UNIVERSITY OF WATERLOO

CS 856: Programmable Networks

Lecture 8: Flexible and Fine-Grained Network Monitoring

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Logistics

- Project progress report is due **Friday, March 10th**
- Reviews due **Monday, March 13th, at 5pm.**

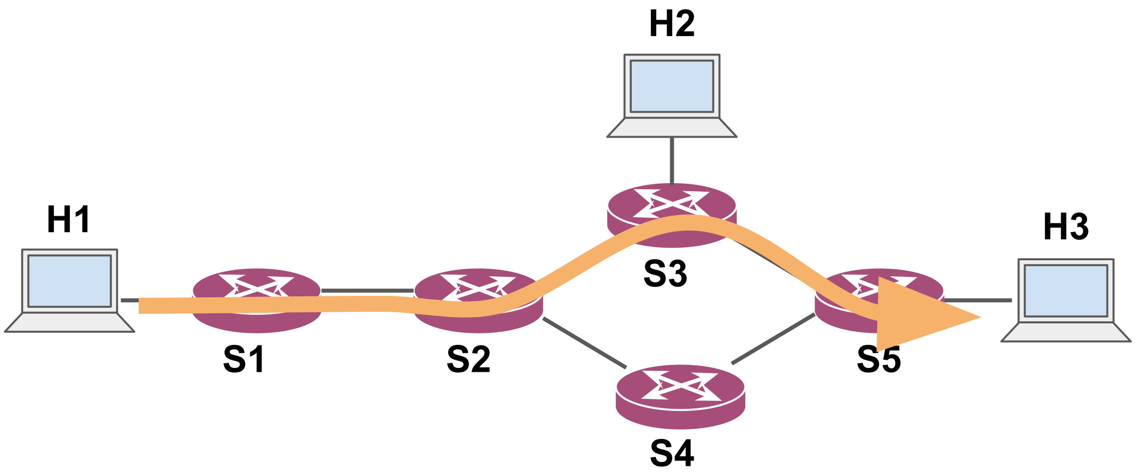
What is network monitoring?

- Understanding what is happening in the network at run-time and in real-time
    - Which links in the network are congested?
    - Which flows are contributing the most to the congestion at link L?
    - Are there flows that experience tail latency larger than X?
    - What are the K largest flows in the network?
    - Are there any unusual traffic patterns to/from certain IP addresses?
    - …

Why is it important?

- Networks are quite dynamic!
    - Traffic patterns change, links and devices fail, …
- More often than not, we need to dynamically re-consider how to network should process traffic in response to changes at run-time.

A simple example



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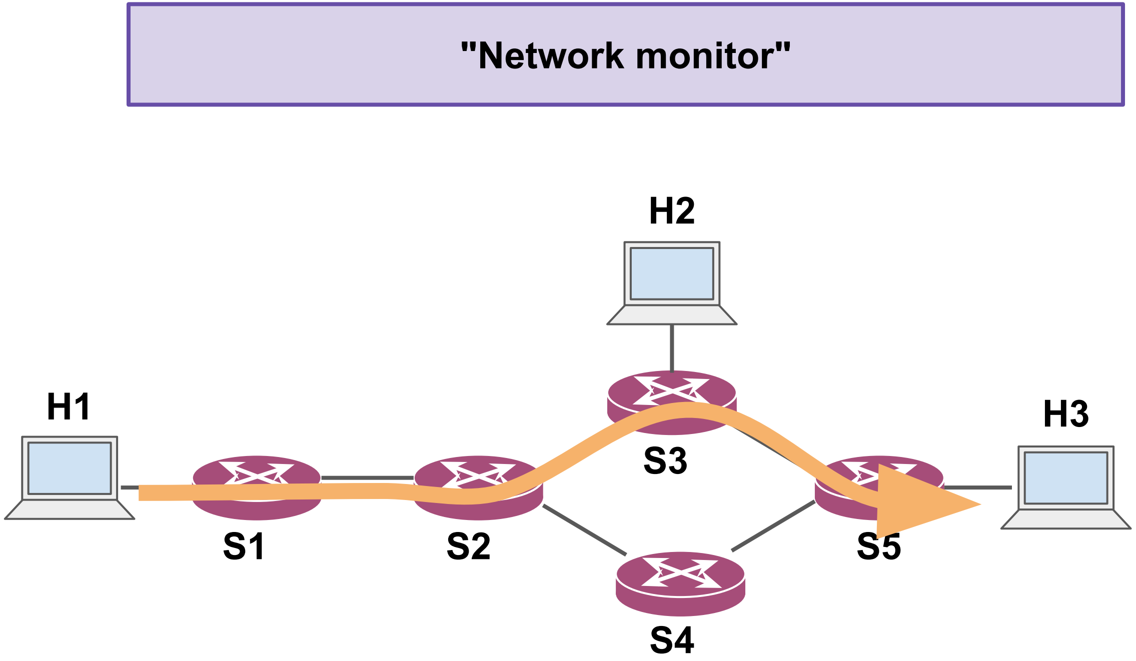

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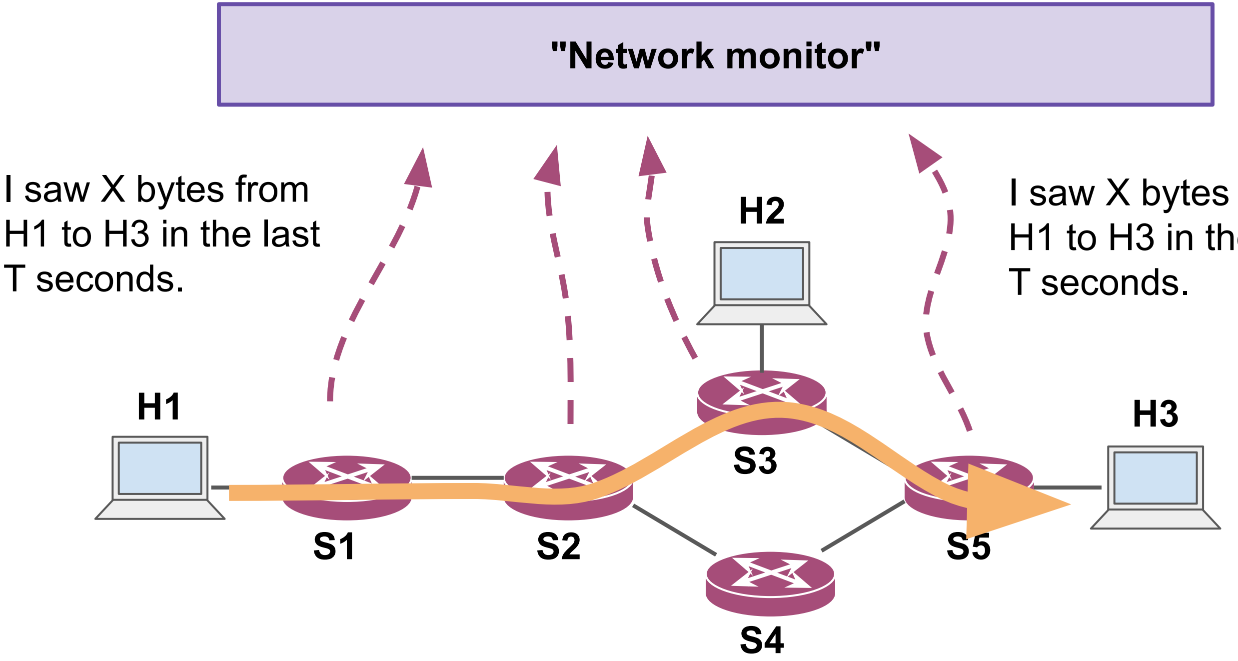
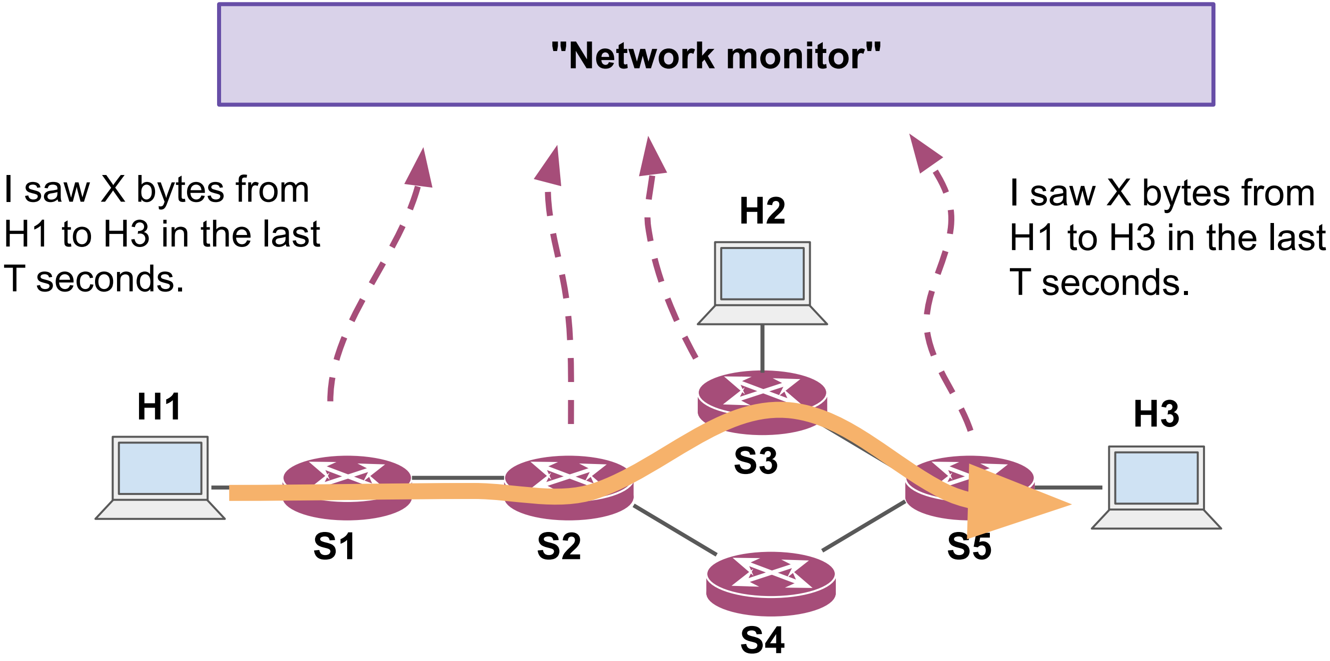


A simple example

- The monitor can *pull* the monitoring data from the device
- or the device can *push* it to the monitor.



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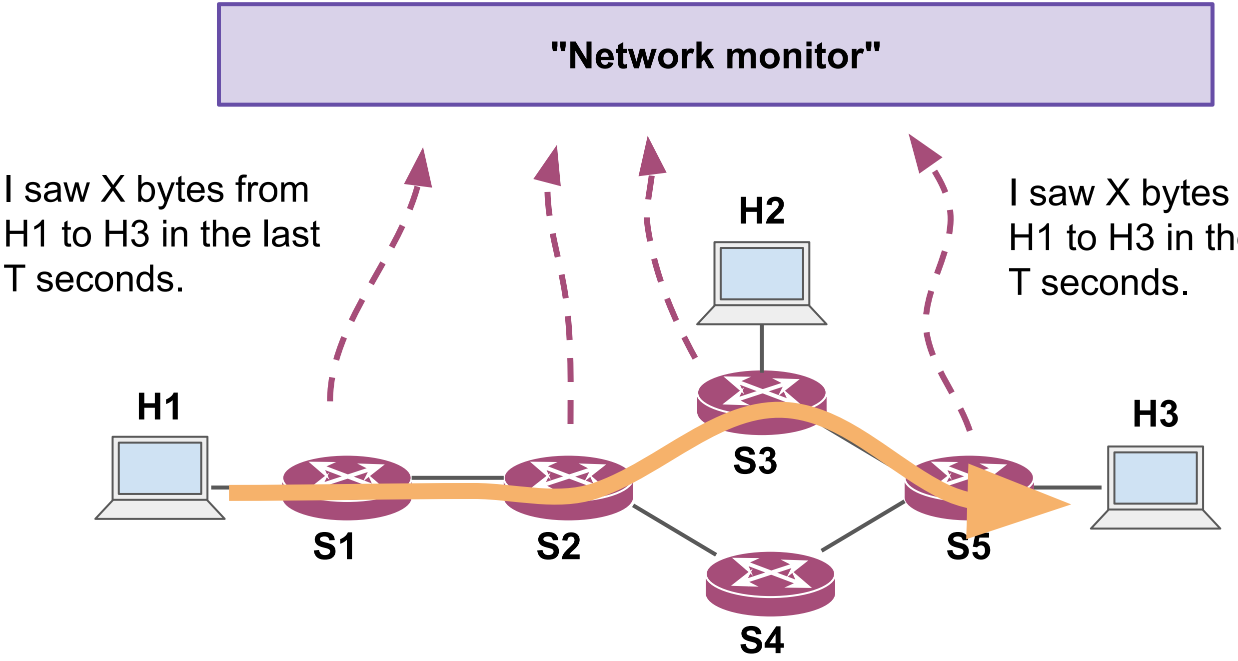

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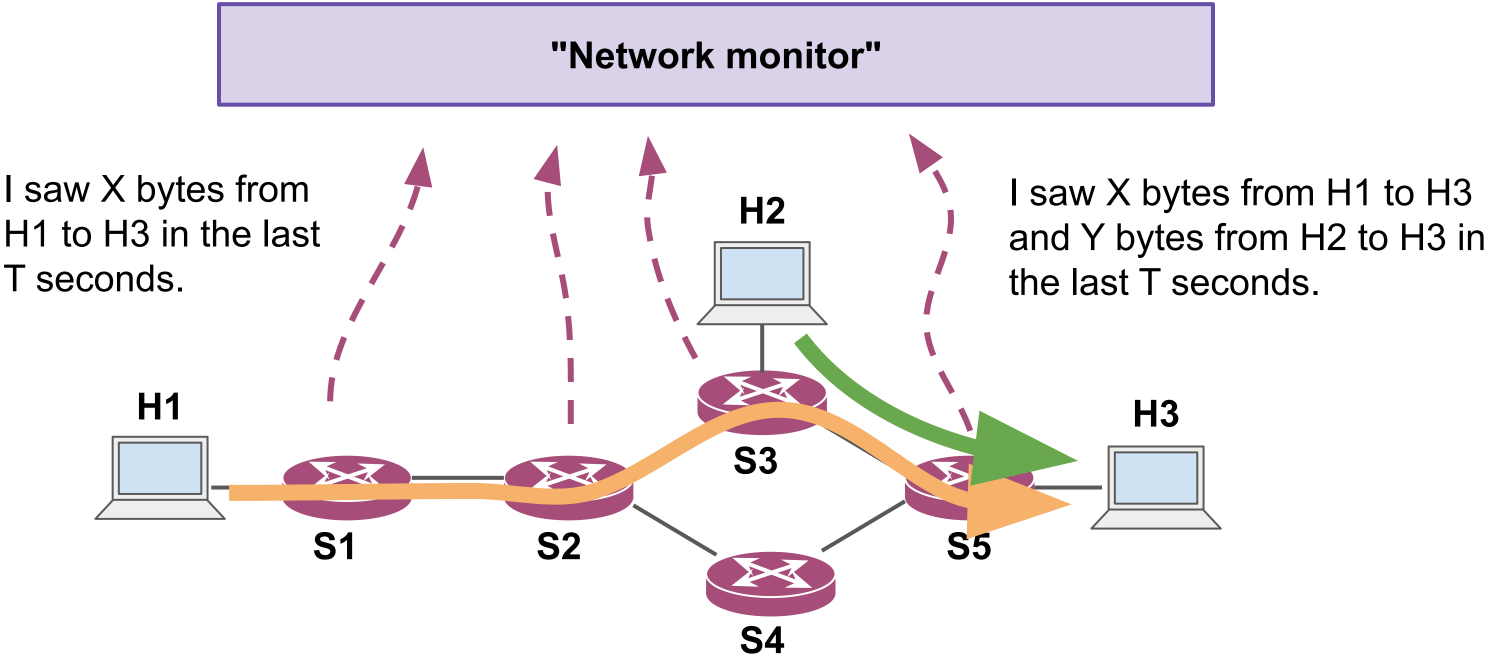

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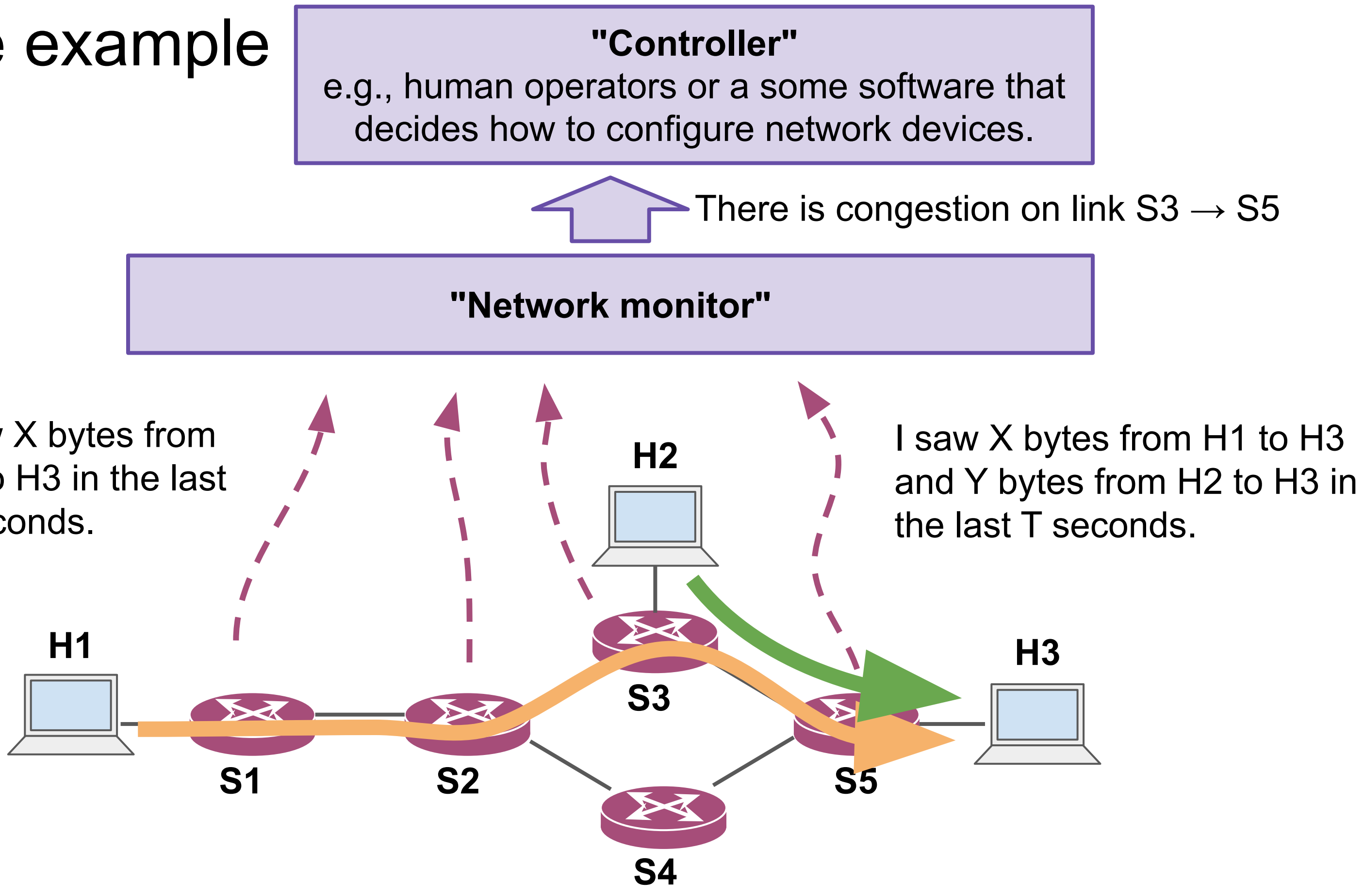

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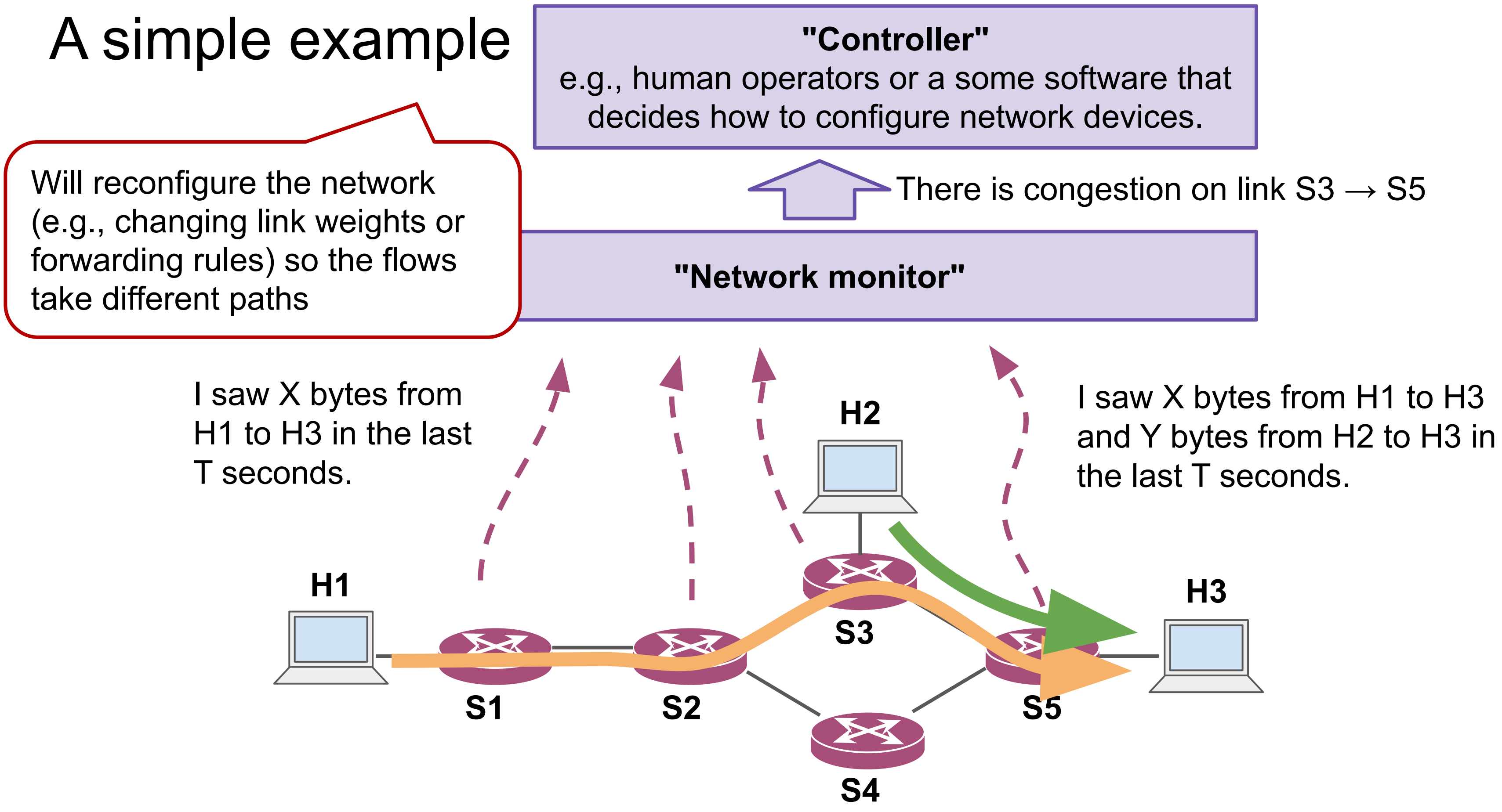
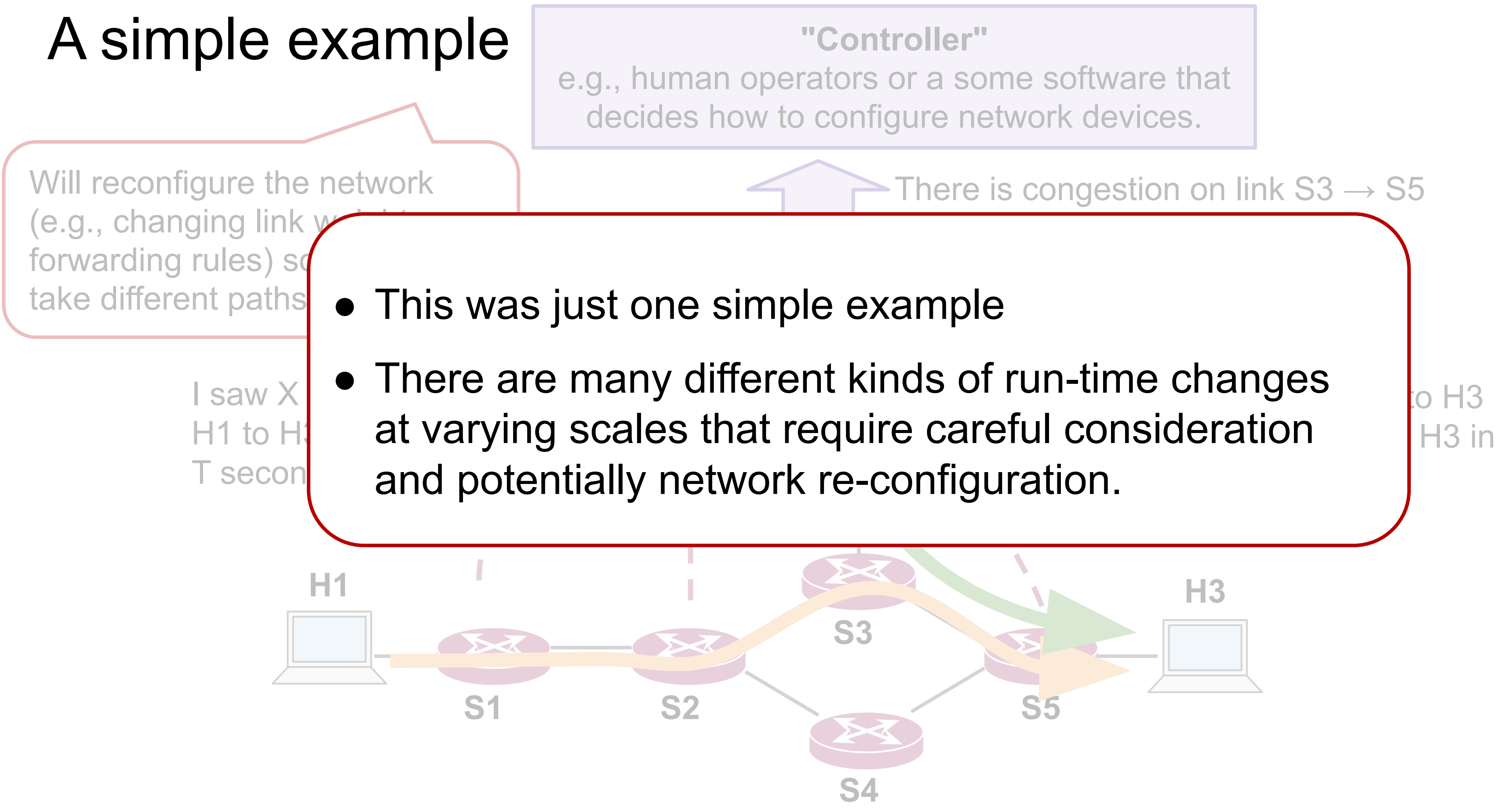


A simple example

- This was just one simple example
- There are many different kinds of run-time changes at varying scales that require careful consideration and potentially network re-configuration.



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- More often than not, we need to dynamically re-consider how to network should process traffic in response to changes at run-time.
- An accurate understanding of the state of the network is crucial for making good decisions :)

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obtained through network monitoring

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We have to observe network traffic and analyze it in real-time.

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- 100s or 1000s of switches in a network

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- What you need to monitor can change over time.

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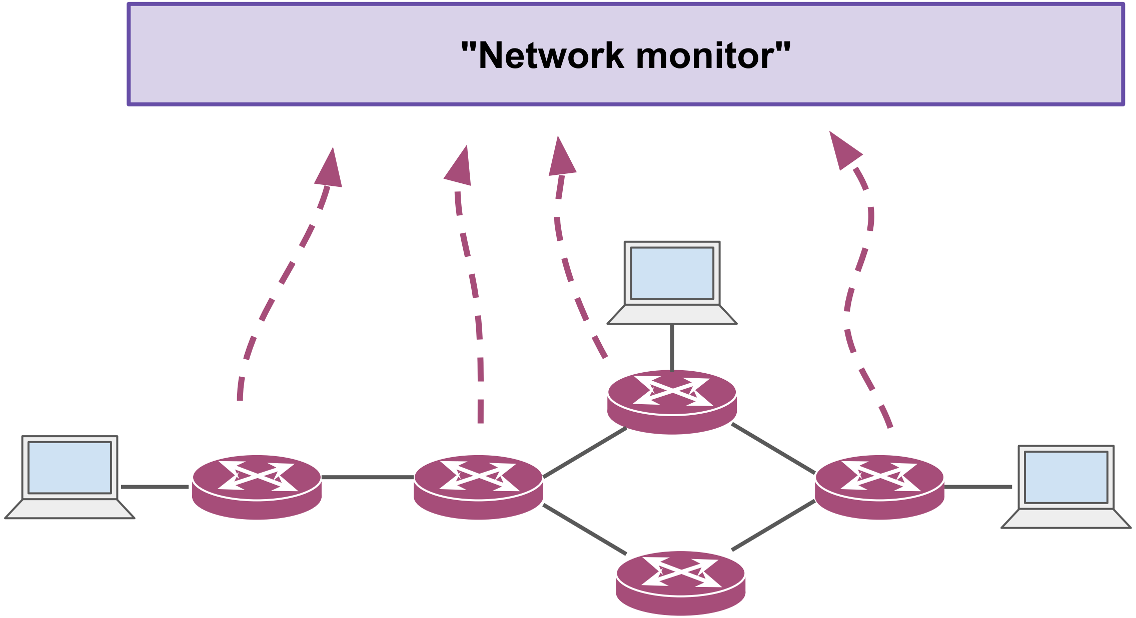
Have to observe and analyze traffic quite fast

- Data plane: fast but has limited resources.
- Control plane: more resources but slower.

The design space



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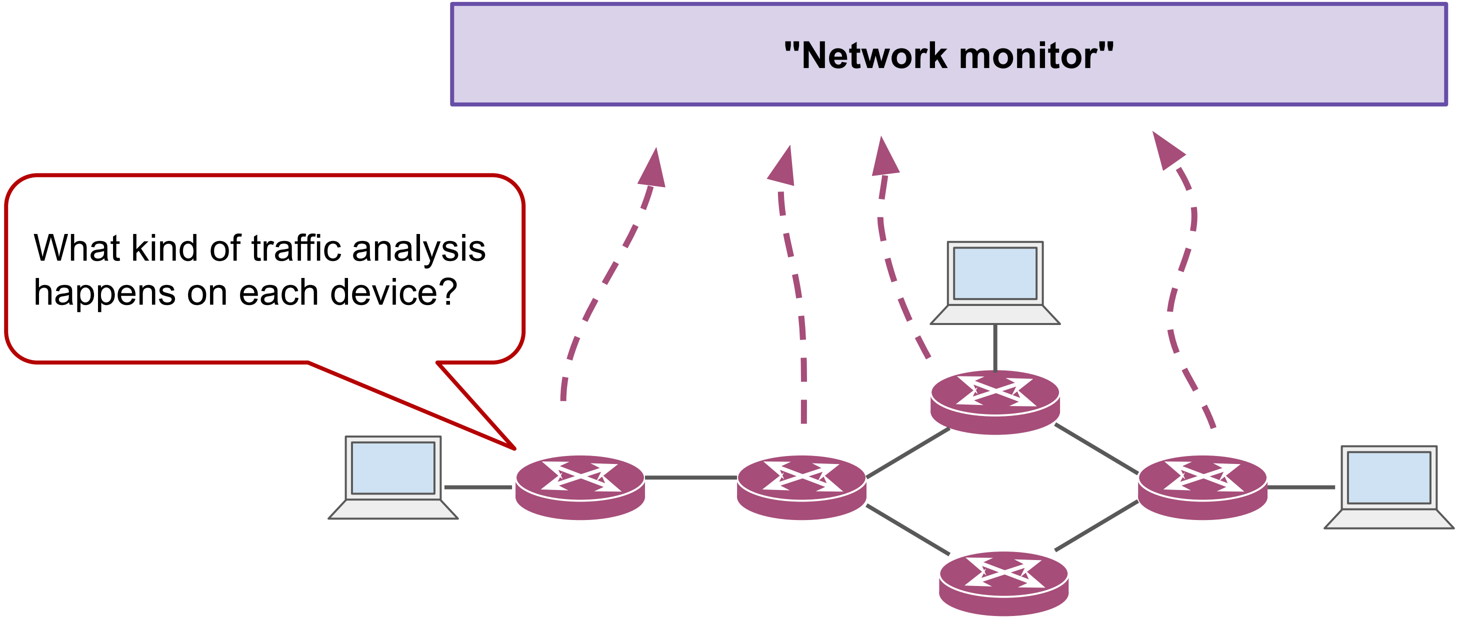

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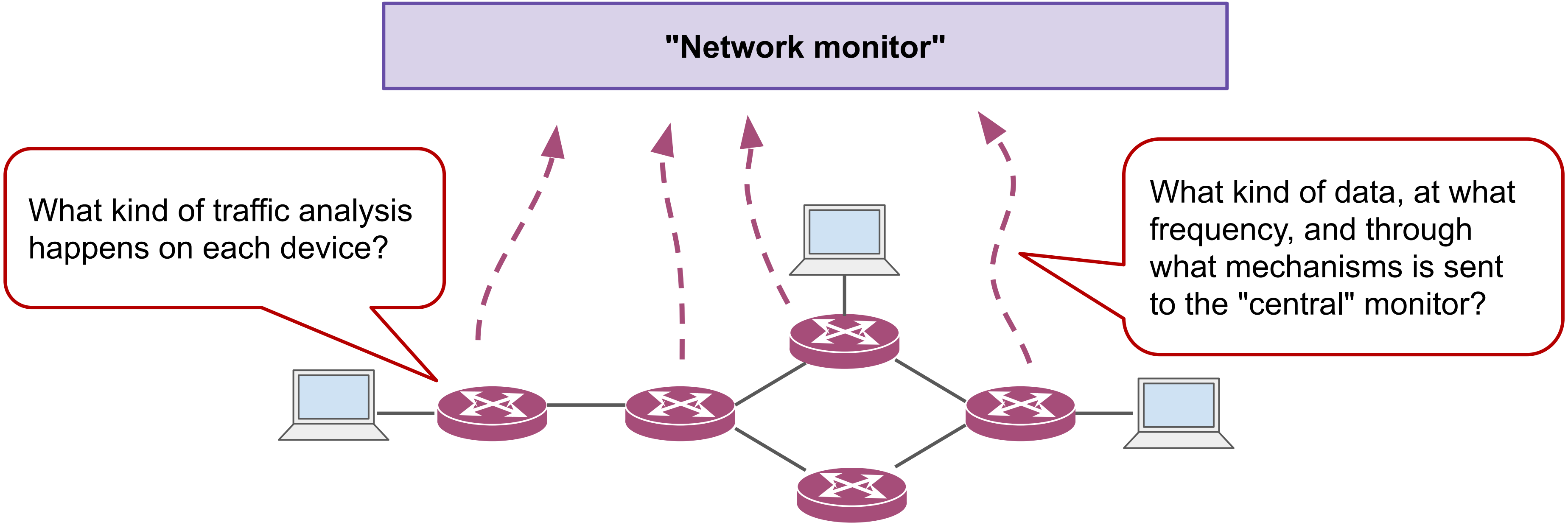

A single "query": K largest flows

- Suppose you want to know which K flows are the largest in your network.
  - largest flow → has sent the largest amount of traffic
  - known as heavy-hitters.
- There are a number of ways you can go about doing that…

A single "query": K largest flows

- You can send the flow identifier and size of each packet to the central network monitor
  - The monitor can count #bytes in each flow, sort the flows, and find the top K
  - Significant communication overhead, but very accurate results

A single "query": K largest flows

- You can count how many bytes of each flow you see in the switch and send a report of that to the network monitor every X seconds.
  - The monitor can merge the information to find flow sizes and the K largest flows.
  - Lower communication overhead, accuracy can depend on reporting frequency and how in-sync the reports are.

A single "query": K largest flows

- You can keep track of only the heavy hitters (as opposed to every flow) on each device and have the network monitor pull the info when needed.
    - What is the communication overhead?
    - How accurate are the results? hint: packets of the same flow may traverse different devices in the network.

Multiple queries

- Do you collect some generic statistics from each device at the network monitor and use that to answer as many queries as you can?
  - What information do you collect? flow sizes? queue sizes?
  - How granular? per-packet? per-flow?
  - How much information do you aggregate on each device and over how long of a time window before analyzing it at the monitor?
- Or, do you tailor what you measure to the kind of queries you are asked?

Monitoring in "traditional" networks

- Not a lot of flexibility to try different points in the design space
- It is up to the vendors what kind of monitoring data they collect on the switches and how it can be reported to a monitoring server.
  - Typically limited to coarse-grained information every few seconds.
  - e.g., NetFlow
- Sounds familiar? :)

Network programmability → Flexible and fine-grained monitoring

- Program the data plane to gather the data that you want
- Program the data plane (and the run-time) to have the data pushed to/pulled form a central monitor when you want.
- Create top-down programmable monitoring frameworks:
    - Users specify the information they are interested as queries
    - The compiler and runtime figure out how to configure each device to collect and report information according to the query.

Network programmability → Flexible and fine-grained monitoring

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- Program ... ed to/pulled ...
- Create to...
  - Users...
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Monitoring is one of the "killer" apps for programmable data planes

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- Sketches
- In-Band Network Telemetry (INT)
- …

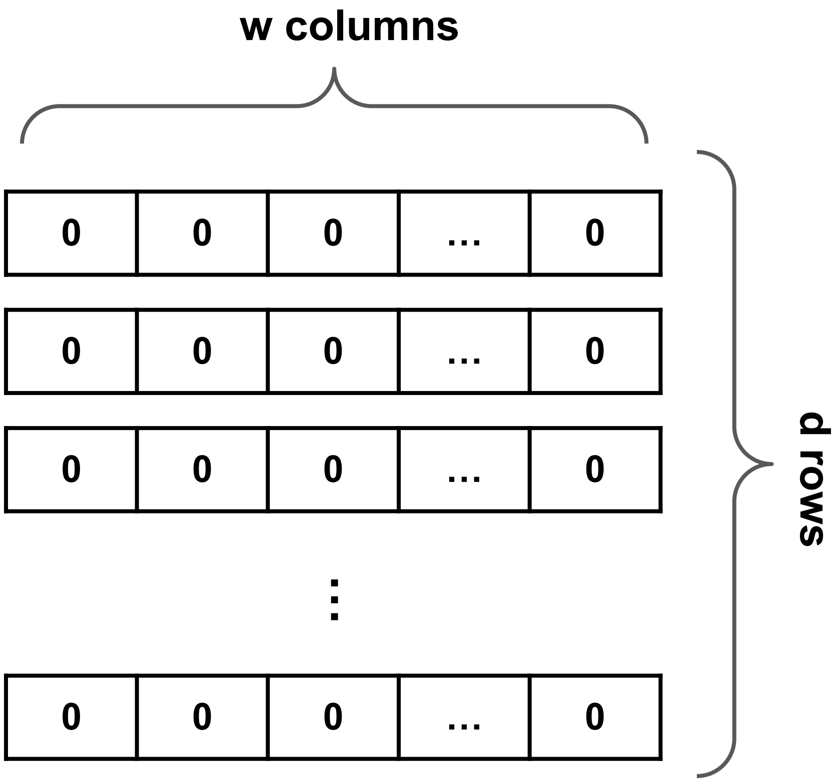
Sketches

- Modern high-speed switches can observe terabits of traffic every second.
- and have limited computational resources
  - Specially memory, which is essential for monitoring purposes, e.g., to keep track of statistics
- Typically, if we have N flows going through a switch, we don't have O(N) memory in the switch to keep information about them.
- So, what do we do?

Sketches

- Sketches are approximate data structures that
    - keep information about a large amount of data in a substantially smaller amount of space
    - and can answer certain queries about it in an approximate way.
- They typically provide a trade-off between resource usage and accuracy.
- If you give them more space, they'll provide a more accurate result.

Example: Count-Min Sketch



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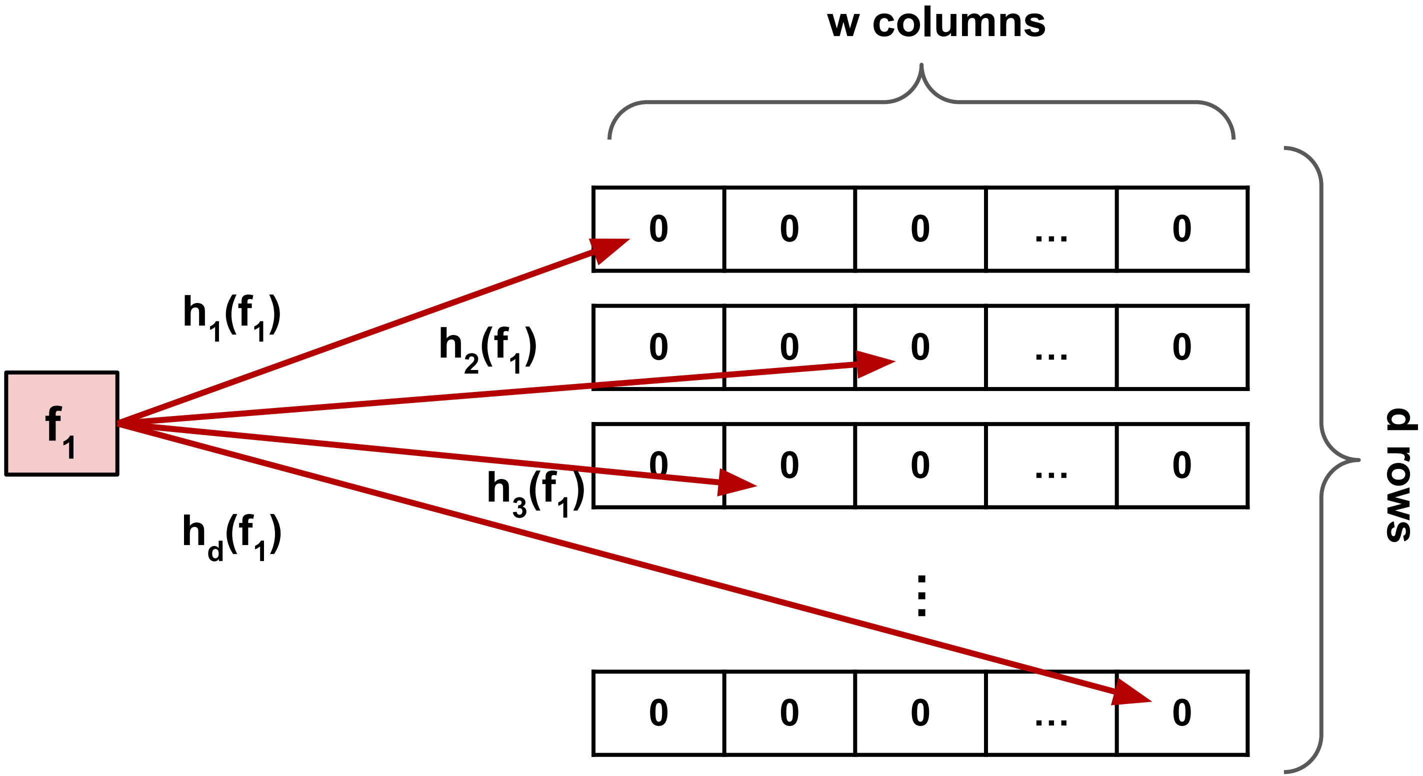

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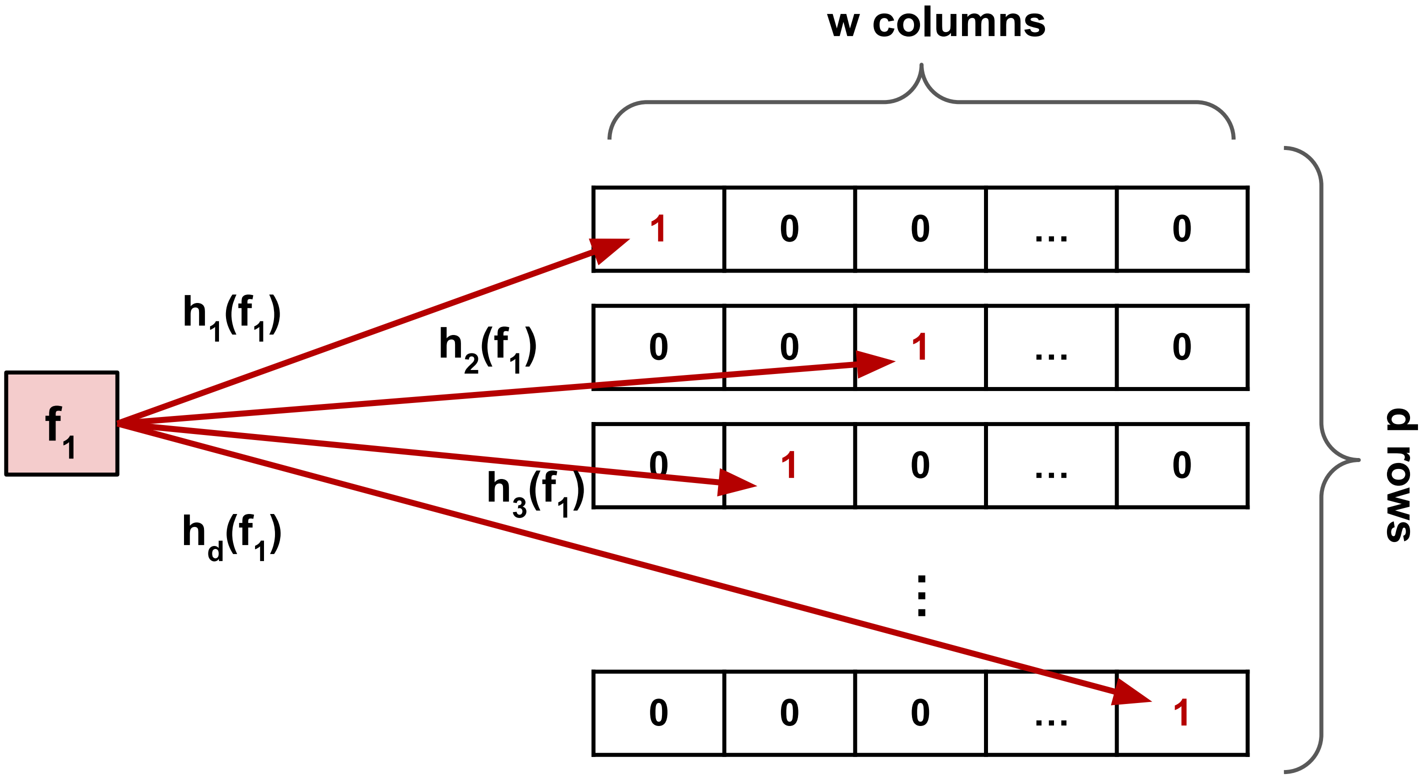

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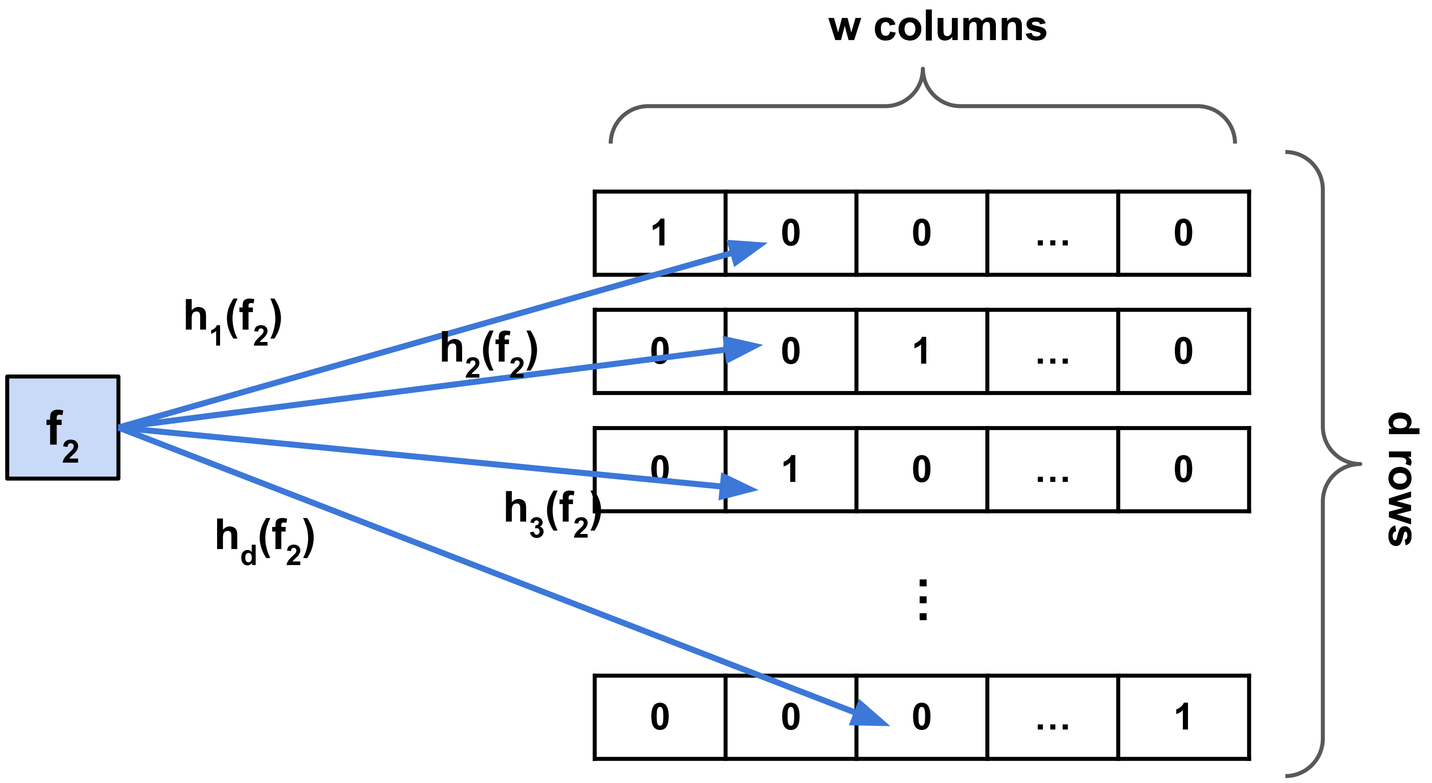

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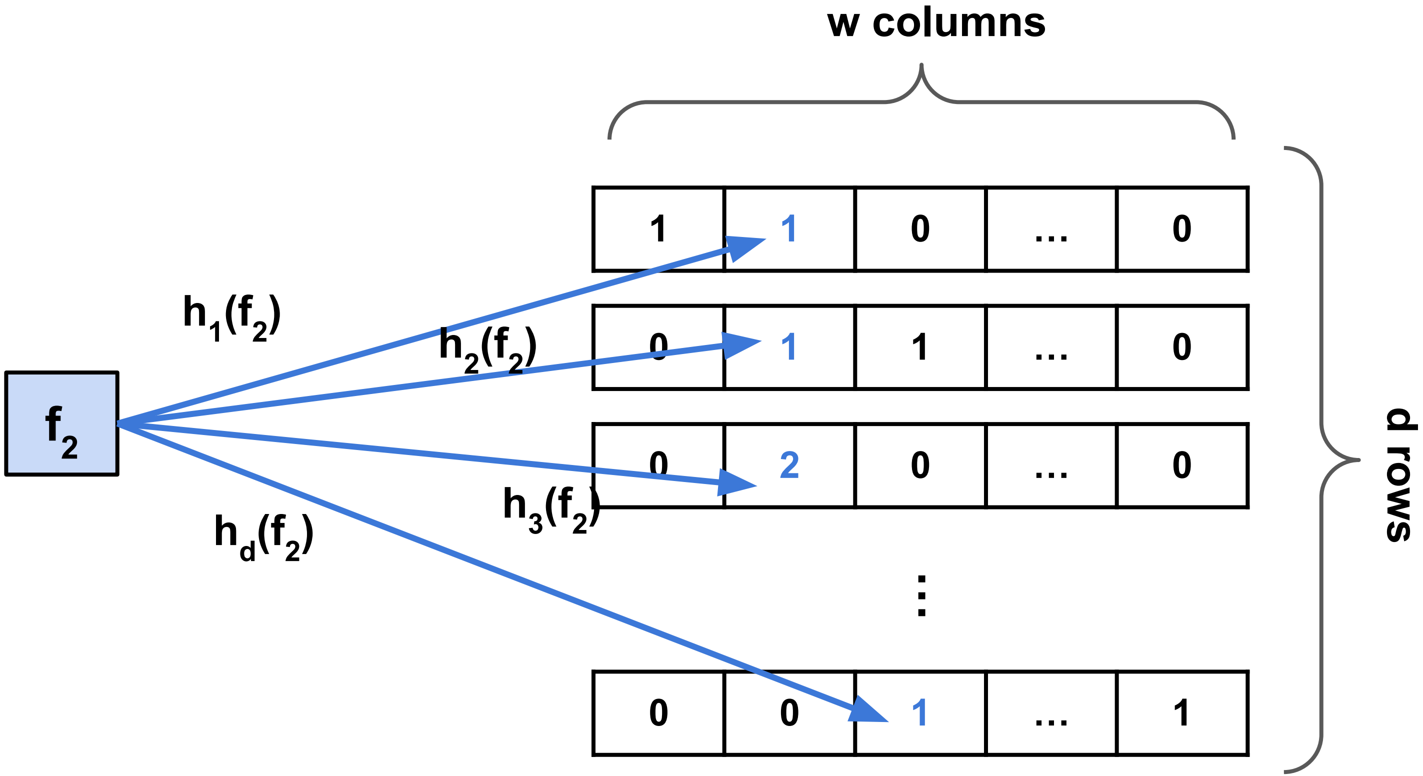

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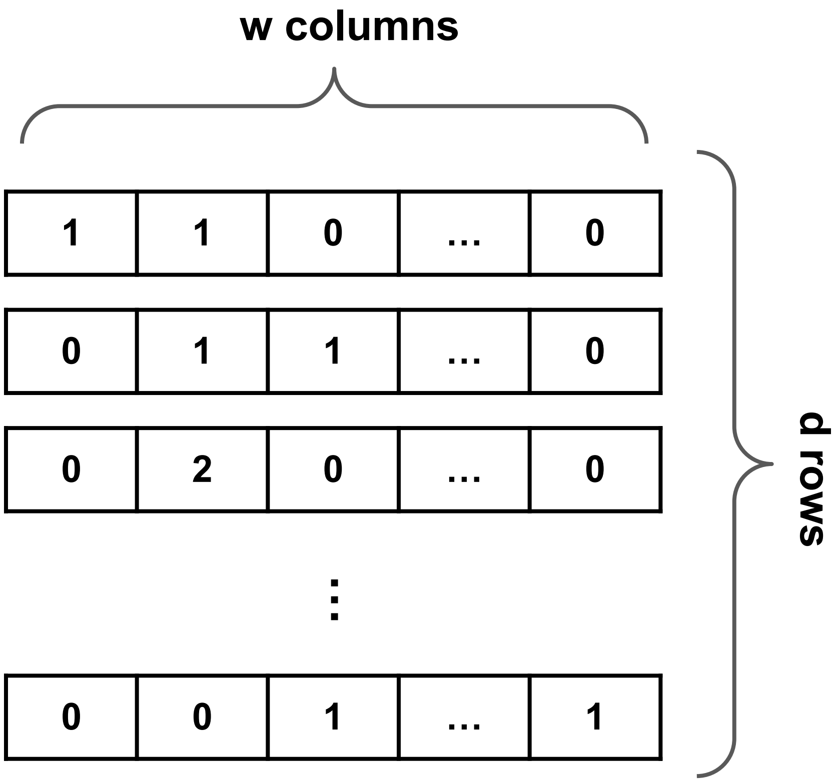
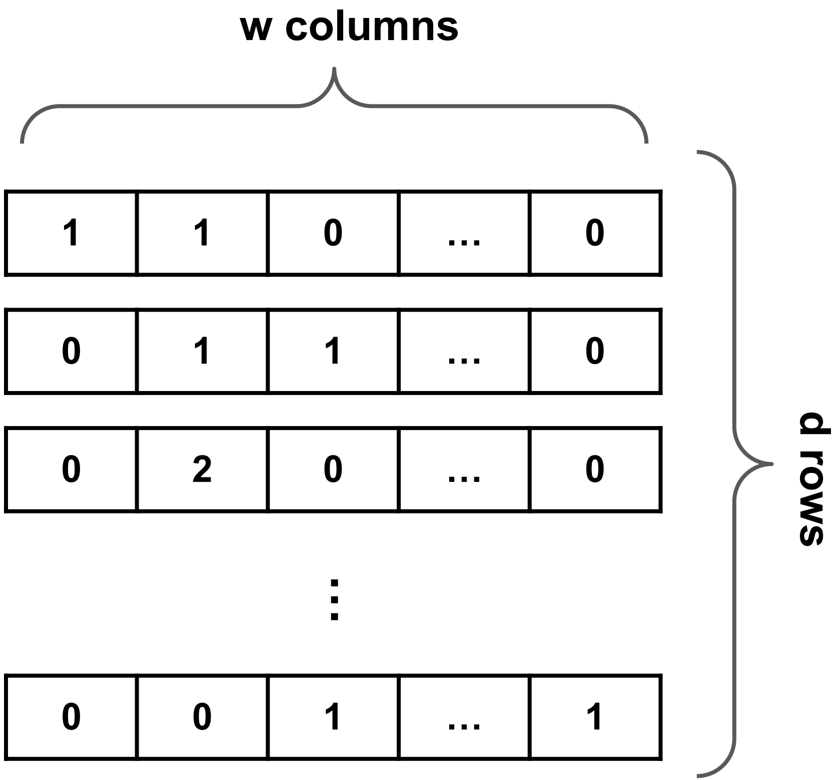


Example: Count-Min Sketch

How many f_1 packets did you see?

- Get the entries at $h_1(f_1)$, $h_2(f_1)$, …, $h_d(f_1)$



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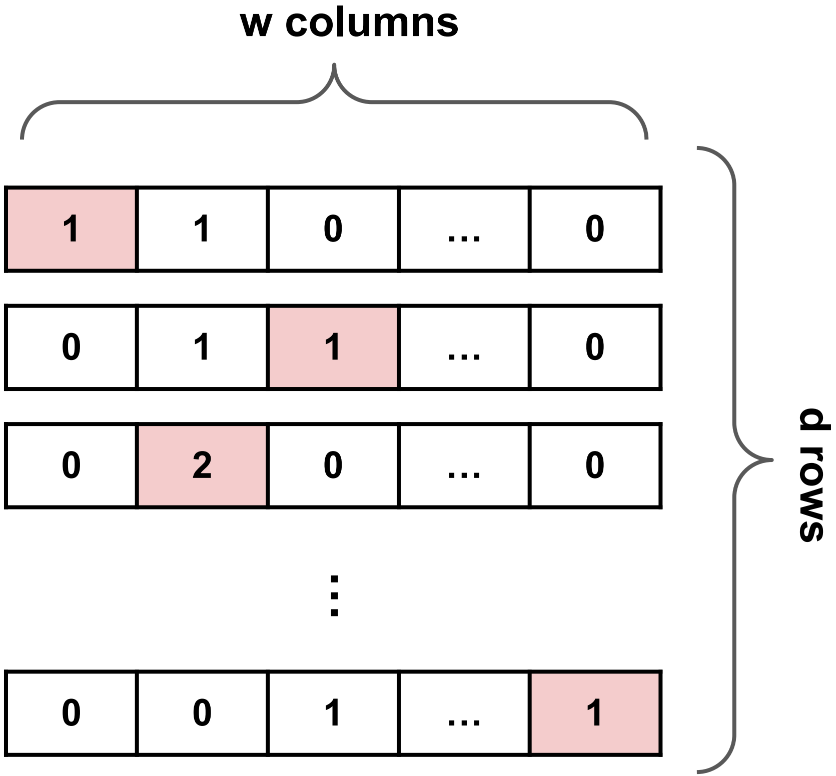
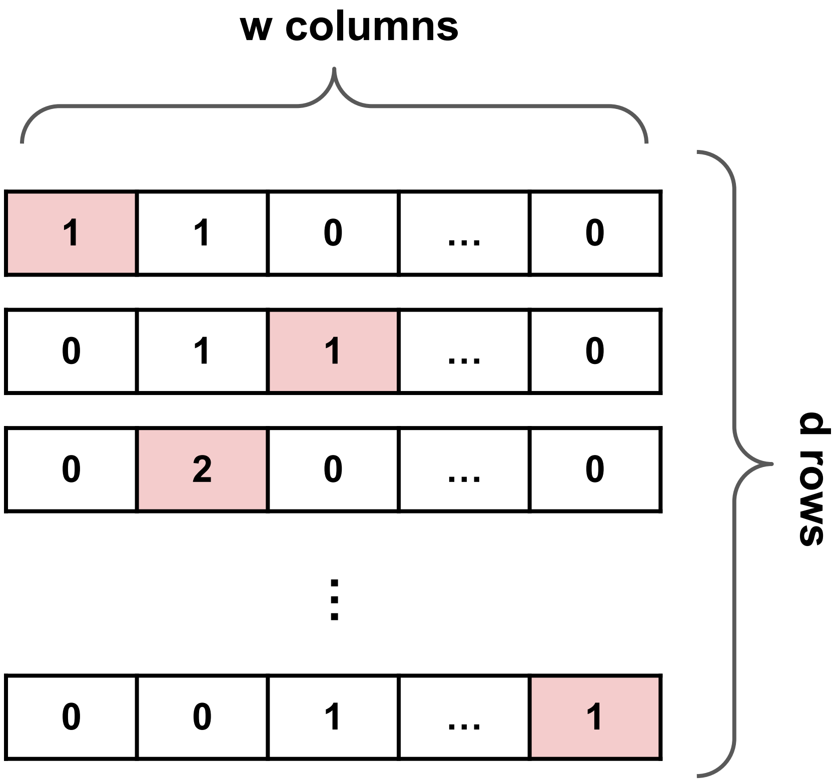


Example: Count-Min Sketch

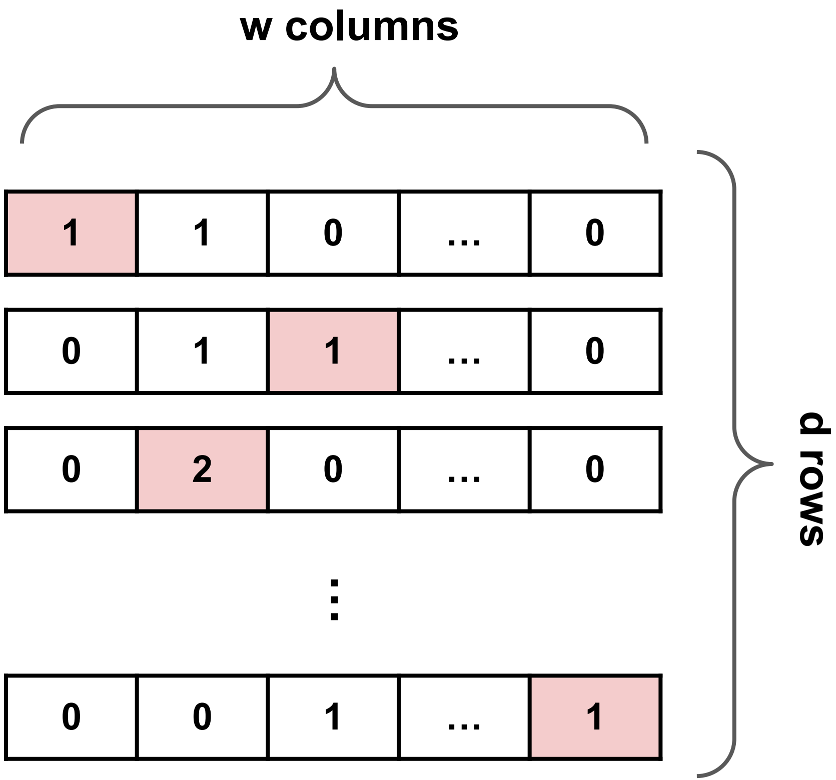
How many f_1 packets did you see?

- Get the entries at $h_1(f_1)$, $h_2(f_1)$, …, $h_d(f_1)$
- Return the minimum
  - i.e., 1



Example: Count-Min Sketch

- Approximation comes from hash collisions
- The larger w and d, the more accurate the result.



Connections to streaming algorithms

- There are lots of synergies between network monitoring and streaming algorithms.
- Algorithms in the streaming setting have more constraint than "regular" algorithms
    - They see the input as a sequence of items examined in a few passes, typically one → packets passing through the switch
    - Operate within limited memory (sublinear) and sometimes limited processing per item → computational constraints of programmable switches

In-Band Network Telemetry (INT)

- In programmable data planes, you can define custom headers and process them however you want.
- INT proposes to add a "telemetry" header and have switches populate it with information that will help network monitoring
  - How long did the packet spend in the switch? How much of it was waiting in a queue?
  - switch id, to help figure out what paths packets take in the network
  - …

In-Band Network Telemetry (INT)

- Once the packet gets to its destination, the information in the INT header can be analyzed there and/or sent to a central monitor.
- Having fine-grained information about what happened to the packet as it traverses a network is extremely useful.
- Specially for detecting and debugging transient and subtle problems.
- There is no free lunch!
    - If every switch adds a large INT header to the packet, that can create throughput overheads.

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Connections to network verification

- It is likely that we can't model *everything* in the network in detail and analyze it proactively.
- To ensure our networks satisfy our desired properties, we need
  - scalable proactive analysis to catch as many violating scenarios as possible before production
  - flexible and fine-grained run-time monitoring to continuously watch for property violations at runtime.

Paper 1: Sonata: Query-Driven Streaming Network Telemetry

- A programmable monitoring platform inspired by stream processing platforms (e.g., Spark)
- Users specify their queries over streams of packets in a map-reduce-style interface
- The compiler and runtime figure out which parts of the query to run in the data plane and which parts in a stream processor in the control plane

Paper 2: One Sketch to Rule Them All: Rethinking Network Flow Monitoring with UnivMon

- Before UnivMon, sketches proposed for network monitoring were customized to specific monitoring tasks.
- Inspired by work on universal streaming, UnivMon proposes data-plane sketching primitives that are can be used to compute several statistics.

Additional Resources

- Network Telemetry: Towards A Top-Down Approach
  - a white paper on how do design flexible, fine-grained monitoring platforms, also taking advantage of programmable networks
- A few more papers on data-plane monitoring primitives and programmable monitoring platforms