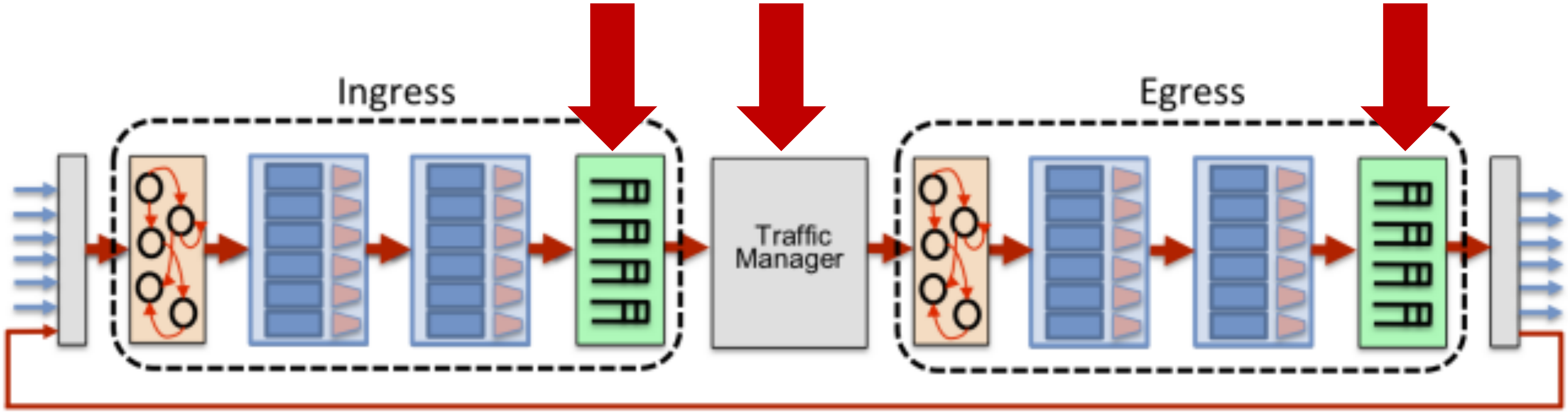
Programmable and Universal Packet Scheduling

ECE/CS598HPN

Radhika Mittal

Scheduling not programmable



Two complementary papers

- Programmable packet scheduling, HotNets'15, SIGCOMM'16
- Universal packet scheduling, HotNets'15, NSDI'16

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- Programmable packet scheduling, HotNets'15, SIGCOMM'16
  - Many slides borrowed from Anirudh Sivaraman.
- Universal packet scheduling, HotNets'15, NSDI'16

The Push-In First-Out Queue

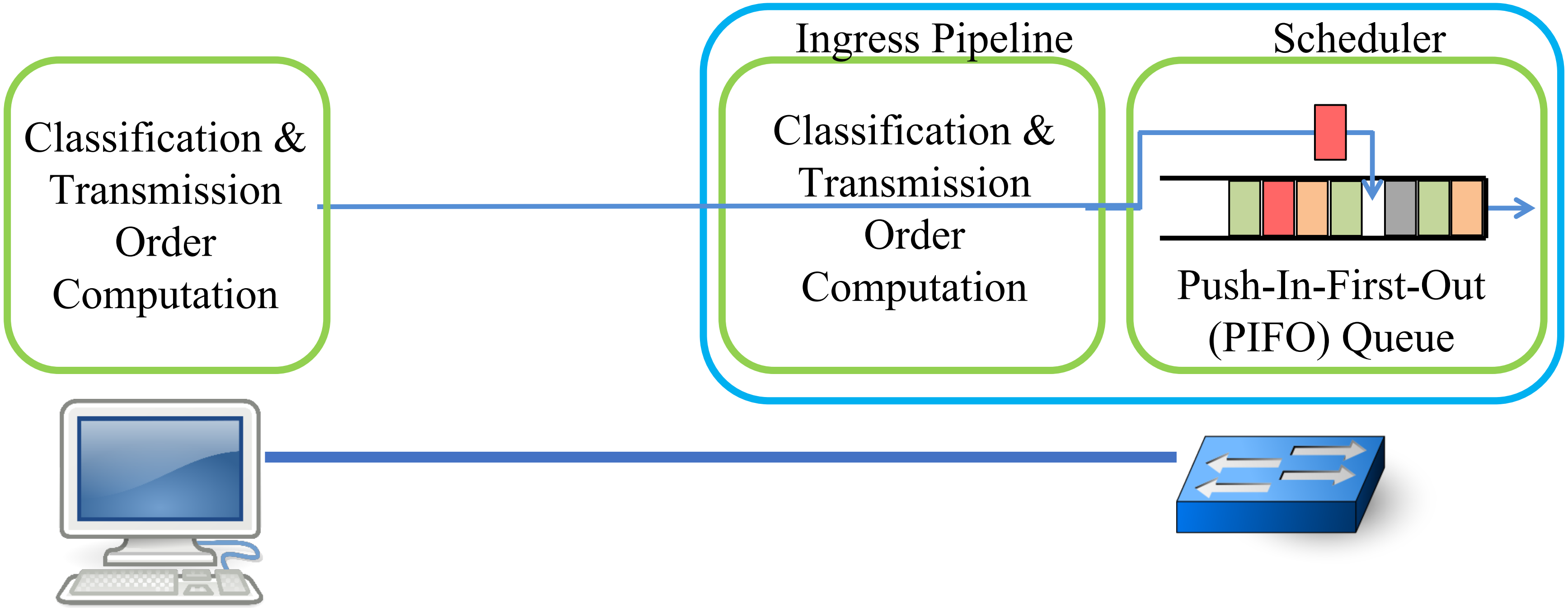
- Many algorithms determine transmission order at packet arrival
- Relative order of packet transmissions of packets in the queue doesn't change with future arrivals
- Examples:
  - SJF: Order determined by flow size
  - FCFS: Order determined by arrival time

- Push-in first-out queues (PIFO) is a good abstraction to capture such algorithms.
  - packets are pushed into an arbitrary location based on a priority, and dequeued from the head
- First used as a proof construct by Chuang et. al.

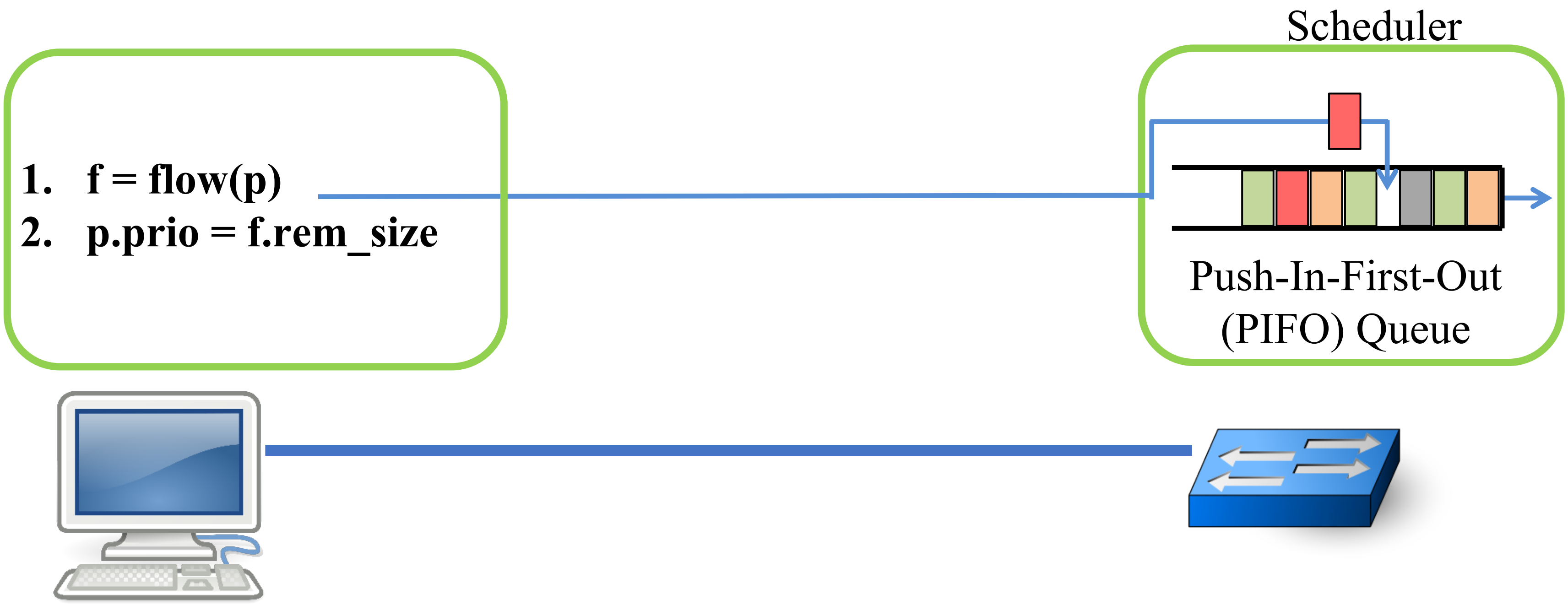
The PIFO abstraction

- PIFO: A sorted array that let us insert an entry (packet or PIFO pointer) based on a programmable priority
  - Entries are always dequeued from the head
  - If an entry is a packet, dequeue and transmit it
  - If an entry is a PIFO, dequeue it, and continue recursively

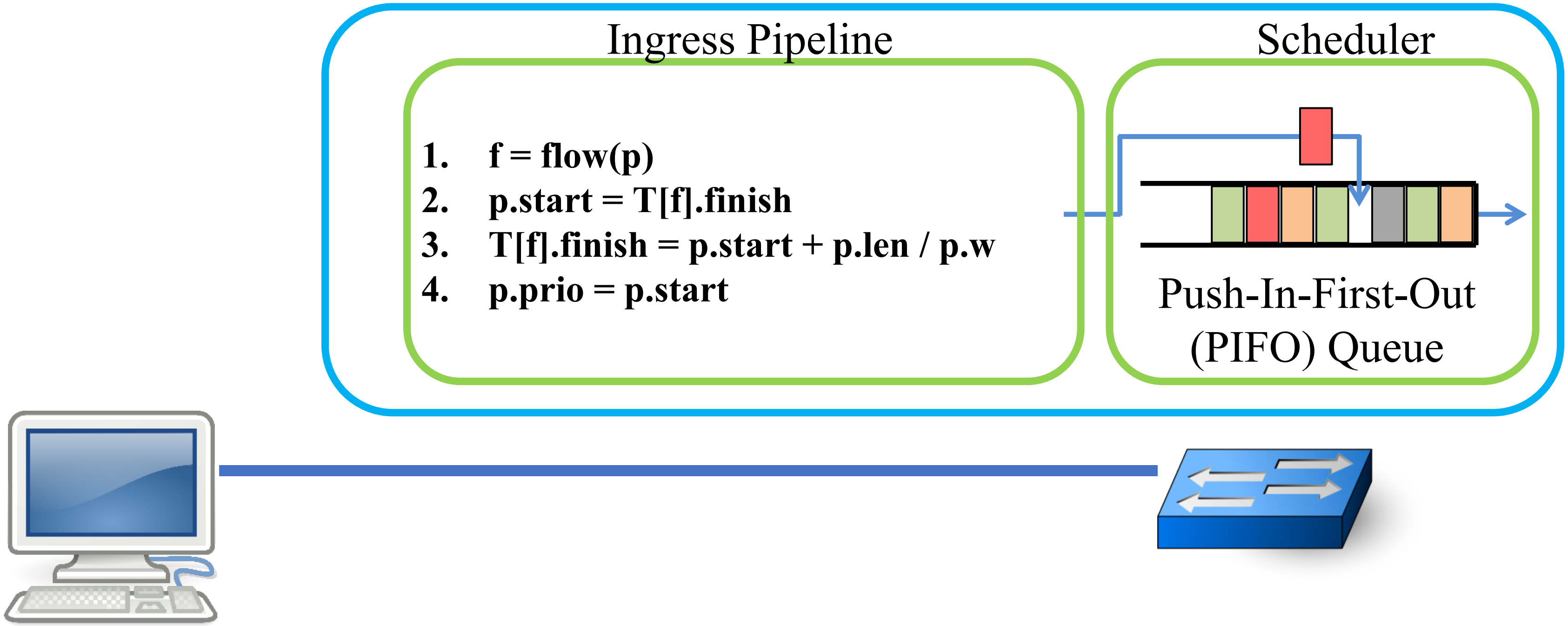
A programmable scheduler



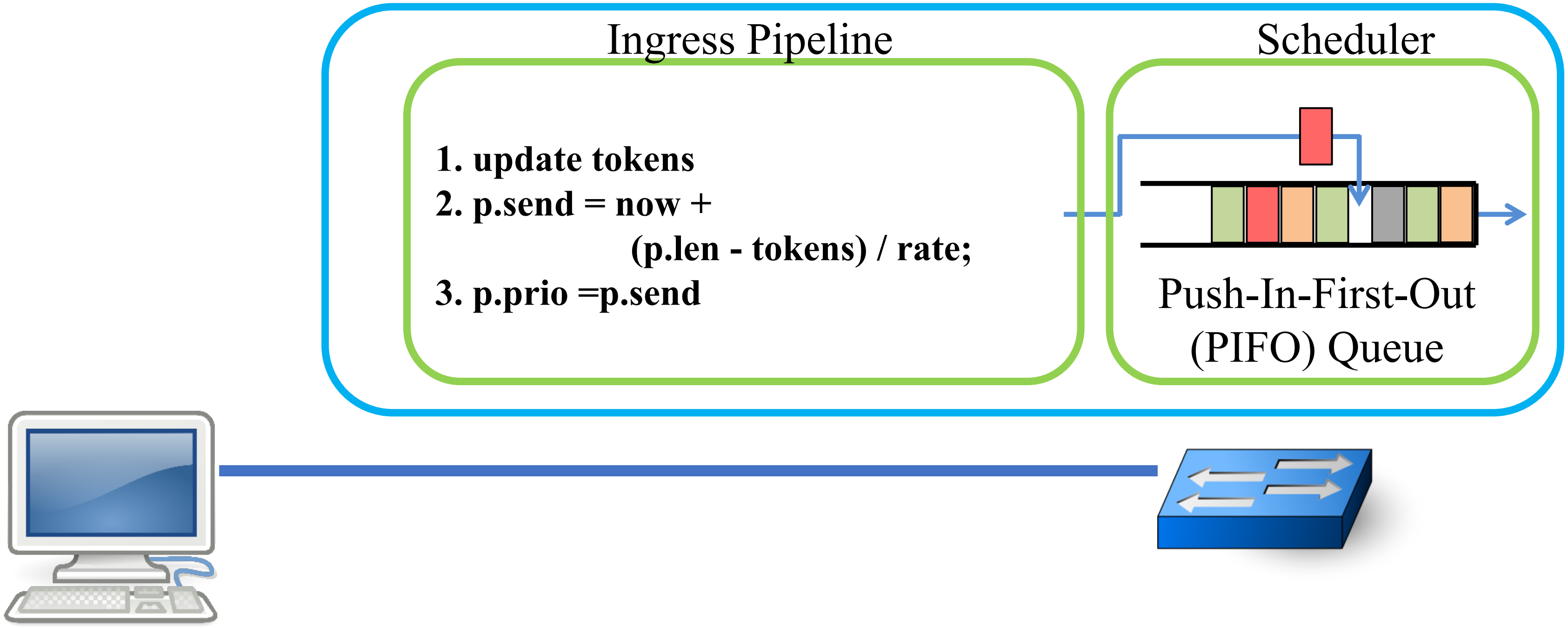
pFabric using PIFO



Weighted Fair Queuing

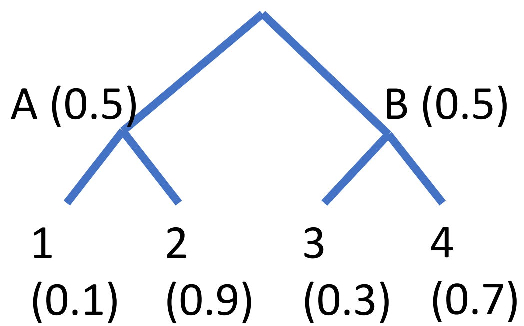


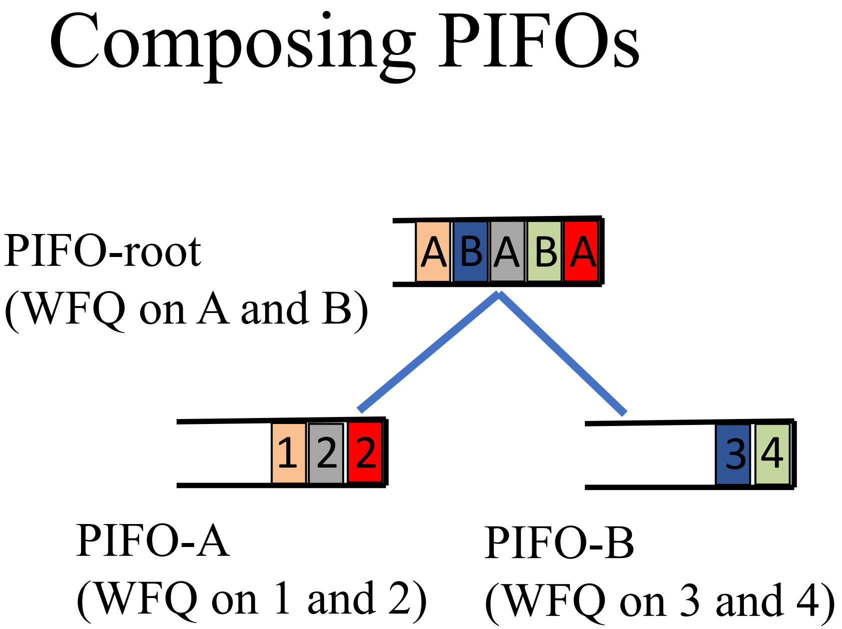
Traffic Shaping



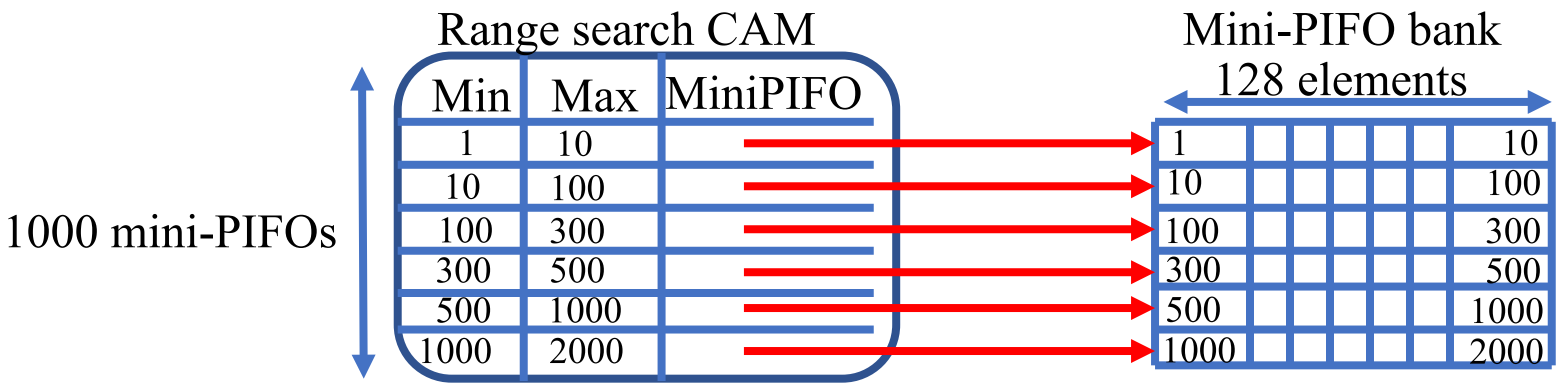
Composing PIFOs

Hierarchical packet-fair queueing (HPFQ)



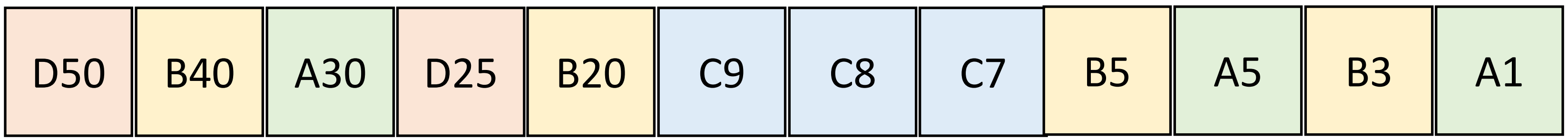


PIFO in hardware

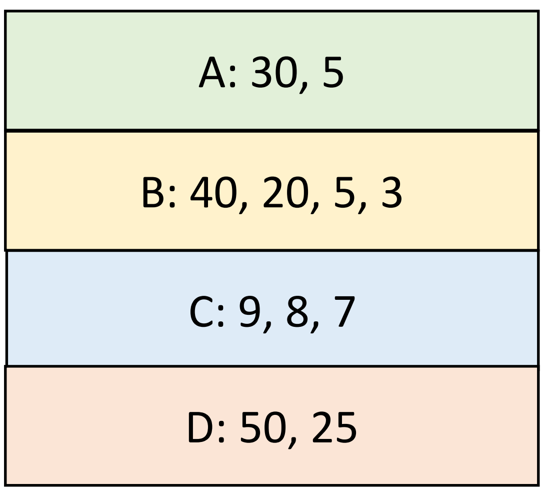


- Meets timing at 1 GHz on a 16 nm node
- 5 % area overhead for 3-level hierarchy
- Challenges wisdom that sorting is hard

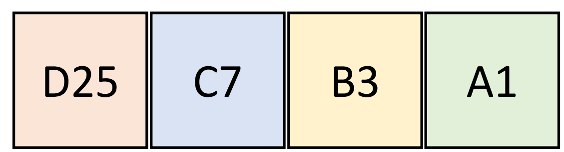
Programmable packet scheduling, SIGCOMM'16



Single array PIFO can be expensive
(lots of comparator circuits required)



Rank Store



Flow scheduler
(fewer comparator circuits required)

Key limitation of the PIFO abstraction

- When priority (relative ordering between two packets) changes after enqueuing them.
- …

Your opinions

- Pros:
  - PIFO and calendar queues are simple and powerful abstractions.
  - Idea of making scheduling programmable is useful and exciting.
  - Shows feasibility of implementation.
  - Can be used to implement composite scheduling algorithms.

Your opinions

- Cons:
  - Supports only a finite range of priorities.
  - How to handle multiple flows with different scheduling requirements?
  - No analysis of how expressive PIFO/calendar queues are.
  - In-switch computation of priority might be limited by switch capabilities.
  - How splitting of mini-PIFOs is handled is questionable.

Your opinions

- Ideas
    - How to use PIFOs?
    - Programming language and compiler for scheduling?
    - How will an operator interact with a programmable scheduler?
    - Anything else in the switch that could be made programmable?
    - Analyze the need for programmable scheduling.
    - Pros and cons compared to UPS.

Two complementary papers

- Programmable packet scheduling, HotNets'15, SIGCOMM'16
- Universal Packet Scheduling, HotNets'15, NSDI'16

Many Scheduling Algorithms

- **Many different algorithms**
  - FIFO, FQ, virtual clocks, priorities…
- **Many different goals**
  - fairness, small packet delay, small FCT…
- **Many different contexts**
  - WAN, datacenters, cellular…

Many Scheduling Algorithms

- Implemented in *router hardware.*
- *How do we support different scheduling algorithms for different requirements?*
  - Option 1: Change router hardware for each new algorithm
  - Option 2: Implement *all* scheduling algorithms in hardware
  - Option 3: Programmable scheduling hardware

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  - Option 3: Programmable scheduling hardware

We are asking a new question…..

~~How do we support different scheduling algorithms for different requirements?~~

Is there a *universal* packet scheduling algorithm?

UPS: Universal Packet Scheduling Algorithm

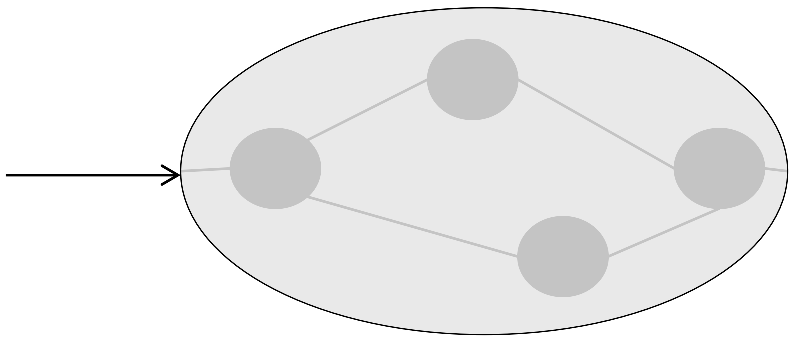
A *single scheduling algorithm* that
can imitate the network-wide output
produced by ***any*** other algorithm.

How can a single algorithm imitate all others?

Network Model

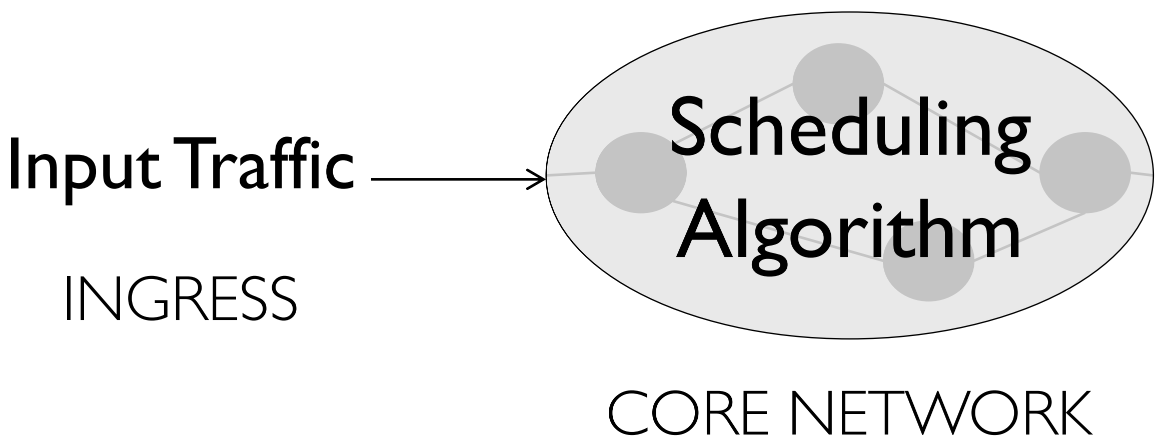
Input Traffic

INGRESS

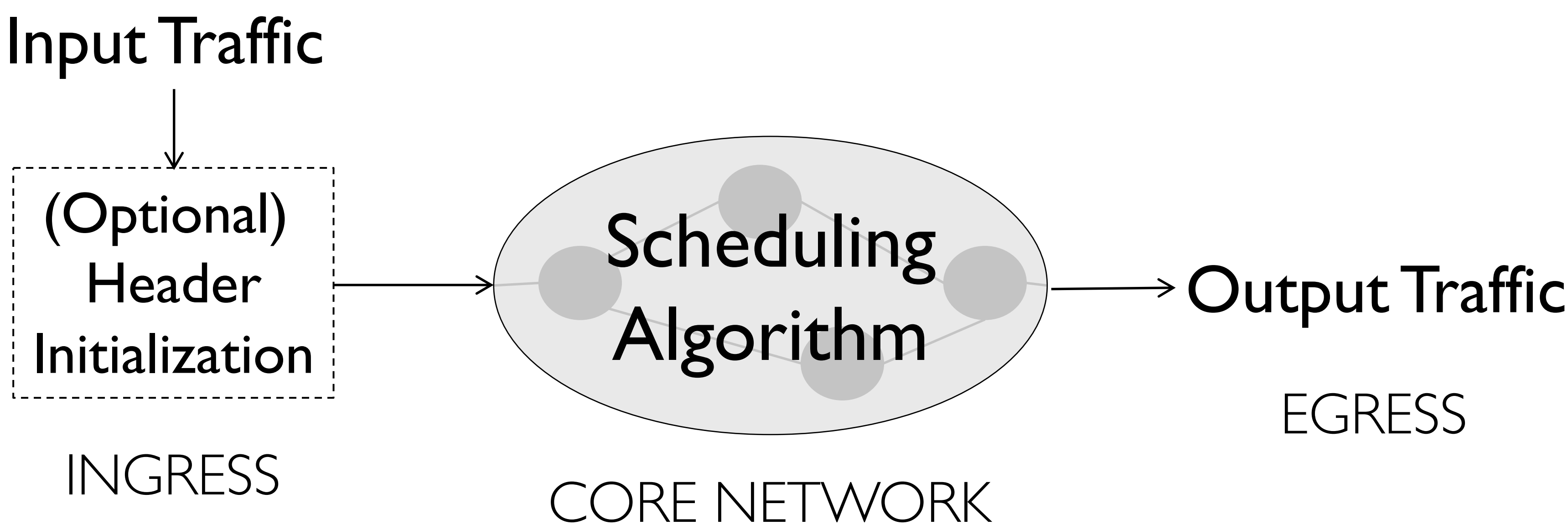


CORE NETWORK

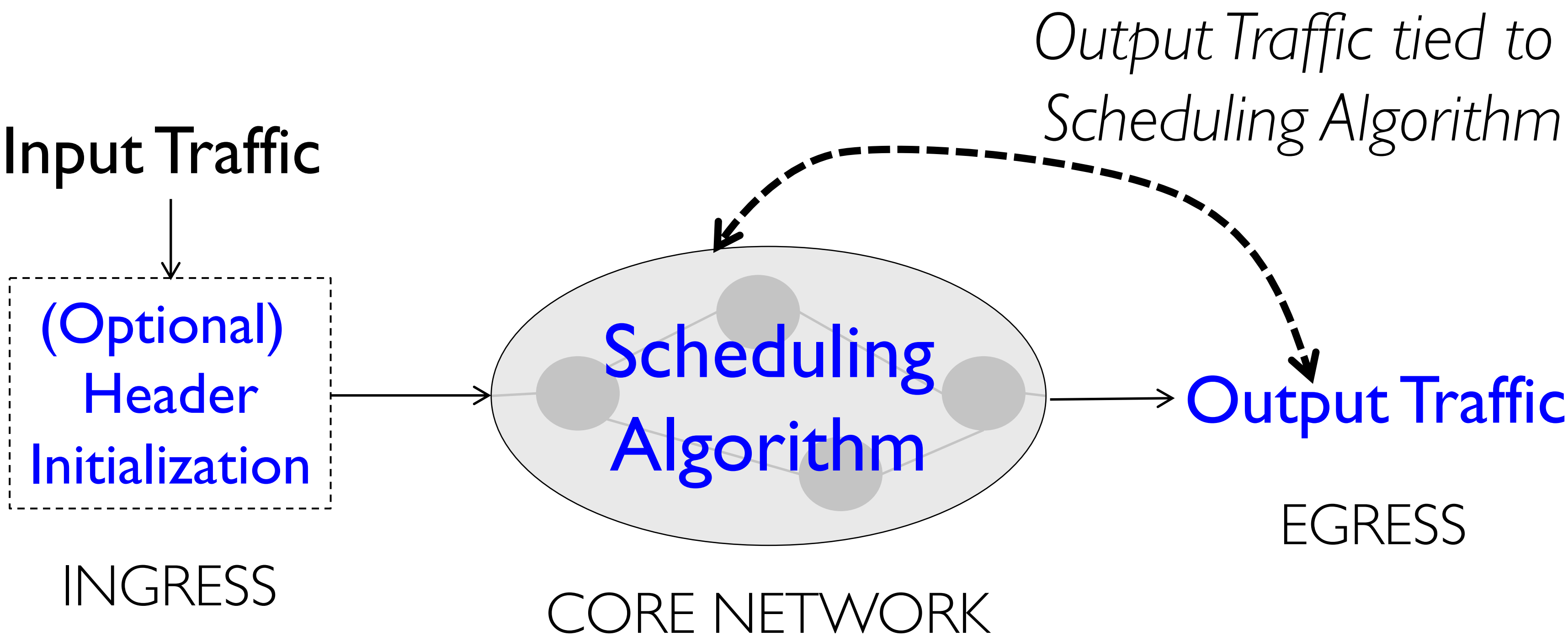
Network Model



Network Model

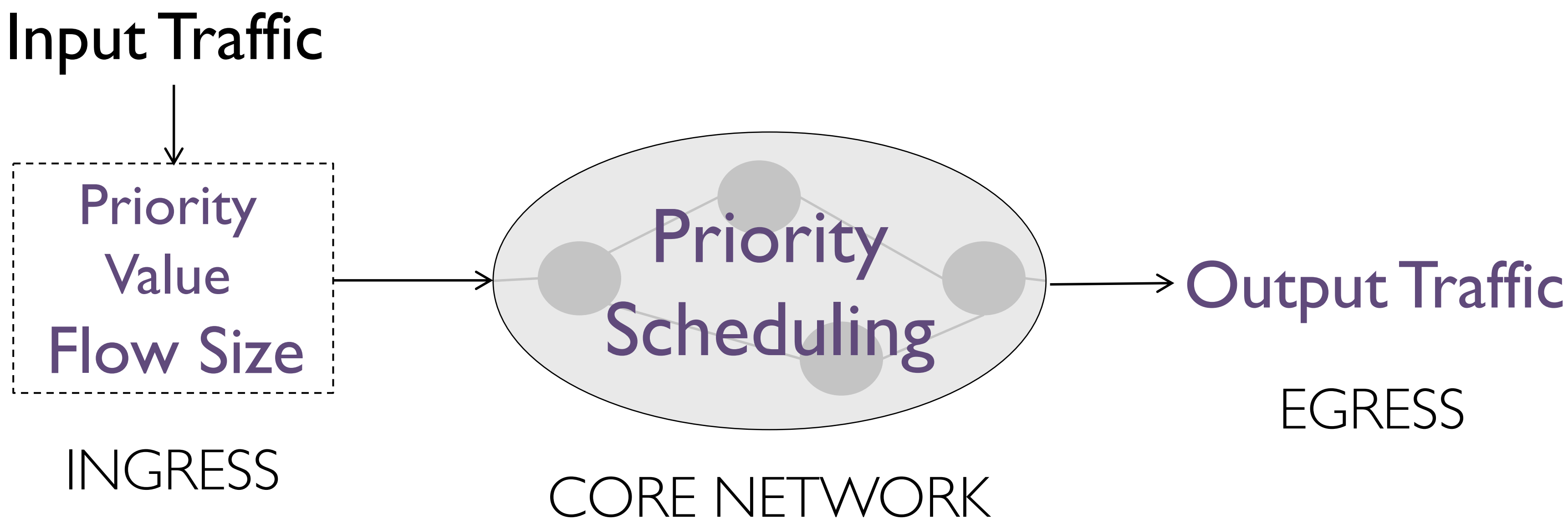


Network Model



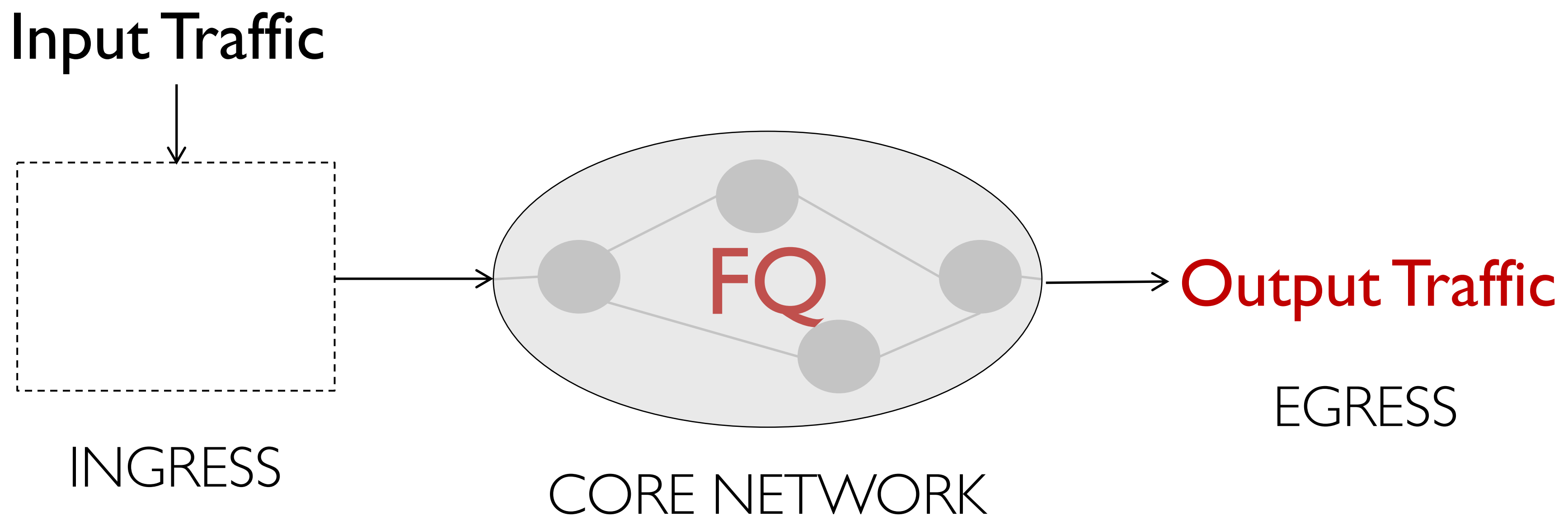
Network Model

Goal: Minimize Mean FCT



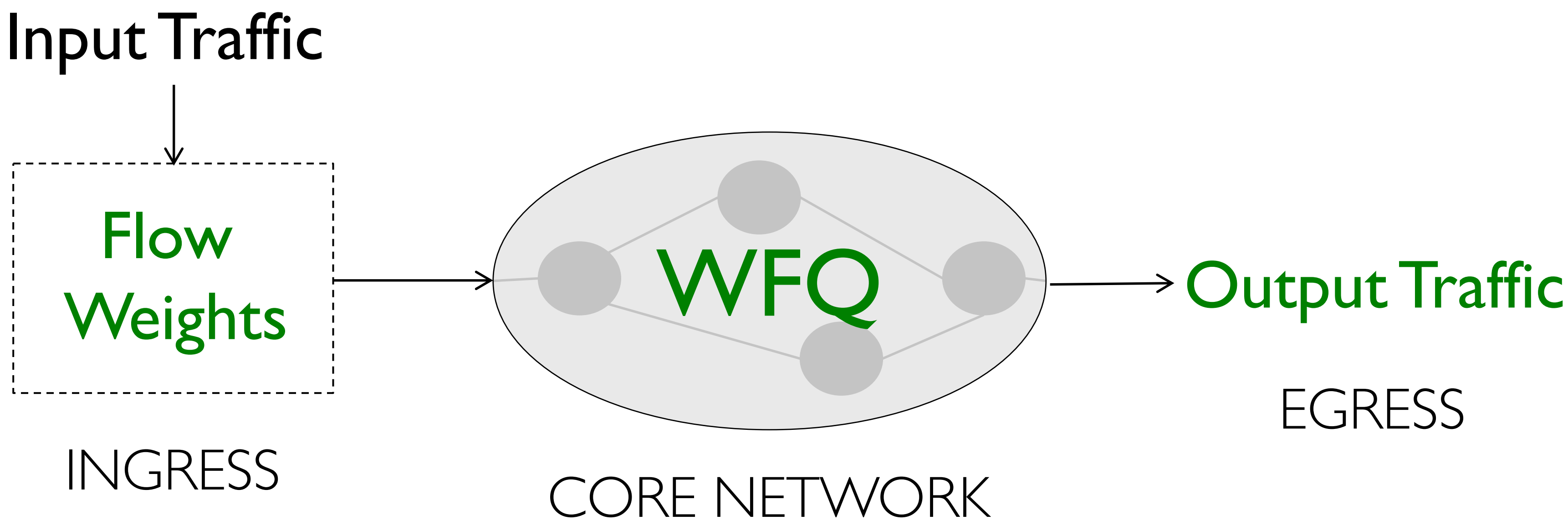
Network Model

Goal: Fairness

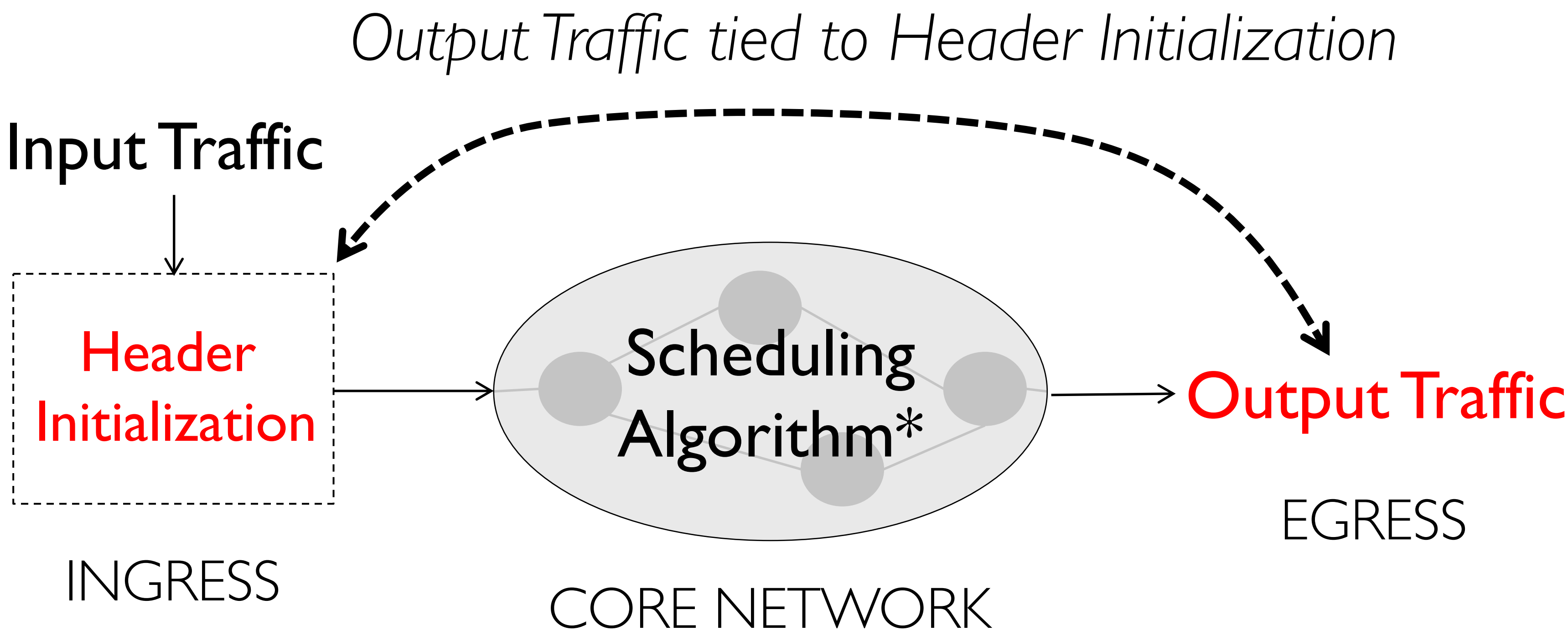


Network Model

Goal: Weighted Fairness

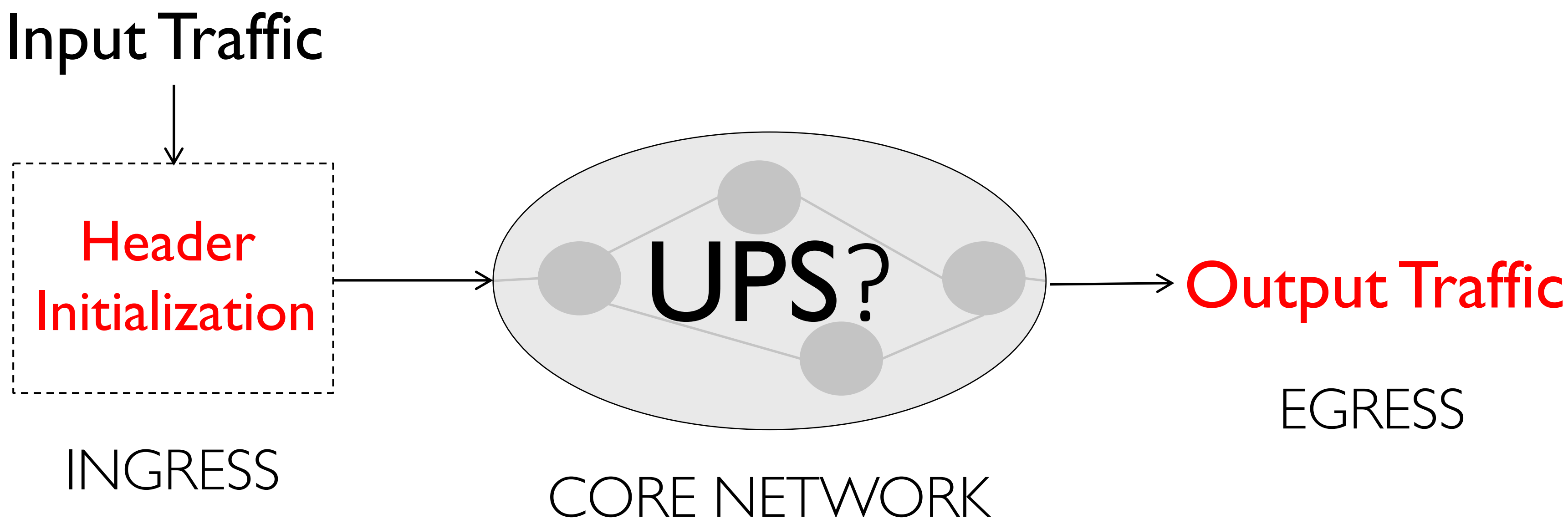


Network Model



* Uses packet header state to make scheduling decisions

Network Model



How do we formally define and evaluate a UPS?

Defining a UPS

Theoretical Viewpoint:

Can it replay a given schedule?

Practical Viewpoint:

Can it achieve a given objective?

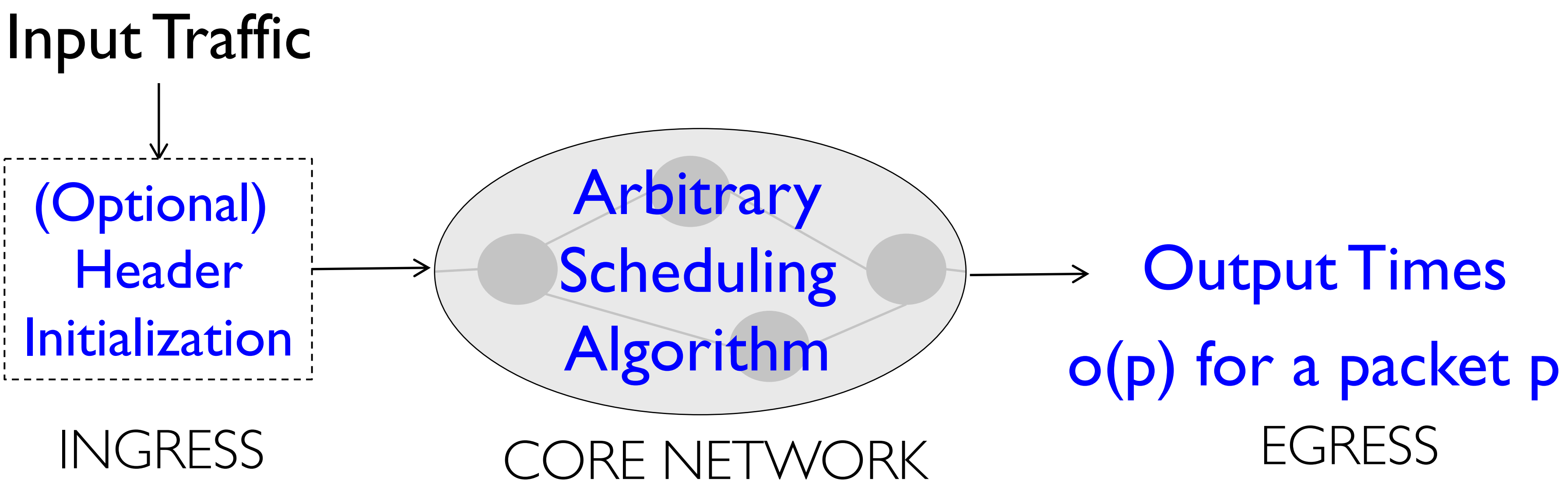
Theoretical Viewpoint

Can it replay a given schedule?

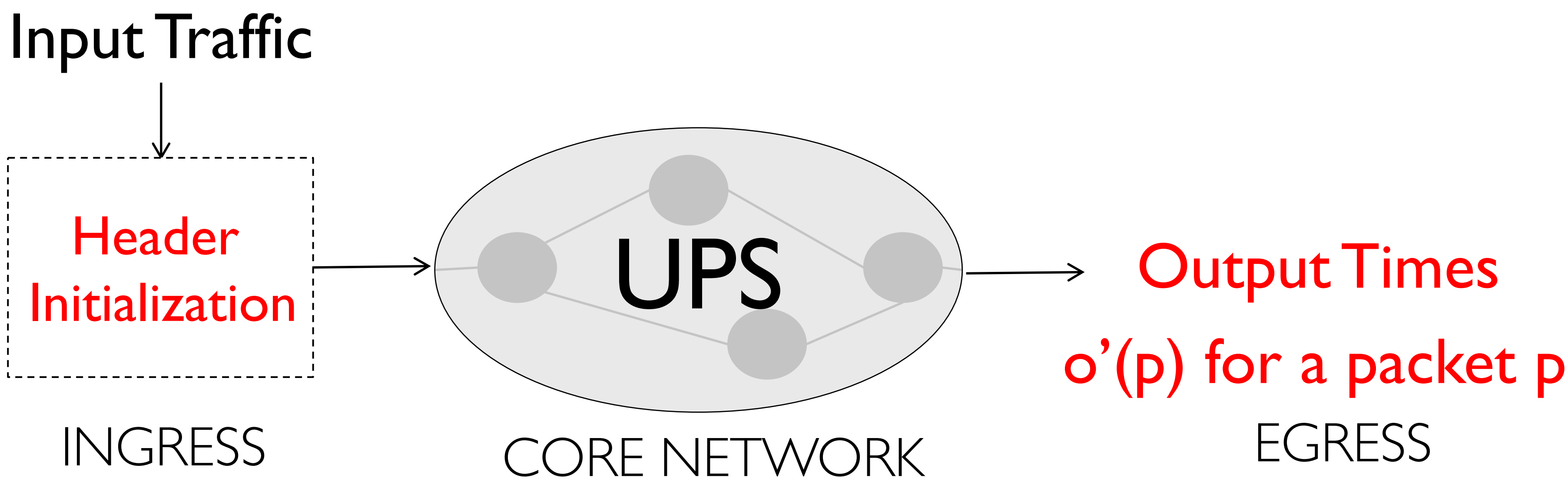
Original Schedule

Only requirement from original schedule:

Output Times are viable

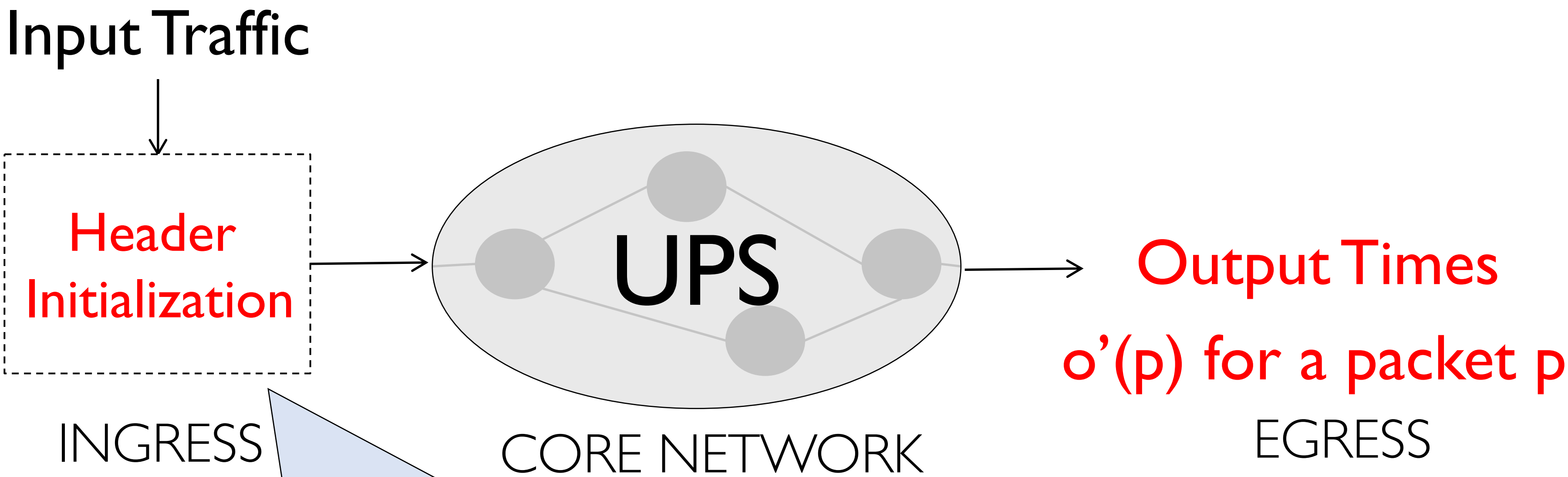


Replaying the Schedule, given o(p)



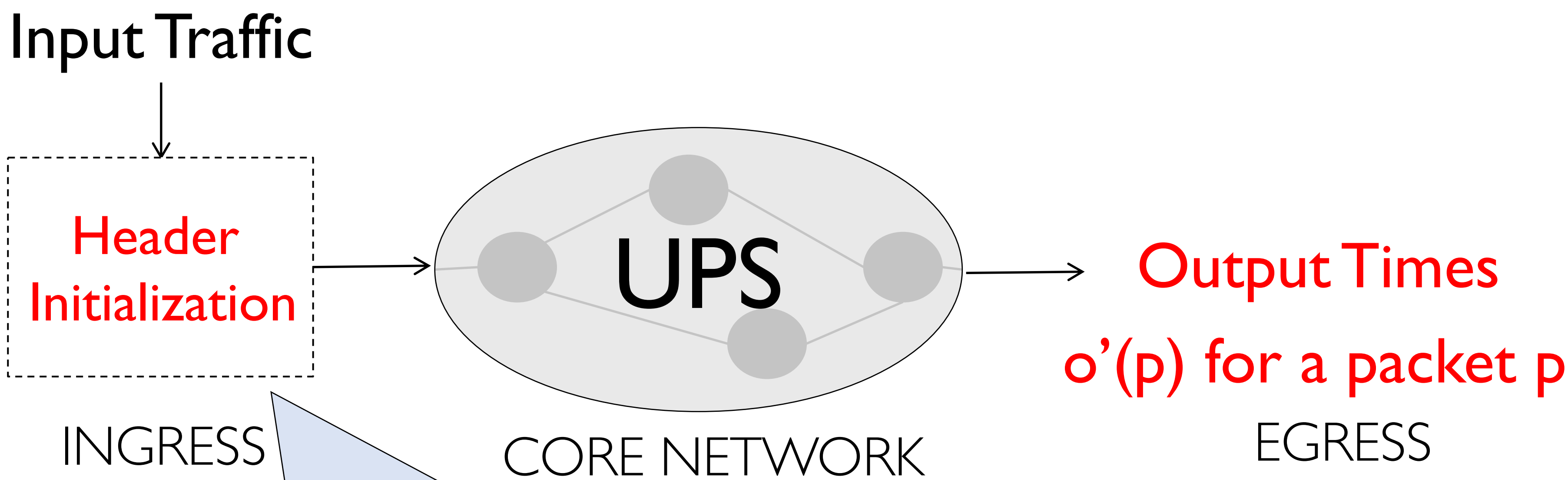
For every packet p, $o'(p) \leq o(p)$

Pragmatic Constraints on a UPS



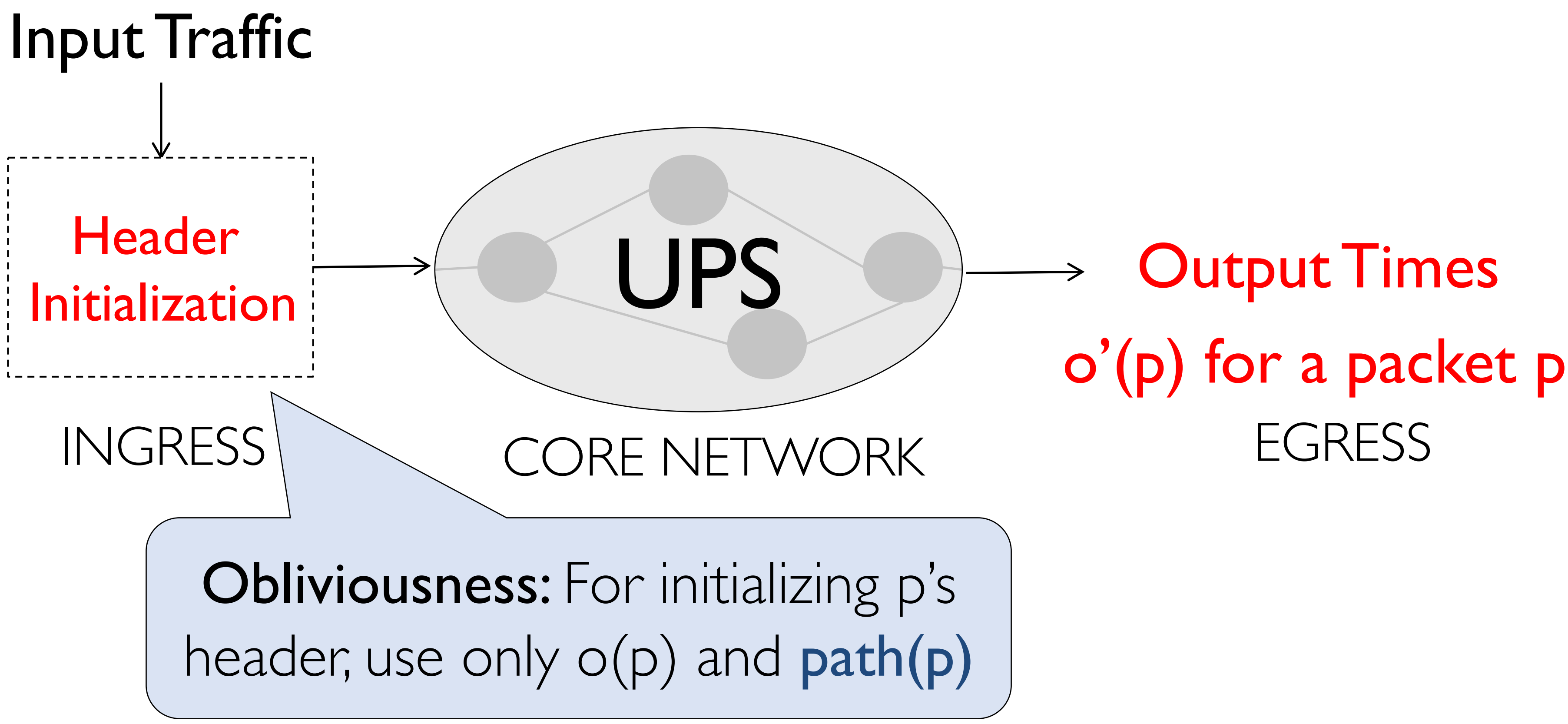
Obliviousness: For initializing p's header, use only o(p) and path(p)

Pragmatic Constraints on a UPS



Obliviousness: For initializing p's header, use only **o(p)** and path(p)

Pragmatic Constraints on a UPS



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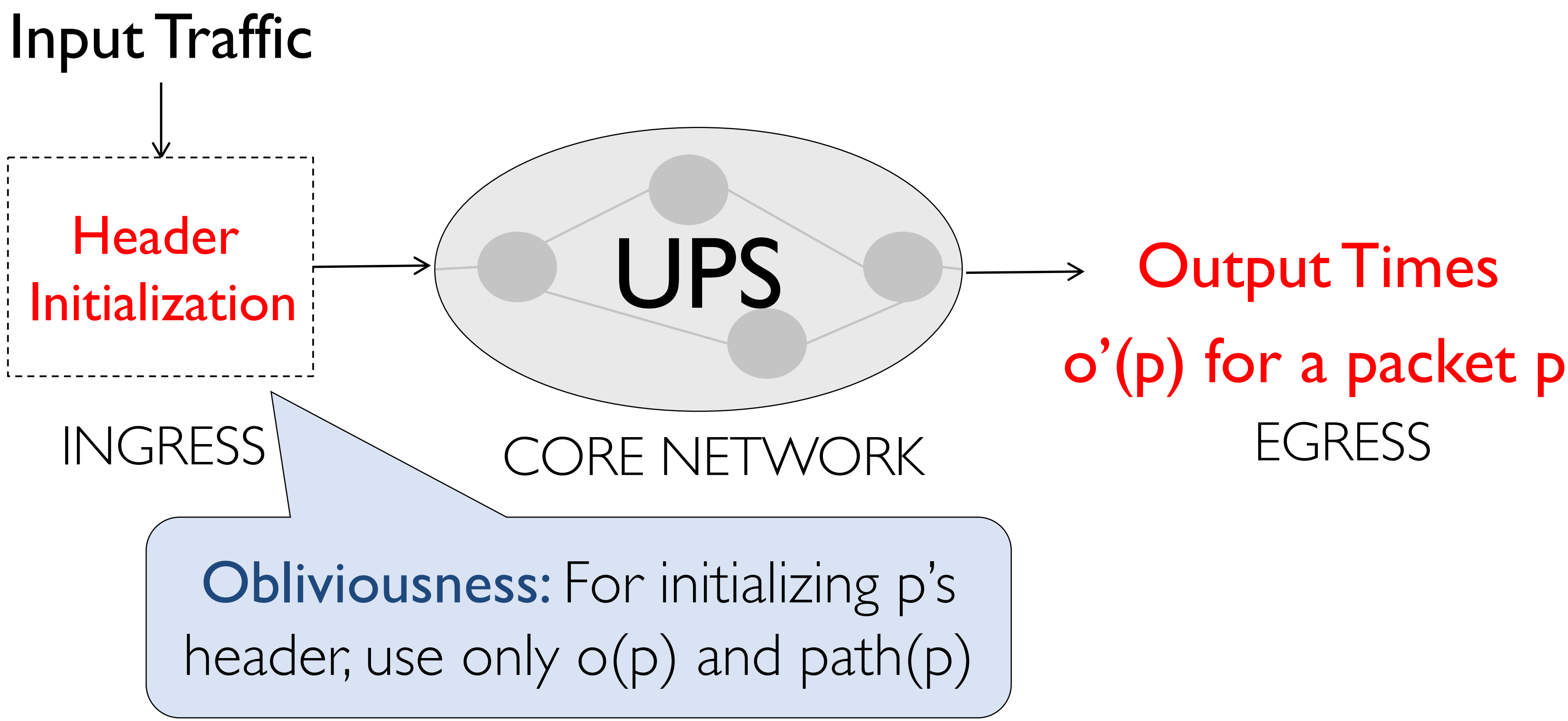
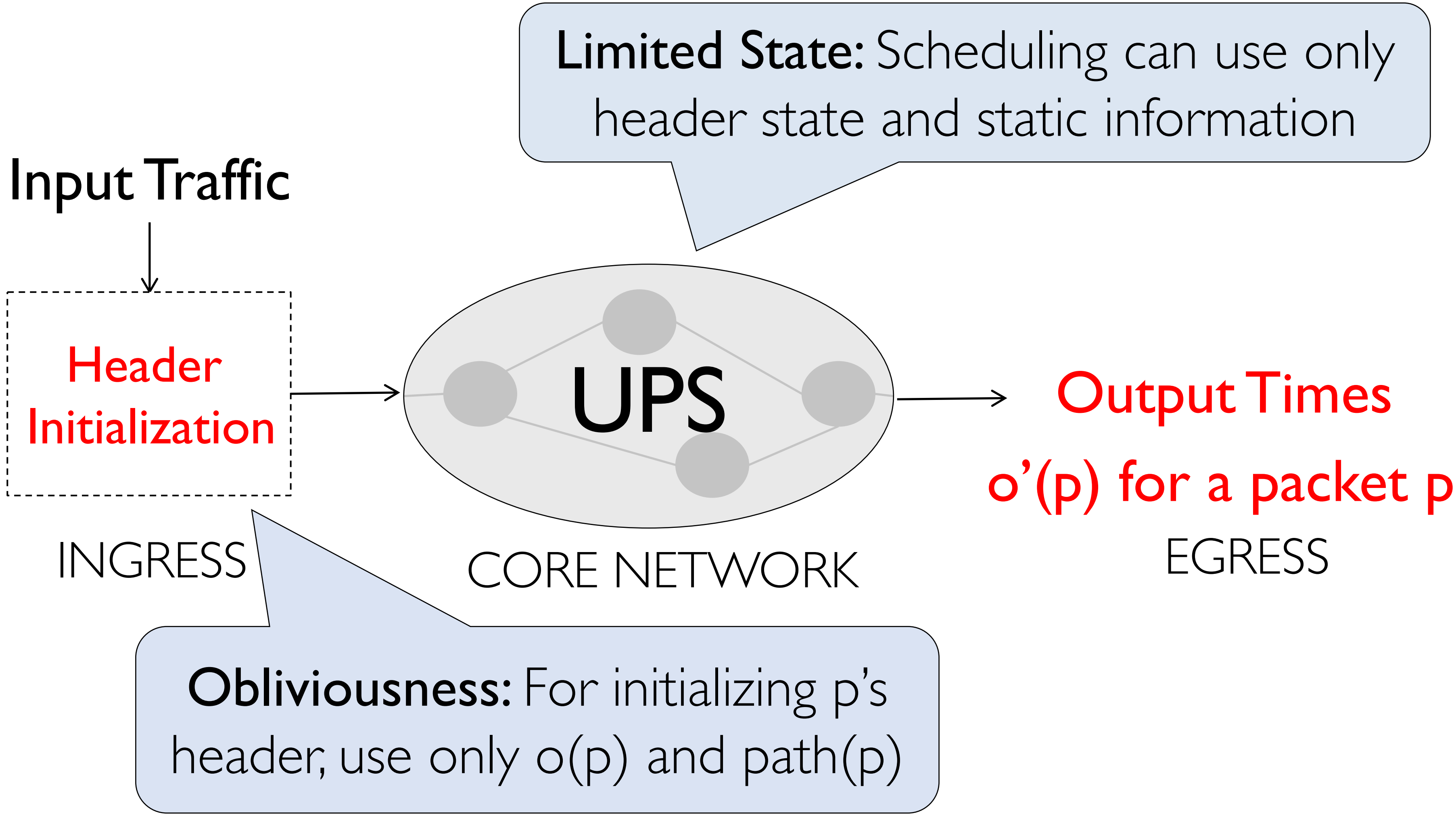


Pragmatic Constraints on a UPS



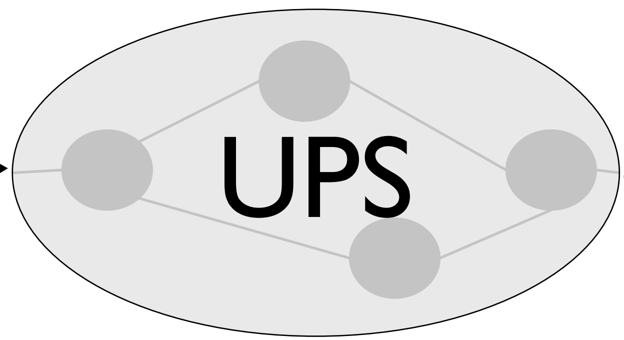
Pragmatic Constraints on a UPS

Limited State: Scheduling can use only header state and static information

Input Traffic

Header Initialization

INGRESS



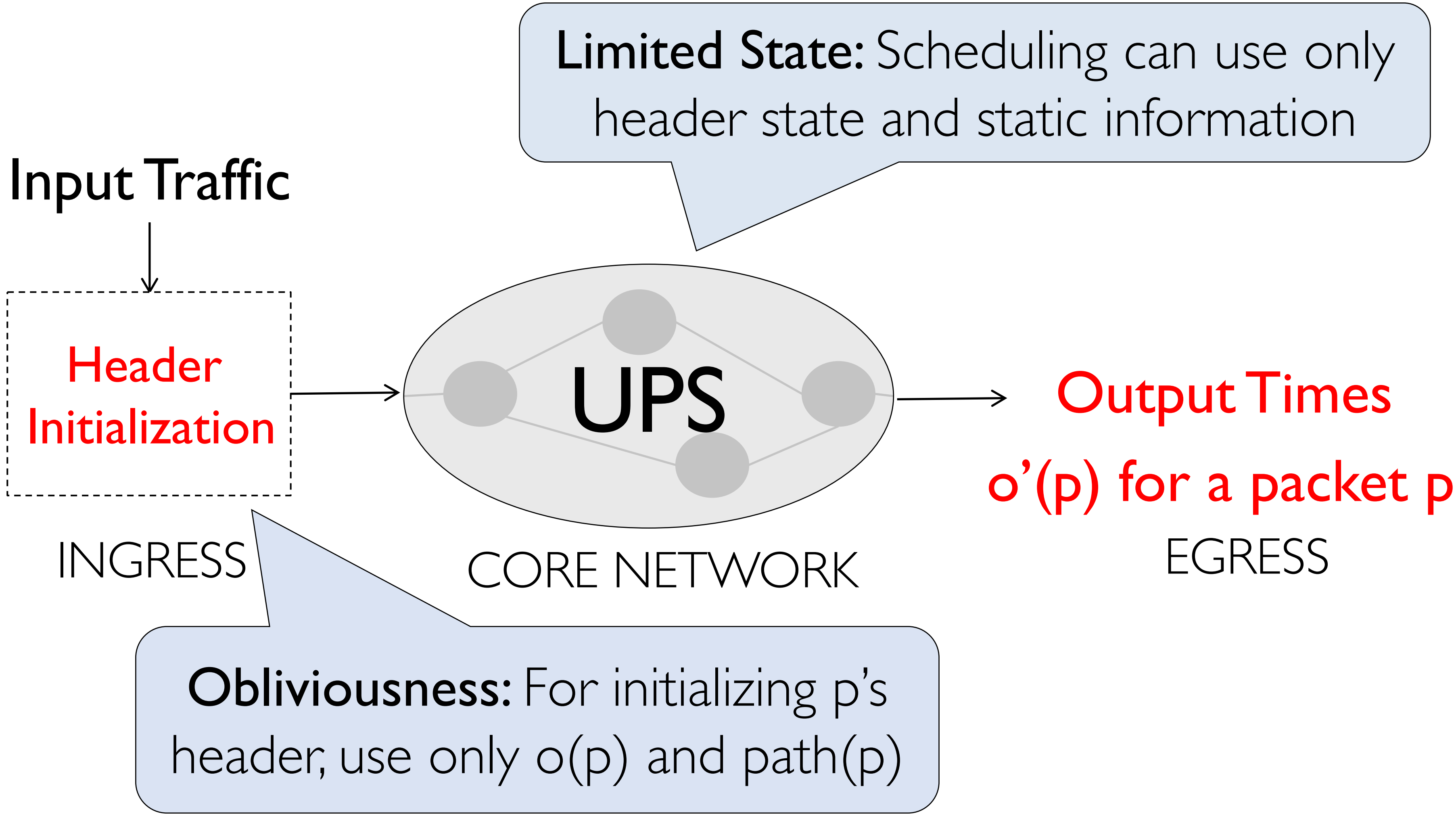
CORE NETWORK

Output Times o'(p) for a packet p

EGRESS

Obliviousness: For initializing p's header, use only o(p) and path(p)

We call this Blackbox Initialization



Basic Existence and Non-existence Results

There exists a UPS under *Omniscient Initialization*
when scheduling time at every hop is known

No UPS exists under *Blackbox Initialization*
when only the final output time is known

See NSDI'16 paper for proofs.

How close can we get to a UPS?

Key Result: Depends on congestion points

No. of Congestion Points per Packet	General
1	✓
2	✓
3	✗

See NSDI'16 paper for proofs.

Can we achieve this upper bound?

Can we achieve this upper bound?

Yes, LSTF!

Least Slack Time First

- Packet header initialized with a slack value
  - slack = maximum tolerable queuing delay
- At the routers
  - Schedule packet with least slack time first
  - Update the slack by subtracting the wait time

Key Results

No. of Congestion Points per Packet	General	LSTF
1	✓	✓
2	✓	✓
3	✗	✗

See NSDI'16 paper for proofs.

Not all algorithms achieve upper bound

No. of Congestion Points per Packet	General	LSTF	Priorities
1	✓	✓	✓
2	✓	✓	✗
3	✗	✗	✗

See NSDI'16 paper for proofs.

How well does LSTF perform empirically?

Empirically, LSTF is (almost) universal

- ns-2 simulation results on realistic network settings
  - Less than 3% packets missed their output times
  - Less than 0.1% packets are late by more than one transmission time

Summarizing the theoretical viewpoint

- Evaluate the ability to replay a schedule, given its final output times

- Analytical Results:
  - No UPS exists
  - LSTF comes as close to a UPS as possible

- Empirical Results: LSTF is *almost* universal!

Practical Viewpoint

Can it achieve a given objective?

Achieving various network objectives

- Slack assignment based on heuristics
- Comparison with state-of-the-art
- Three objective functions
  - Tail packet delays
  - Mean Flow Completion Time
  - Fairness

Tail Packet Delays

Slack Assignment: Same slack for all packets

State-of-the-art: FIFO, FIFO+

Results:

- Identical to FIFO+.
- Smaller tail packet delays compared to FIFO.

Mean Flow Completion Time

Slack Assignment: Proportional to flow size

State-of-the-art: SJF, SRPT

Results:

- Mean FCTs comparable to both SJF and SRPT.

Fairness

Slack Assignment: Inspired by Virtual Clocks

$\text{slack}(p_0) = 0$

$\text{slack}(p_i) = \max(0, \text{slack}(p_{i-1}) + (1/r_{est}) - (i(p_i) - i(p_{i-1}))$

r_{est} = Estimate of fair share rate

State-of-the-art: Fair Queuing (FQ)

Results:

- Eventual convergence to fairness for long-lived flows.
- FCTs roughly comparable to FQ for short-lived flows.
  - Higher sensitivity to fair share rate estimate (r_{est})

Results Summary

- Theoretical results show that
  - There is no UPS under blackbox initialization
  - LSTF comes as close to a UPS as possible
  - Empirically, LSTF is very close

- LSTF can be used in practice to achieve a variety of network-wide objectives.

Implication

- Less need for many different scheduling algorithms.
- Can just use LSTF, with varying initializations.

Limitations

- Policies for which the required information is not available during header initialization at the ingress.
  - When relative ordering between two packets changes after enqueuing them.
  - Class-based weighted fairness.

Your opinions

- Pros:
  - Good/intriguing motivation.
  - Understanding universality in terms of congestion points is useful.
  - Both theoretical and empirical results.
  - Concrete usecases.

Your opinions

- Cons:
  - No. of congestion points can be high in practice.
  - No discussion of implementation overhead.
  - A systematic framework for how to use LSTF/UPS.
  - What happens when there are more than one objectives/goals?
  - Is the theoretical model reasonable?
  - Lack of real internet-wide implementation.

Your opinions

- Ideas
  - Use LSTF for a broader range of scheduling algorithms.
  - Under what (relaxed) conditions is universality feasible?
  - Universal AQM scheme?
  - Are results valid only within data center or AS, or across the Internet (multiple ASes)?
  - What are the difficulties of implementing LSTF?
  - Better way to estimate o(p).

Recent work along similar lines…

- Most switches have only 8-16 queues. What's the best we can do with existing switch hardware?
  - SP-PIFO (NSDI'20)

- A packet's priority may change after it has been enqueued at a particular priority level. How to handle that?
  - Programmable Calendar Queues (NSDI'20)