Exploiting Multi-Core Processors For Parallelizing Network Intrusion Prevention

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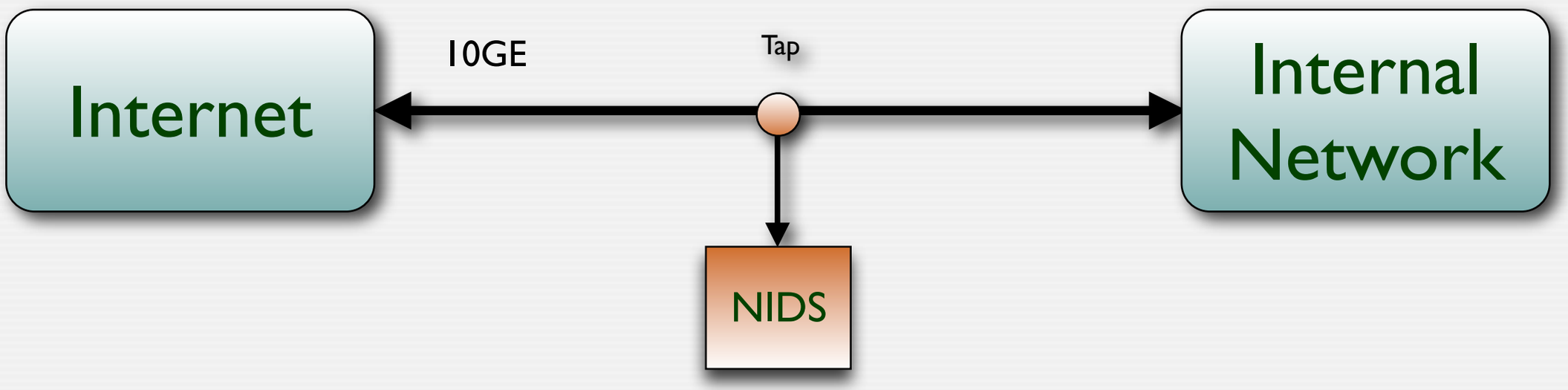
TRUST Seminar Series
UC Berkeley

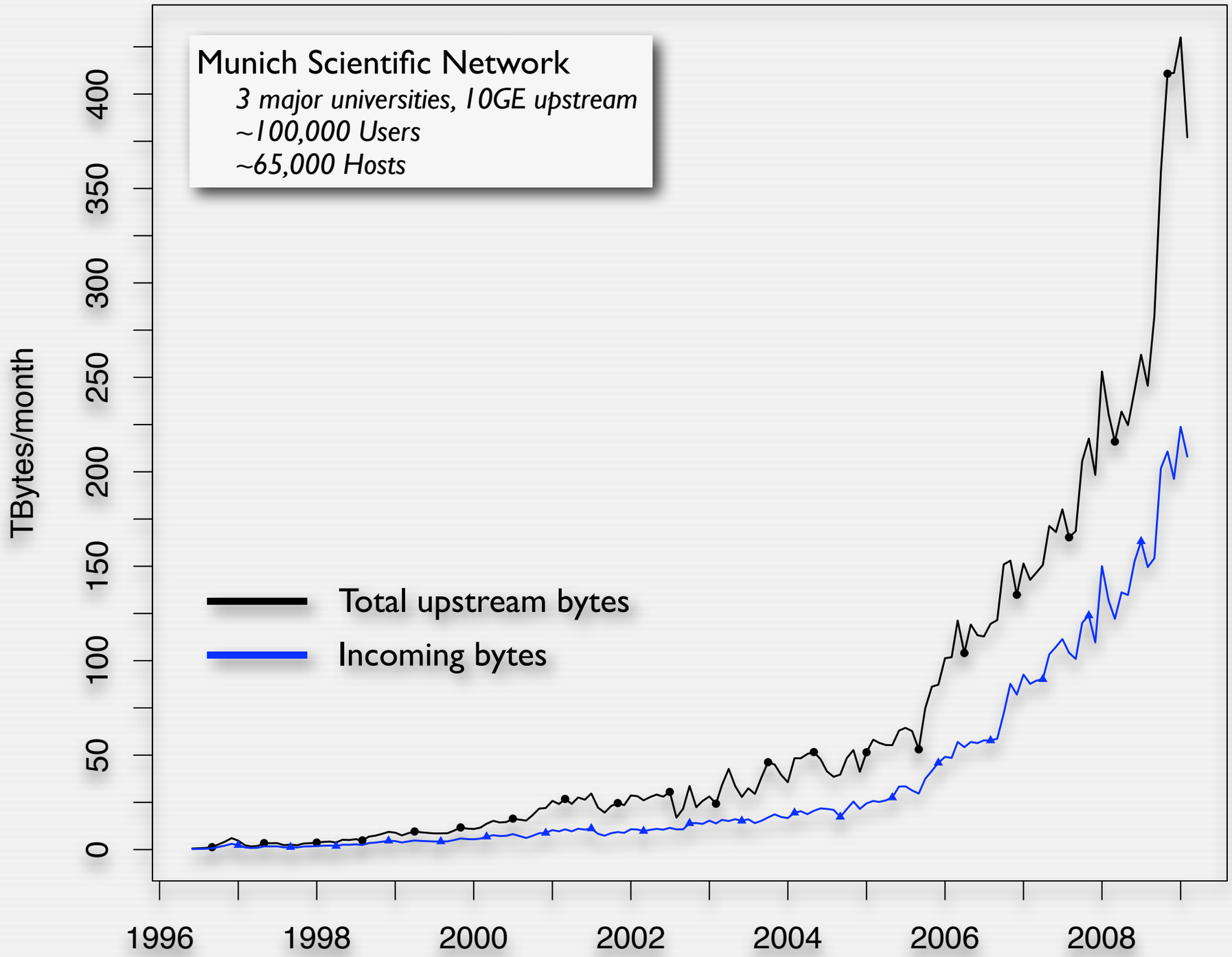
Network Intrusion Detection Systems

- NIDS are typically deployed at a site's upstream link
  - Monitor all external traffic, *packet by packet*
  - Follow the protocol dialogues closely
  - Alert on suspicious activity

  - Face stringent performance requirements due to volume and real-time demands

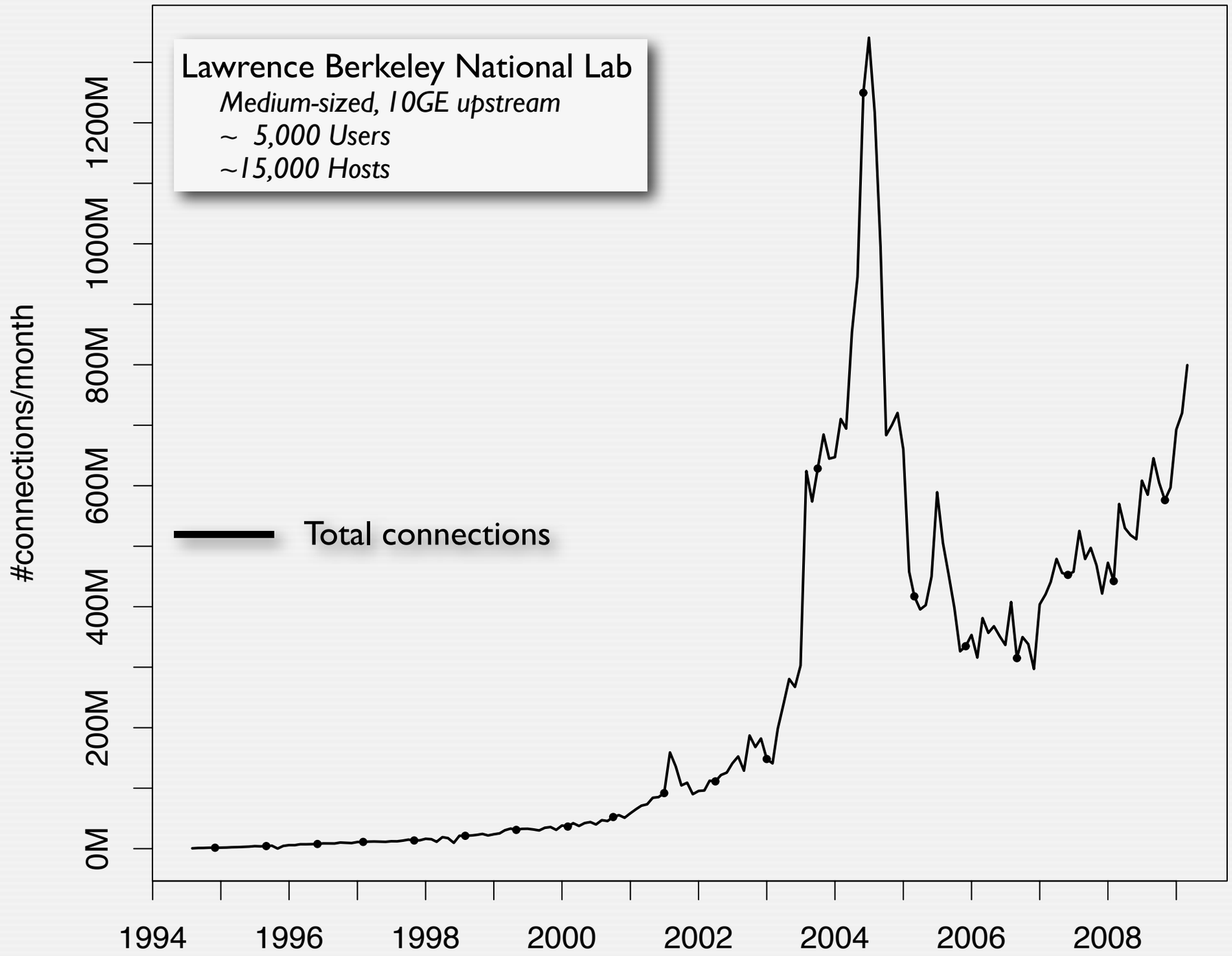


Development of Internet Traffic



Data: Leibniz-Rechenzentrum, München

Internet Traffic: Connections



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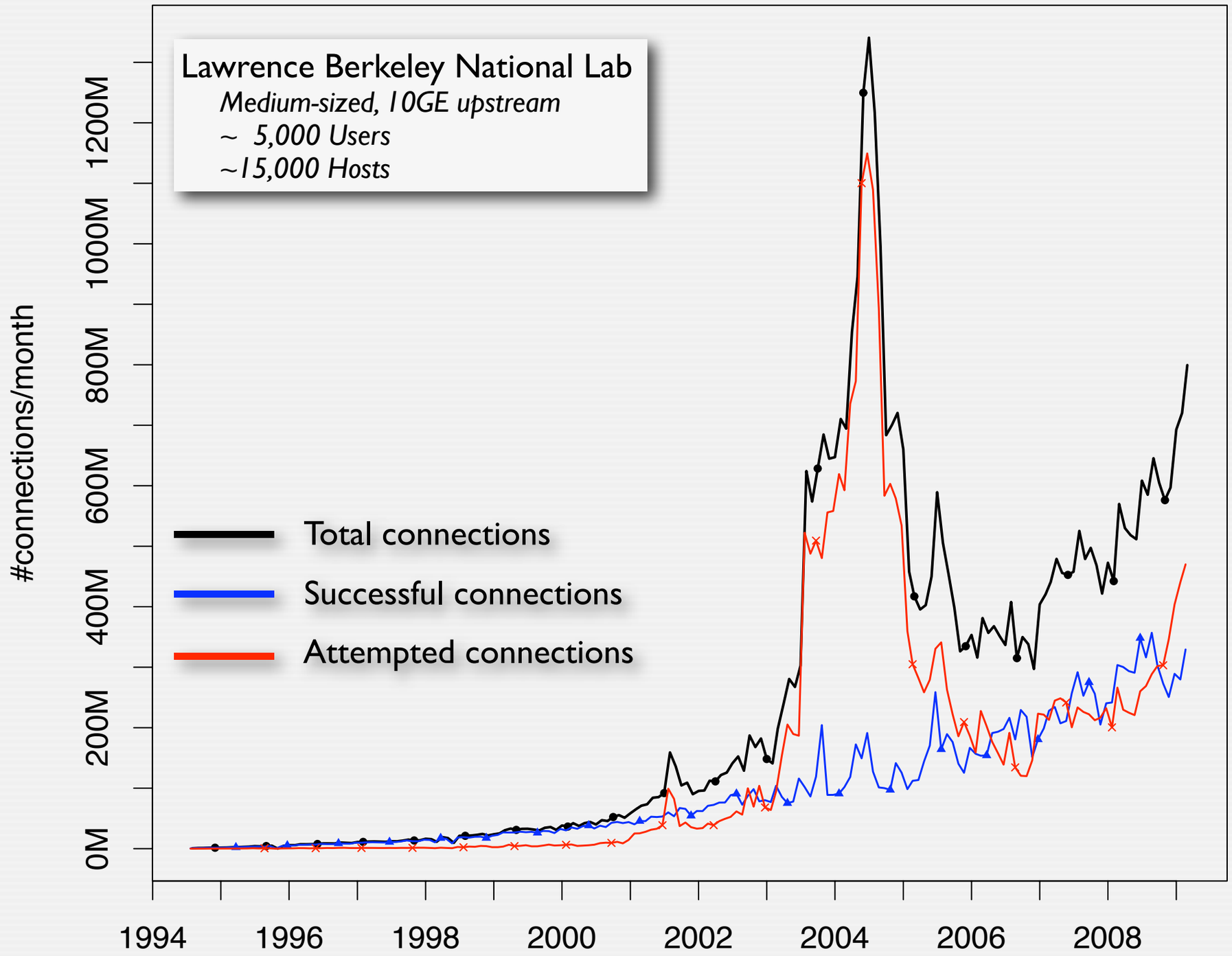

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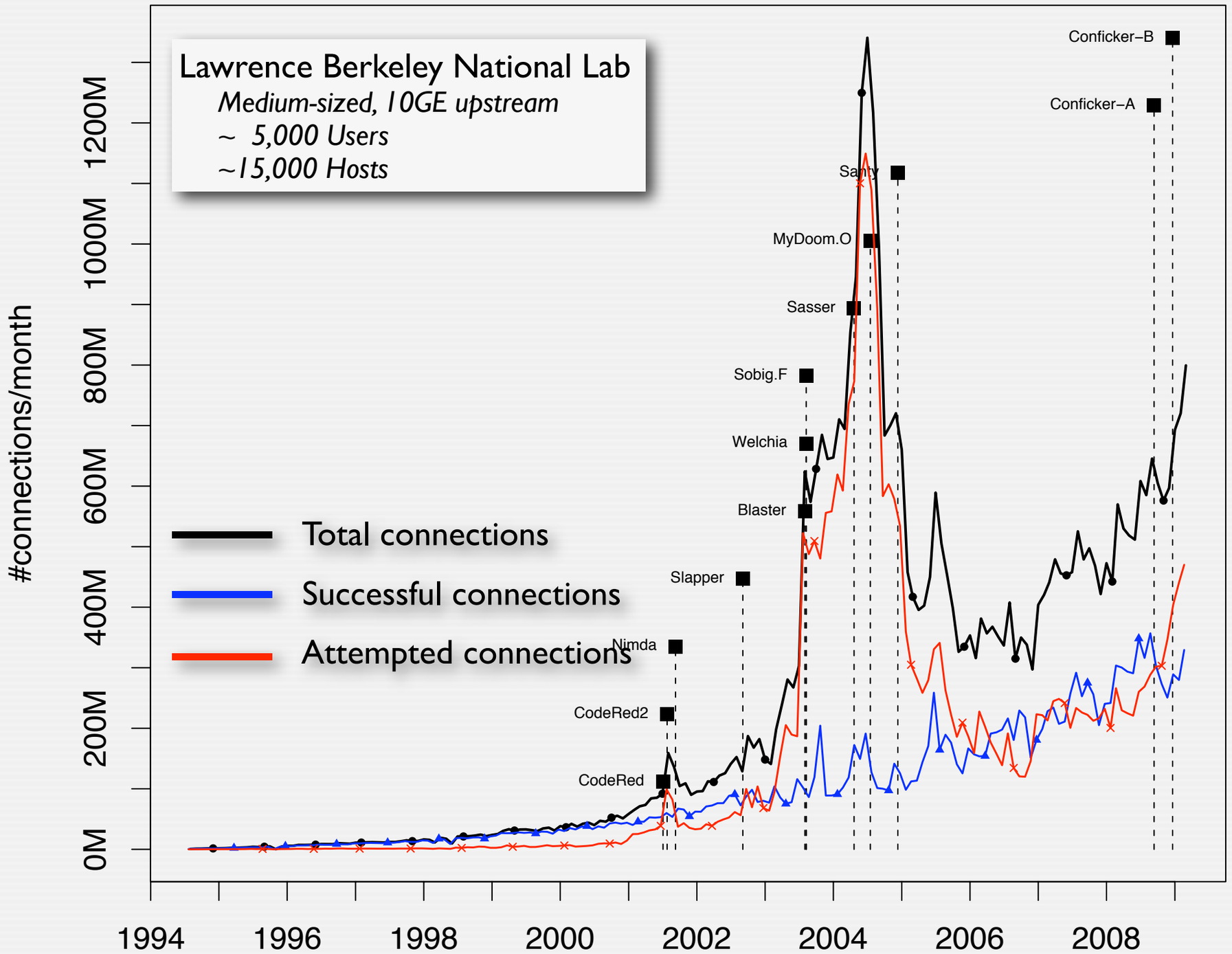


Data: Lawrence Berkeley National Lab

Need for Performance

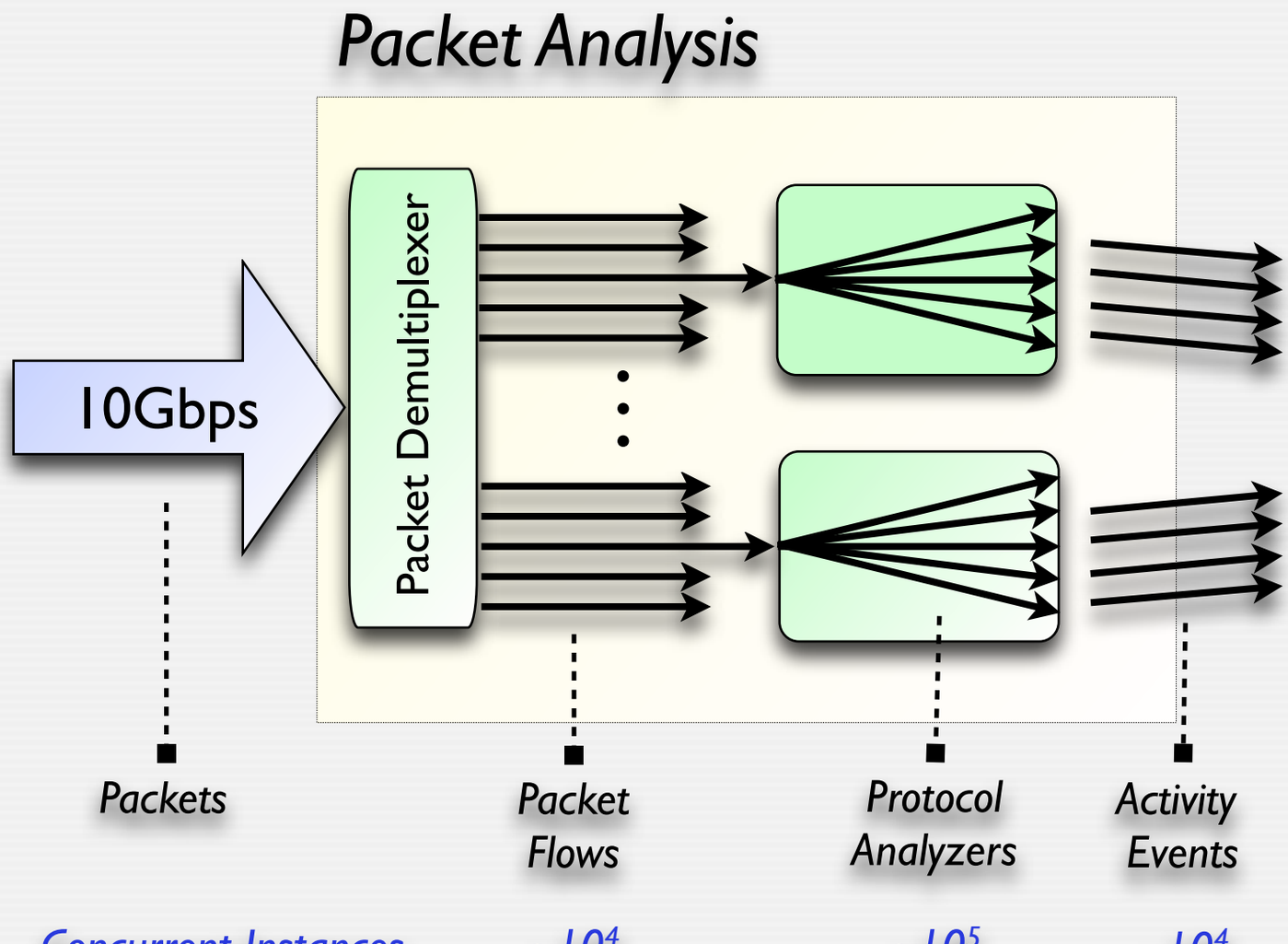
- NIDS used to run successfully on commodity hardware
  - In particular open-source NIDS (e.g., Snort, Bro)
- Not any more!
  - Keep needing to do *more analysis* on *more data* at *higher speeds*
  - Moore's law doesn't hold for single-core performance anymore
  - Unfortunately, traditional NIDS are single-threaded and thus limited
- To overcome, we can
  - Significantly restrict the amount of analysis, *or*
  - Turn to expensive & inflexible custom hardware, *or*
  - *Parallelize to leverage commodity multi-core architectures*
- Parallelizing an application is inherently *domain-specific*
  - There's no generic approach to concurrency
  - Need examine carefully where the concurrency potential is that we can exploit

Outline

1. *Concurrency Potential in Network Traffic Analysis*
   - A pipeline of highly concurrent stages
2. *Coarse-grained Parallelism: The NIDS Cluster*
   - A load-balancing solution
3. *Fine-grained Parallelism: Building a multi-threaded NIDS*
   - Turning a traditional NIDS into a highly concurrent system
4. *Future Directions*

Concurrency Potential in Network Traffic Analysis

Traffic Analysis Pipeline



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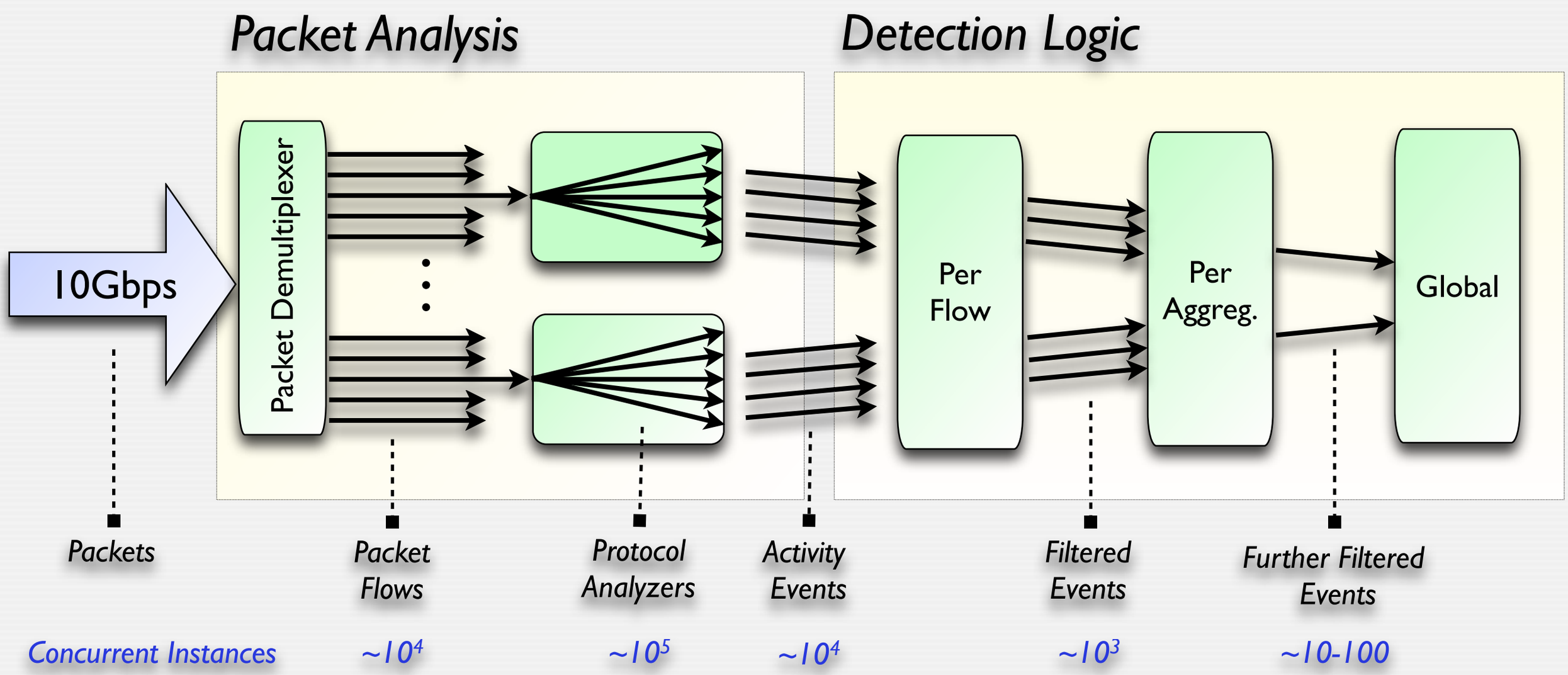

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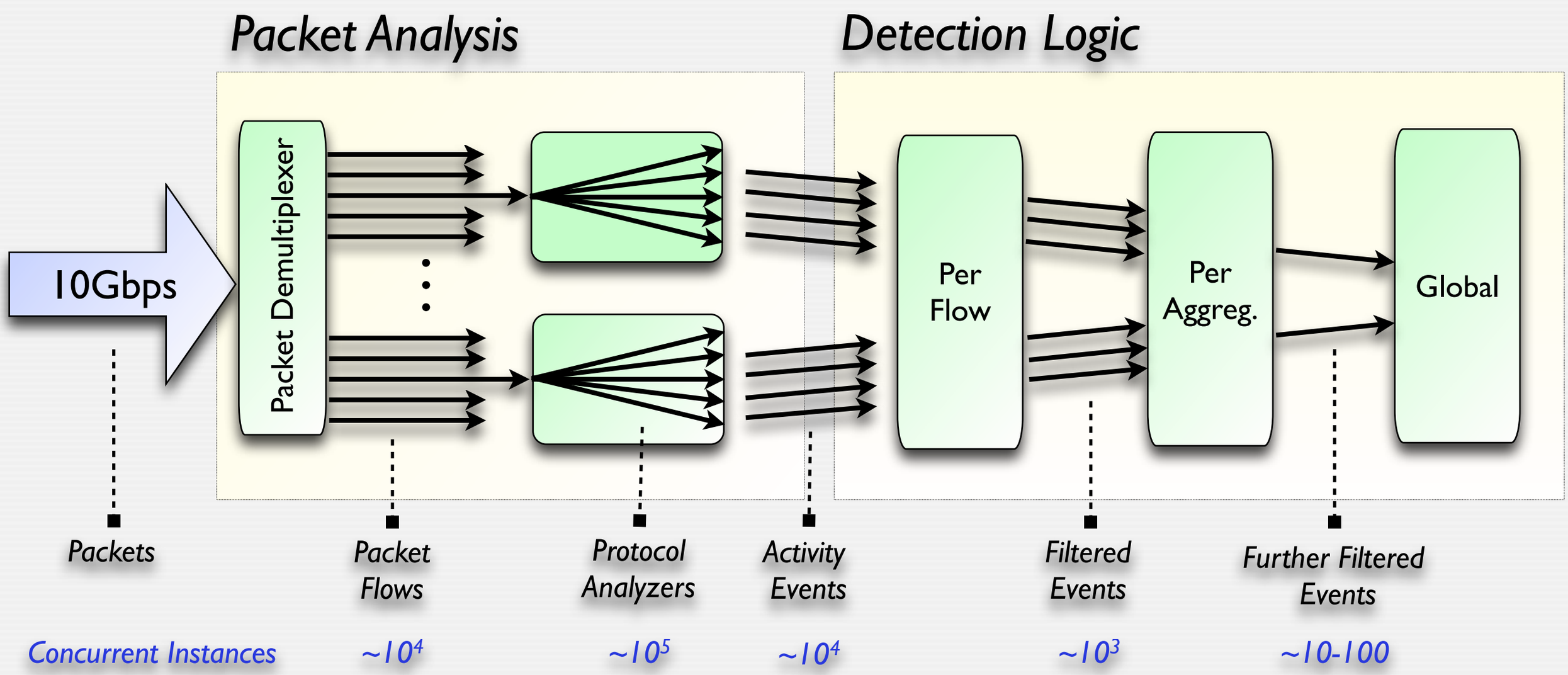

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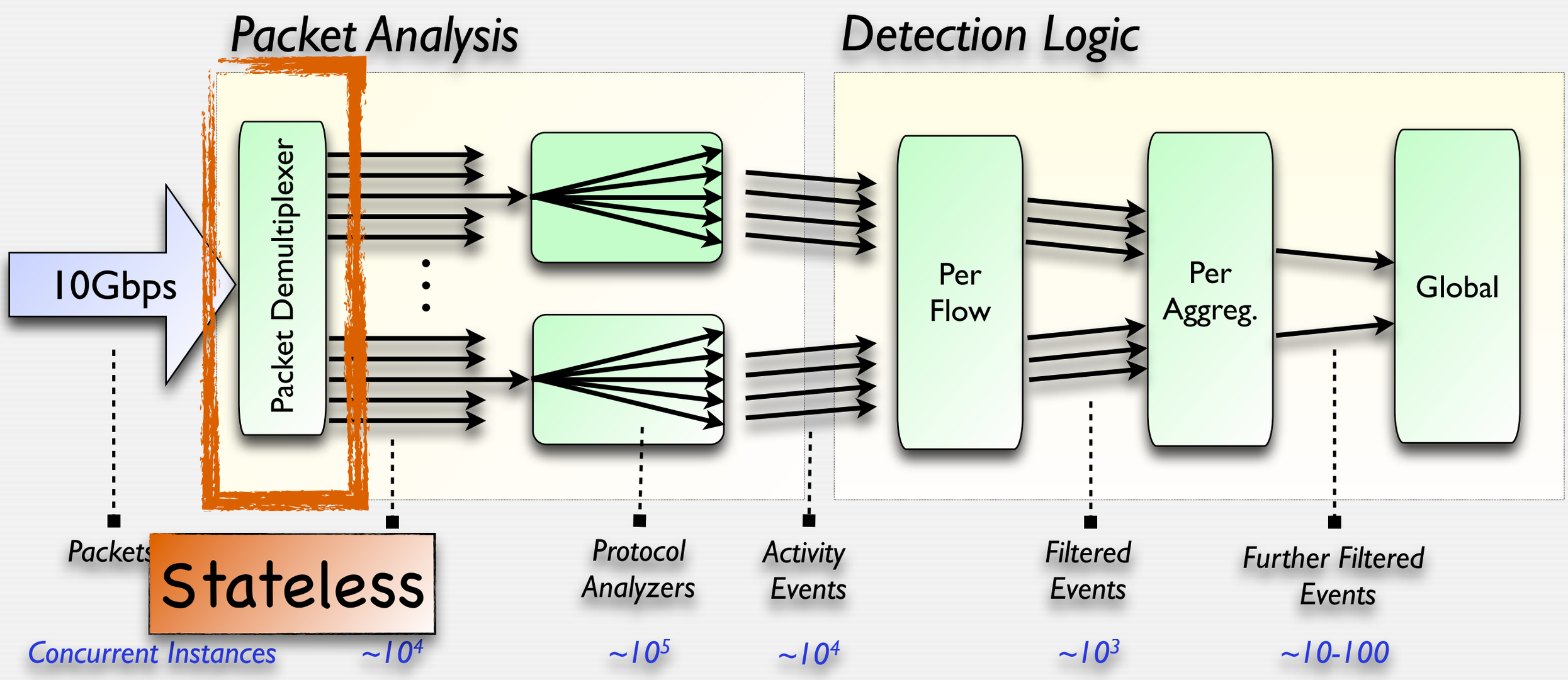

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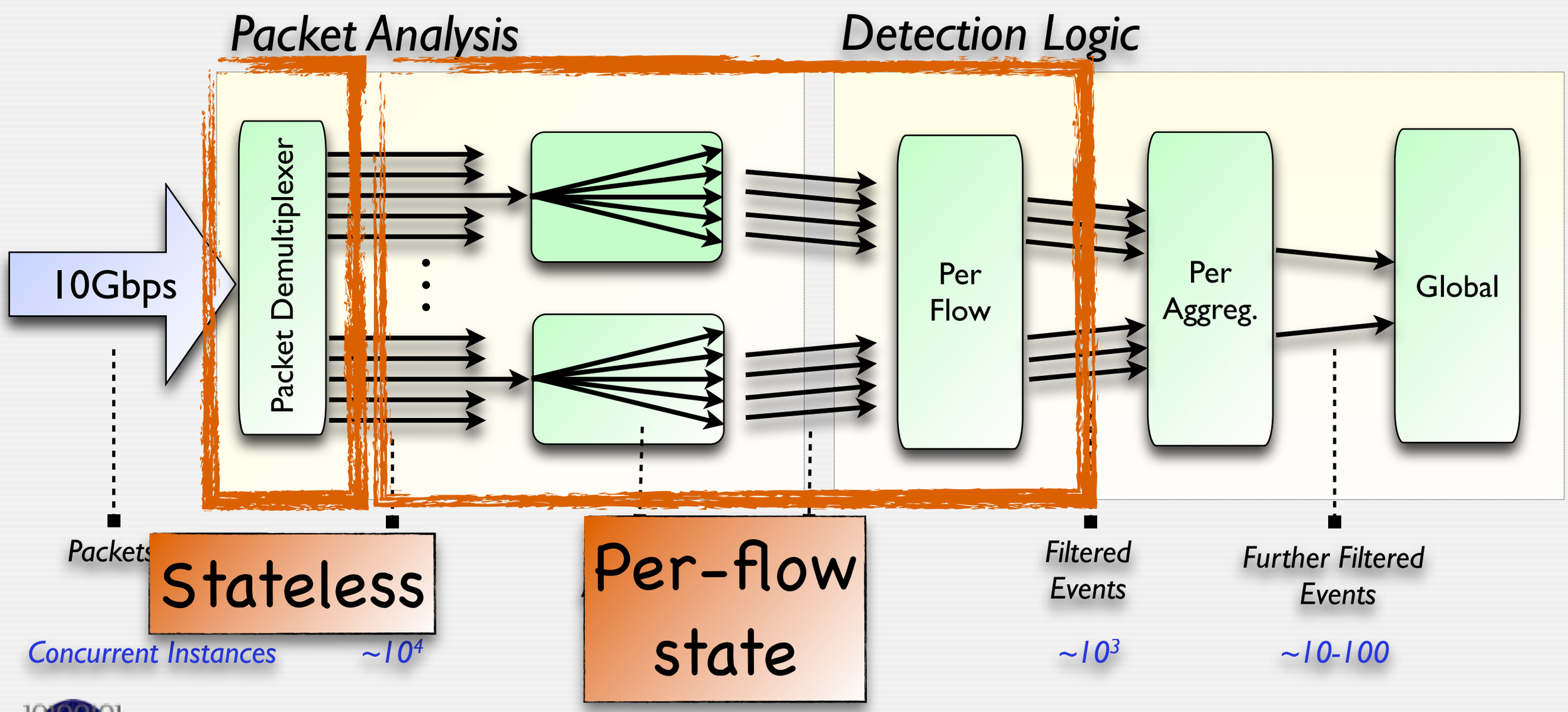

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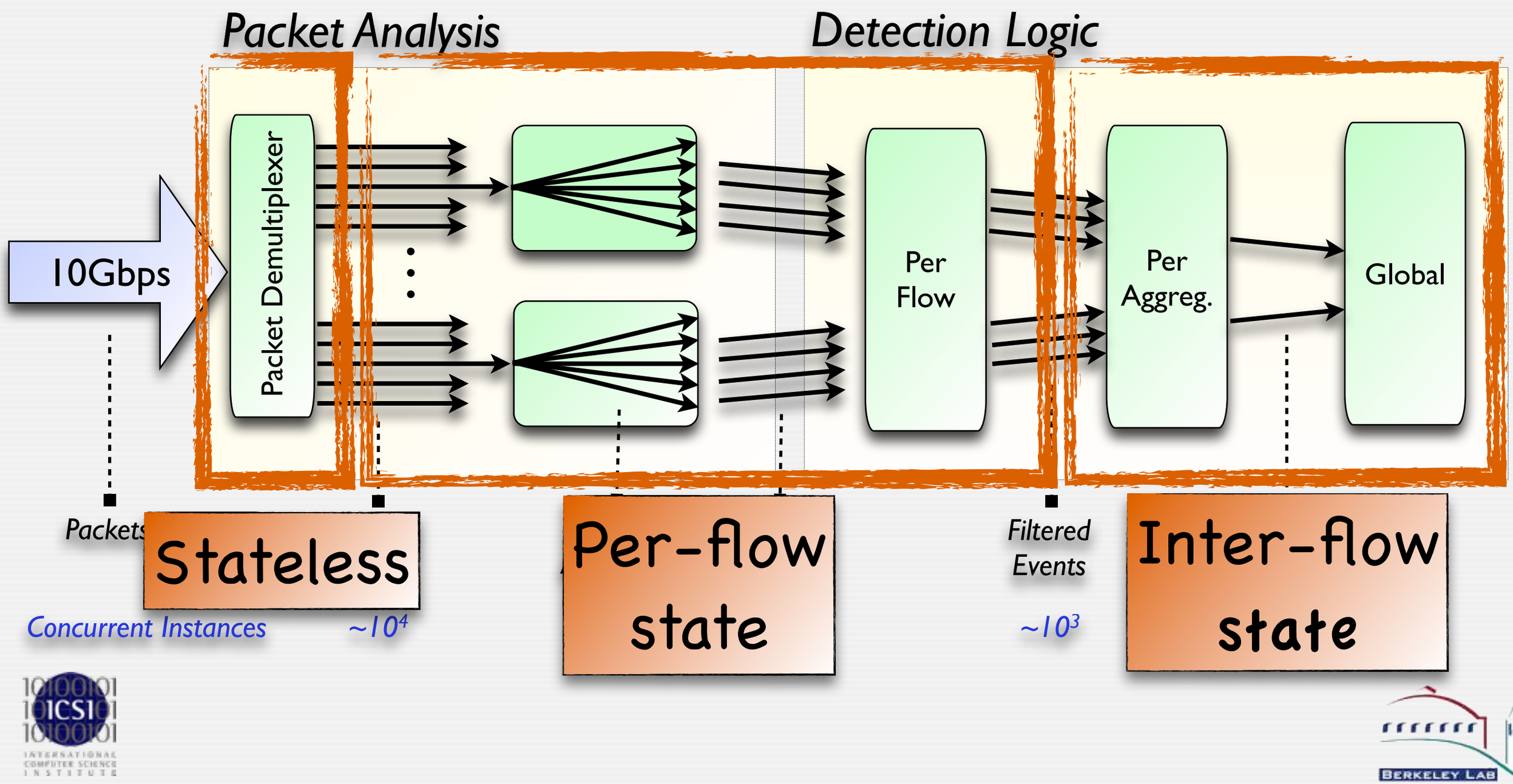
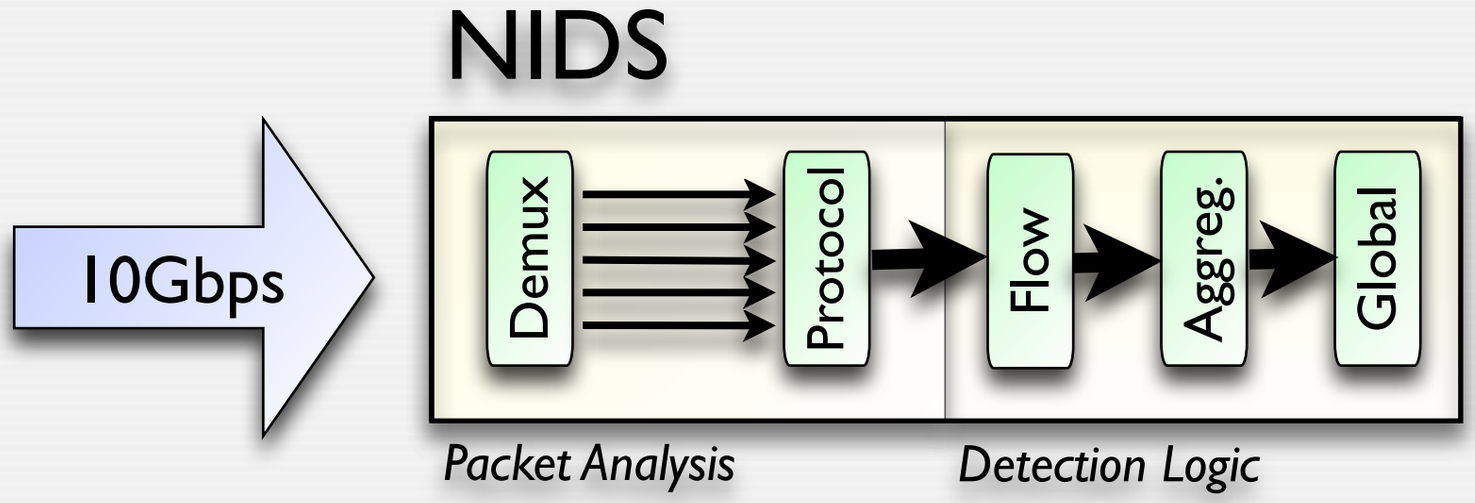


Building a Concurrent NIDS

- Don't really want to build a new NIDS from scratch ...
  - Can we parallelize an existing one?
- Our group at ICSI has been developing the Bro NIDS for more than a decade now.
  - Originally designed by Vern Paxson, who is still leading the project.
  - Open-source, with contributions from many external people.
  - Bro has been the corner-stone of LBNL's operational security for >10 years.
  - It's single-threaded however ...
- Can Bro exploit the concurrency of the pipeline?
  - We are talking about 160K lines of C++ code, plus another 25K lines of script code
- Two strategies:
  - Coarse-grained parallelism: The Bro Cluster
  - Fine-grained parallelism: Multi-core Bro

Coarse-grained Parallelism
The Bro Cluster

Load-Balancer Approach



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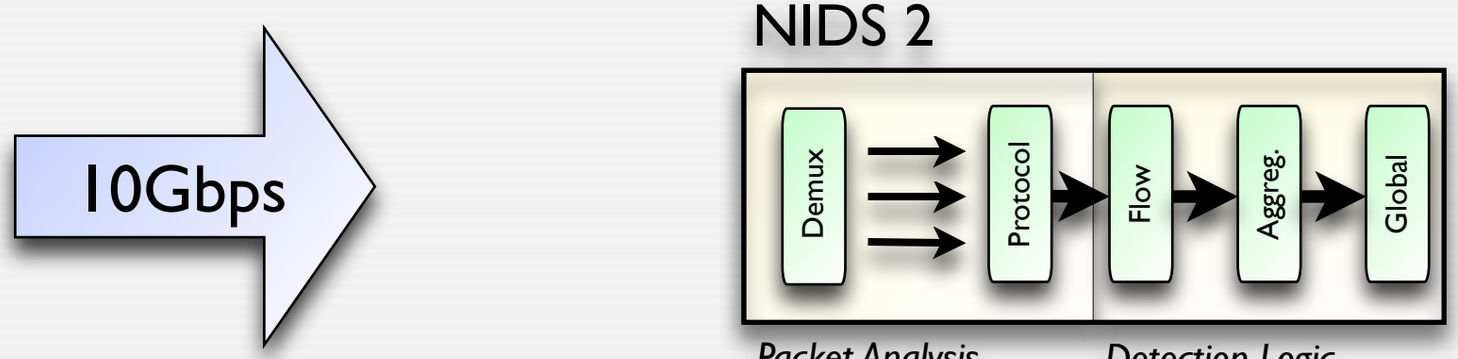

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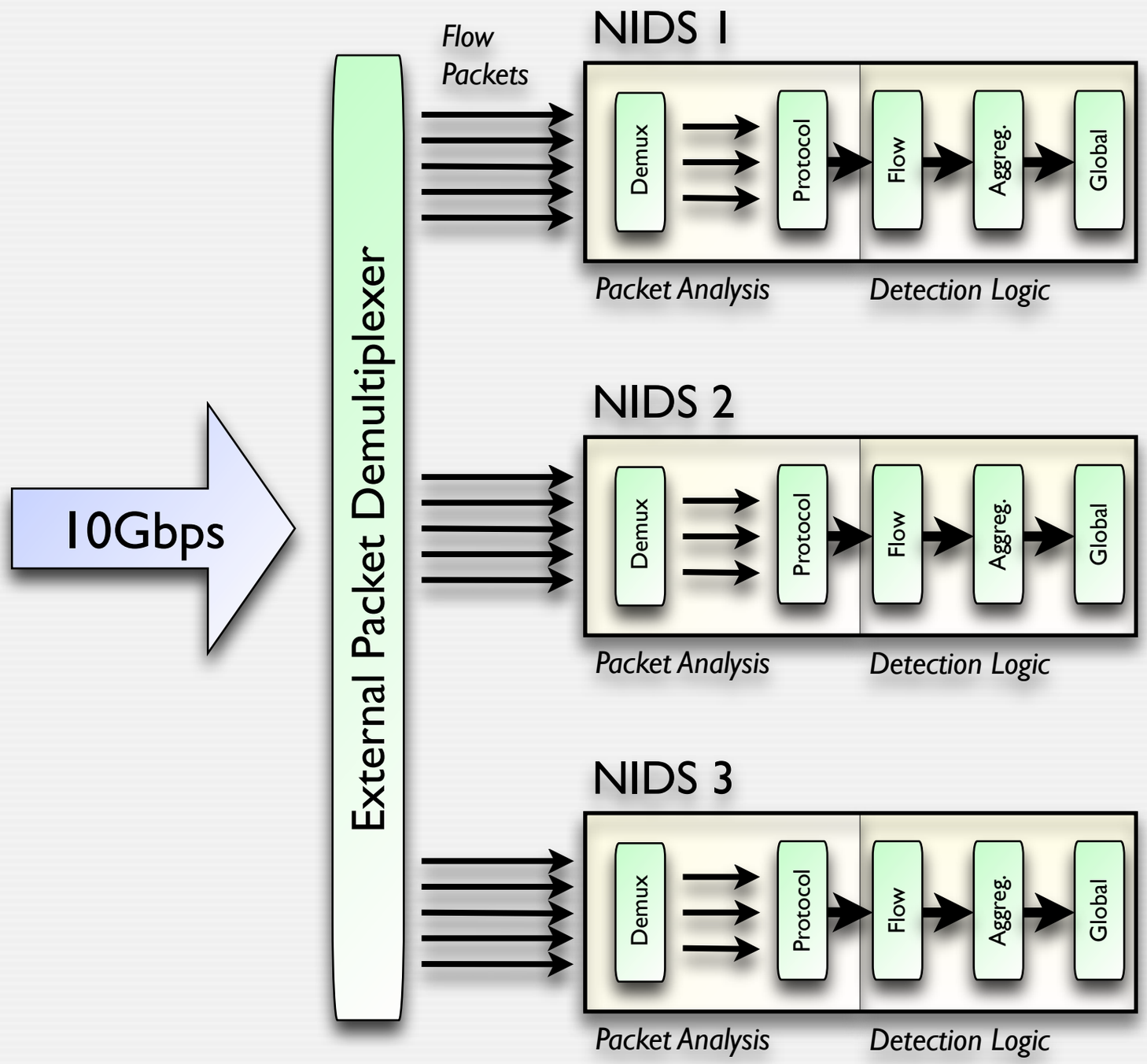

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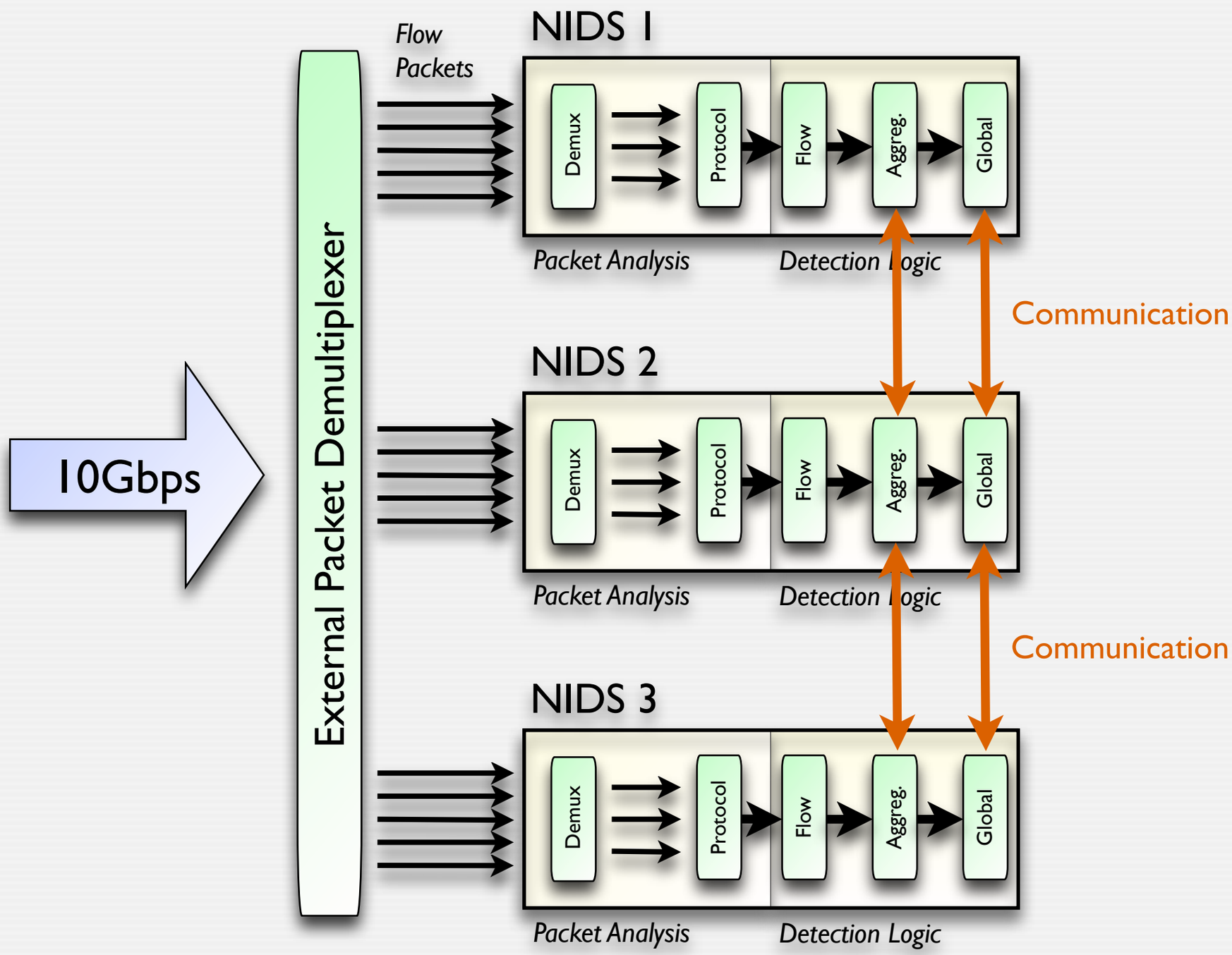


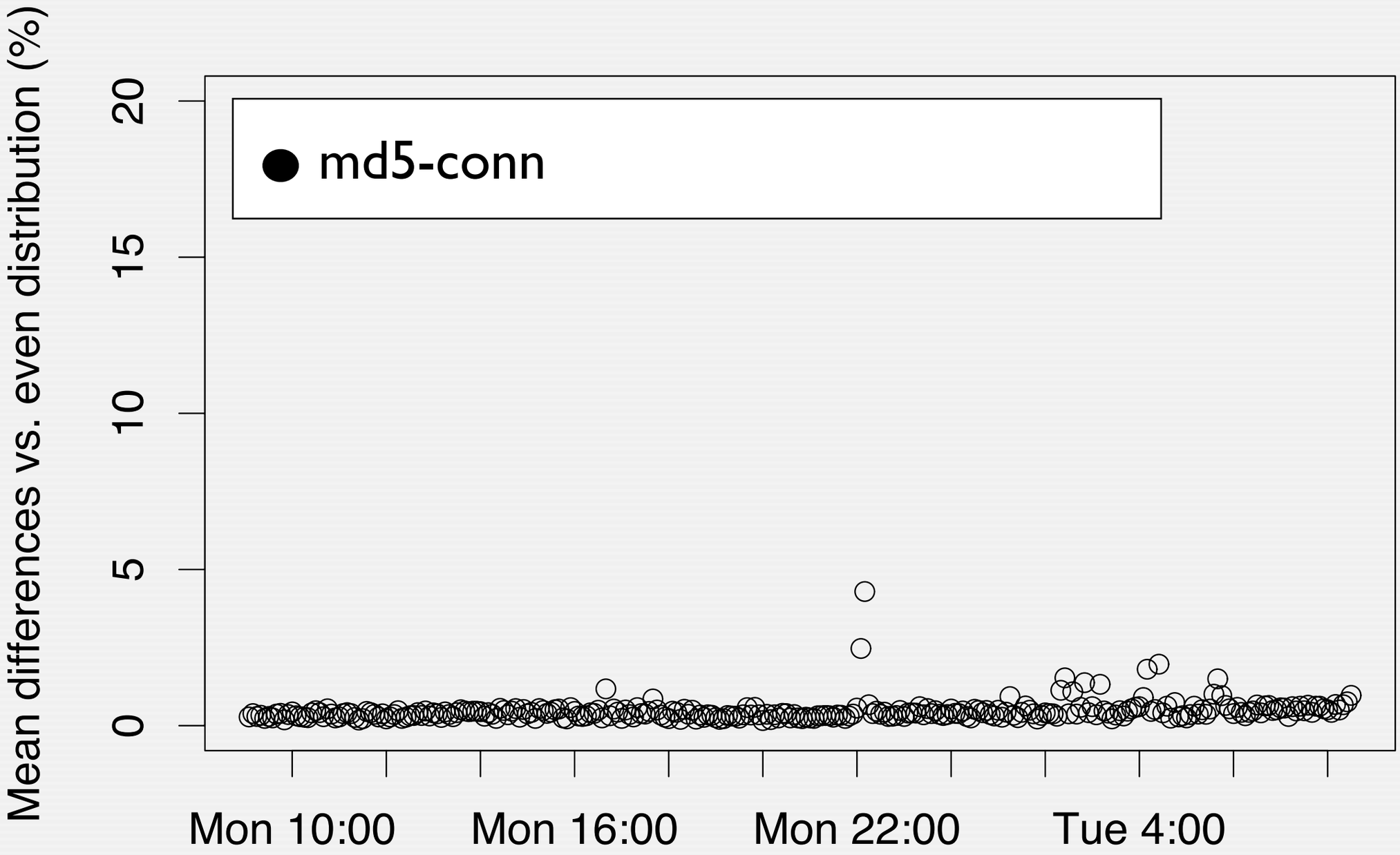
The Bro Cluster

- We built such a *cluster* using the Bro NIDS
- There are a number of practical challenges:
  - Communication capability required
    Fortunately, Bro has communication primitives built-in
  - External demultiplexer needs to operate line-rate
    Worked with a vendor to build an appliance implementing our dispatching scheme
  - Management of multi-machine setup is tedious
    Build a management interface transparently hiding the complexity for the operator
- Installations
  - Research cluster at LBNL with 10 NIDS machines (backends)
  - Transitioning into production mode; will replace Labs' operational monitoring
  - Planing much larger research cluster on the Berkeley campus

External Packet Dispatcher

- How to decide where to send a packet?
- We want the dispatcher to
  - Keep flows together
  - Be simple and stateless for implementation in hardware
- Observation: Each packet contains a flow identifier
  - 4-tuple of IP addresses and TCP/UDP port numbers
- Dispatcher can calculate hash over the 4-tuple
  - `backend := hash(`*`tuple`*`) mod N`
- But how smooth a distribution does that yield?

Simulation of Packet Dispatcher



1 day of UC Berkeley campus TCP traffic (231M connections), n = 10

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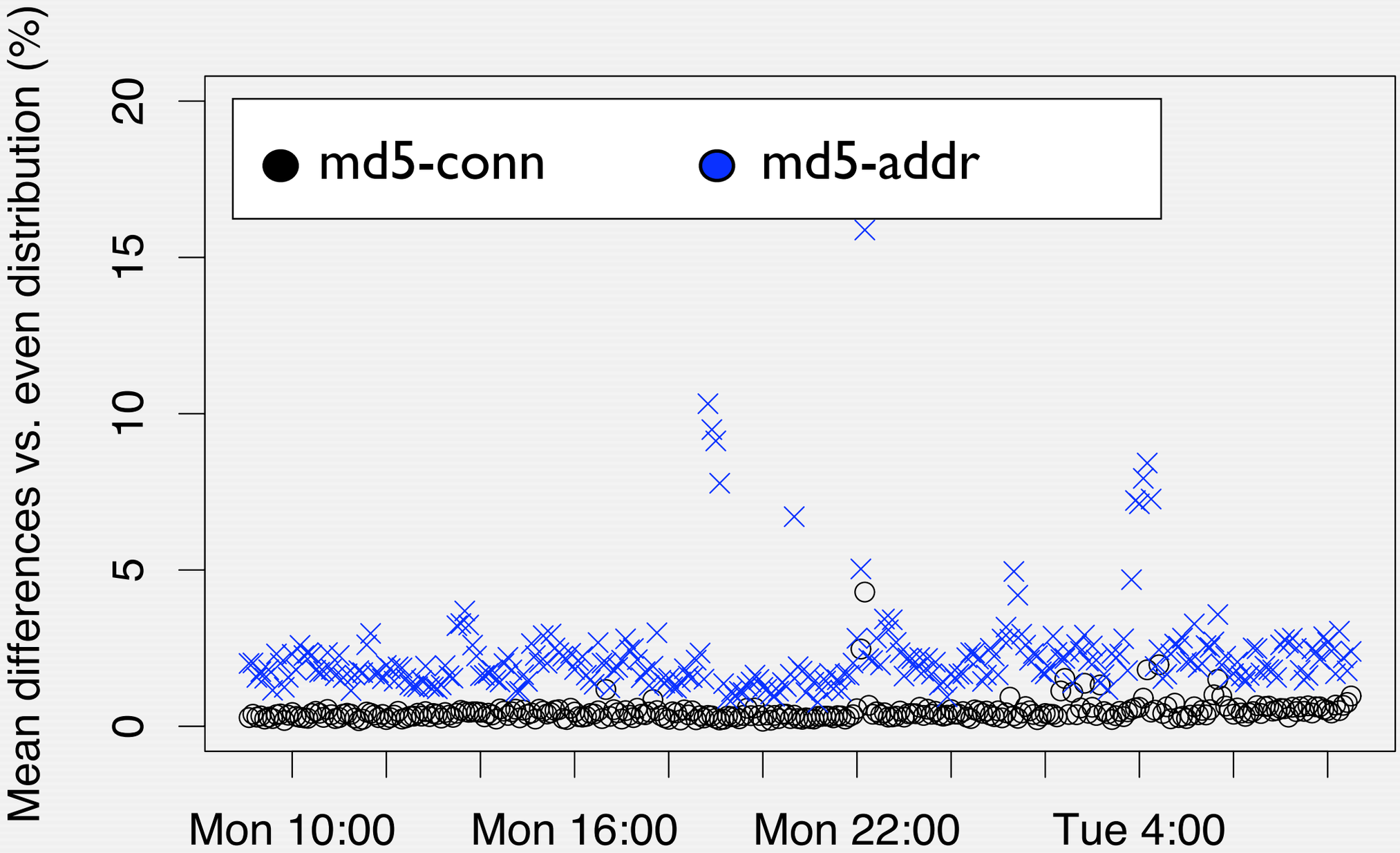


1 day of UC Berkeley campus TCP traffic (231M connections), n = 10

Fine-grained Parallelism
Building a Multi-Threaded NIDS

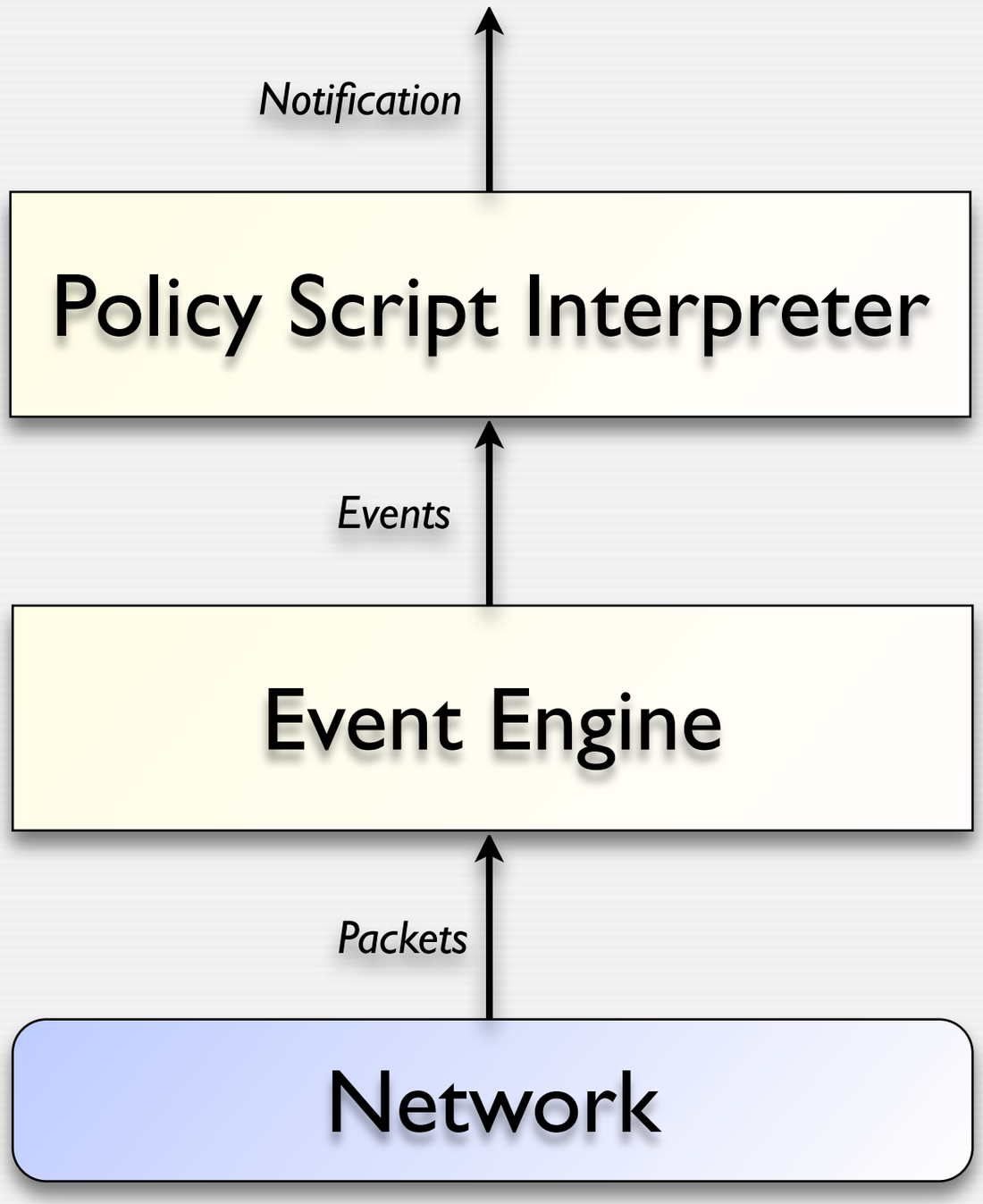
"Real" Multi-Core NIDS

- Cluster has short-comings:
  - Chances are that today's backends have multiple cores, which will be wasted
  - State is unnecessarily duplicated across all backends
  - Communication introduces race-conditions
  - Setup requires quite a bit of effort (and money)
- What we really want is a multi-threaded NIDS
  - ... and we want it to scale well with increasing numbers of cores
- Still don't want to write a new NIDS from scratch
  - Turn the traditional Bro into a multi-threaded application
- But do that *transparently:*
  - Do not expose parallel processing to the operator
  - But parallelize internally "under the hood"

Bro's Architecture

Detection Logic

Packet Analysis



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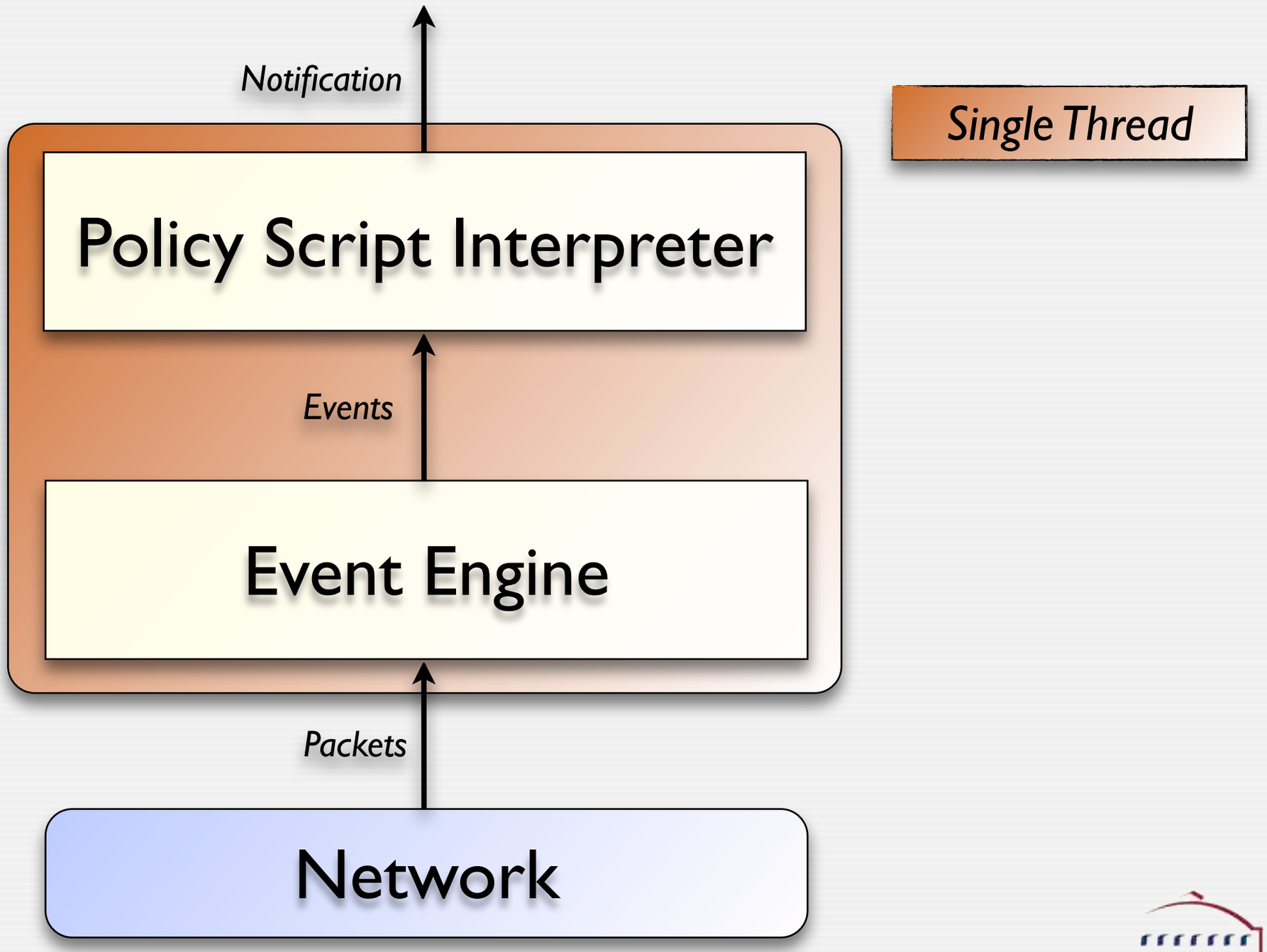
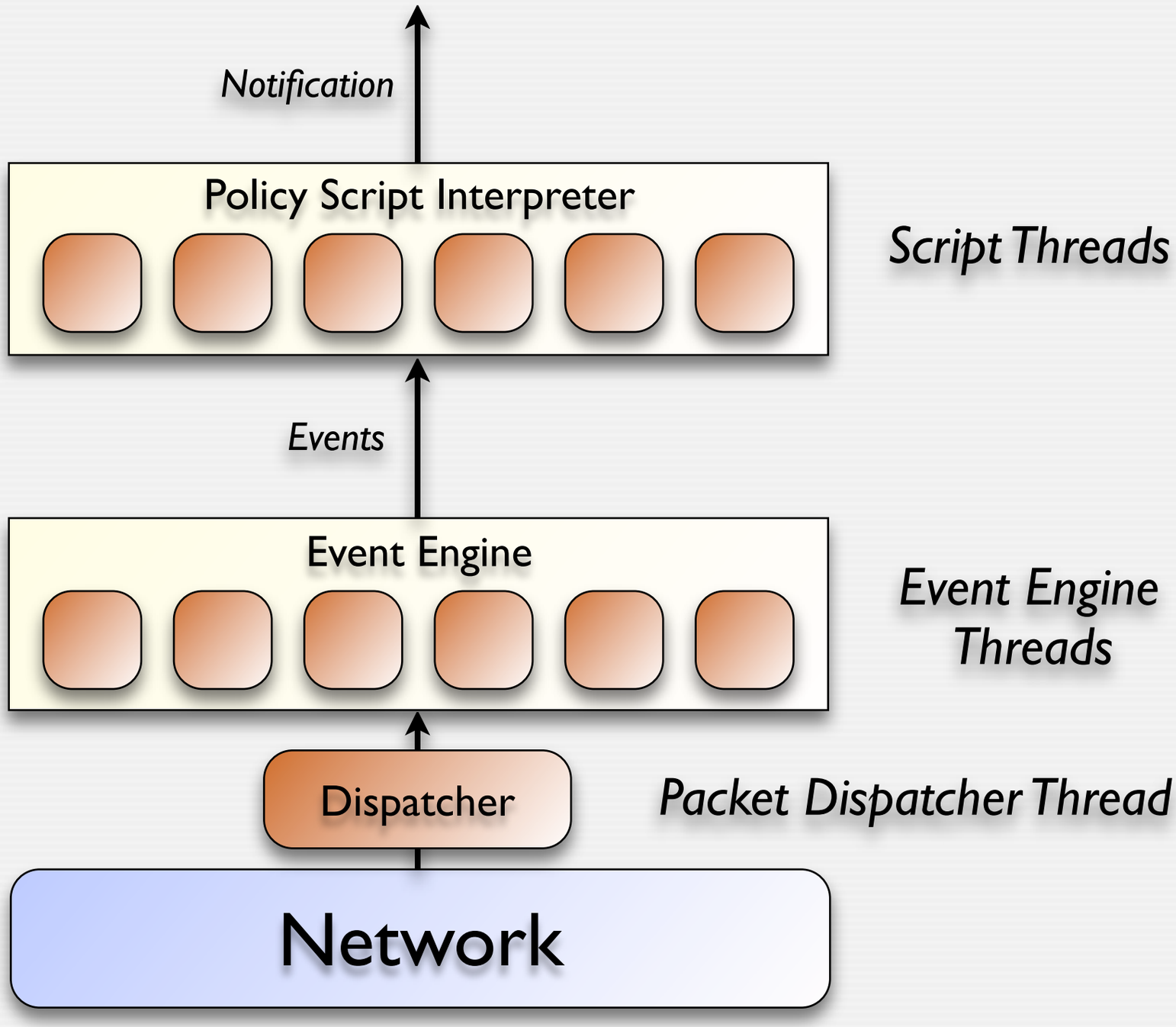


Single Thread

Bro's Architecture

Detection Logic



Script Threads

Packet Analysis

Event Engine Threads

Packet Dispatcher Thread

Bro's Architecture

Detection Logic

Notification

Policy Script Interpreter

Script Threads

Events

Event Engine

Event Engine Threads

Packet Analysis

"Cluster in a Box"

Dispatcher

Packet Dispatcher Thread

Network

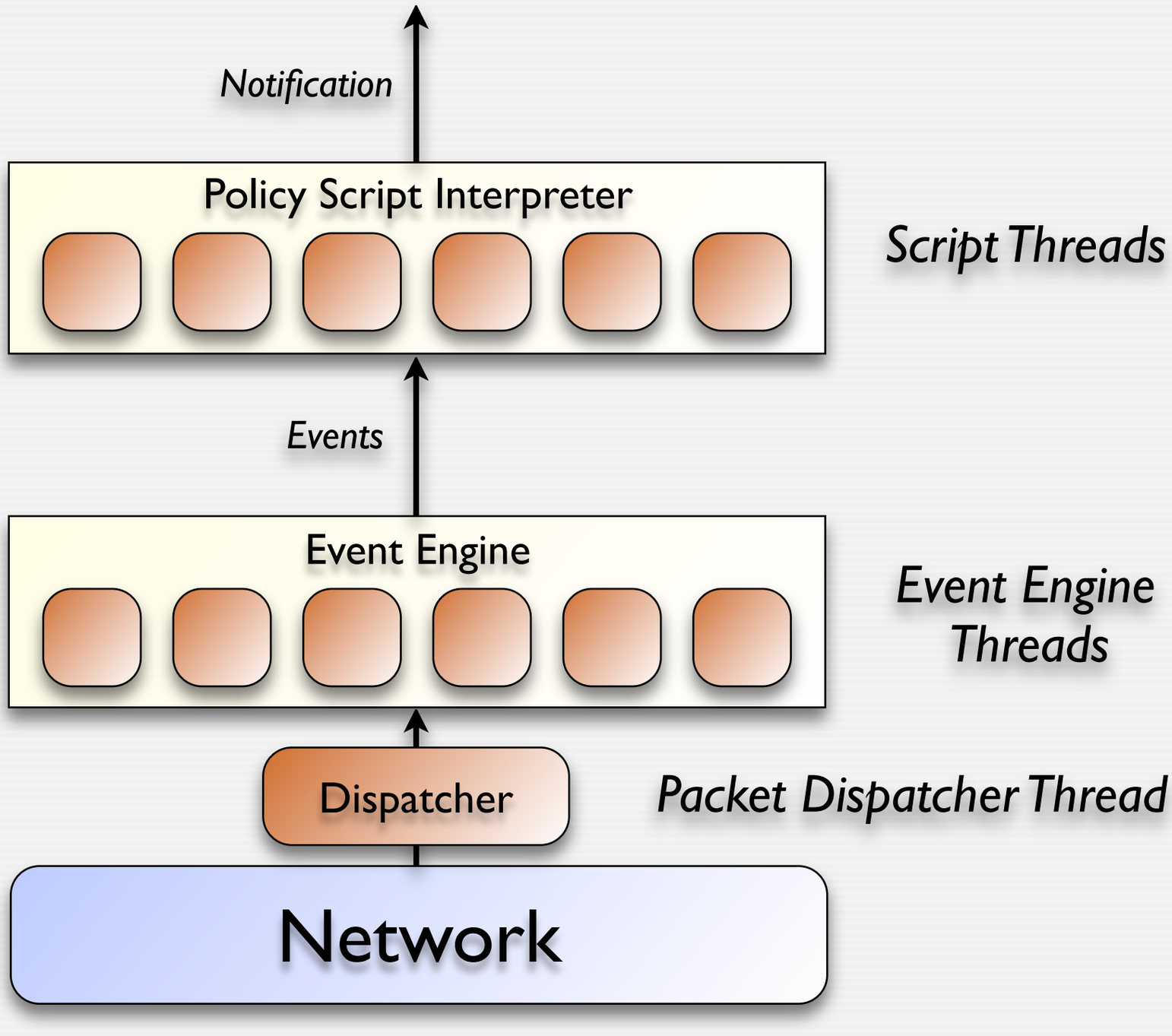
Bro's Architecture

How to parallelize a scripting language?

Detection Logic

Packet Analysis

"Cluster in a Box"



Script Example: Matching URLs

Task: Report all Web requests for files called "`passwd`".

```
event http_request(c: connection, method: string, path: string)
{
    if ( method == "GET" && path == /.*passwd/ )
        NOTICE(SensitiveURL, c, path); # Alarm.
}
```

(Syntax simplified.)

Example: ***http_request(1.2.3.4/4321⇒5.6.7.8/80, "GET", "/index.html")***

Script Example 2: Flow-based

Task: *Report all successful HTTP requests for files called "`passwd`".*

```
global potentially_sensitive: table[connection] of string;

event http_request(c: connection, method: string, path: string)
{
    if ( method == "GET" && path == /.*passwd/ )
        potentially_sensitive[c] = path; # Add to table.
}

event http_reply(c: connection, response: int, reason: string) )
{
    if ( response == OK && c in potentially_sensitive )
        NOTICE(SensitiveURL, c, potentially_sensitive[c]);
}
```

(Syntax simplified.)

Script Example 3: Aggregated

Task: *Count failed connection attempts per source address*.

```
global attempts: table[addr] of int &default=0;

event connection_rejected(c: connection)
{
    local source = c.orig_h;         # Get source address.
    local n = ++attempts[source];    # Increase counter.
    if ( n == SOME_THRESHOLD )       # Check for threshold.
        NOTICE(Scanner, source);     # If so, report.
}
```

(Syntax simplified.)

"Scheduling Scopes"

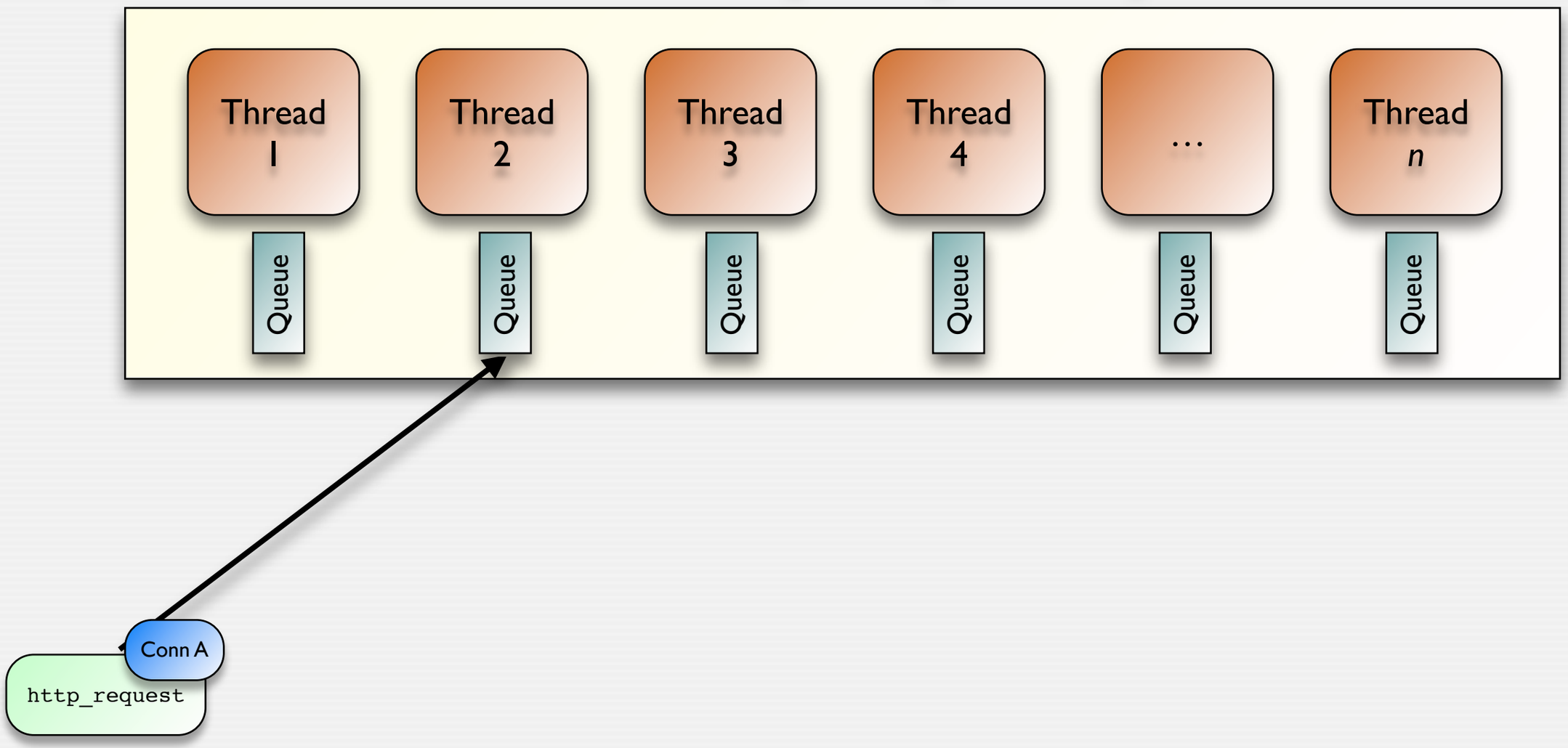
- Accessing a piece of state from only *one* thread buys us:
  - Lock-free memory accesses
  - Preservation of temporal order of event execution
- We add the concept of *scopes* to Bro's script language:
  - For each variable, one specifies the semantic granularity of accesses
    (e.g., *connection, originator, responder, host pair*)
    - All accesses with the same underlying unit will come from the same thread.
    - Internally, we keep thread-local versions of each variable
  - For each event handler, Bro derives a scope based on which variables it accesses
    - When it is scheduled, the scope & current unit determine which thread it goes to

```
global potentially_sensitive: table[connection] of string
   &scope=connection;

global attempts: table[addr] of int &default=0
   &scope=originator;
```

Parallel Event Scheduling

Threaded Policy Script Interpreter



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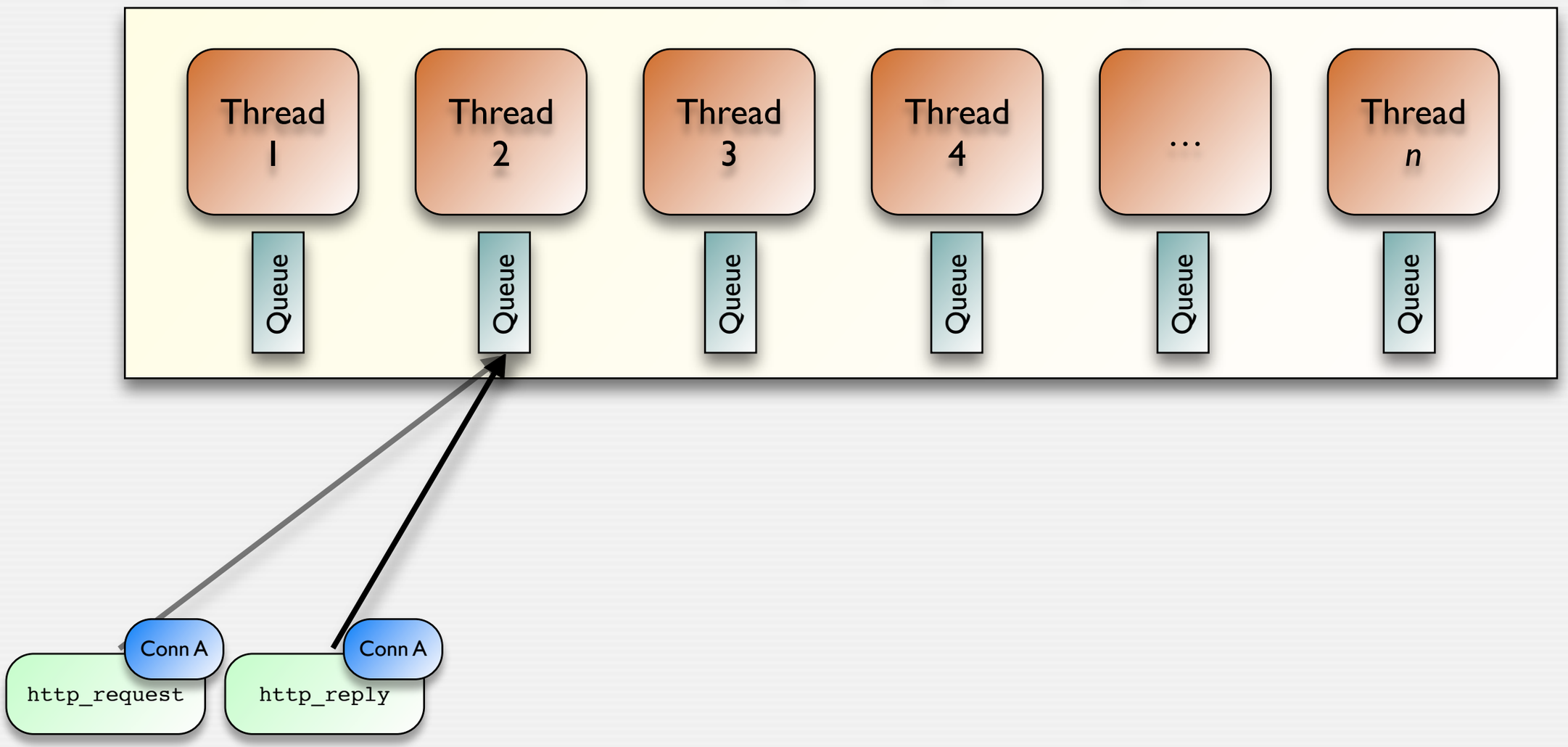

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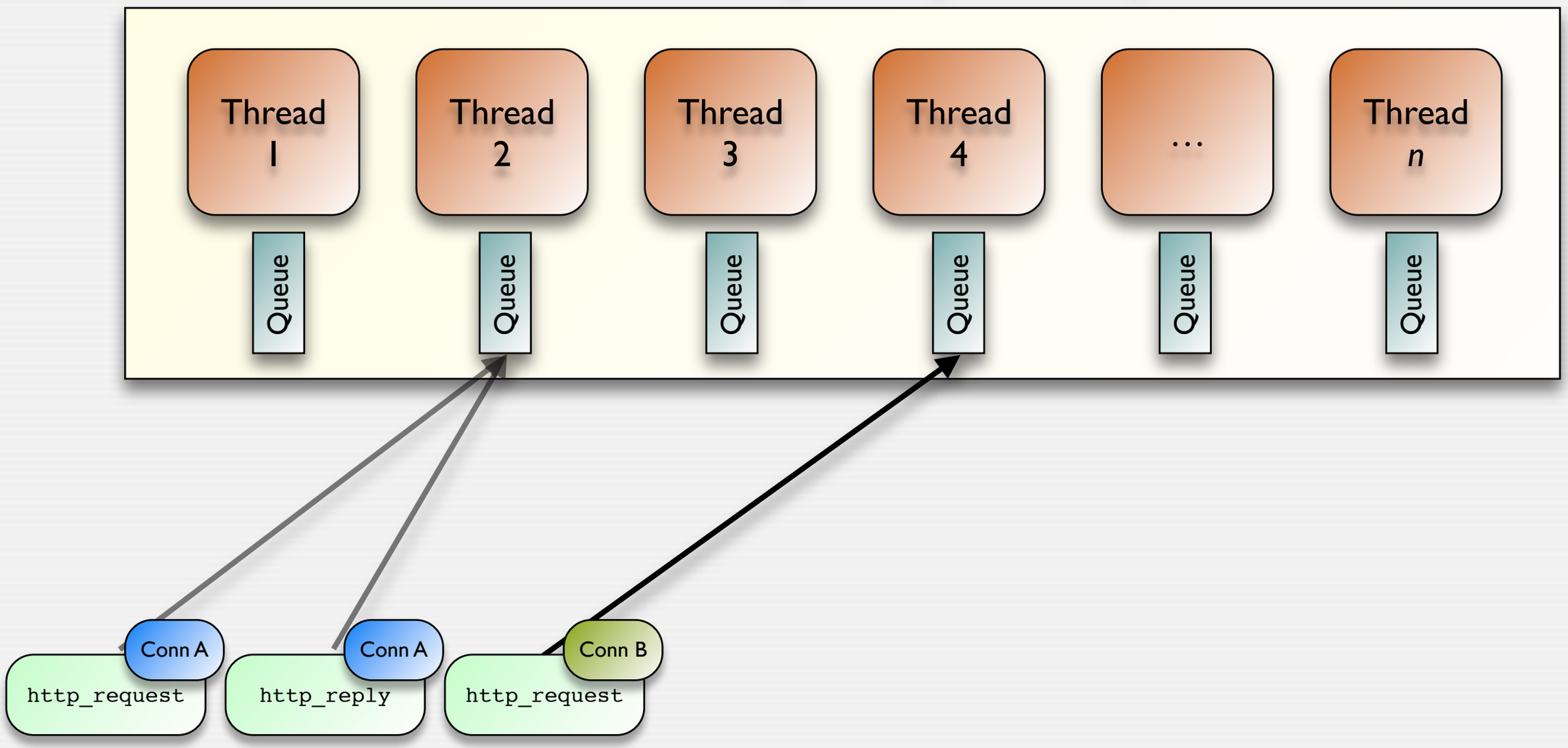

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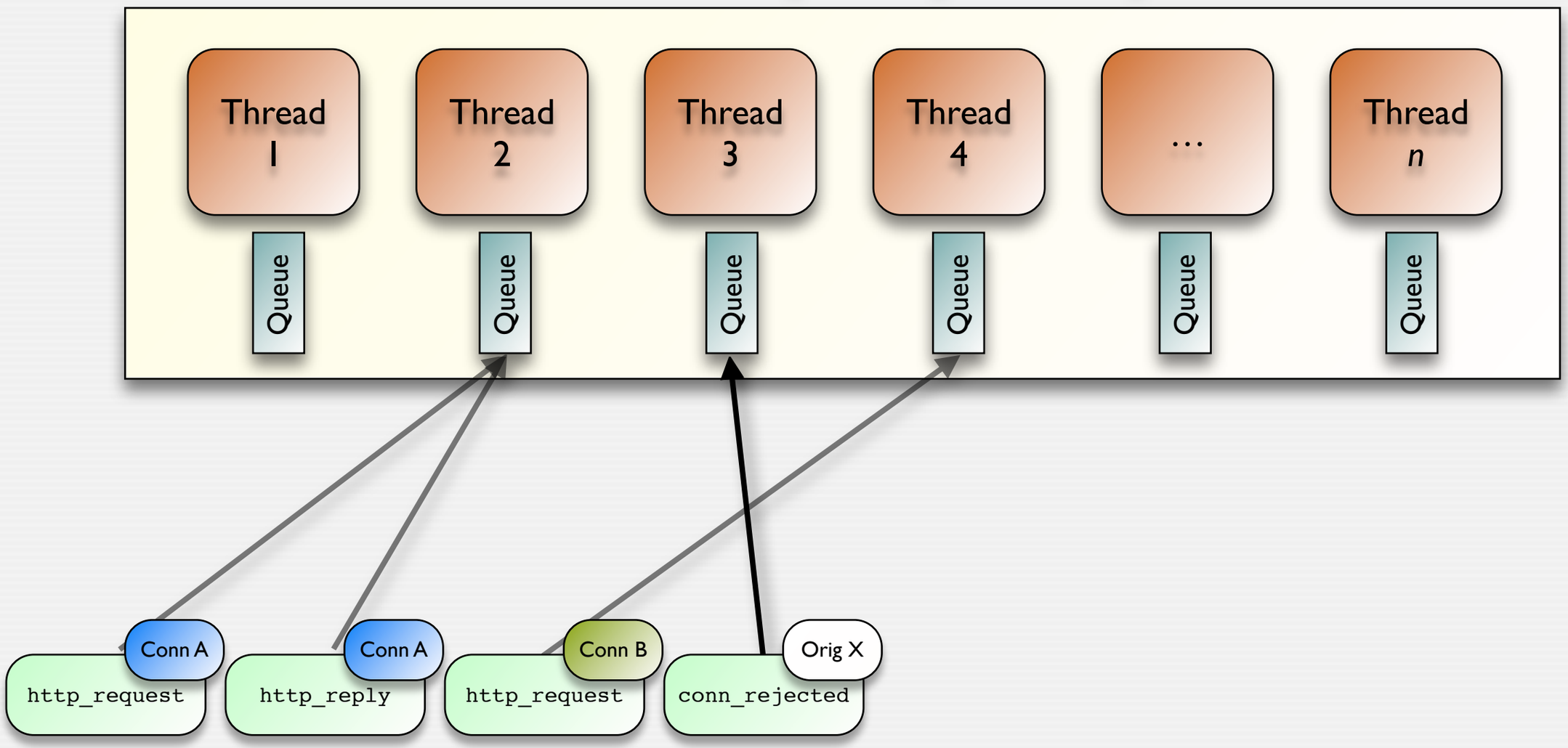

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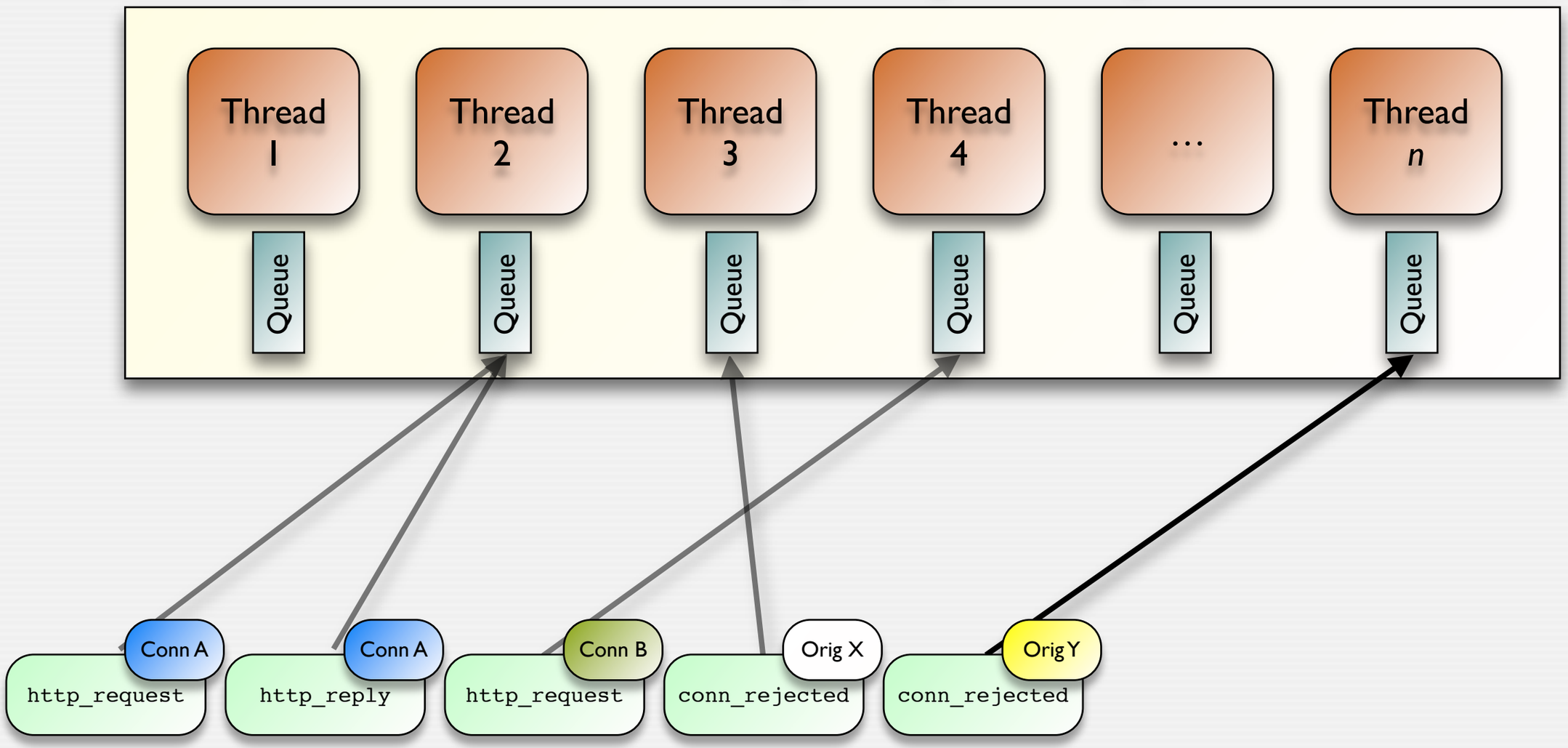

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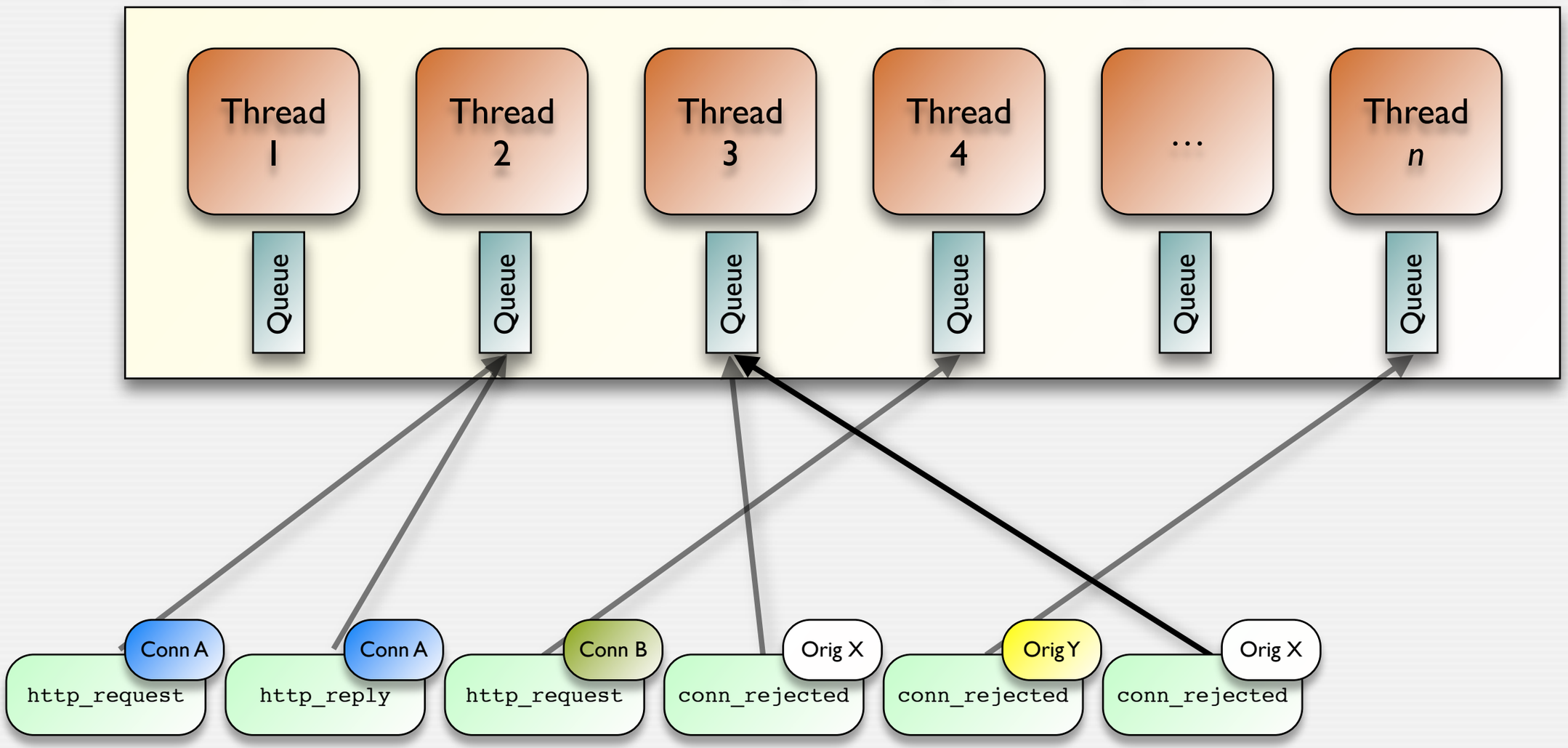

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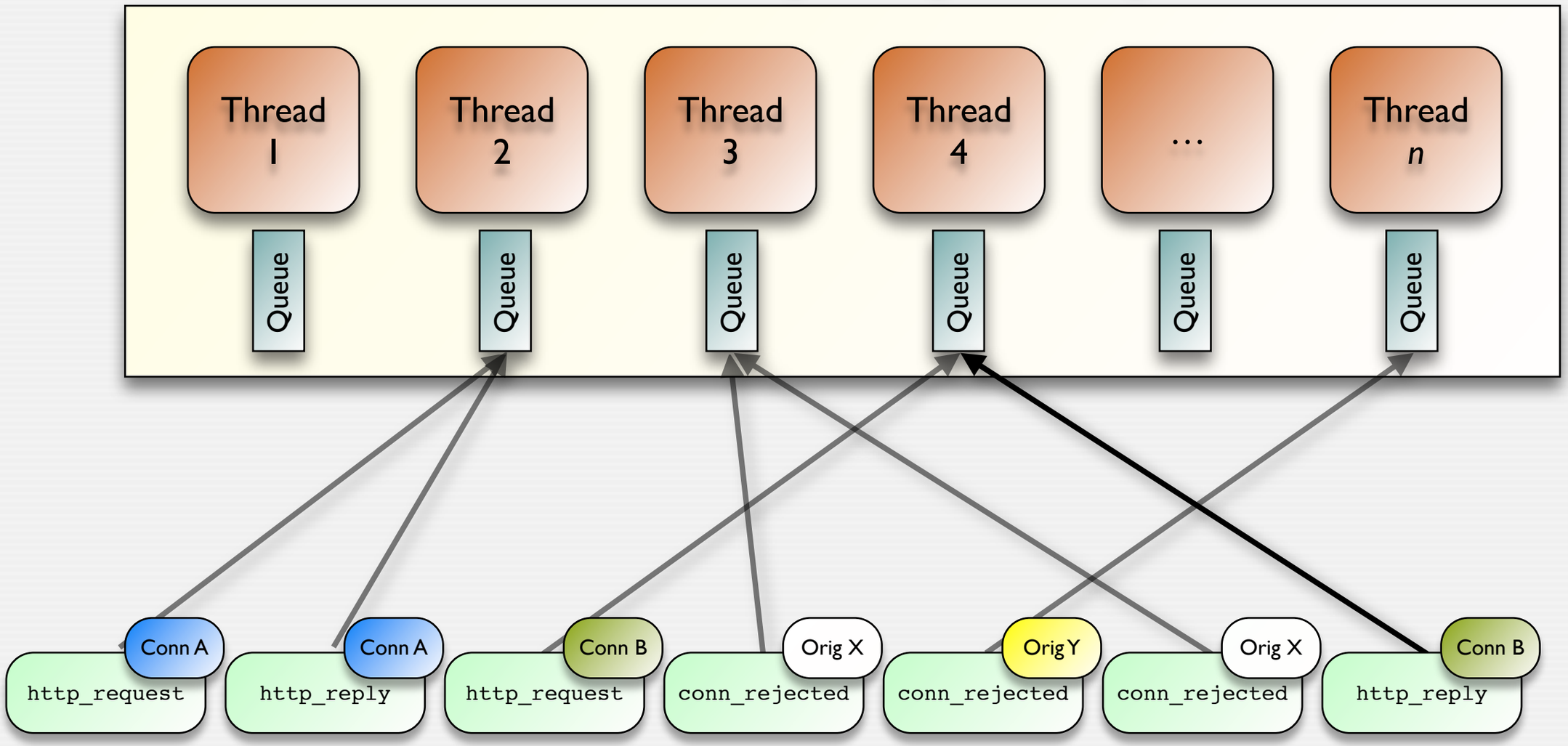

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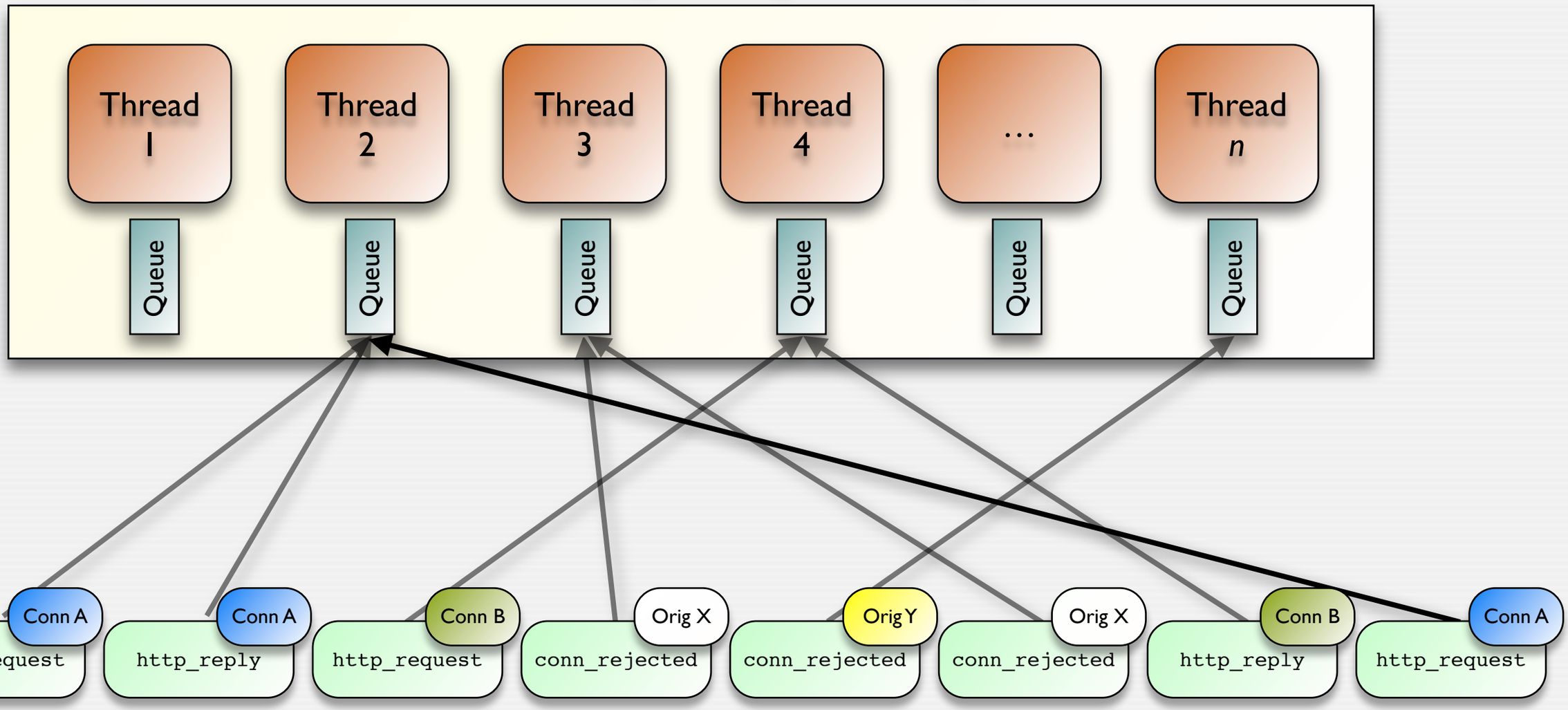
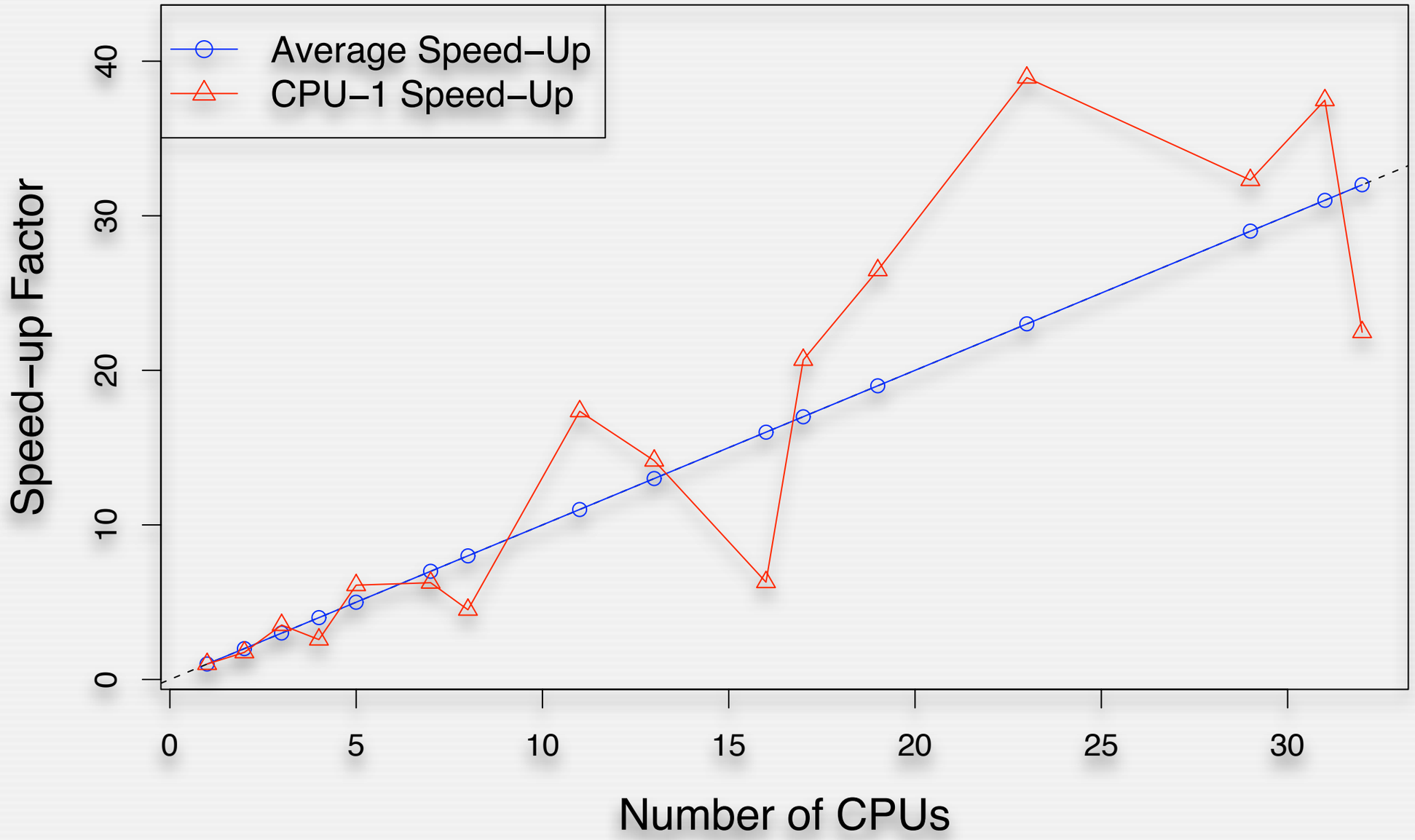


Does the Scoping Model Scale?



Simulation based on 15 minutes of LBNL traffic (24GB, 50M events)

Implementation of Multi-Core Bro

- We have a prototype that we are now examining
  - Parallelization based Intel's Threading Building Blocks
  - We do not use on TBB's task concept; just a portable thread abstraction
- Spent a lot of time in making Bro's code thread-safe
  - Extensive use of globals and statics ...
  - Race conditions, e.g., in memory management
  - Not pretty ...
- Assigned scopes to the most important globals
  - Profiling showed which global variables are accessed the most (>100)
  - Surprisingly many are covered with a small set of scopes
  - Some minor script adaptations to observe scoping rules
  - "Real" globals are fully locked
- First evaluation with a small ICSI trace on an 8-core system
  - Speedup of 2-3 compared with single-thread Bro.
  - However, at this point we are still profiling and optimizing

Future Directions

Future: Understand the bottlenecks

- More realistic setting
  - Running on larger-scale traffic on new hardware
- Concurrent execution is just the start
  - "Just" parallelizing execution does not necessarily yield the perfect speed-up
- Extensive profiling and optimization
  - CPU usage
  - Impact of the memory hierarchy
  - Explore different scheduling strategies
- Evaluation on different hardware platforms
  - Potentially using simulators to explore a wide variety of options
- Speeding-up the packet dispatcher:
  - In contact with a vendor of a NIC that directly schedules packets to threads

Future: Automate the Scoping

- Scopes are assigned manually in our prototype
  - Not ideal, as it's not completely transparent to the user
- We believe that Bro could infer scopes automatcially
  - Static and dynamic analysis of access patterns

- Scoping rules require minor script modifications
- Likewise, Bro could rewrite code internally
  - For example, auto-split event handlers

Future: An Abstract Machine

- In a initially independent project, we are building an abstract machine for network traffic analysis
  - Instruction set with domain-specific support for typical operations
  - Compiler to turn it into highly efficient native code
- The abstract machine will also provide a concurrency abstraction that fits well with the scoping model
  - Eventually, Bro scripts will be compiled into this execution model which is much better suited for concurrent execution than the Bro C++ code.

Summary

- We are building a highly-concurrent NIDS
  - Based on the open-source Bro NIDS
- Designed concurrency models for its main components
  - Packet analysis, based on pure per-flow analysis, no state correlation
  - Detection logic, based on scheduling scopes corresponding to processing units
  - Leveraging domain-specific knowledge for parallelization
- Simulations and the Cluster predict excellent performance
- Prototype ready for intensive profiling now
  - Analyzing real-world performance, in particular memory effects
- Optimistic that multi-core Bro will eventually be able to scale to a large number of cores in production environments

Thanks for your attention.

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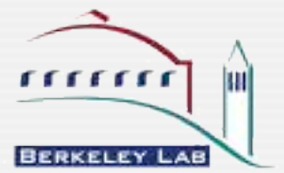
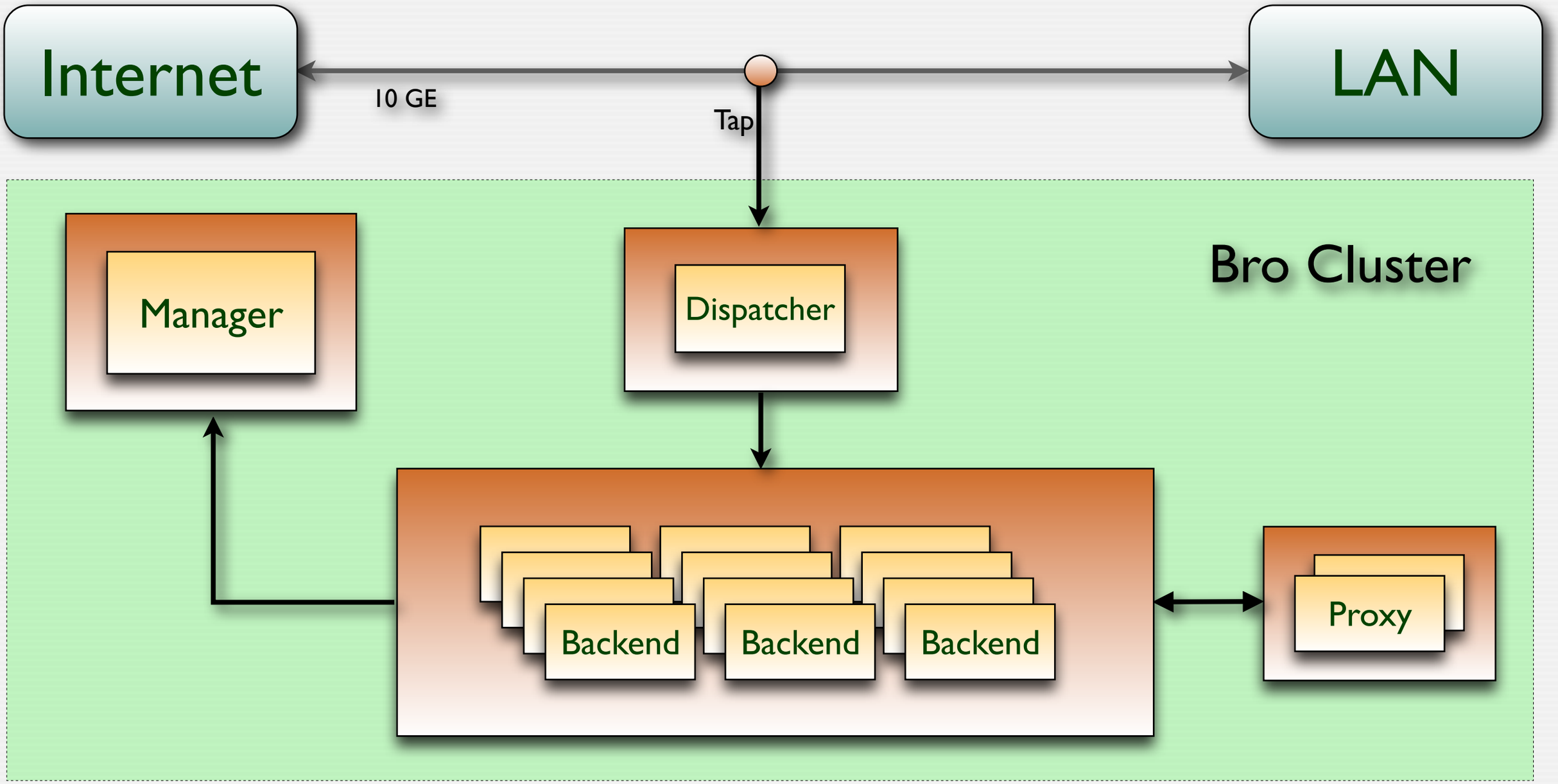


Backup Slides

Bro Cluster Architecture



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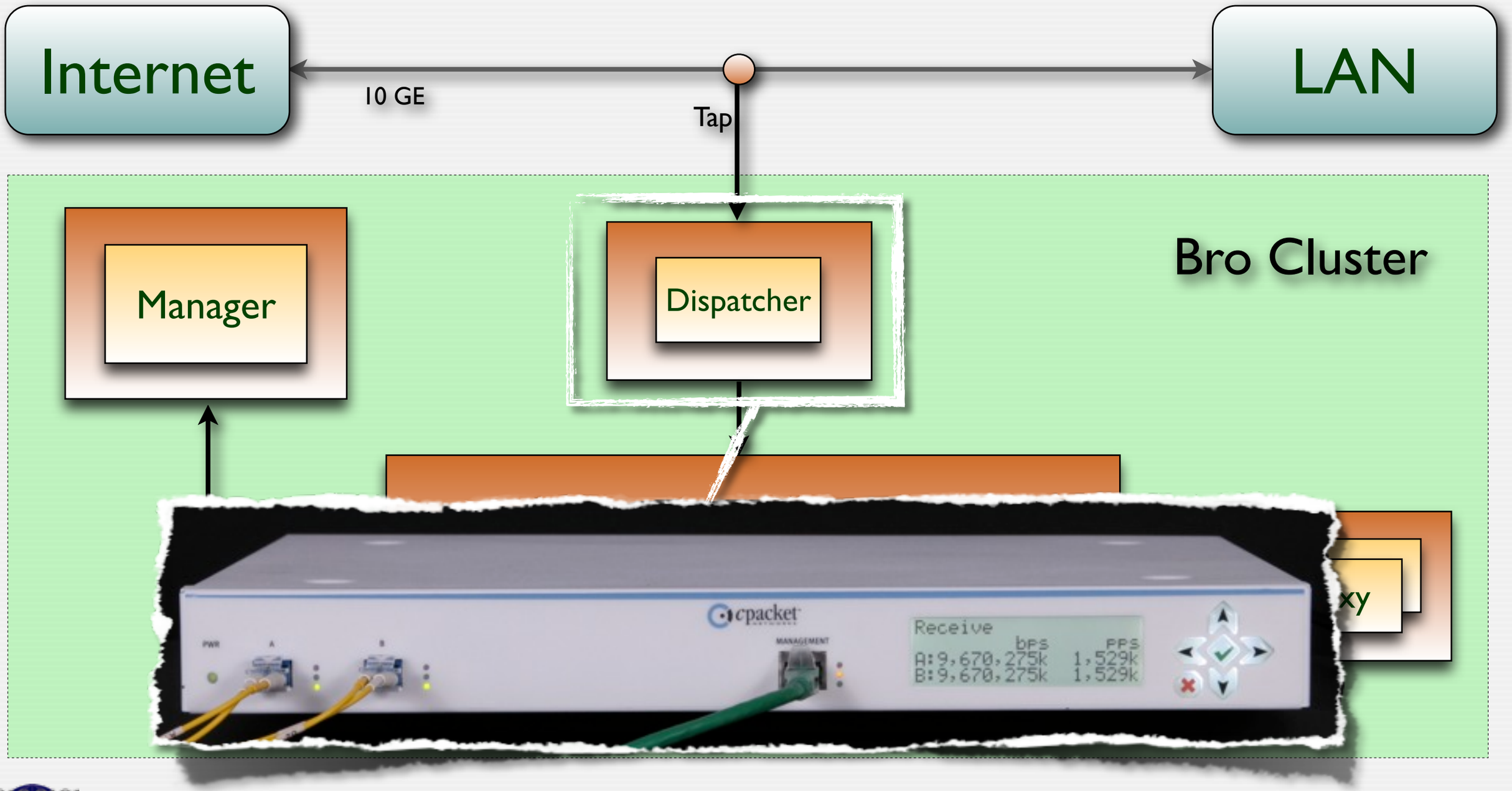
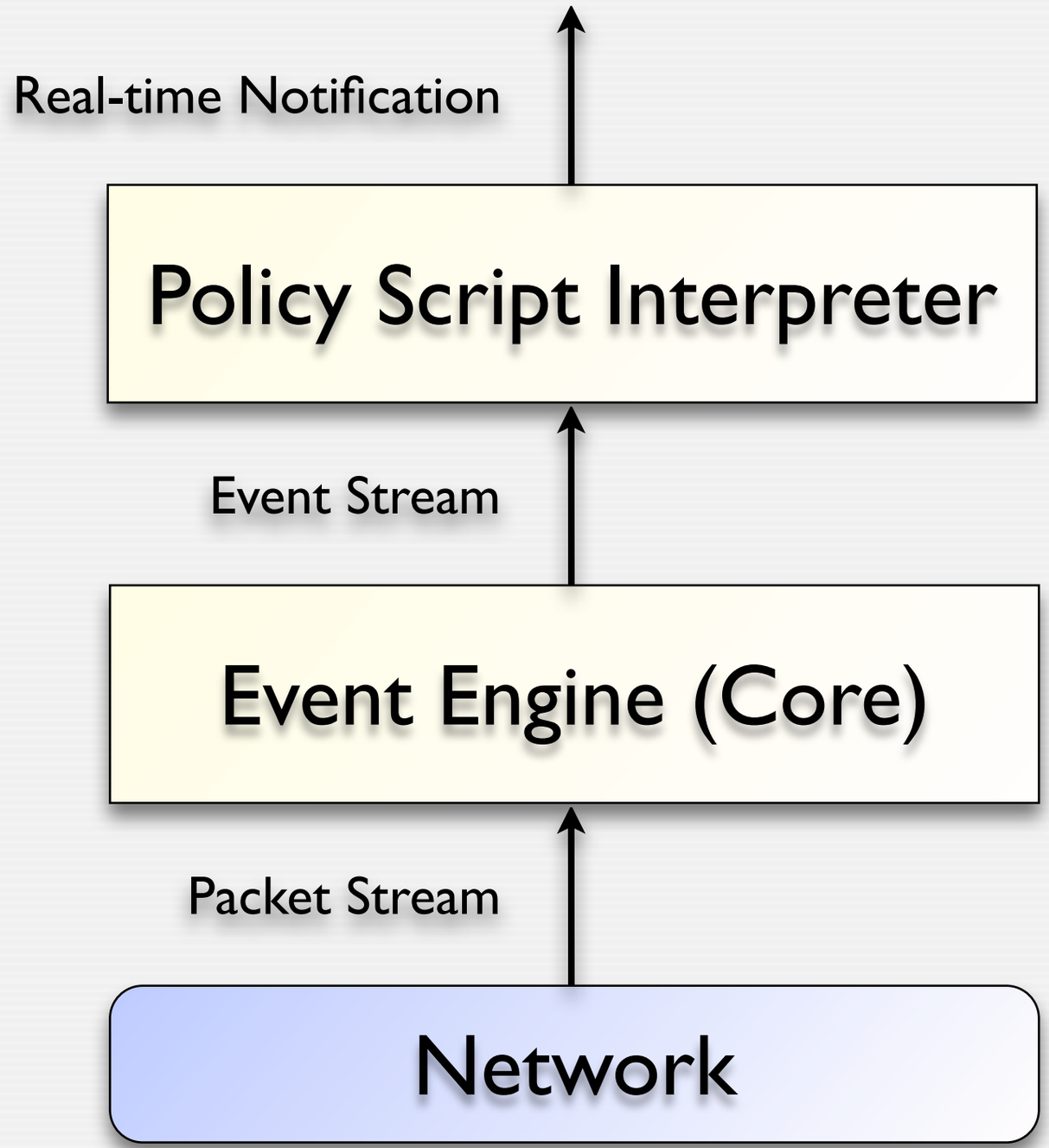


10GE line-rate load-balancer

Event Model - Example



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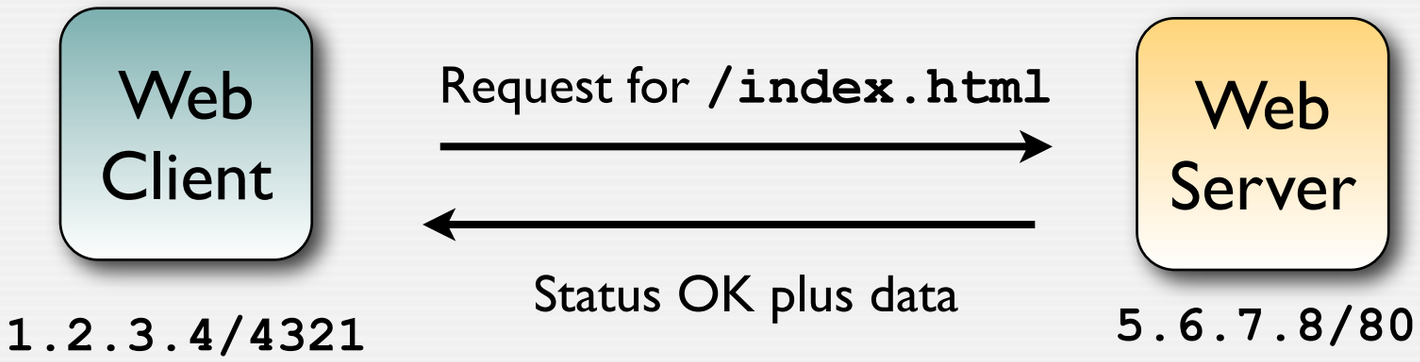

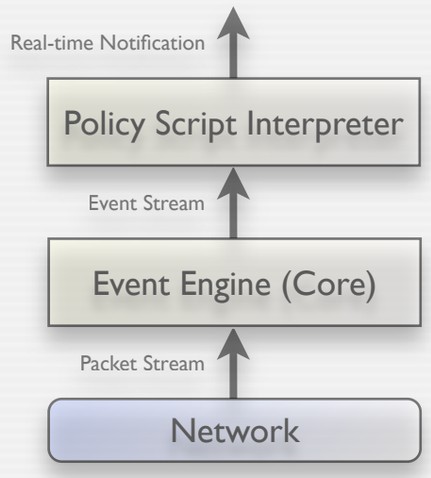

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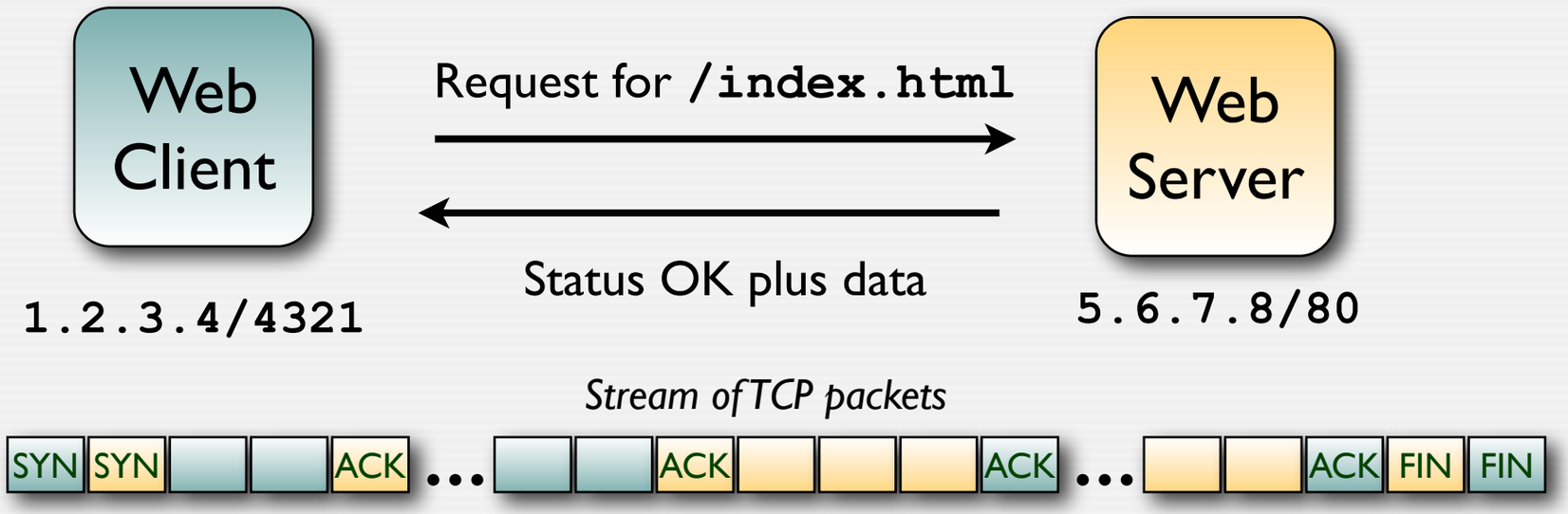
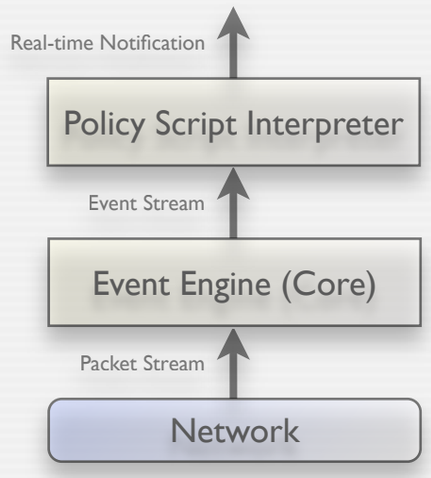
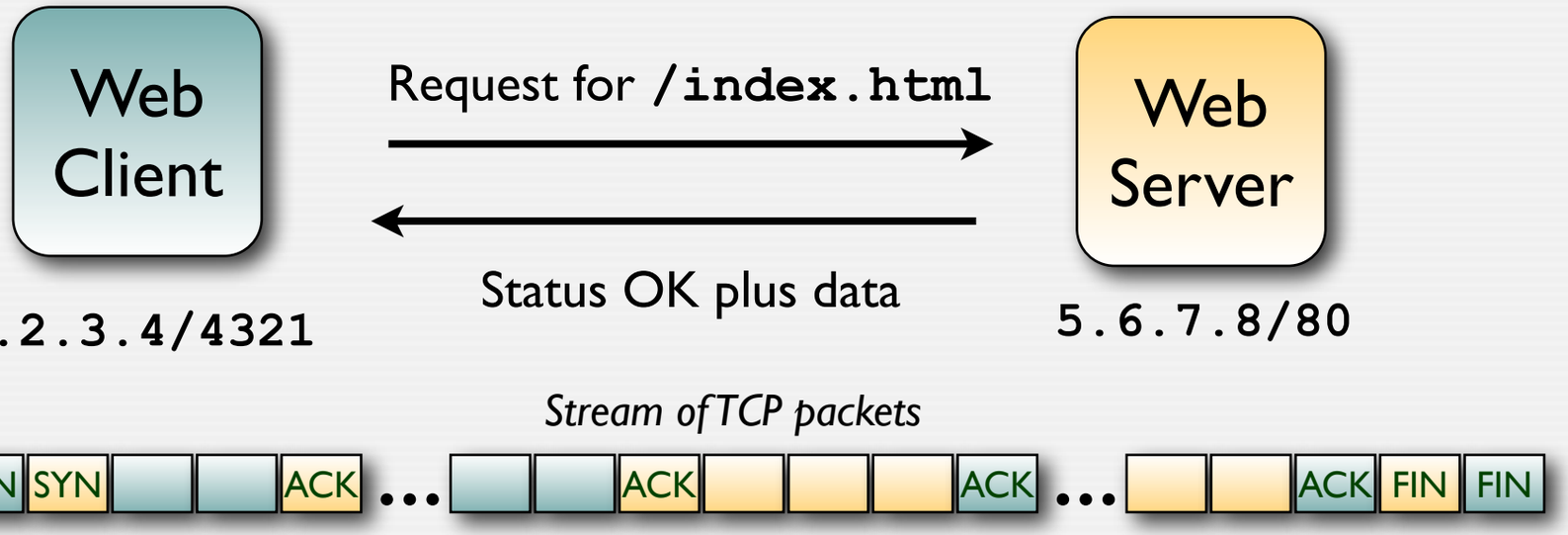
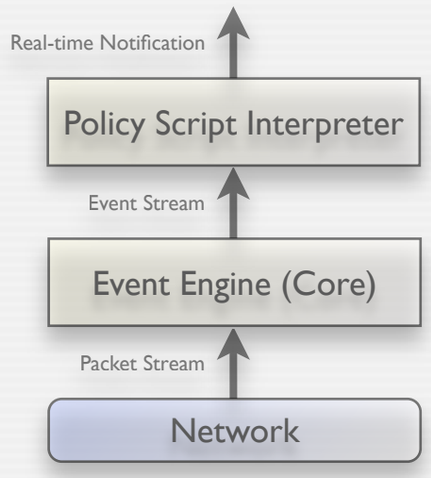


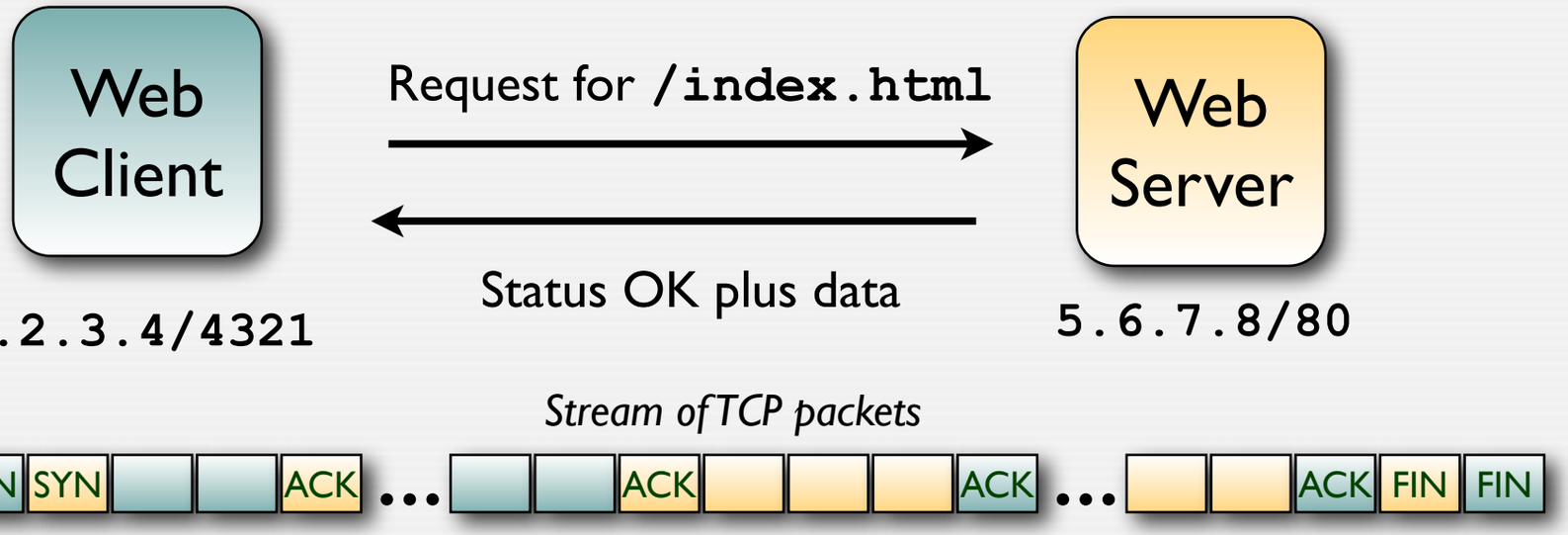


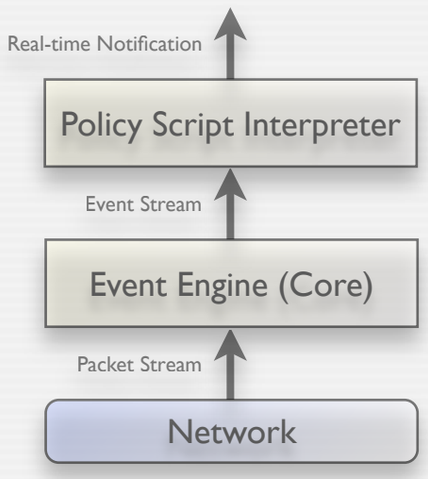
Event Model - Example



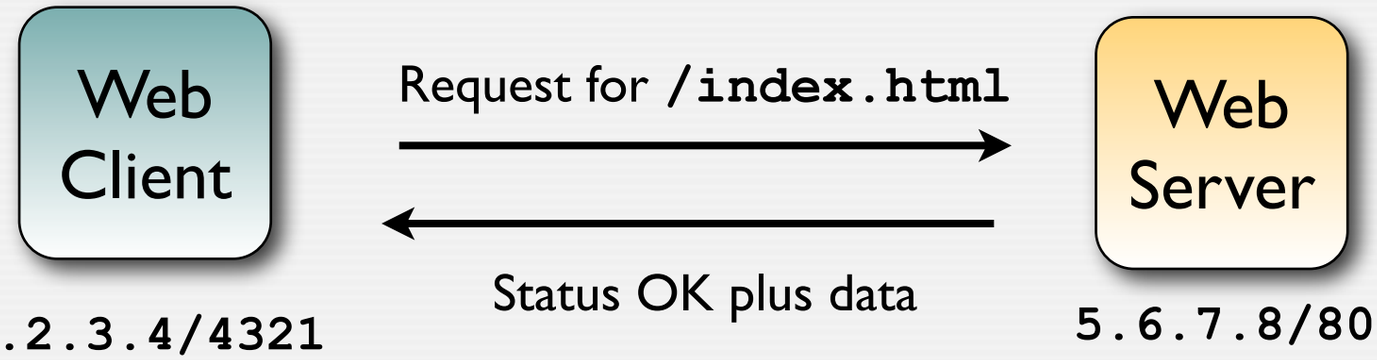


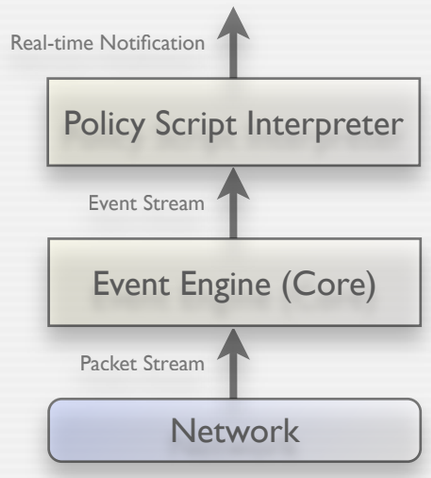
Event Model - Example





Event Model - Example





Stream of TCP packets

Event → `connection_established(1.2.3.4/4321⇒5.6.7.8/80)`

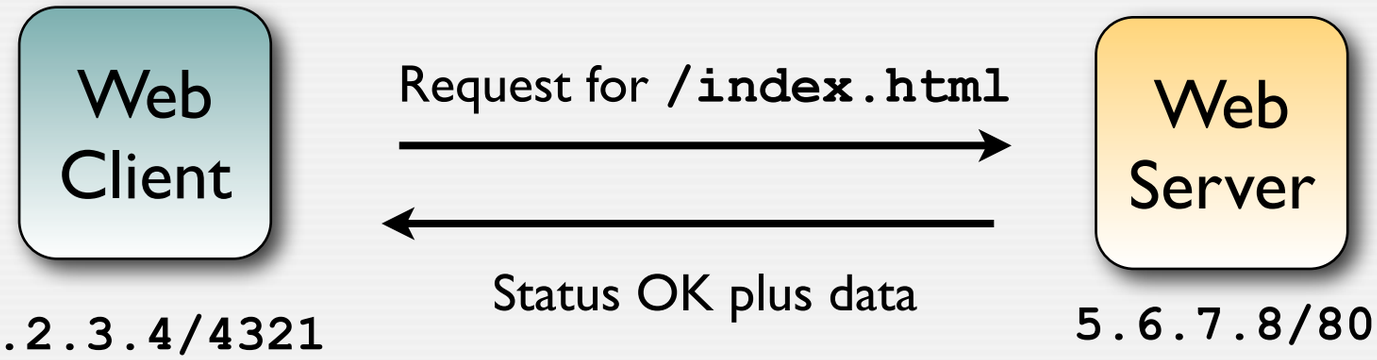
TCP stream reassembly for originator

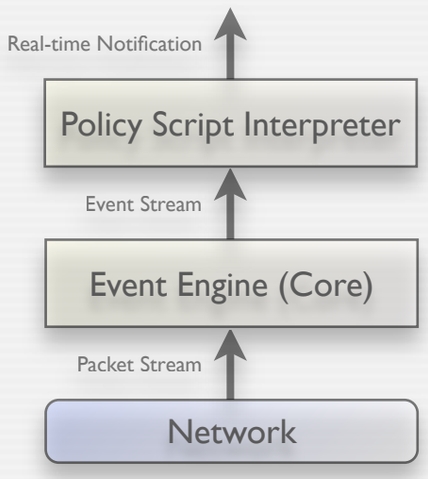
Event → `http_request(1.2.3.4/4321⇒5.6.7.8/80, "GET", "/index.html")`

TCP stream reassembly for responder

Event → `http_reply(1.2.3.4/4321⇒5.6.7.8/80, 200, "OK", data)`

Event Model - Example





Stream of TCP packets

Event → `connection_established(1.2.3.4/4321⇒5.6.7.8/80)`

TCP stream reassembly for originator

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TCP stream reassembly for responder

Event → `http_reply(1.2.3.4/4321⇒5.6.7.8/80, 200, "OK", data)`

Event → `connection_finished(1.2.3.4/4321, 5.6.7.8/80)`

Bro's Architecture