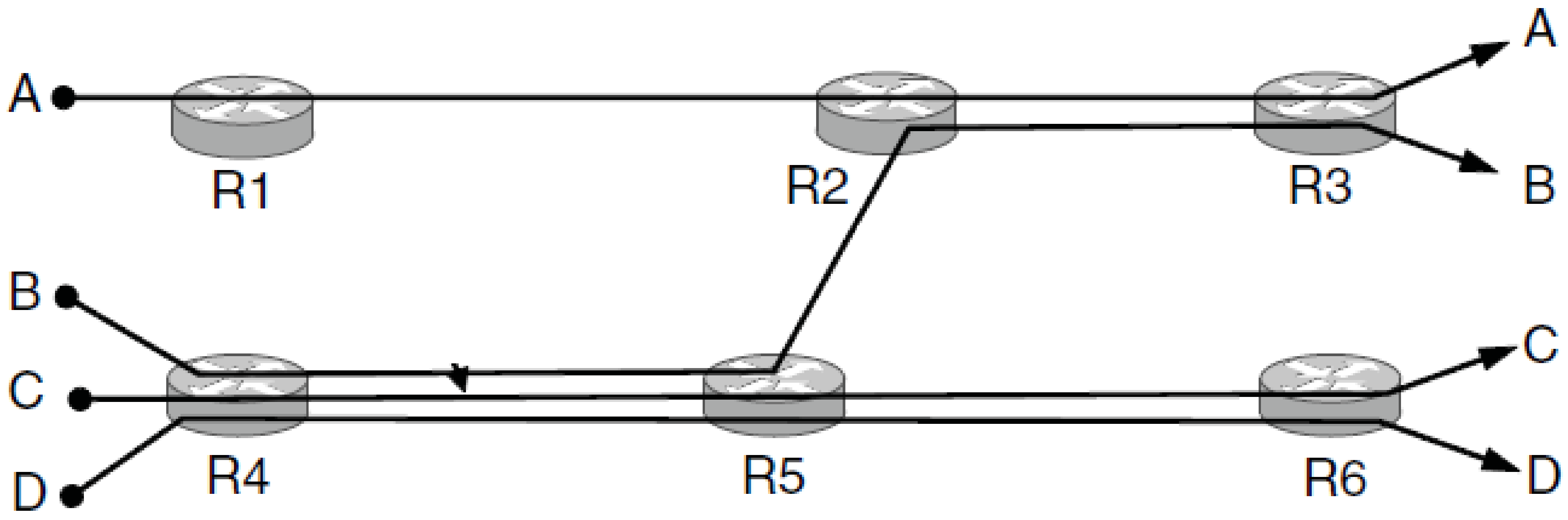
- Intuitively, flows bottlenecked on a link get an equal share of that link
- Max-min fair allocation is one that:
  - Increasing the rate of one flow will decrease the rate of a smaller flow
  - This “maximizes the minimum” flow

Max-Min Fairness (2)

- To find it given a network, imagine "pouring water into the network"
  1. Start with all flows at rate 0
  2. Increase the flows equally until there is a new bottleneck in the network
  3. Hold fixed the rate of the flows that are bottlenecked
  4. Go to step 2 for any remaining flows

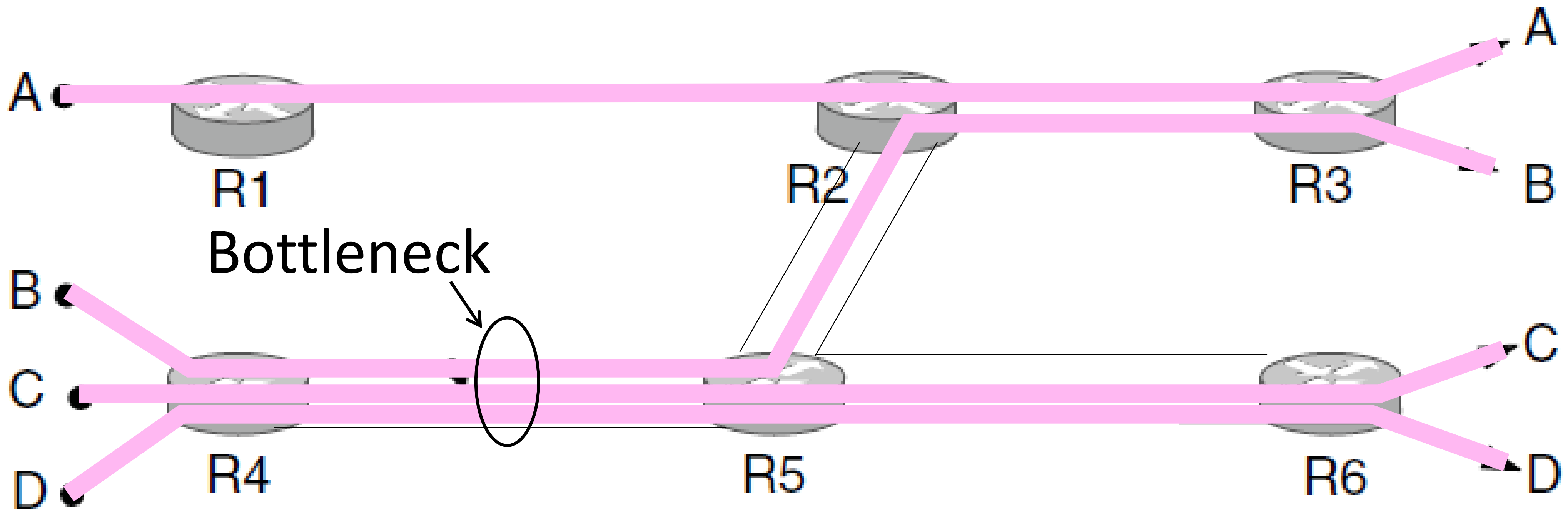
Max-Min Example

- Example: network with 4 flows, links equal bandwidth



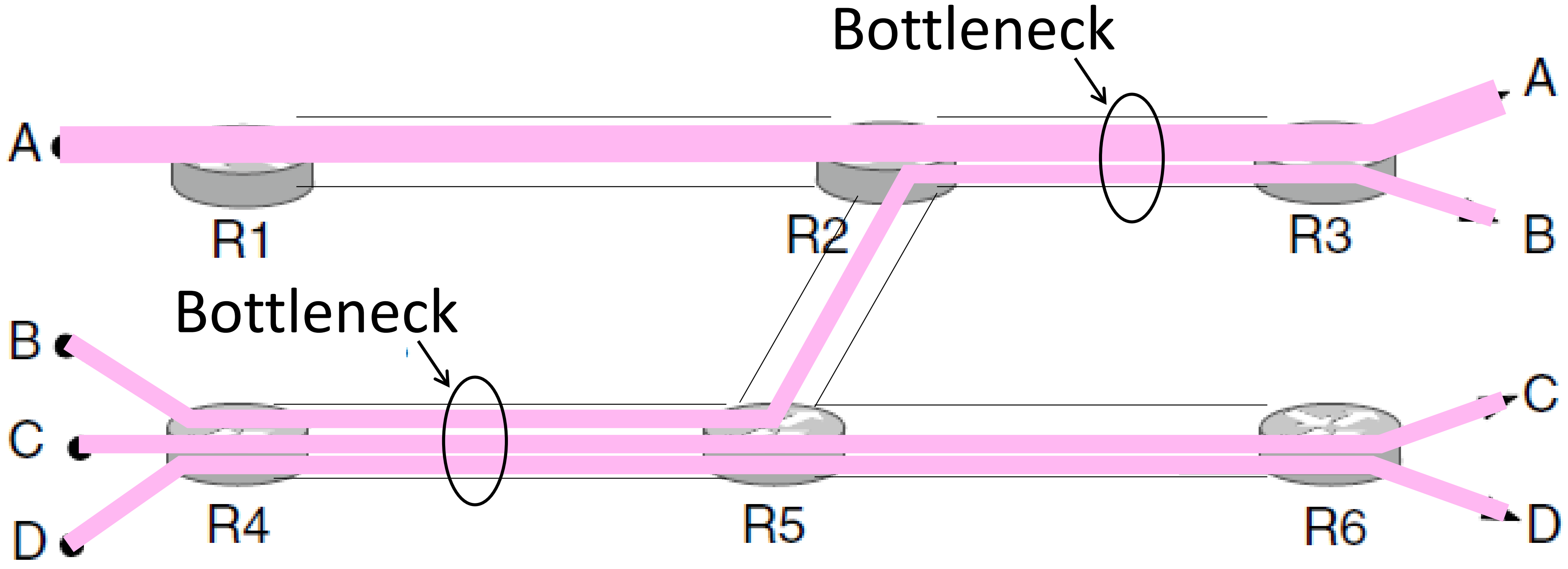
Max-Min Example (2)

- When rate=1/3, flows B, C, and D bottleneck R4—R5
  - Fix B, C, and D, continue to increase A



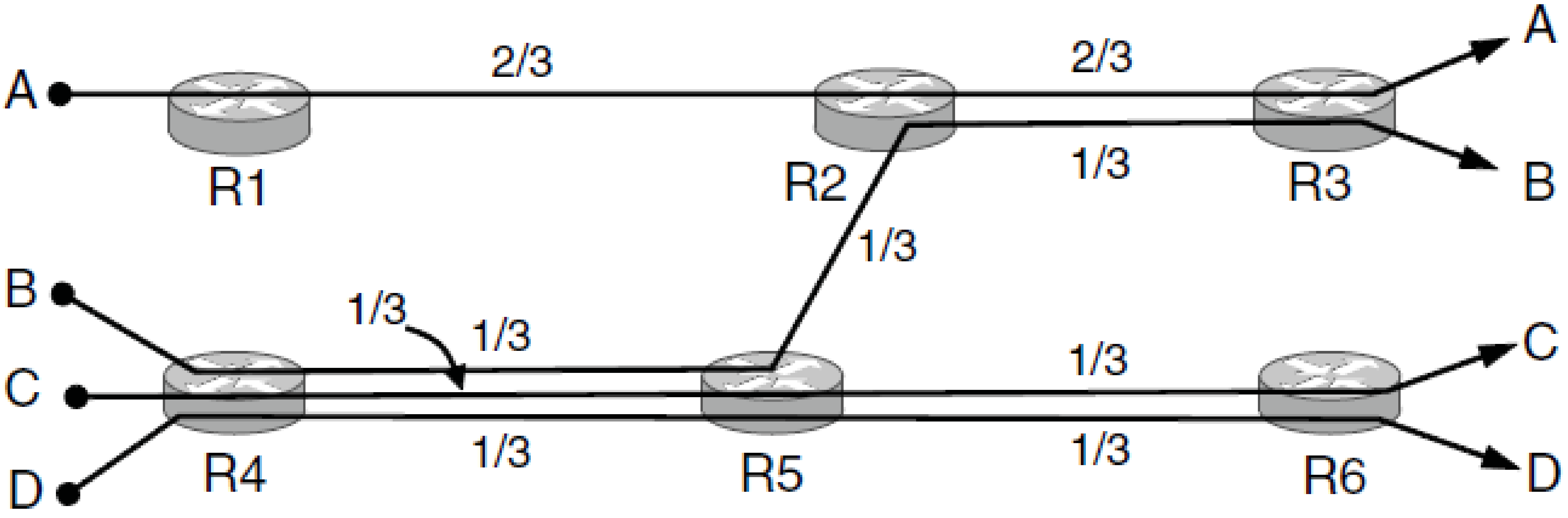
Max-Min Example (3)

- When rate=2/3, flow A bottlenecks R2—R3. Done.



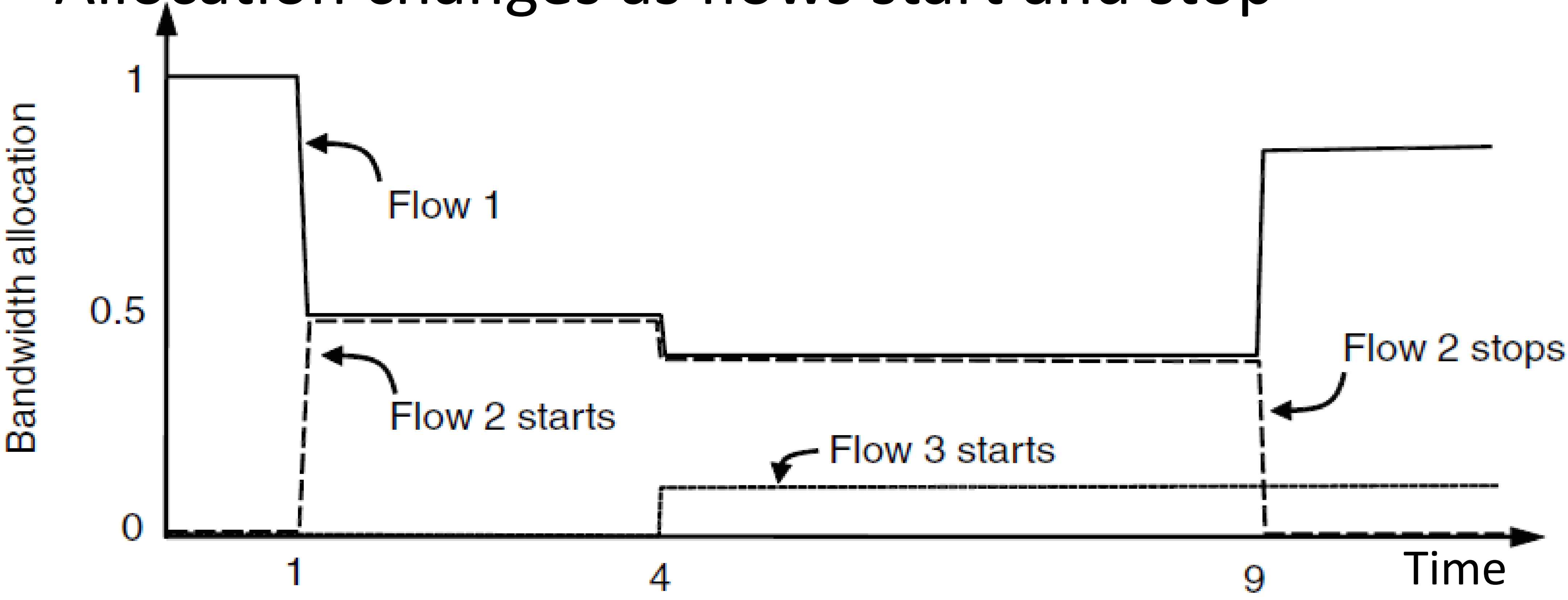
Max-Min Example (4)

- End with A=2/3, B, C, D=1/3, and R2—R3, R4—R5 full

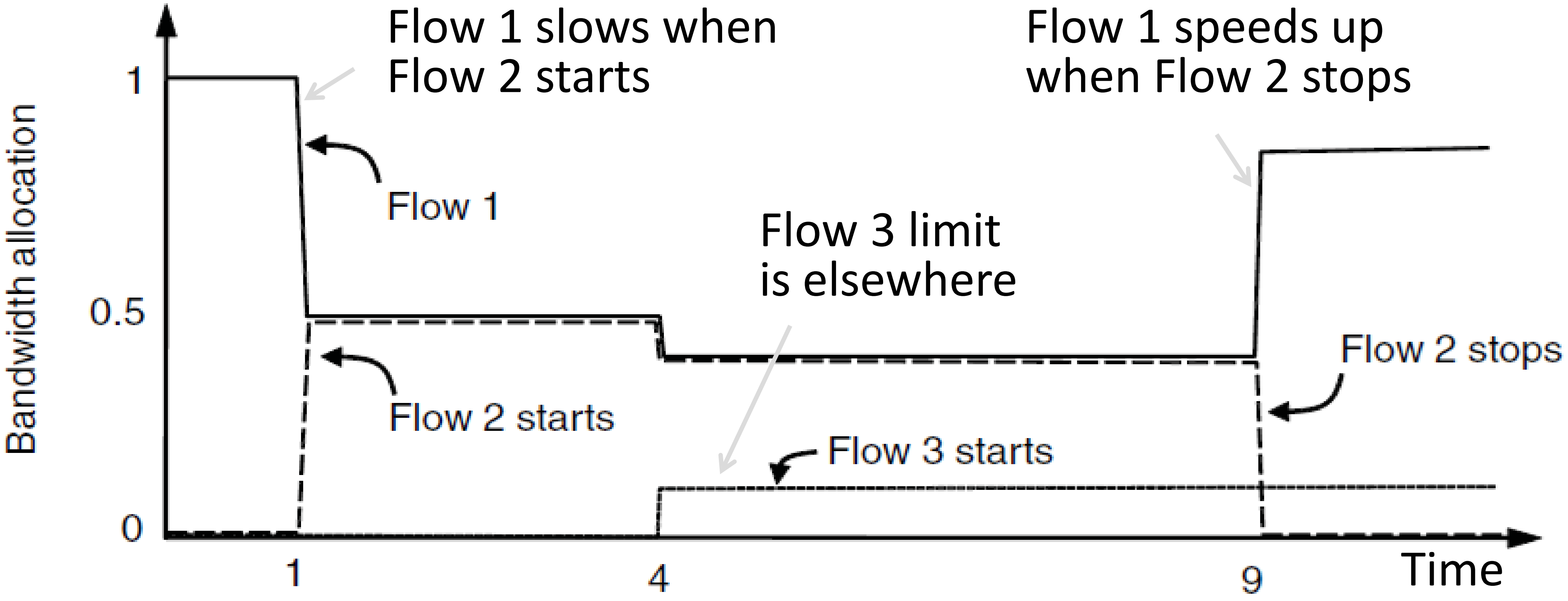


Adapting over Time

- Allocation changes as flows start and stop



Adapting over Time (2)



Bandwidth Allocation

Recall

- Want to allocate capacity to senders
  - Network (router) layer provides feedback
  - Transport (TCP) layer adjusts offered load
  - A good allocation is efficient and fair
- How should we perform the allocation?
  - Several different possibilities …

Bandwidth Allocation Models

- Open loop versus closed loop
  - Open: reserve bandwidth before use
  - Closed: use feedback to adjust rates
- Host versus Network support
  - Who is sets/enforces allocations?
- Window versus Rate based
  - How is allocation expressed?

TCP is a closed loop, host-driven, and window-based

Bandwidth Allocation Models (2)

- We'll look at closed-loop, host-driven, and window-based too
- Network layer returns feedback on current allocation to senders
  - At least tells if there is congestion
- Transport layer adjusts sender's behavior via window in response
  - How senders adapt is a <u>control law</u>

Additive Increase Multiplicative Decrease

- AIMD is a control law hosts can use to reach a good allocation
  - Hosts additively increase rate while network not congested
  - Hosts multiplicatively decrease rate when congested
  - Used by TCP

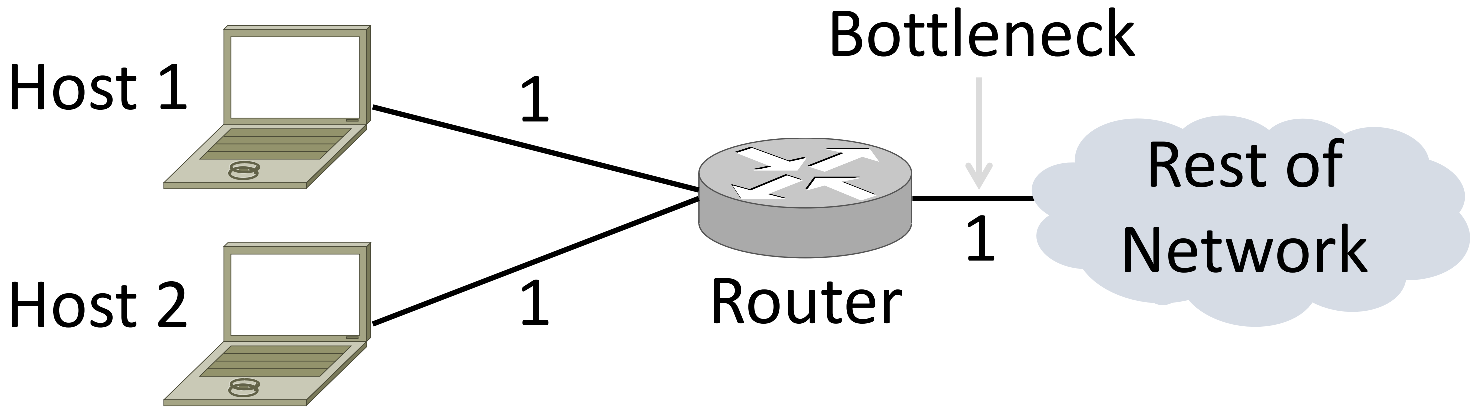
AIMD

- When things are going well, increase offered load by adding a constant (additive)
  - That is, increase offered load conservatively
  - The increase is the same whether you’re currently using a lot or a little
- When things are going poorly, decrease offered load by multiplying by a constant less than one (multiplicative)
  - That is, aggressively decrease load
  - The more load you’re offering, the larger the amount by which you reduce it

AIMD Fairness / Efficiency

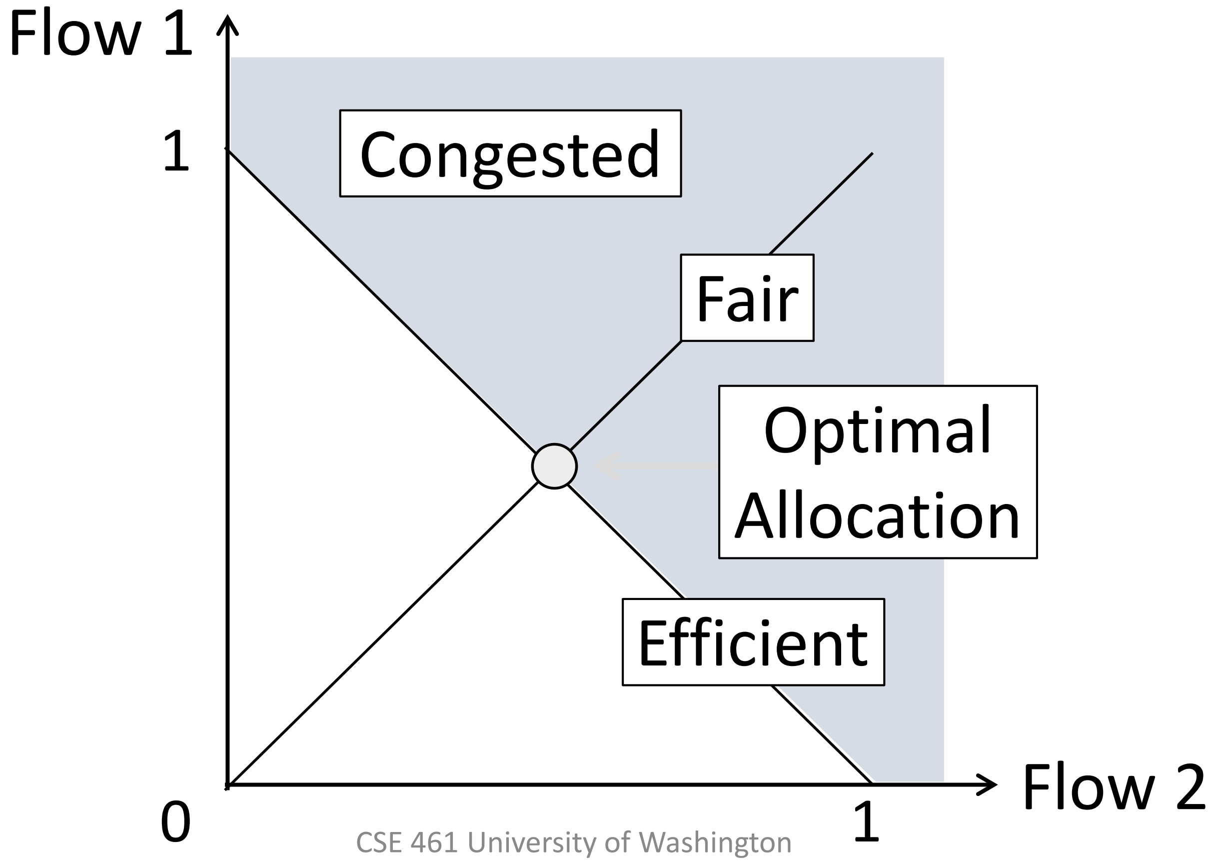
- Flows 1 and 2 share a bottleneck
  - But do not talk to each other directly

- Router provides binary feedback
  - “Tells” flow if network is congested



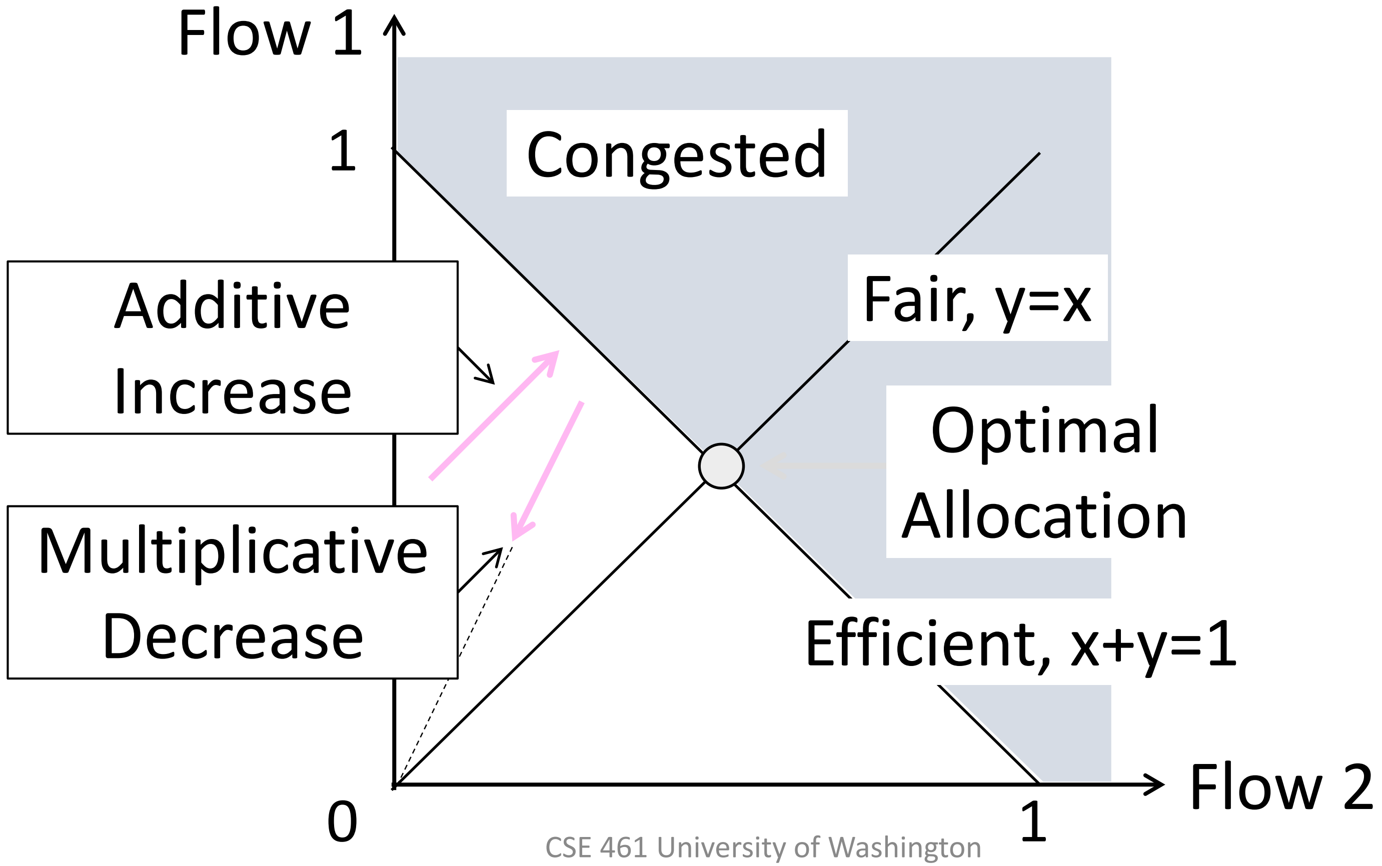
AIMD Game (2)

- Each point is a possible allocation



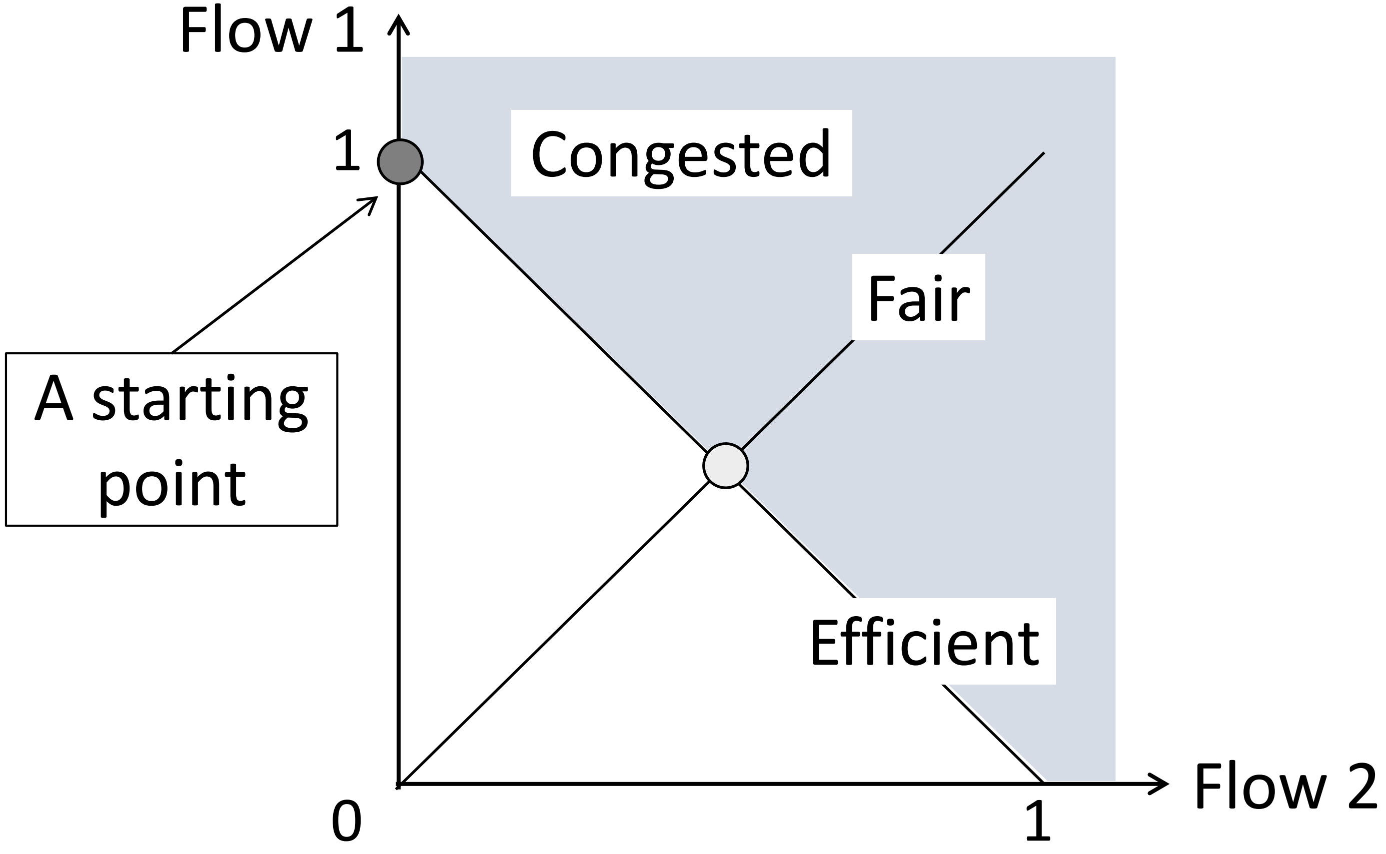
AIMD Game (3)

- AI and MD move the allocation



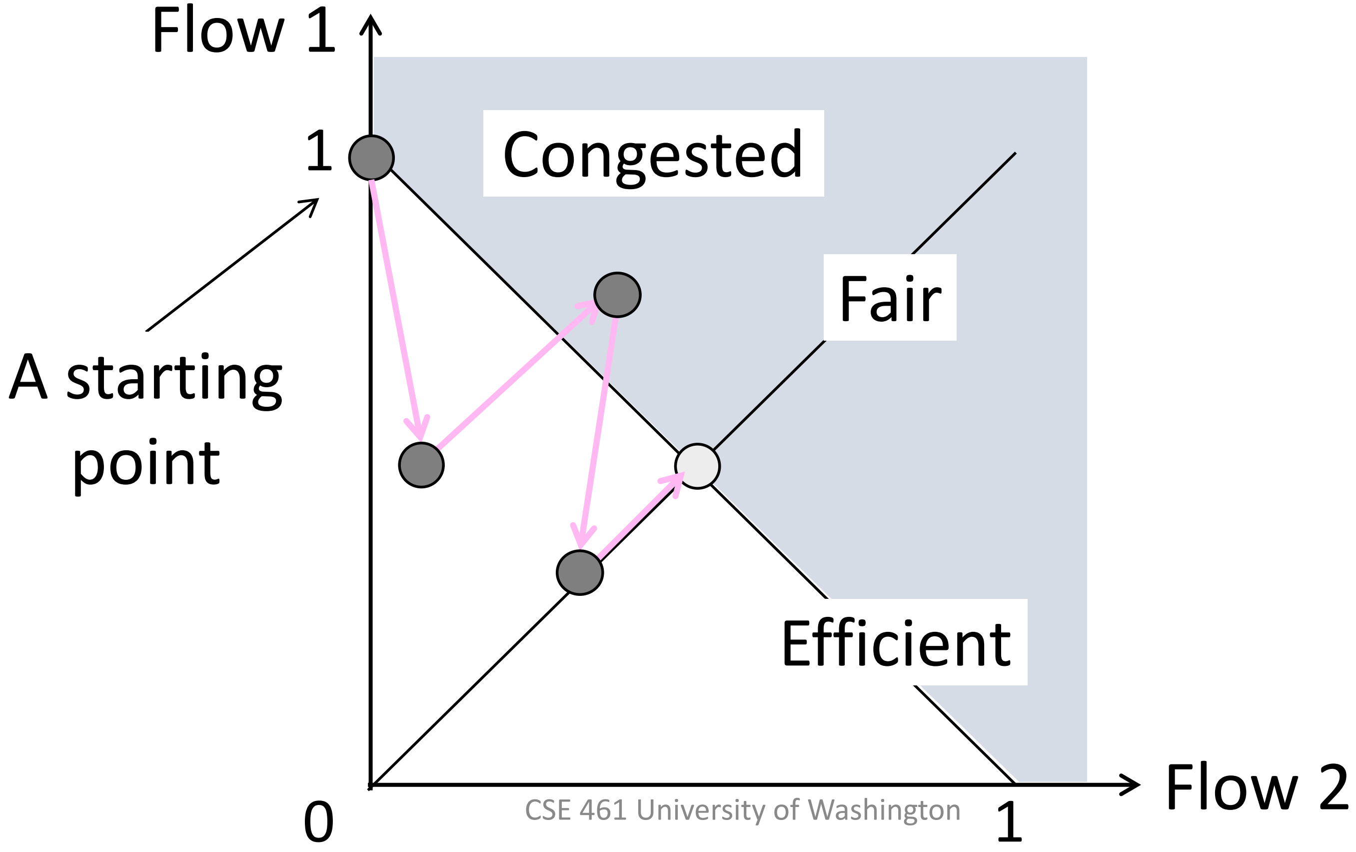
AIMD Game (4)

- Here we go...



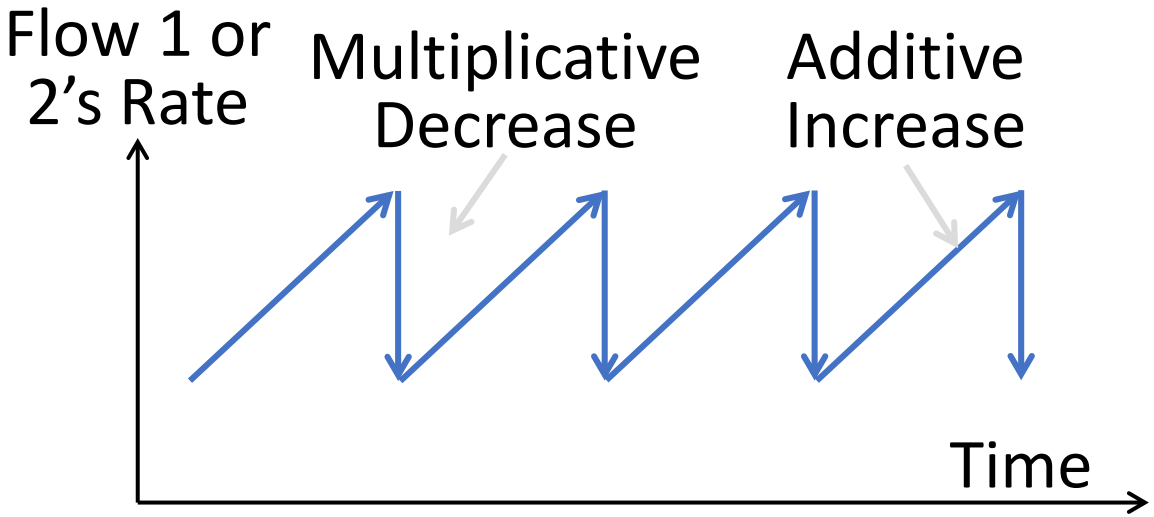
AIMD Game (5)

- Converges to a good allocation!



AIMD Sawtooth

- Produces a “sawtooth” pattern over time for rate of each flow
  - This is the TCP sawtooth



AIMD Properties

- Converges to a set of allocations that are efficient and fair
  - Holds for more general topologies
- Other increase/decrease control laws do not! (Try MIAD, MIMD, MIAD)
- Requires only binary feedback from the network
  - “Try going faster” or “Slow down!”

Feedback Signals

- Several possible signals, with different pros/cons
  - We'll look at classic TCP that uses packet loss as a signal

Signal	Example Protocol	Pros / Cons
Packet loss	TCP NewReno Cubic TCP (Linux)	Hard to get wrong Hear about congestion late
Packet delay	Compound TCP (Windows)	Hear about congestion early Need to infer congestion
Router indication	TCPs with Explicit Congestion Notification	Hear about congestion early Require router support