Exploiting Multi-Core Processors For Parallelizing Network Intrusion Prevention

Robin Sommer

International Computer Science Institute, &
Lawrence Berkeley National Laboratory

robin@icsi.berkeley.edu
http://www.icir.org

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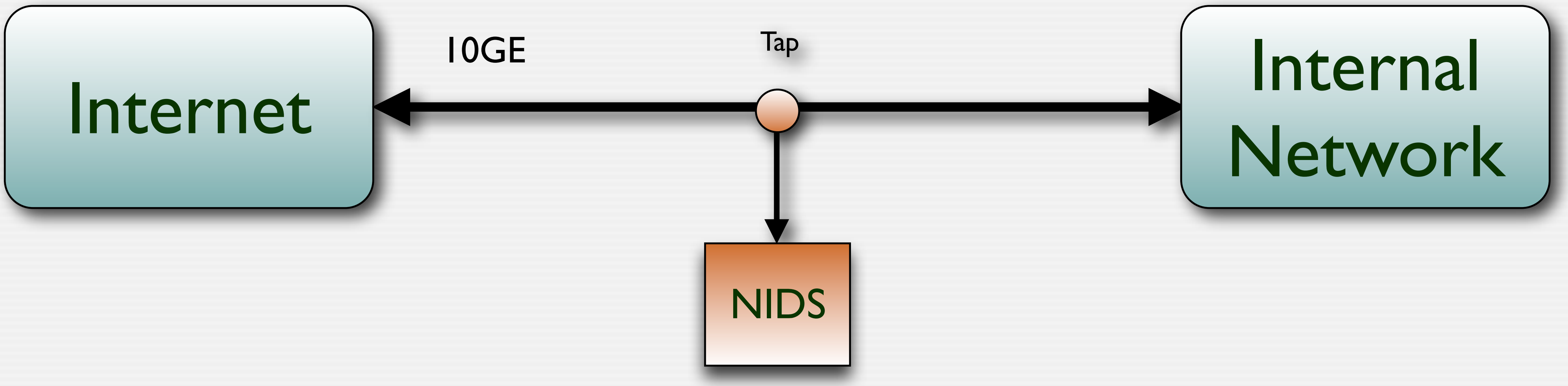
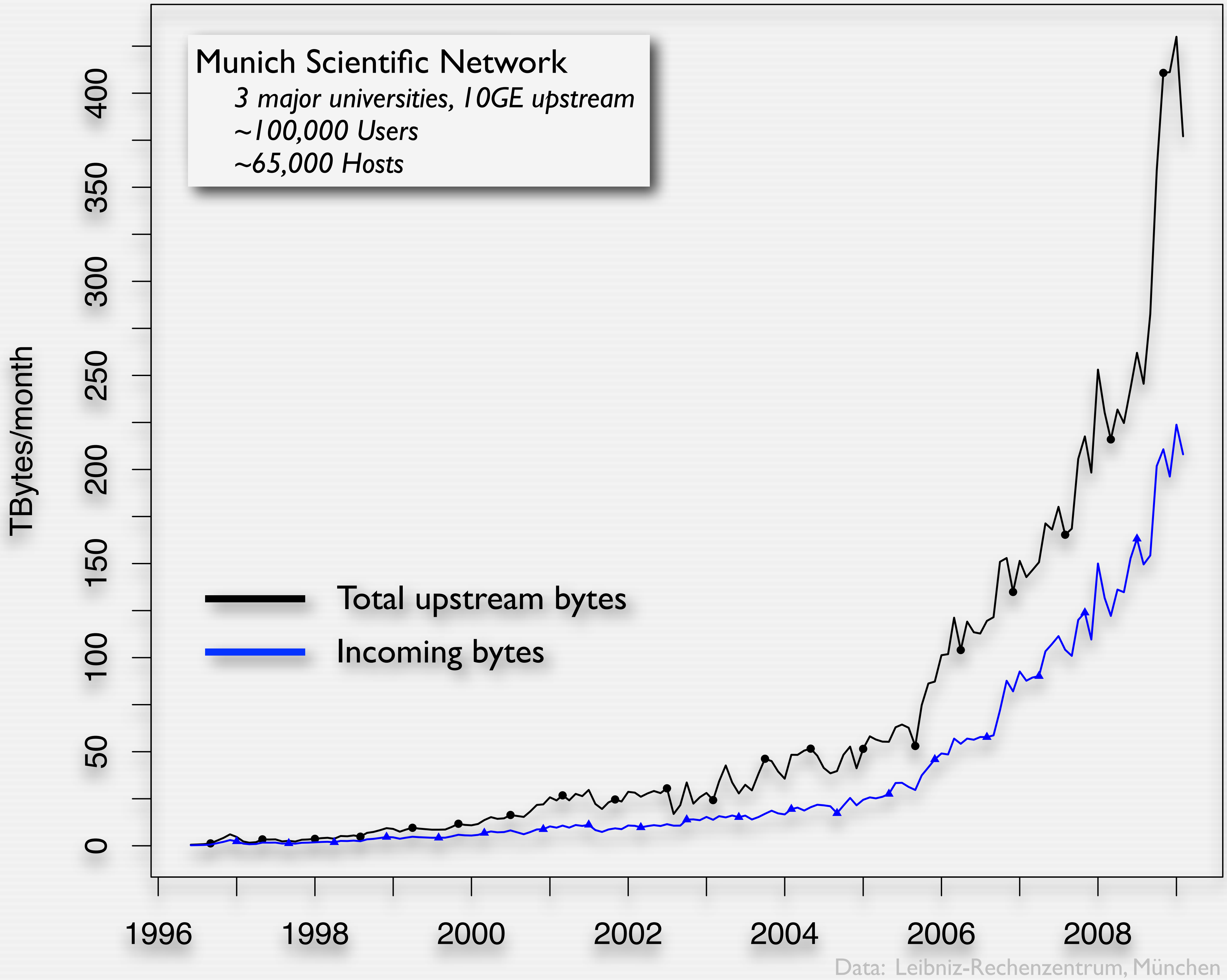
Network Intrusion Detection Systems

- 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



Need for Performance

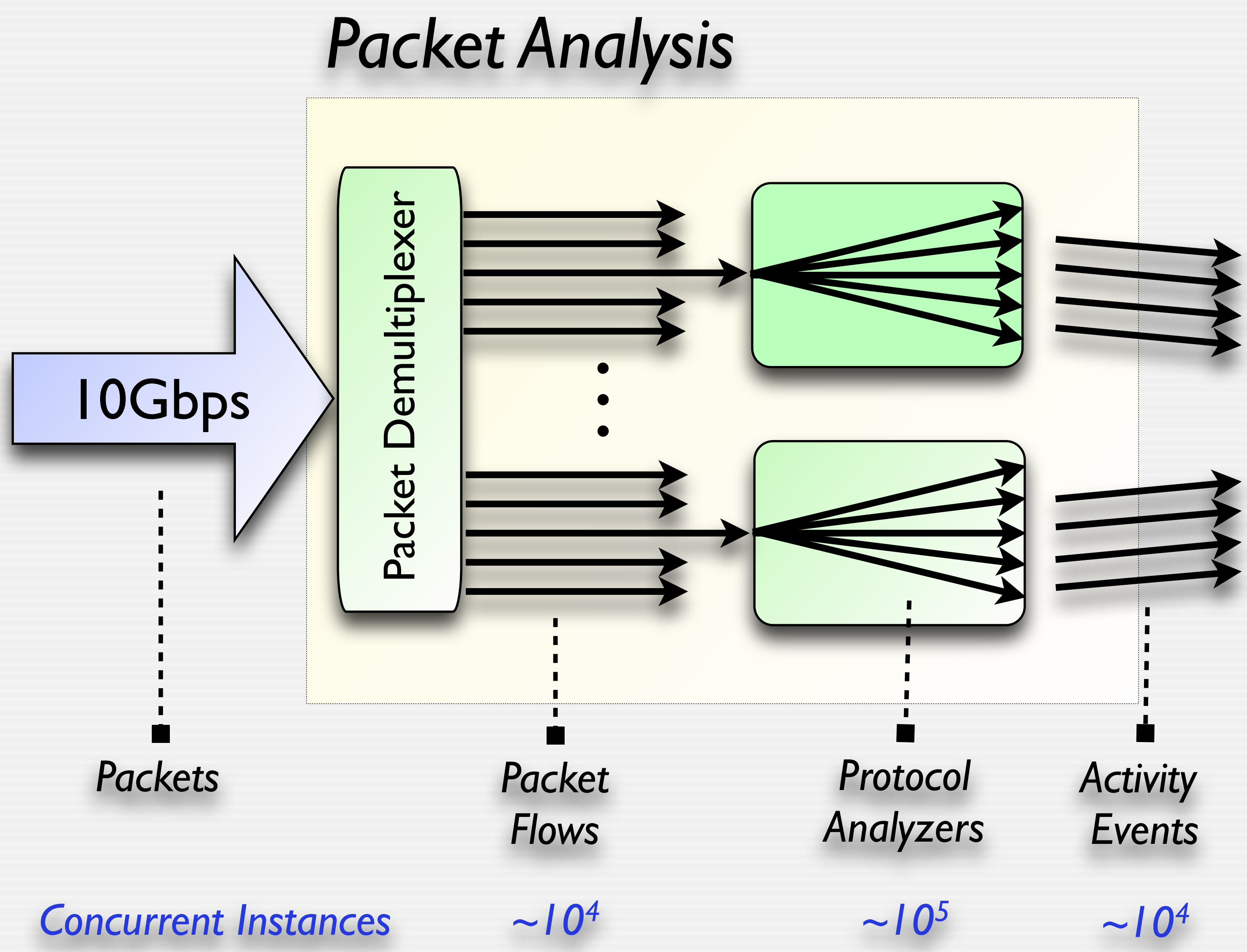
- Keep needing to do *more analysis* on *more data* at *higher speeds*
- NIDS used to run successfully on commodity hardware
  - In particular important for open-source NIDS (e.g., Snort, Bro)
- Not any more!
  - Moore's law doesn't hold for single-core performance anymore
  - Unfortunately, today's NIDS implementations 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 processing 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

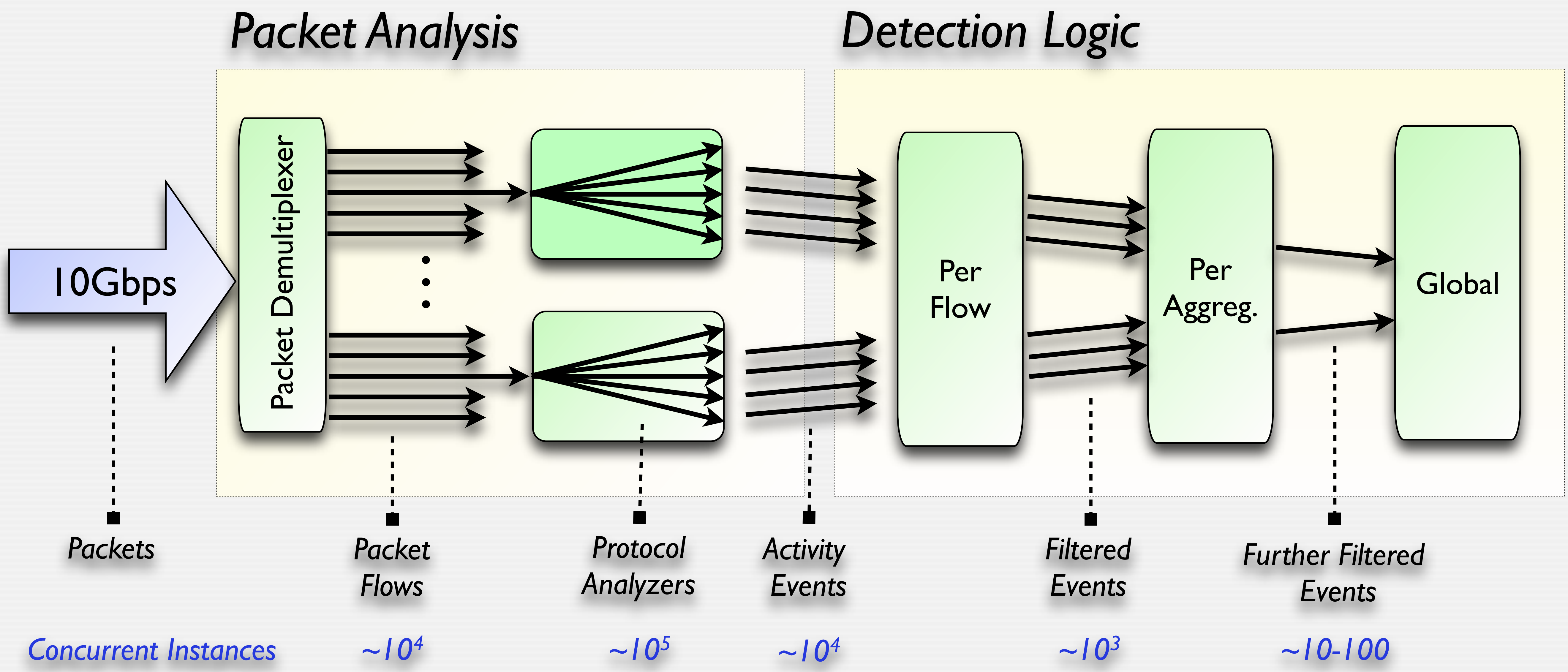
1. *Concurrency Potential in Network Traffic Analysis*
   - A pipeline of highly concurrent stages
2. *Coarse-grained Parallelism: The NIDS Cluster*
   - A load-balancing solution
3. *Fine-grained Parallelism: Building a multi-threaded NIDS*
   - Turning a traditional NIDS into a highly concurrent system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

Concurrency Potential in Network Traffic Analysis

Traffic Analysis Pipeline



Traffic Analysis Pipeline



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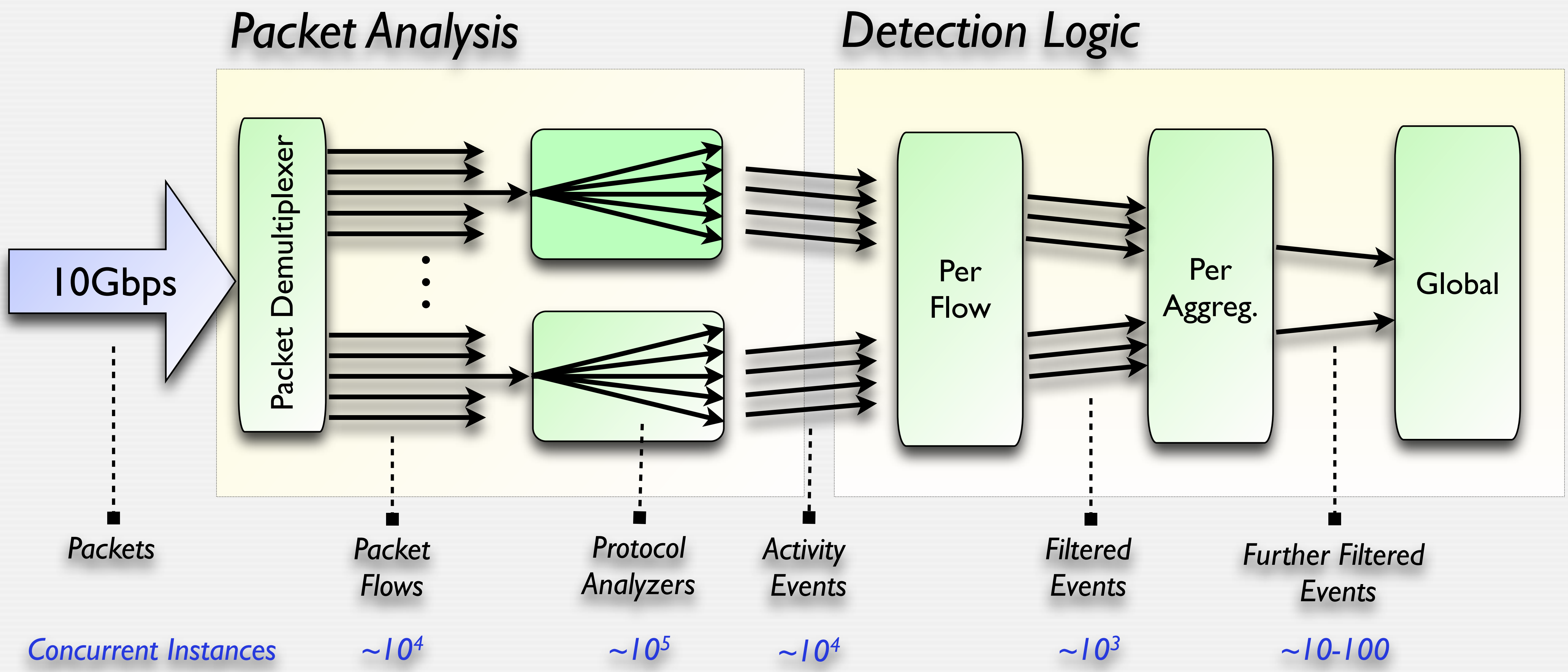

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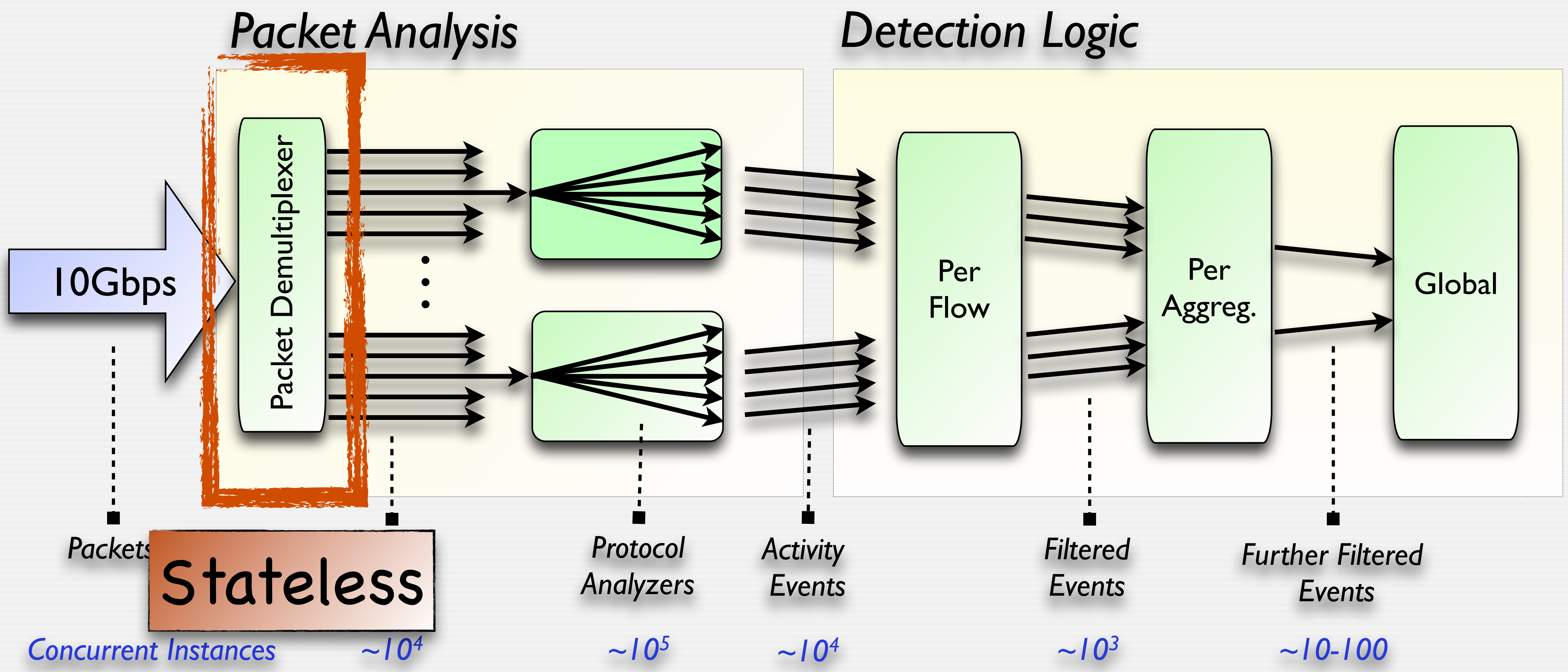

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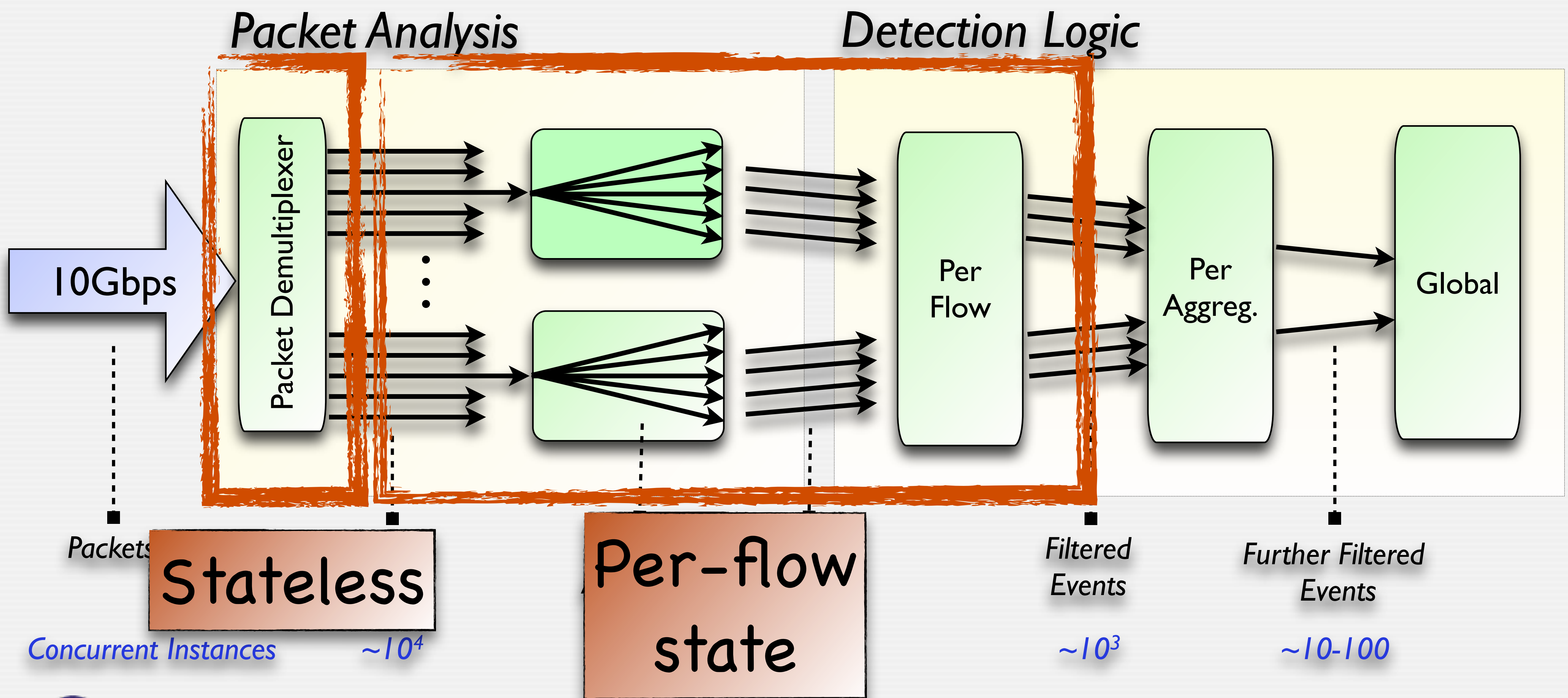

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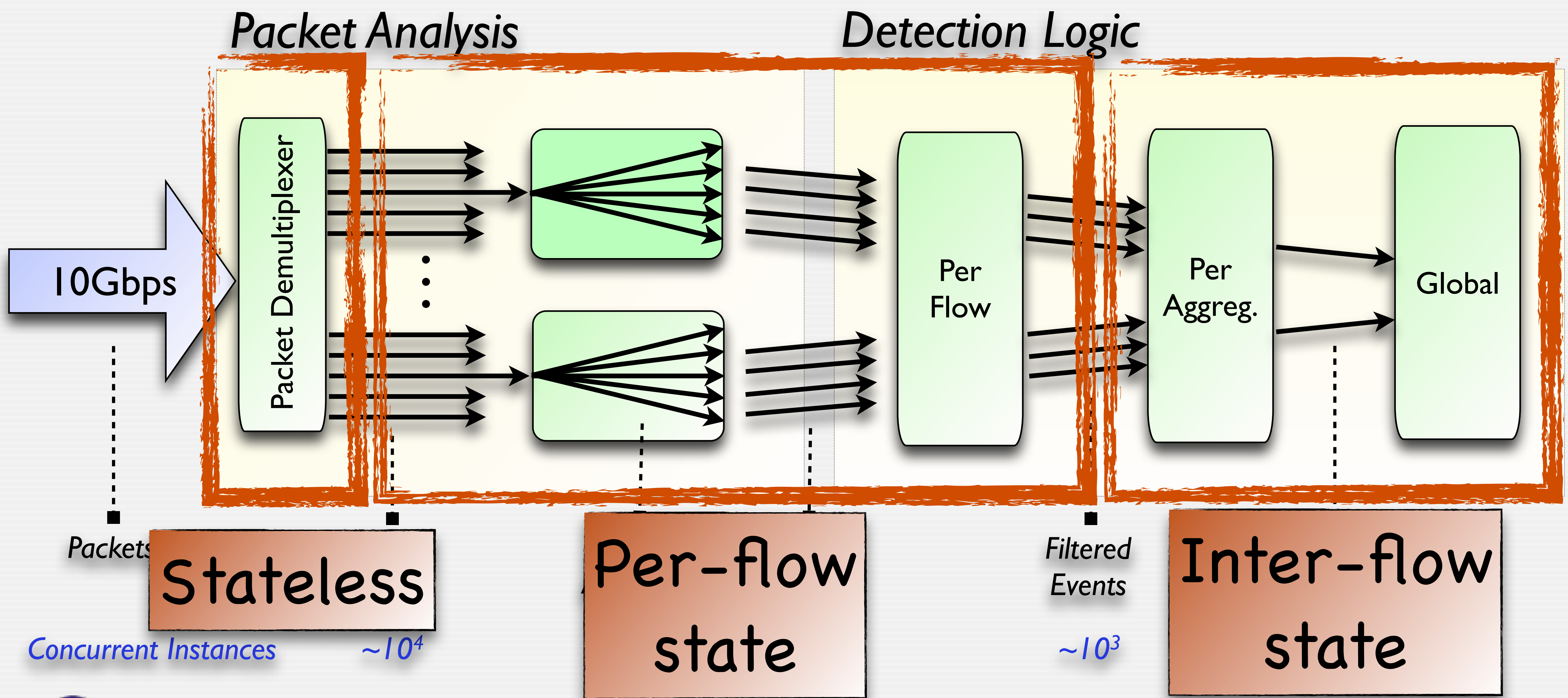
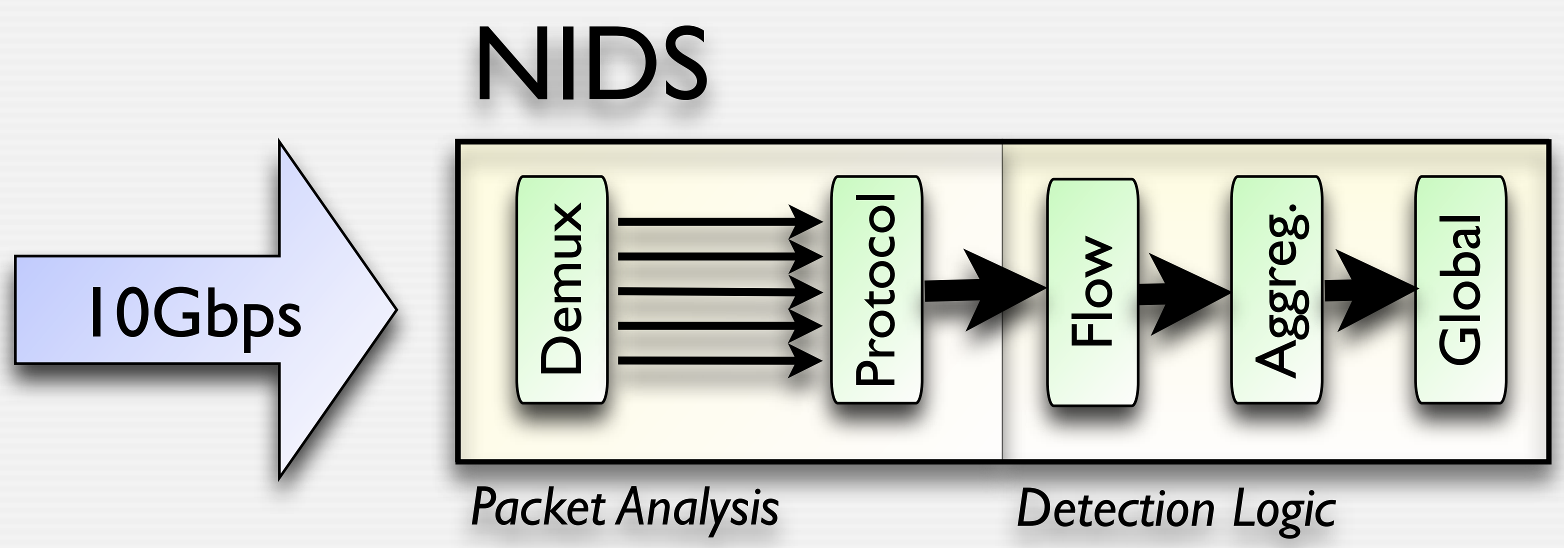


Building a Concurrent NIDS

- 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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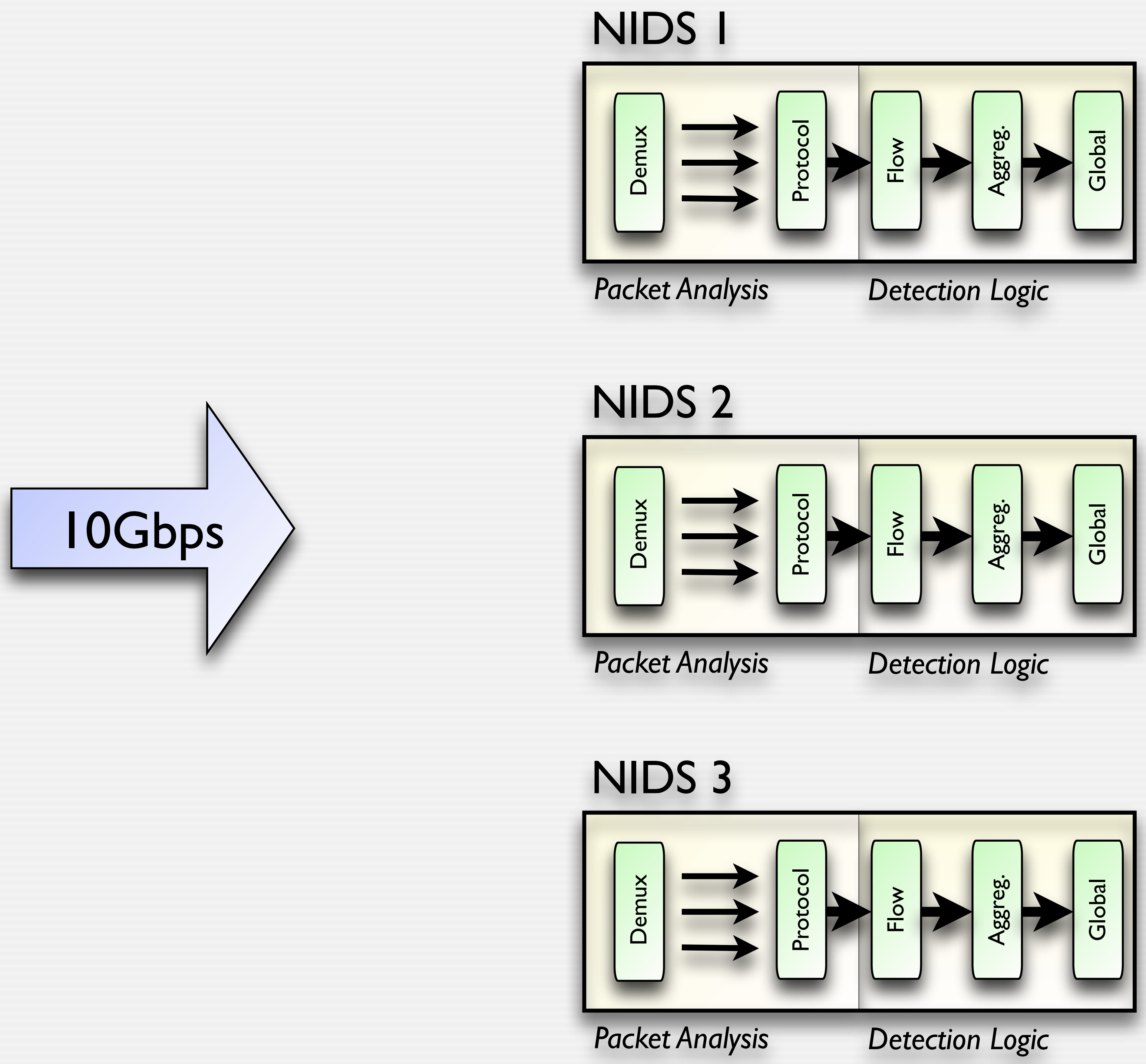

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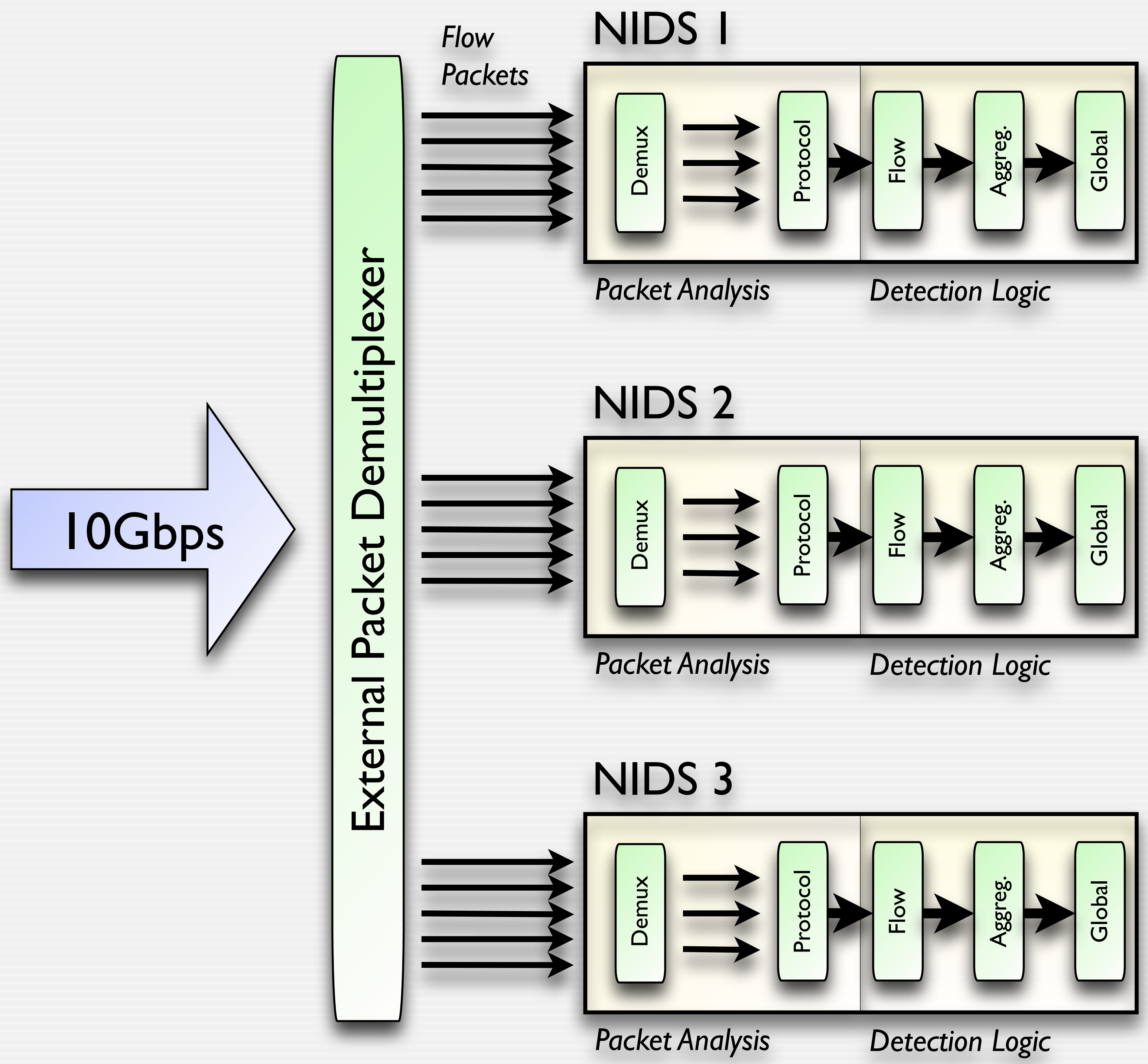

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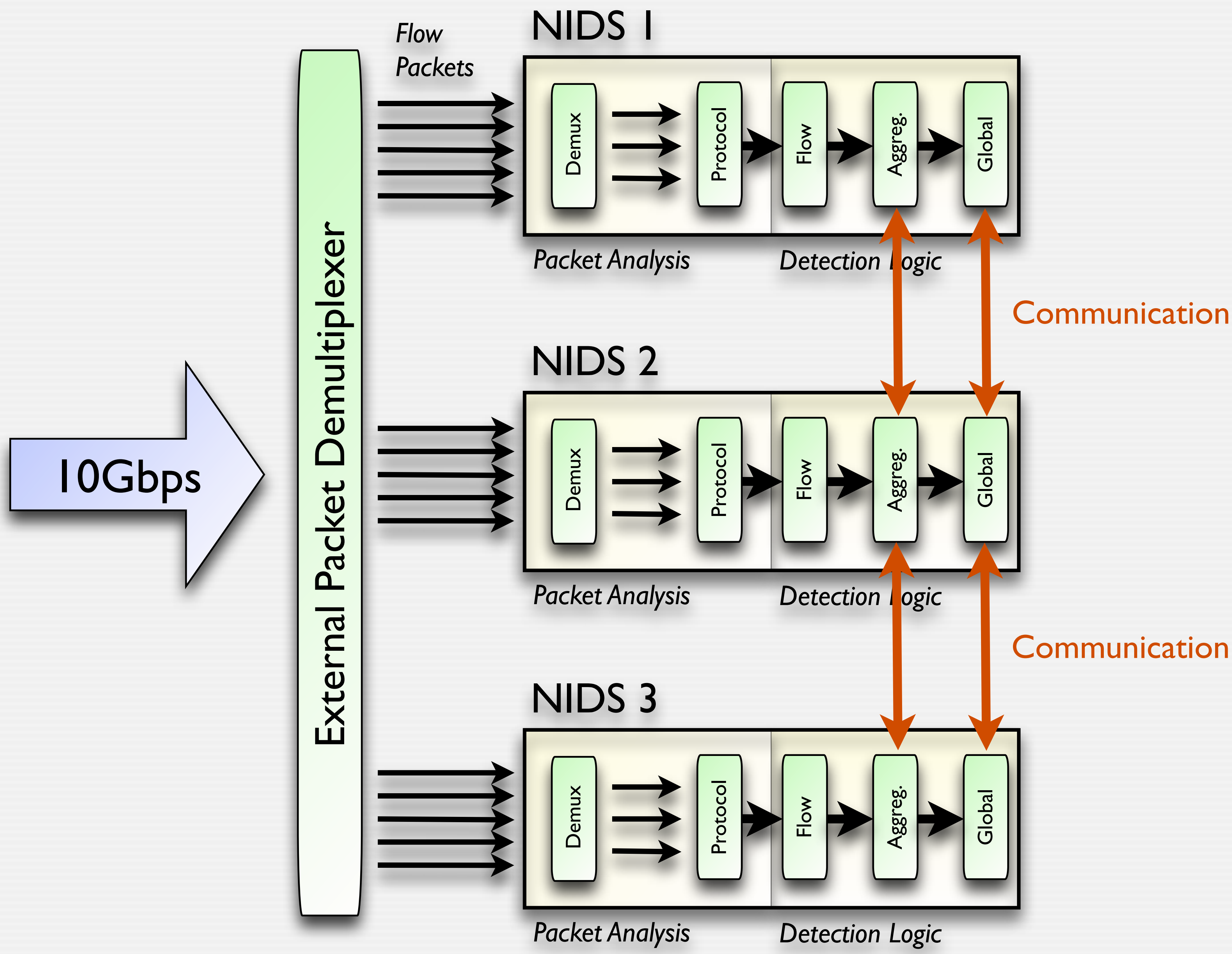


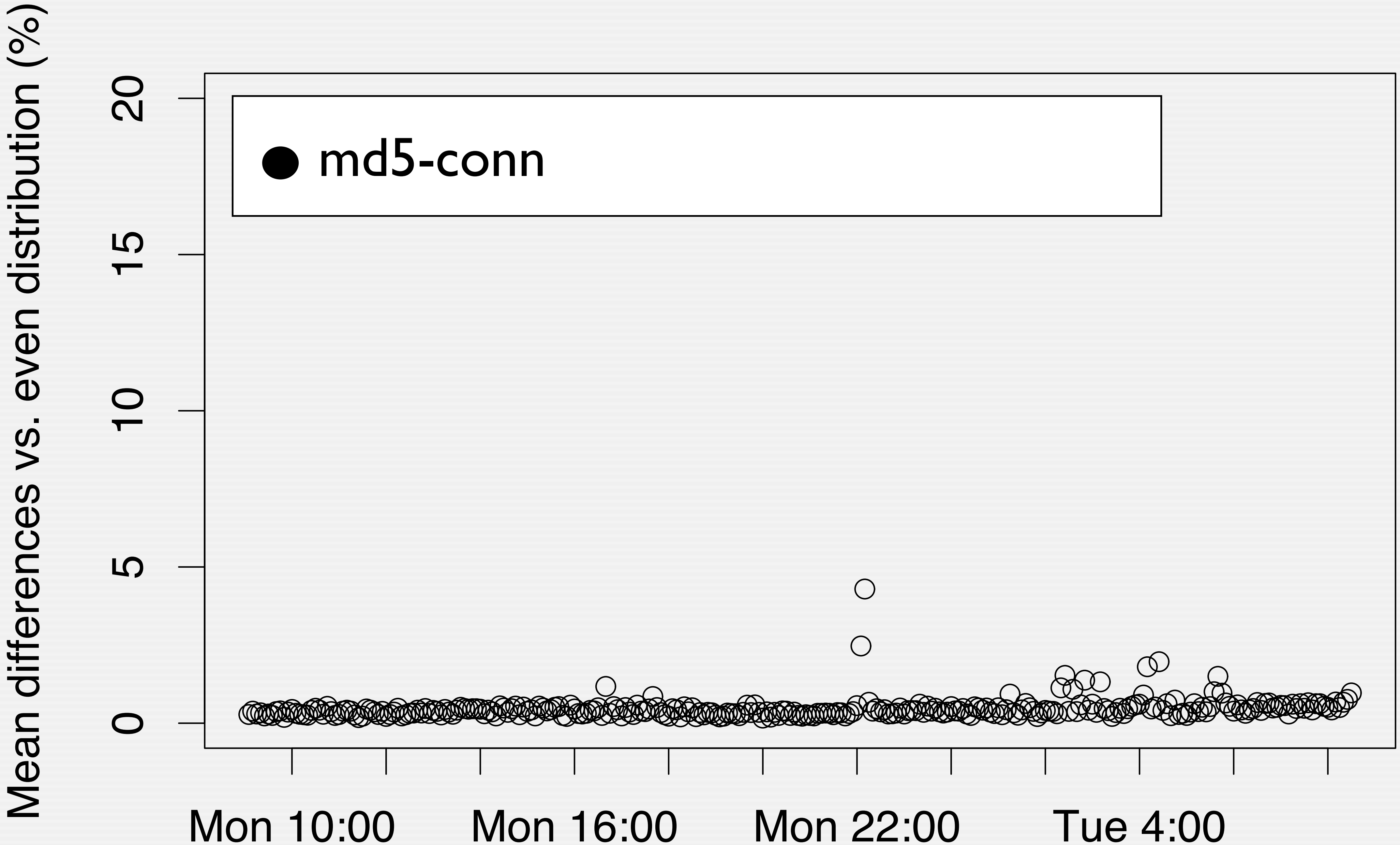
The Bro Cluster

- 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 w/ 10 NIDS machines (backends)
  - Operational cluster at LBNL w/ 15 NIDS, replacing Labs' security monitoring
  - Other sites are running, or planing to run, similar setups
  - Planing much larger research cluster on the Berkeley campus

External Packet Dispatcher

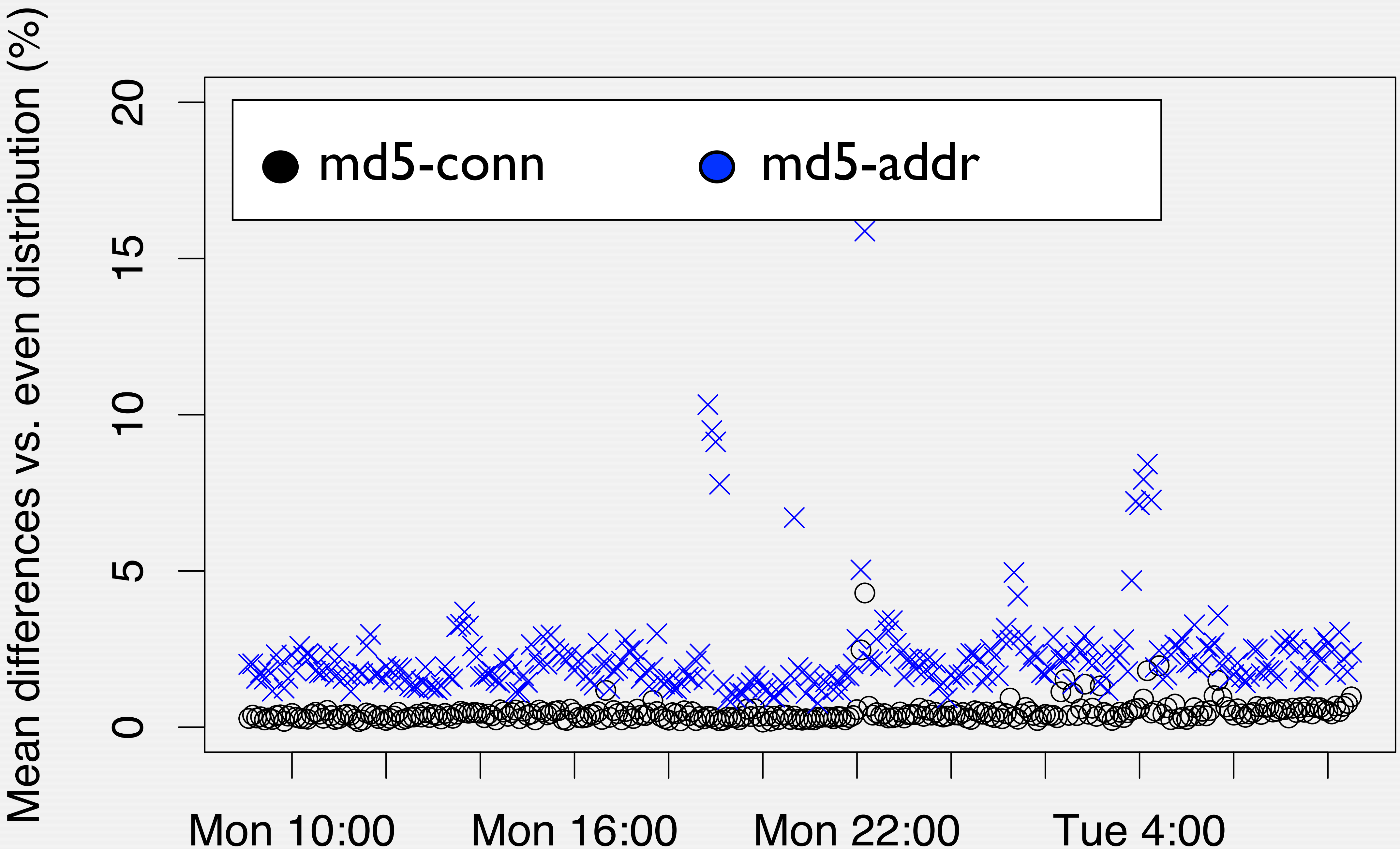
- How to decide where to send a packet?
- We want the dispatcher to
  - Keep flows together
  - Be simple and stateless for implementation in hardware
- Observation: Each packet contains a flow identifier
  - 4-tuple of IP addresses and TCP/UDP port numbers
- Dispatcher can calculate hash over the 4-tuple
  - `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

Simulation of Packet Dispatcher



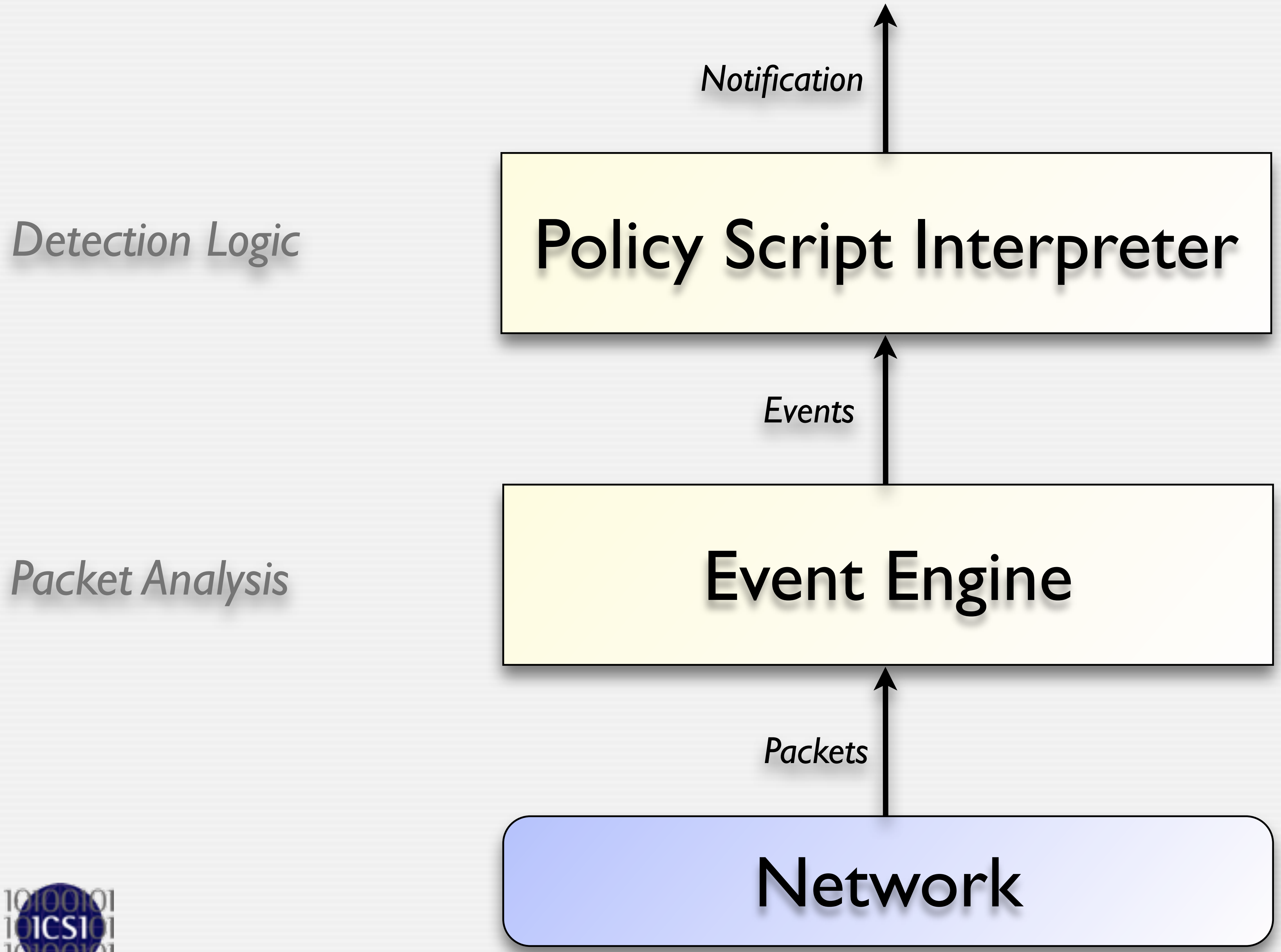
`1 day of UC Berkeley campus TCP traffic (231M connections), n = 10`

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
- Main objective is doing that *transparently:*
  - Do not expose parallel processing to the operator
  - But parallelize internally “under the hood”

Bro's Architecture



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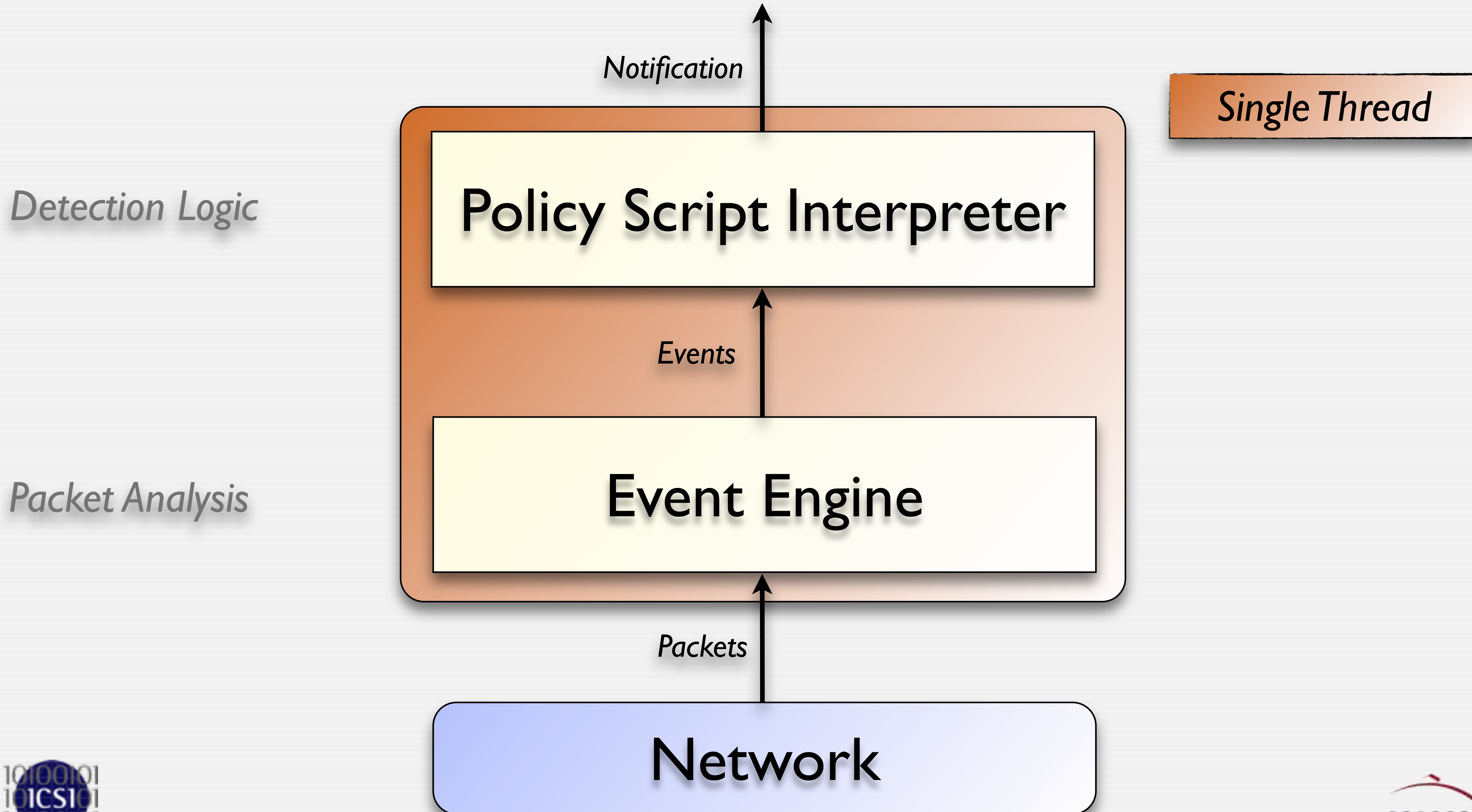

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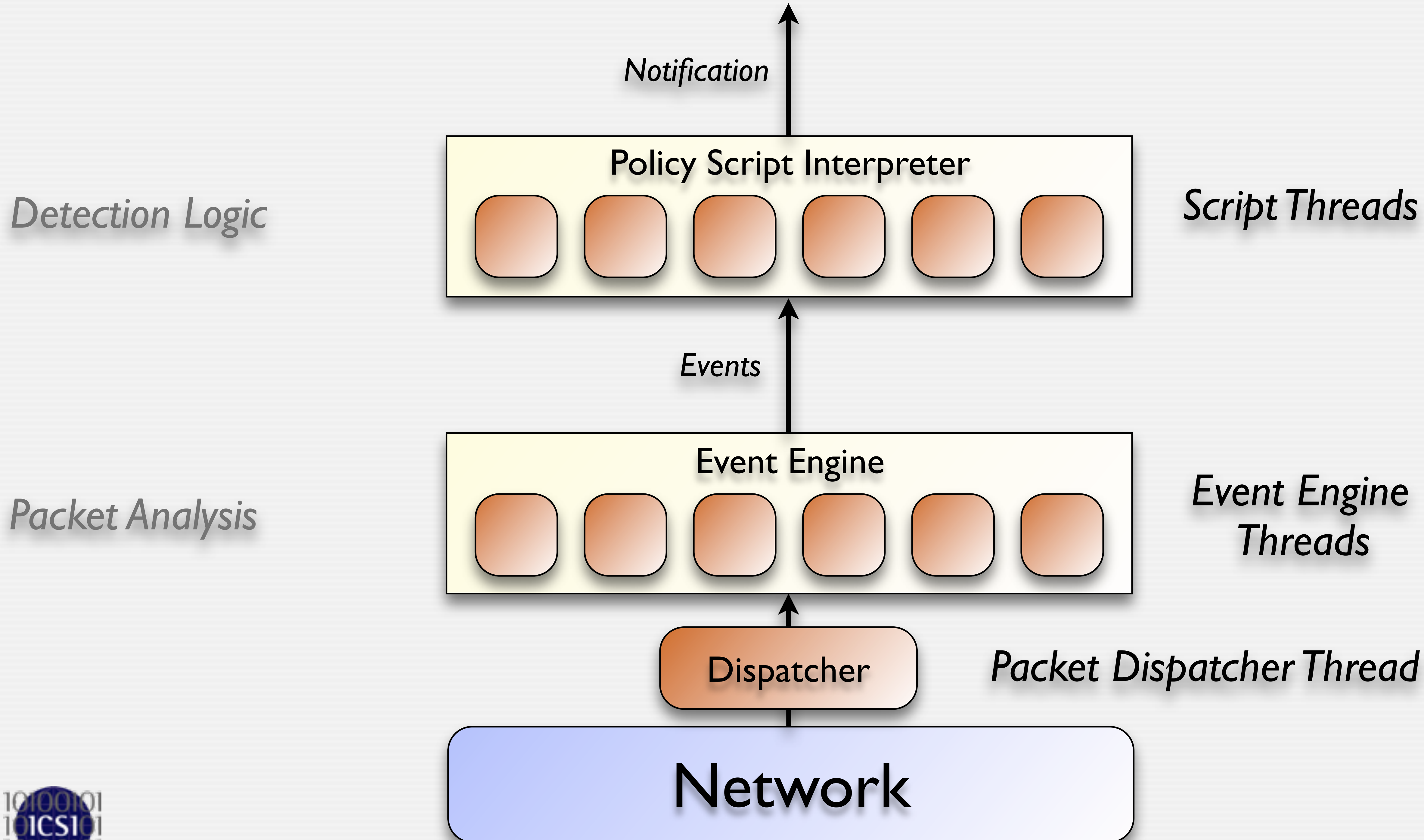
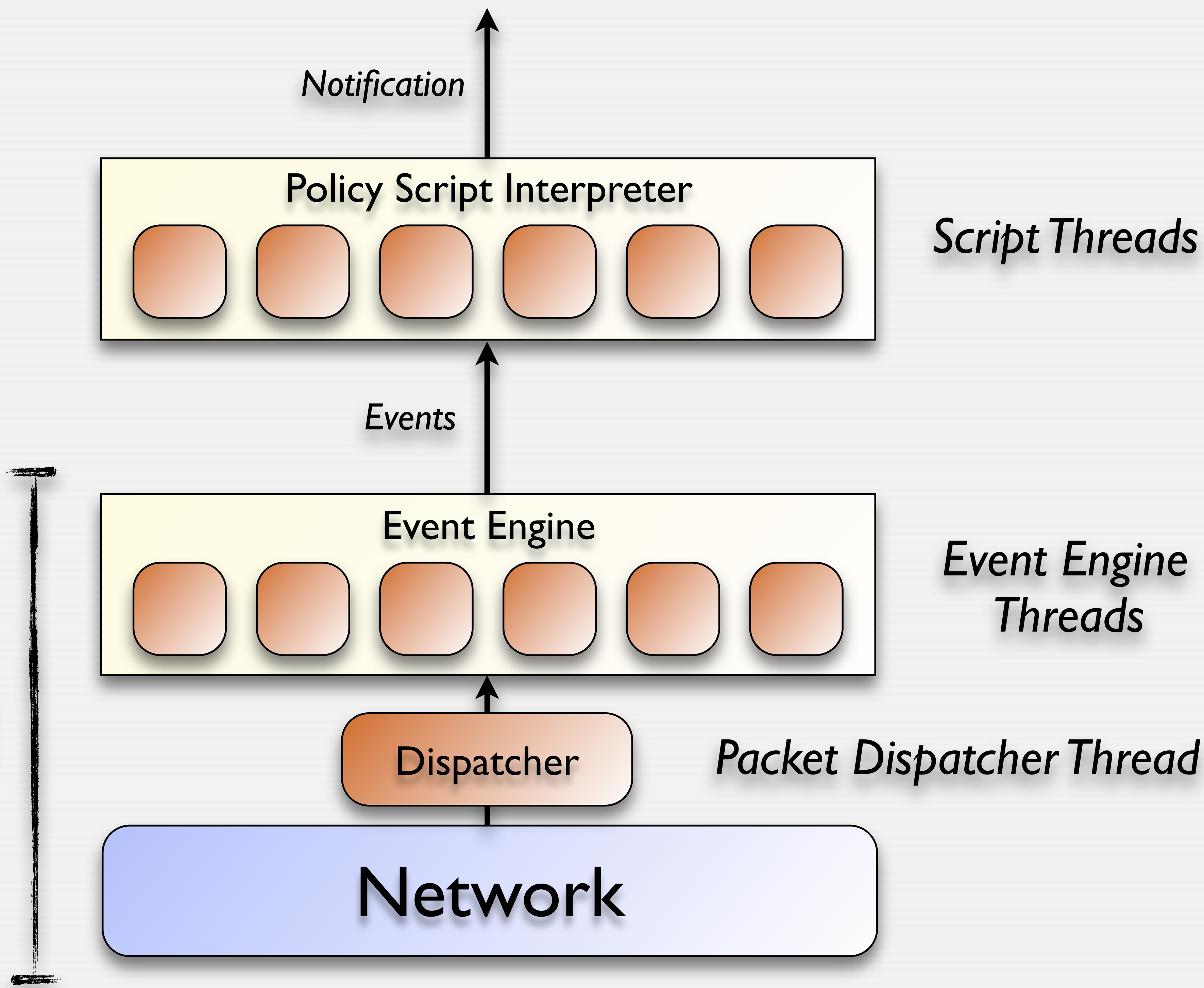


Bro's Architecture

Detection Logic

Packet Analysis

"Cluster in a Box"



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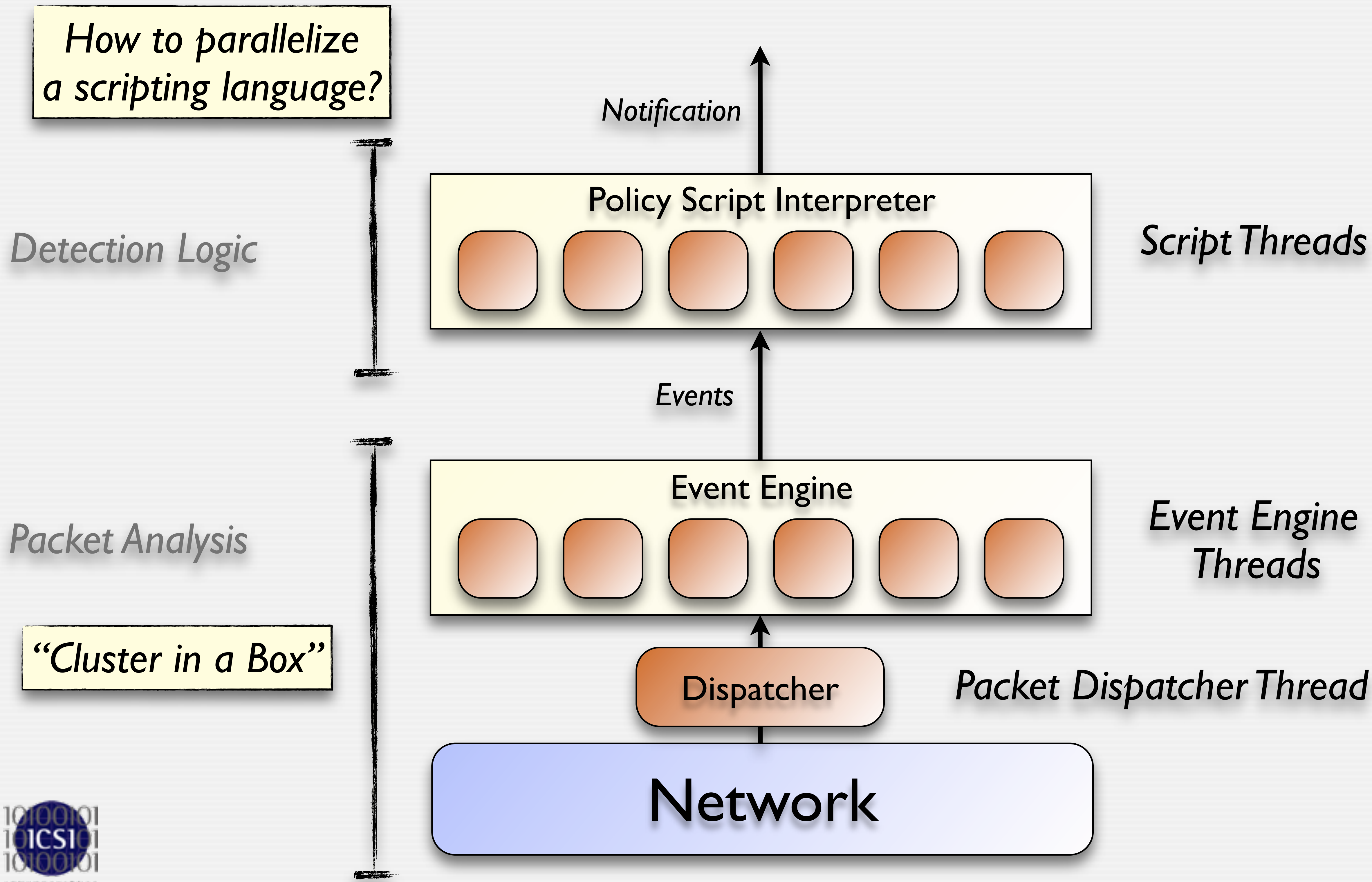


Script Example: Matching URLs

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.)

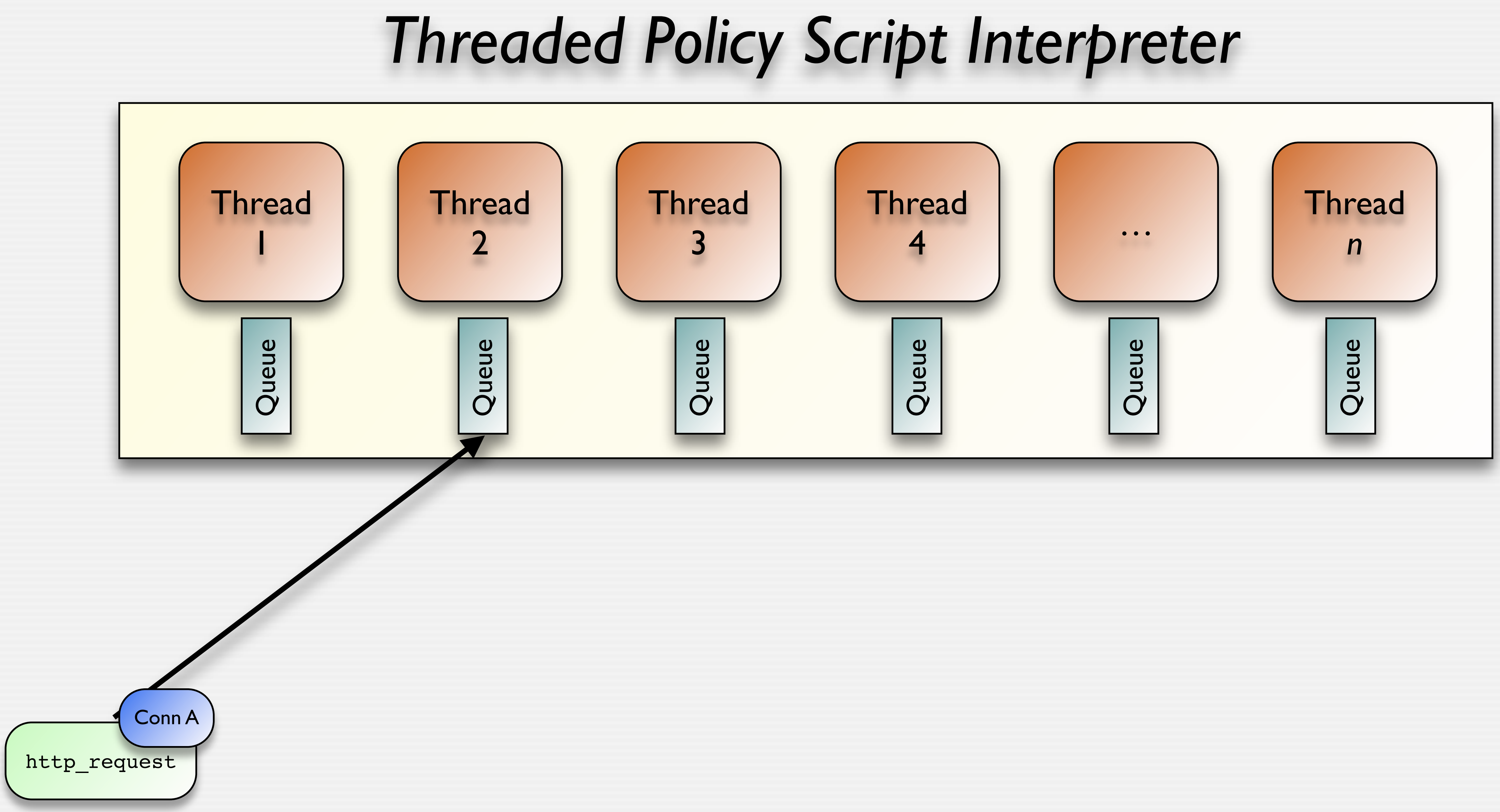
“Scheduling Scopes”

- 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

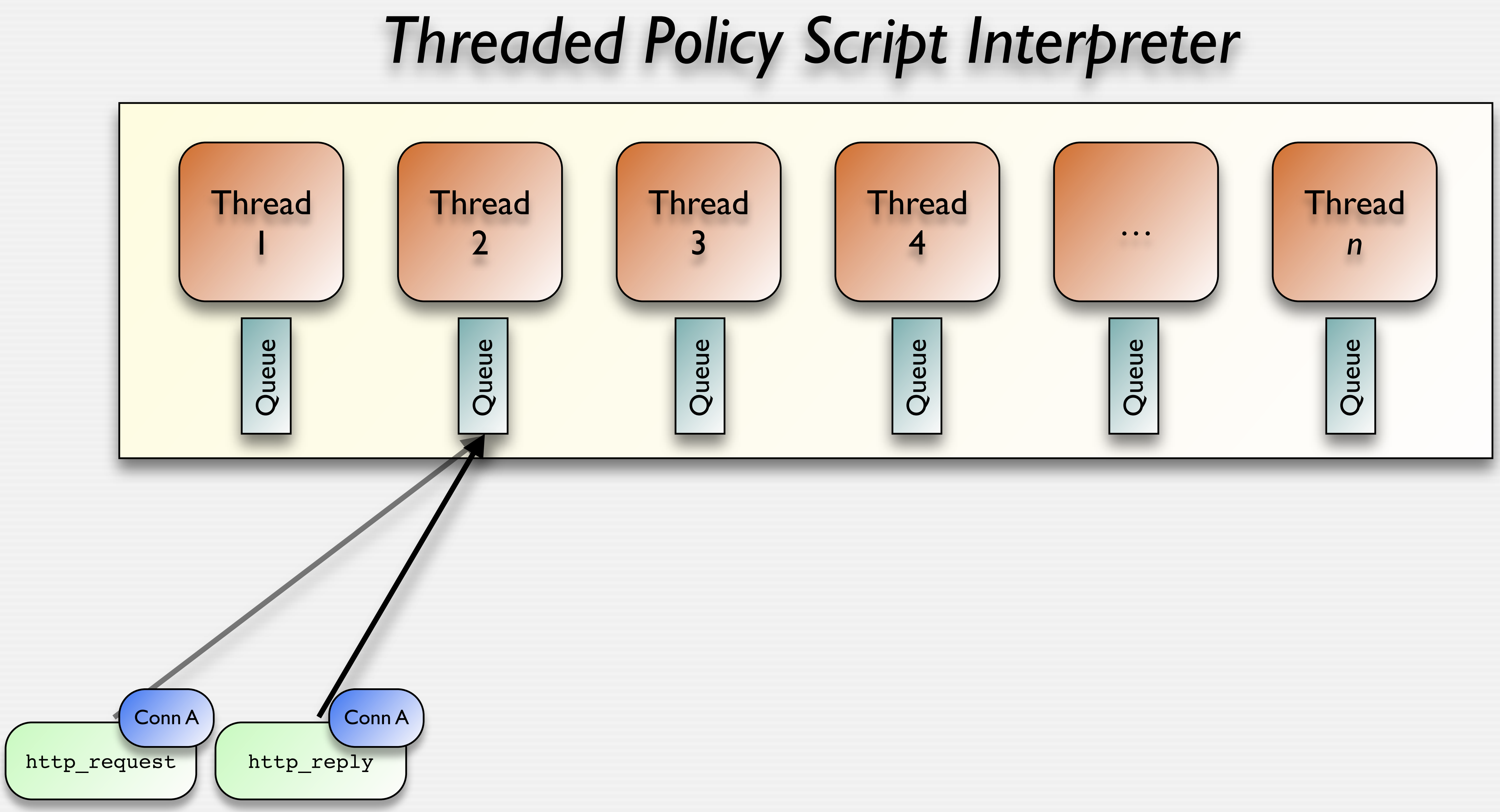
```
global potentially_sensitive: table[connection] of string
   &scope=connection;

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

Parallel Event Scheduling



Parallel Event Scheduling



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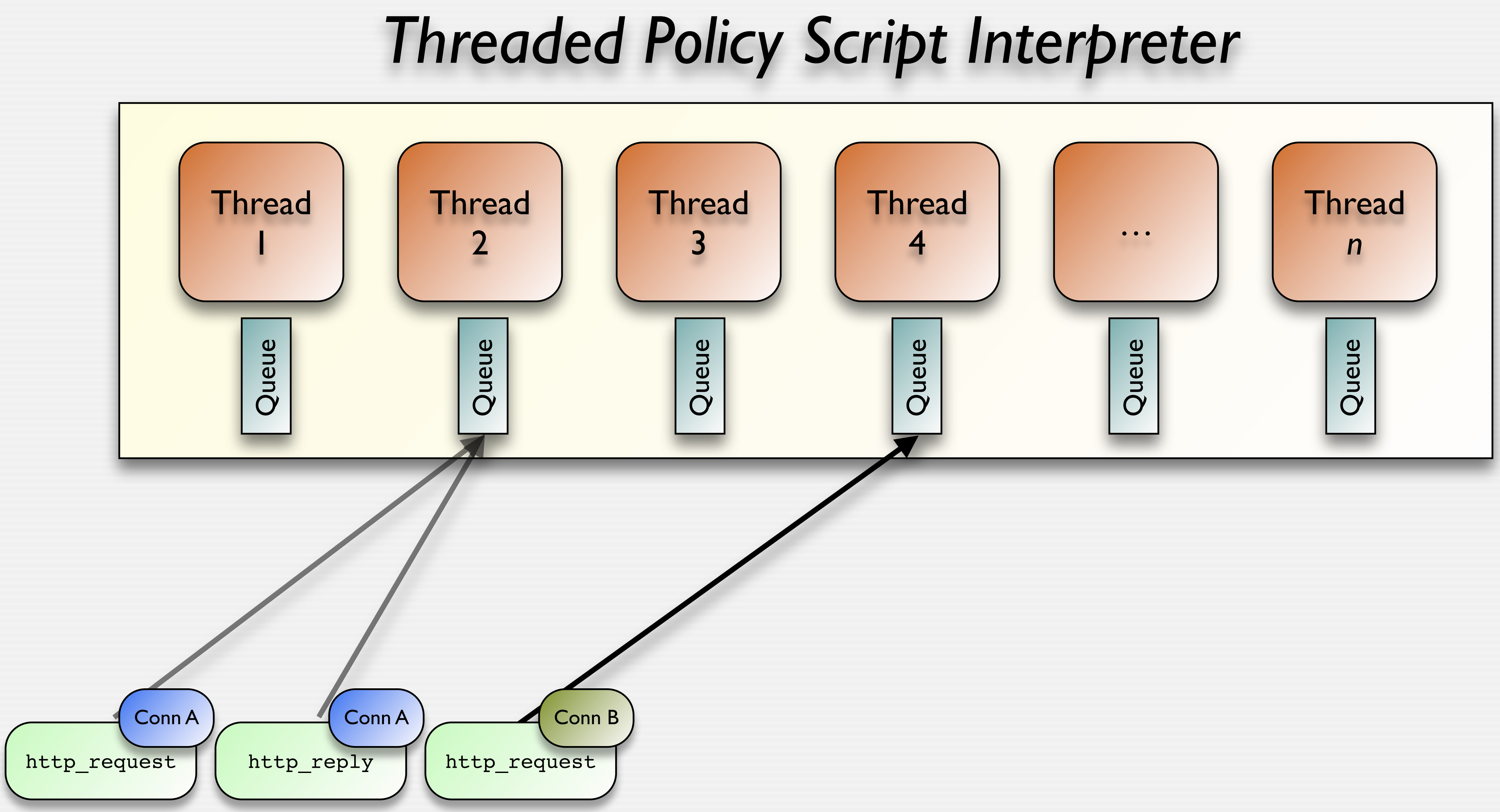

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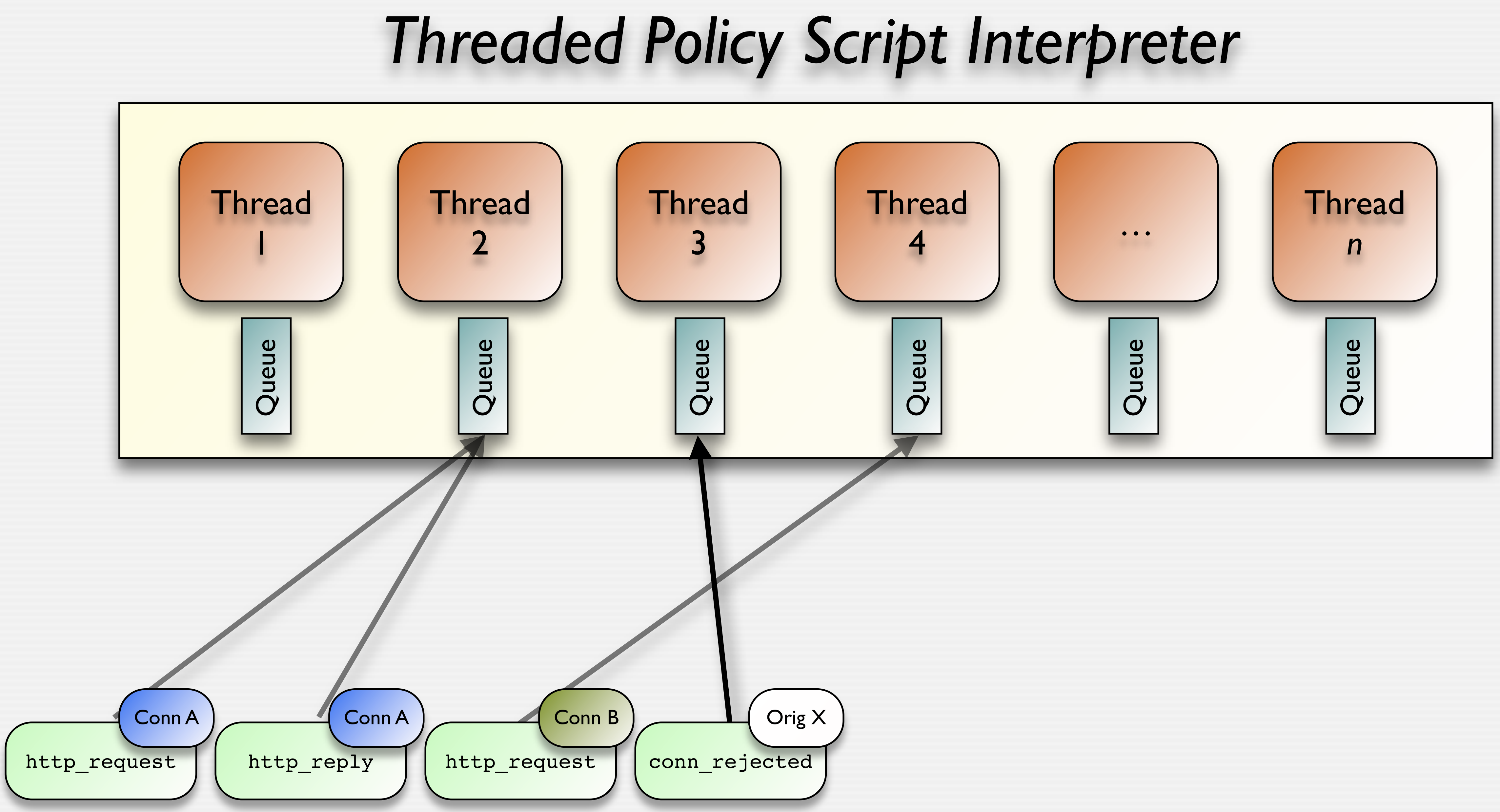

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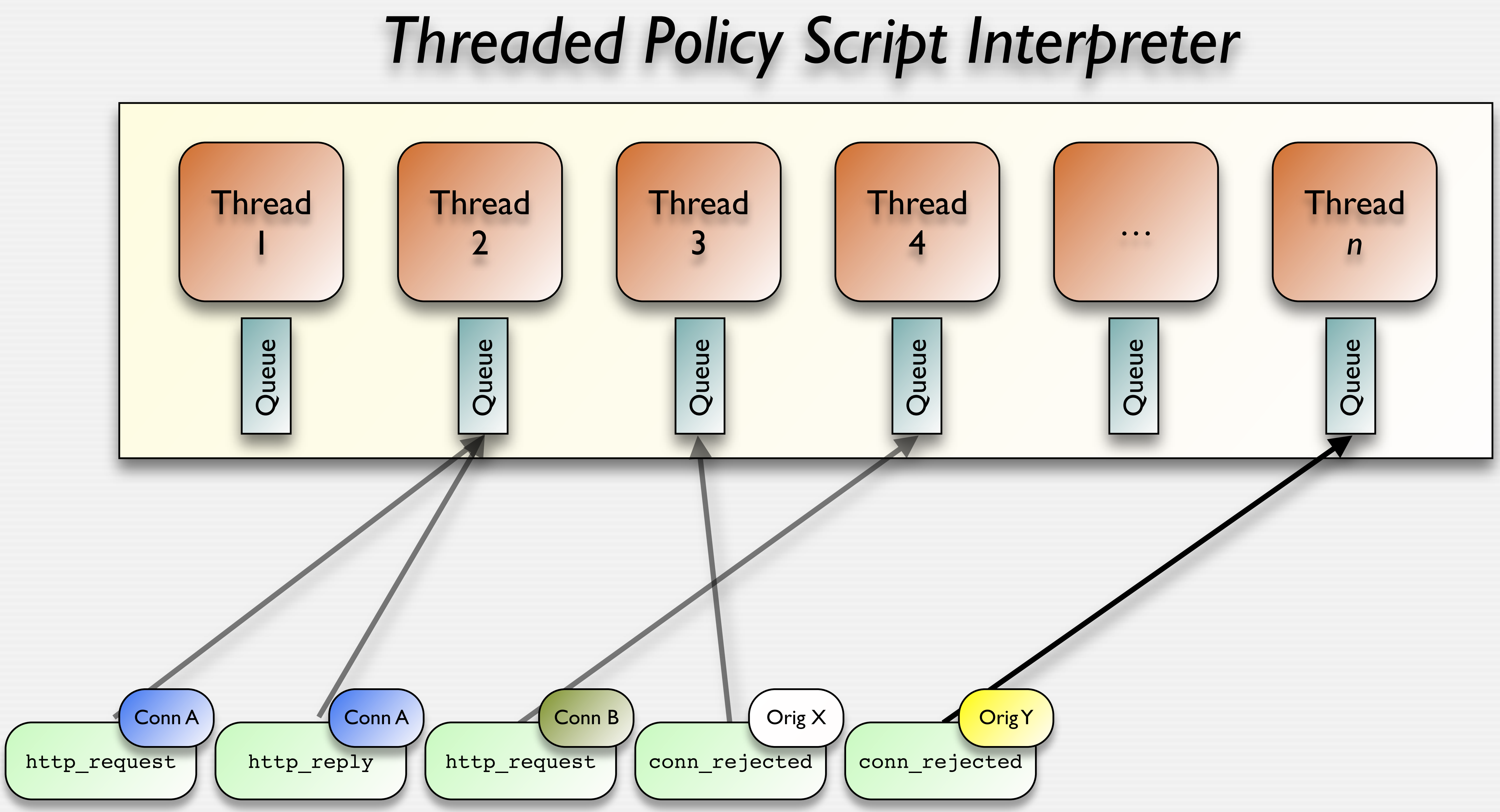

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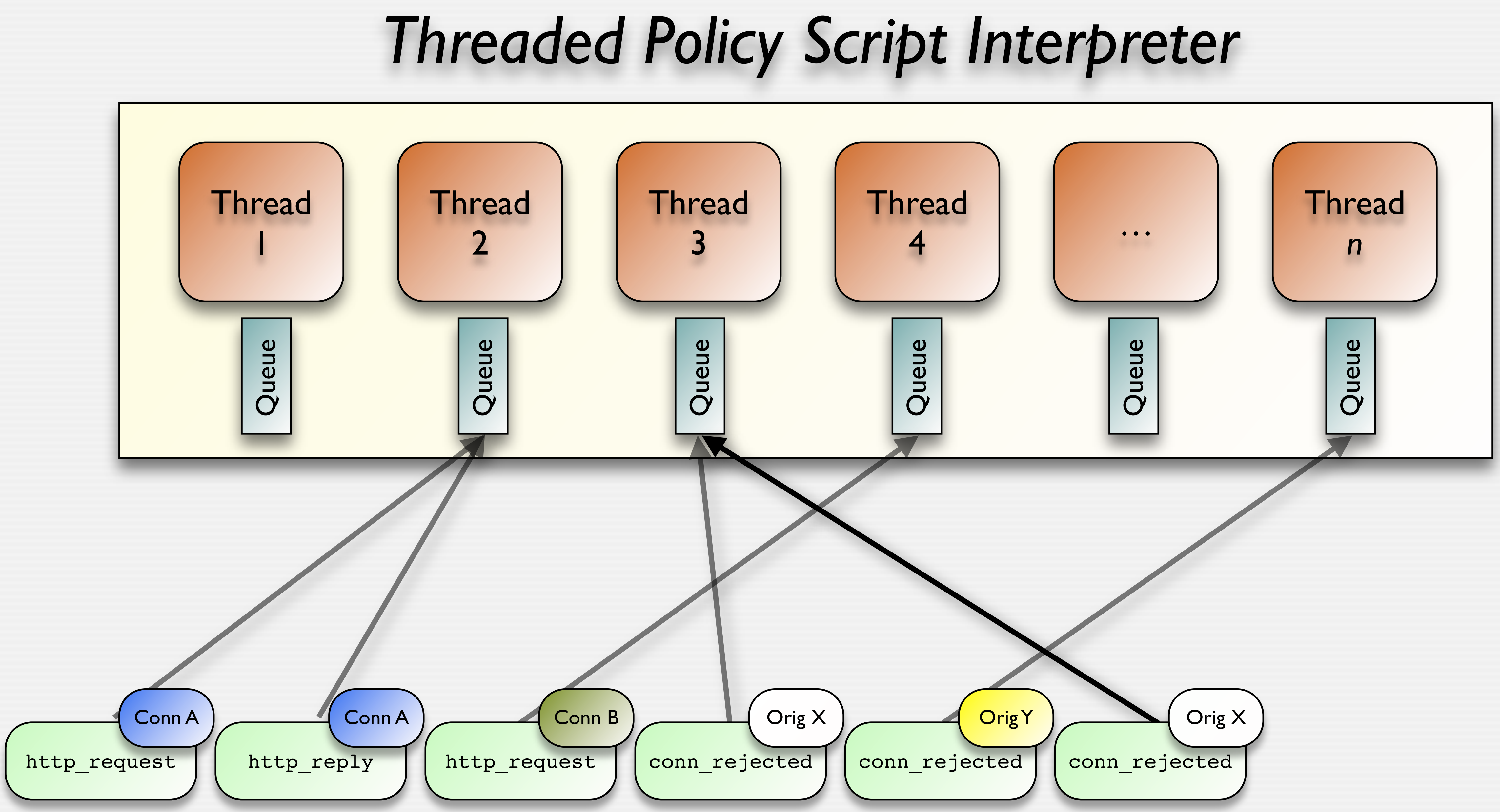

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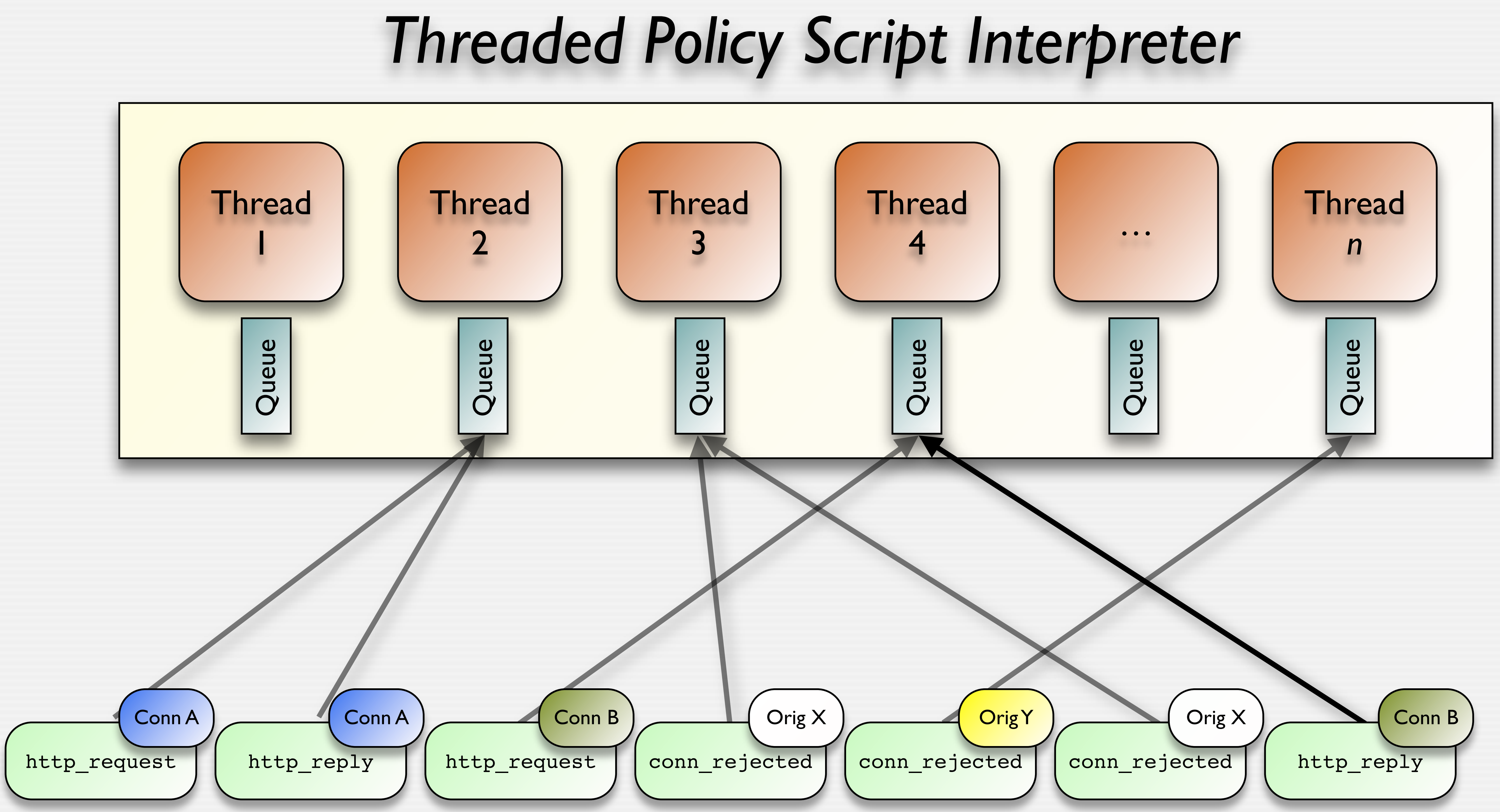

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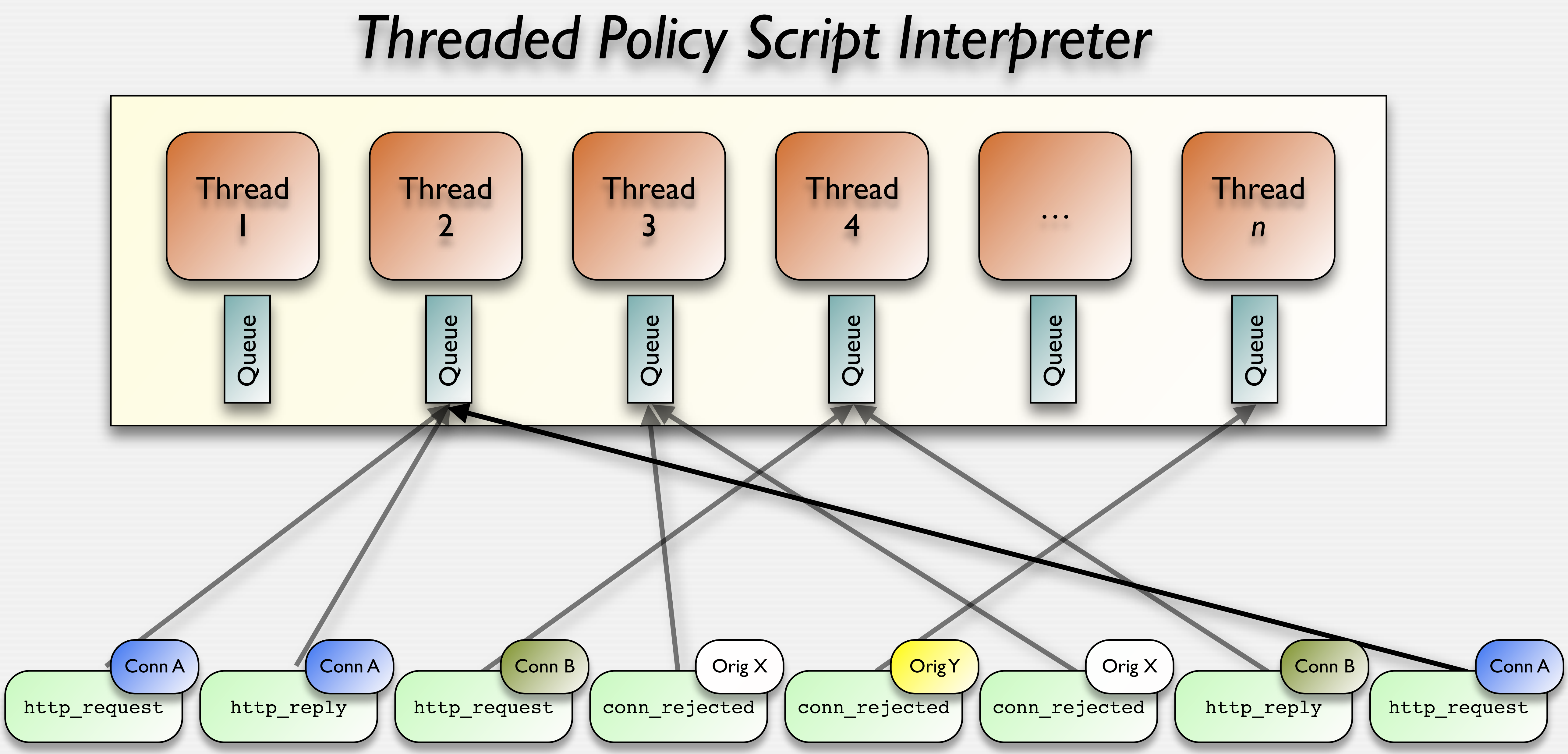
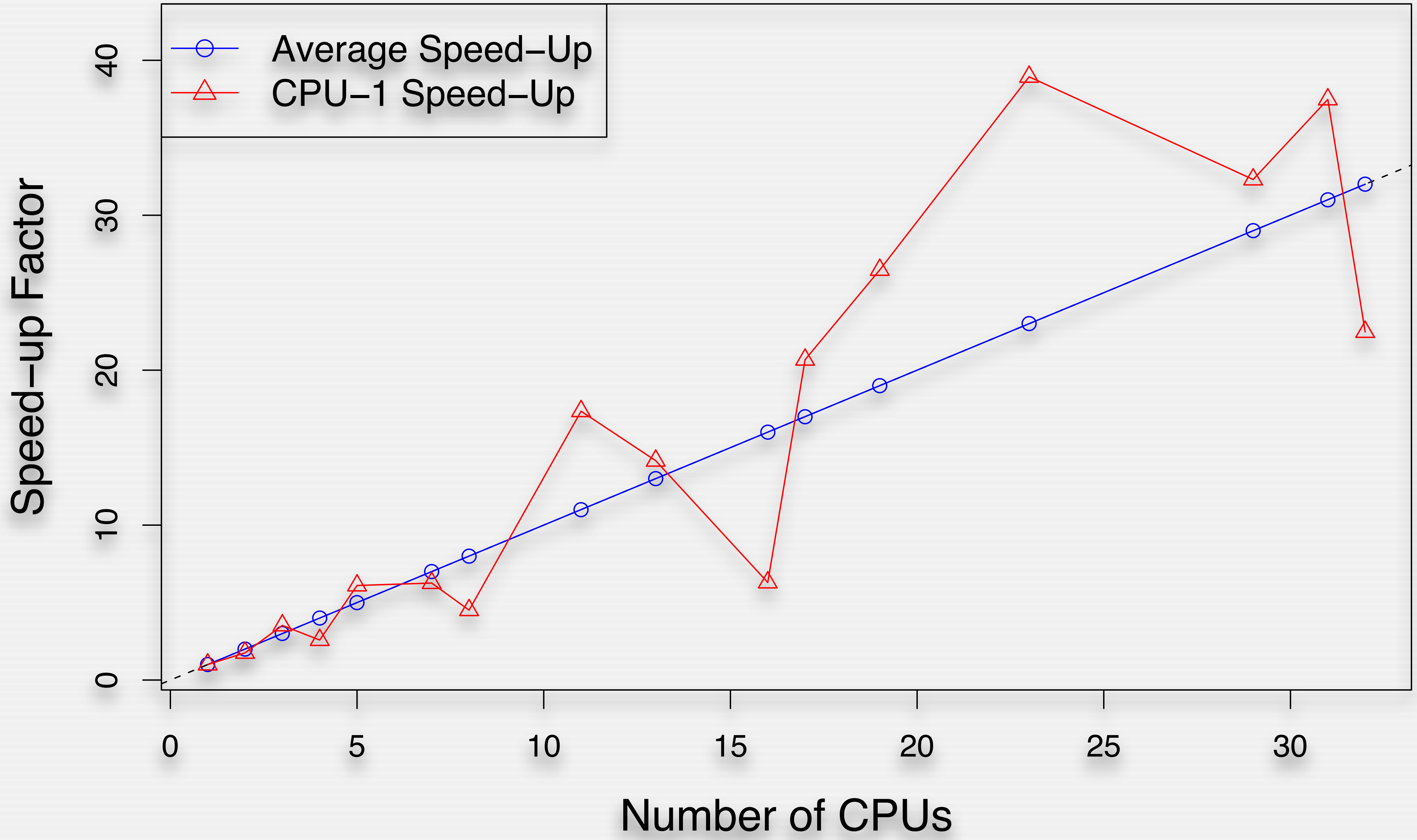


Does the Scoping Model Scale?

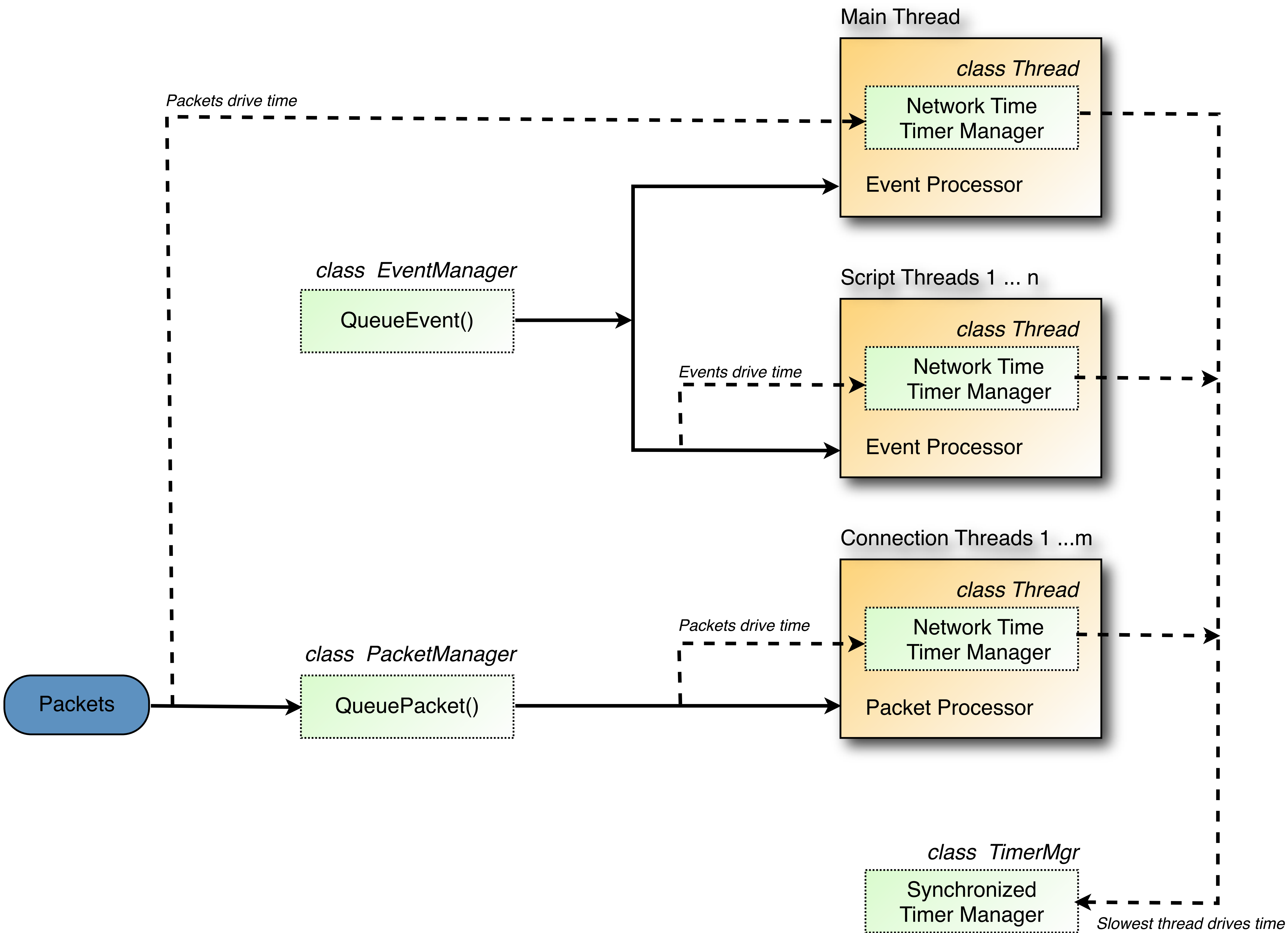


Simulation based on 15 minutes of LBNL traffic (24GB, 50M events)

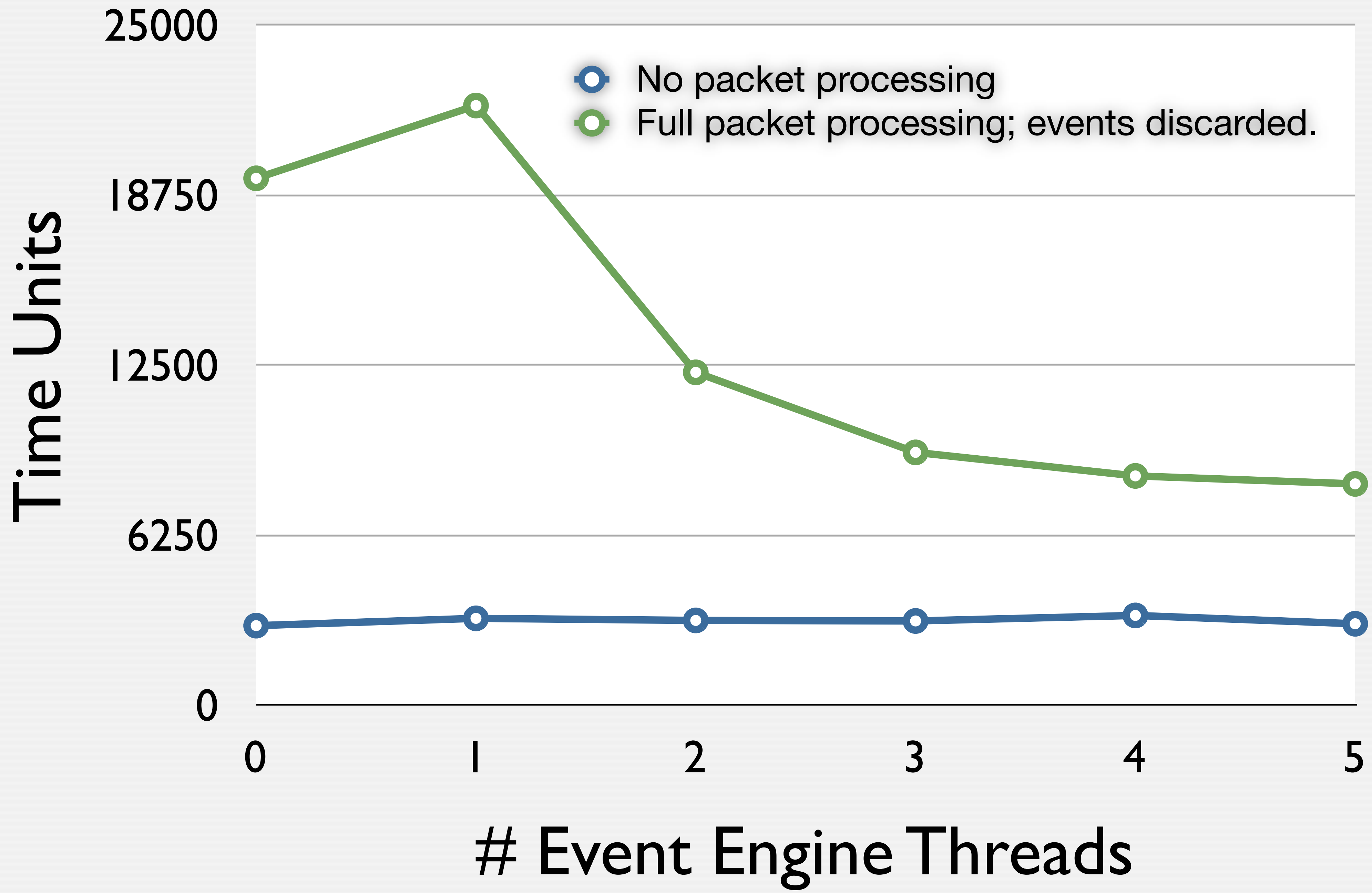
Implementation of Multi-Core Bro

- We have a prototype that we are now profiling further
  - 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

Multi-Core Bro Data Flow

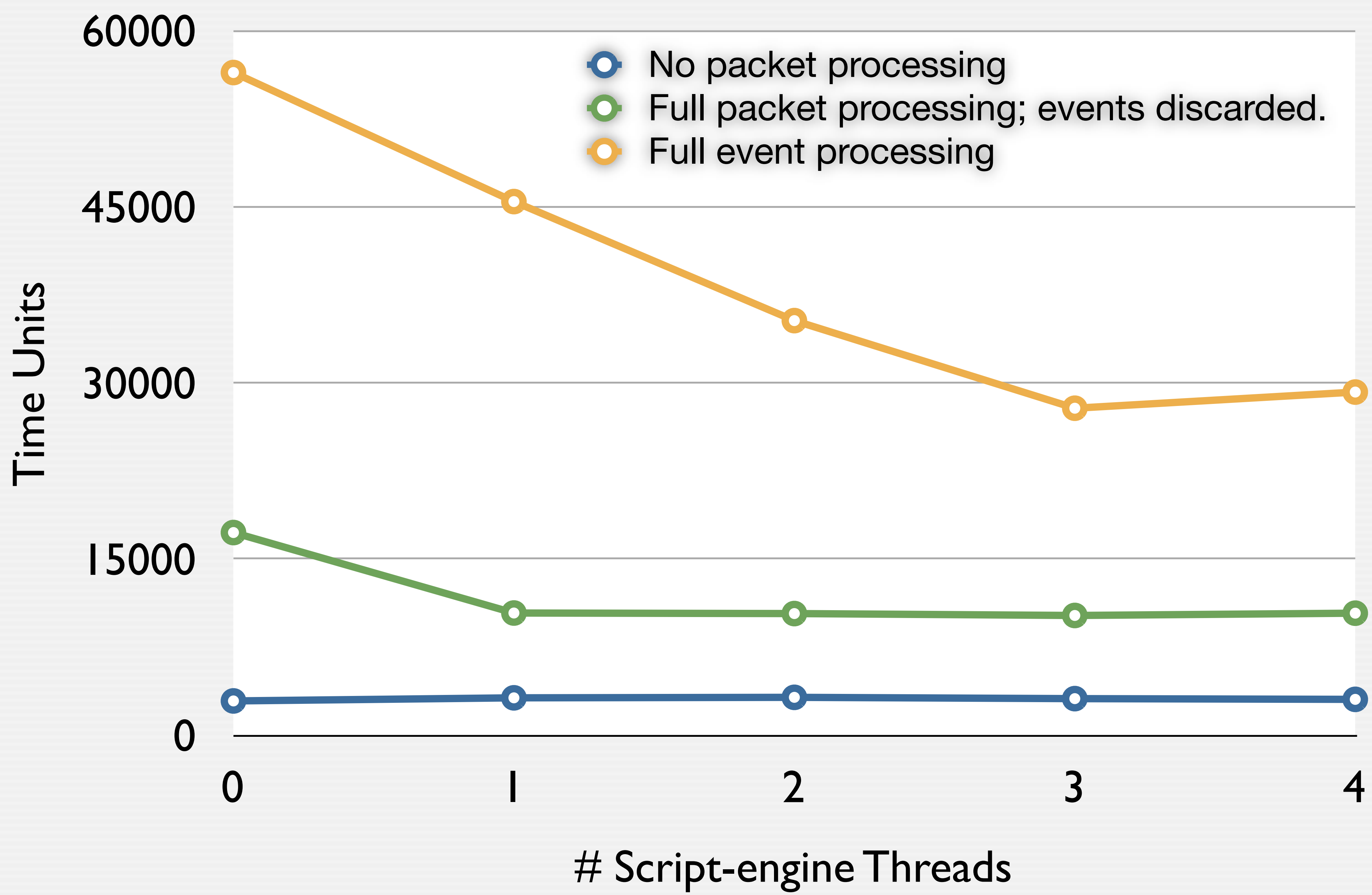


Event Engine Performance So Far ...



Dual quad-core Xeon system with 10min/11GB of LBL traffic
1 script-engine thread

Script-Engine Performance So Far ...



Dual quad-core Xeon system with 10min/11GB of LBL traffic
2 event-engine threads

Future Directions

Understanding the Bottlenecks

- Concurrent execution is just the start
  - “Just” parallelizing execution does not necessarily yield the expected speed-up
- Extensive profiling and optimization
  - CPU usage
  - Impact of the memory hierarchy
  - Explore different scheduling strategies

  - Use well-defined input traffic to understand the effects.
  - Offline vs. online
- Evaluation on different hardware platforms
  - Commodity systems with dual quad-core Xeons
  - 64-core Tilera platform
  - Simics simulator to explore a wide variety of options
- Parallelizing the packet dispatcher
  - Several vendors provides platforms that directly schedule packets to threads
  - Tilera can do that as well

Future: Automate the Scoping

- Scopes are assigned manually in our prototype
  - Not ideal, as it's not completely transparent to the user
- Bro should be able to 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

- Working on an abstract machine for traffic analysis
  - Instruction set with domain-specific support for typical operations
  - Compiler to turn it into highly efficient native code
- Will provide a concurrency abstraction
  - Will work well for the scoping model.
  - Eventually, Bro scripts will be compiled into this execution model

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

ICSI is hiring ...

We have an opening for a post-doc position to work on highly concurrent network traffic analysis.

http://www.icir.org/jobs.html

Thanks for your attention.

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robin@icsi.berkeley.edu
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