Traffic Analysis Using Streaming Queries

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Outline

- Intro to Continuous Query Systems
  - a.k.a Streaming Databases
  - Relevance to data networks
- Optimizing the evaluation of multiple Boolean queries
  - Counting Algorithm
  - Snort
  - Static Dataflow Optimization
    - Common Subexpression
    - Vector Algorithms
- Performance Comparisons

Observations

- Traffic analysis tools are data-type-specific
  - Flowtools – netflow
  - Snort – pcap
  - Psad – iptables logs
  - …
- Most analysis systems lack a framework for optimizing rules/queries
  - Reordering boolean expressions
  - Grouping (common sub-expressions)
  - Vector/set operations

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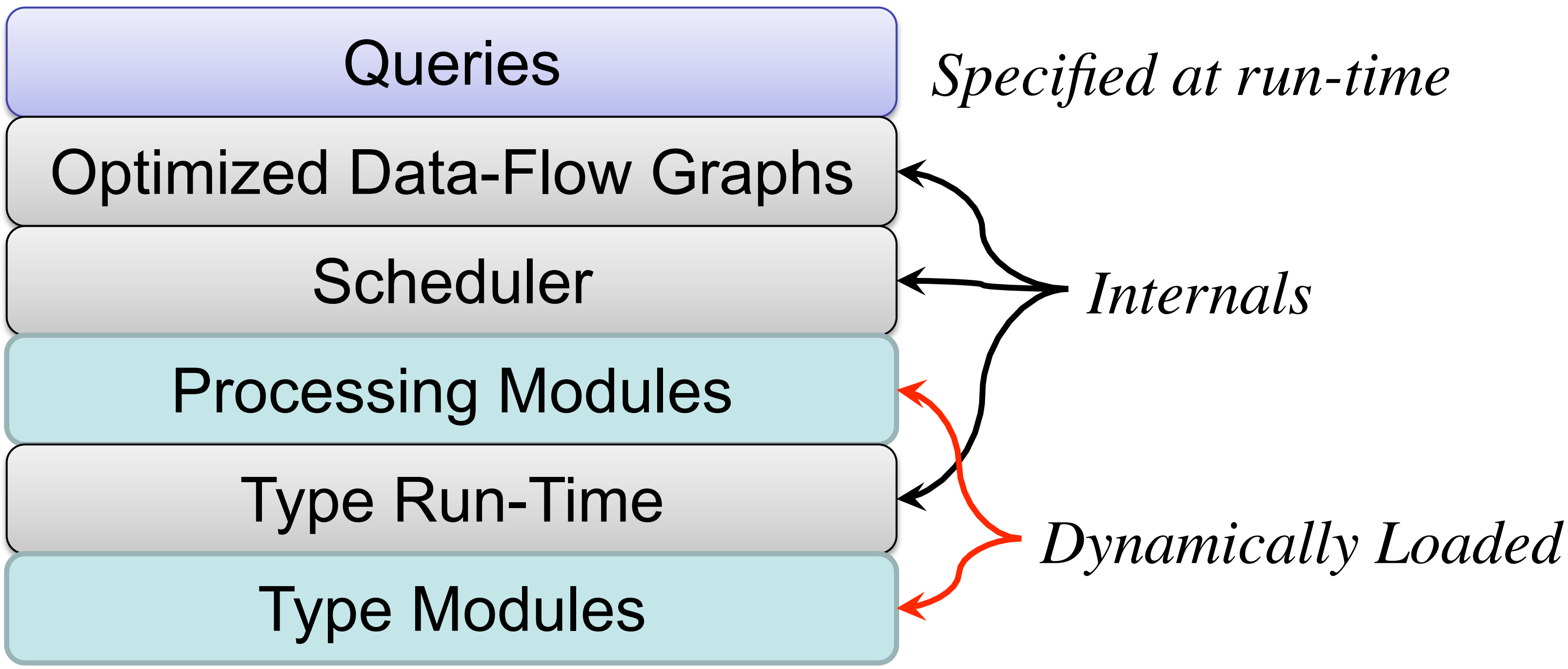
Continuous Query Systems

- Continuous Query systems are to streaming data what Relational Database systems are to stored data
  - Filtering, summarization, aggregation
- Example datasets:
  - Sensor data (temperature, traffic, etc)
  - Stock exchange transactions
  - Packets, flows, logs
- Inefficient and high latency to load data into a traditional database and query periodically.
  - How often could you afford to re-execute the query?
- Example systems:
  - NiagraCQ (Wisc), Telegraph (Berkeley), SMACQ, etc.
  - Commerical: StreamBase, etc.
- Example systems in disguise:
  - Snort, router ACLs, firewall filters, packet classification, egrep

System for Modular Analysis & Continuous Queries



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Type Model

- Stream of dynamically & heterogeneously typed objects
  - Each object can have different type
  - Types need not be statically defined in advance
- Objects refer to storage locations
  - Internal to the object, or references into other objects or external memory
- Objects have fields
  - Fields are (indifferently) struct elements, enums, unions, casts, string conversions, etc.
  - Fields are first-class objects
  - Fields can be dynamically attached to objects
- Objects are immutable
  - Enables parallelism without locking

Type Module Definition

- There are no fundamental types
- Pcap packet example

```
struct dts_field_spec dts_type_packet_fields[] = {
//Type          Name              Access Function if not fixed
{ "timeval",    "ts",             NULL },  // Fixed-length, fixed-location
{ "uint32",     "caplen",         NULL },
{ "uint32”,     "len",            NULL },
{ "ipproto”,    "ipprotocol",     dts_pkthdr_get_protocol },  // Function-pointer
{ "string”,     "packet",         dts_pkthdr_get_packet },
{ "macaddr”,    "dstmac",         dts_pkthdr_get_dstmac },
{ "nuint16",    "ethertype",      dts_pkthdr_get_ethertype },
{ "ip",         "srcip",          dts_pkthdr_get_srcip },
…
```

SMACQ Processing Modules

- Modules are the atoms of query optimization
- Written in C++ or Python
- Take arbitrary flags and arguments
  - Unix command-line style
- Introspection: Can ask runtime to identify downstream invariants
  - When module can do eager pre-filtering (e.g. hardware prefilter on NIC, database query, etc.)
- Event-driven (produce/consume) API
  - Can use "threaded" wrapper if lazy (really co-routines)
- Can embed other query instantiations
  - Can instantiate new scheduler, or share primary (preferred)

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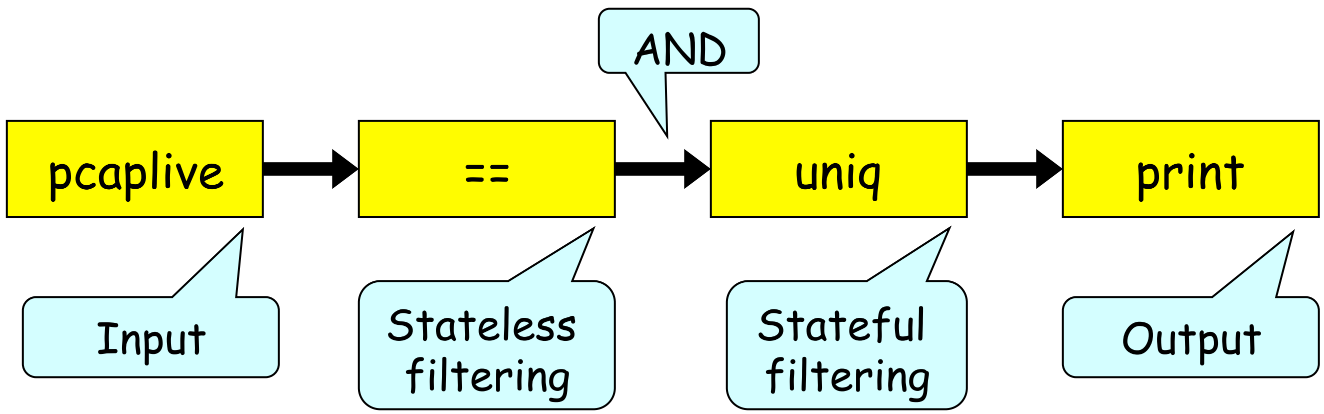
Example Processing Module (Python)

```
Class Dumper:
    “””Print a few elements of each datum and pass every 5th”””
    def __init__(self, smacq, *args):
        print ('init', args)
        self.smacq = smacq      #Save reference to runtime
        self.buf = []           #List of objects received

    def consume(self, datum):
        for i in 'srcip', 'dstip', 'ipprotocol', 'len':
            v = datum[i].value
            print (i, datum[i].type, type(v), v)
        self.buf.append(datum)
        if len(self.buf) == 5:
            self.smacq.enqueue(datum)   # Output object downstream
            self.buf = []
```

Query Model: Dataflow Graphs

- Queries are dataflow graphs



- Modules declare algebraic properties:
  - *stateless (map), annotation, vector, demux, (associative)*
  - Enables optimization, rewriting, parallelization, map/reduce
- Static optimizer applies all data-flow optimizations permitted by algebraic properties of the involved modules

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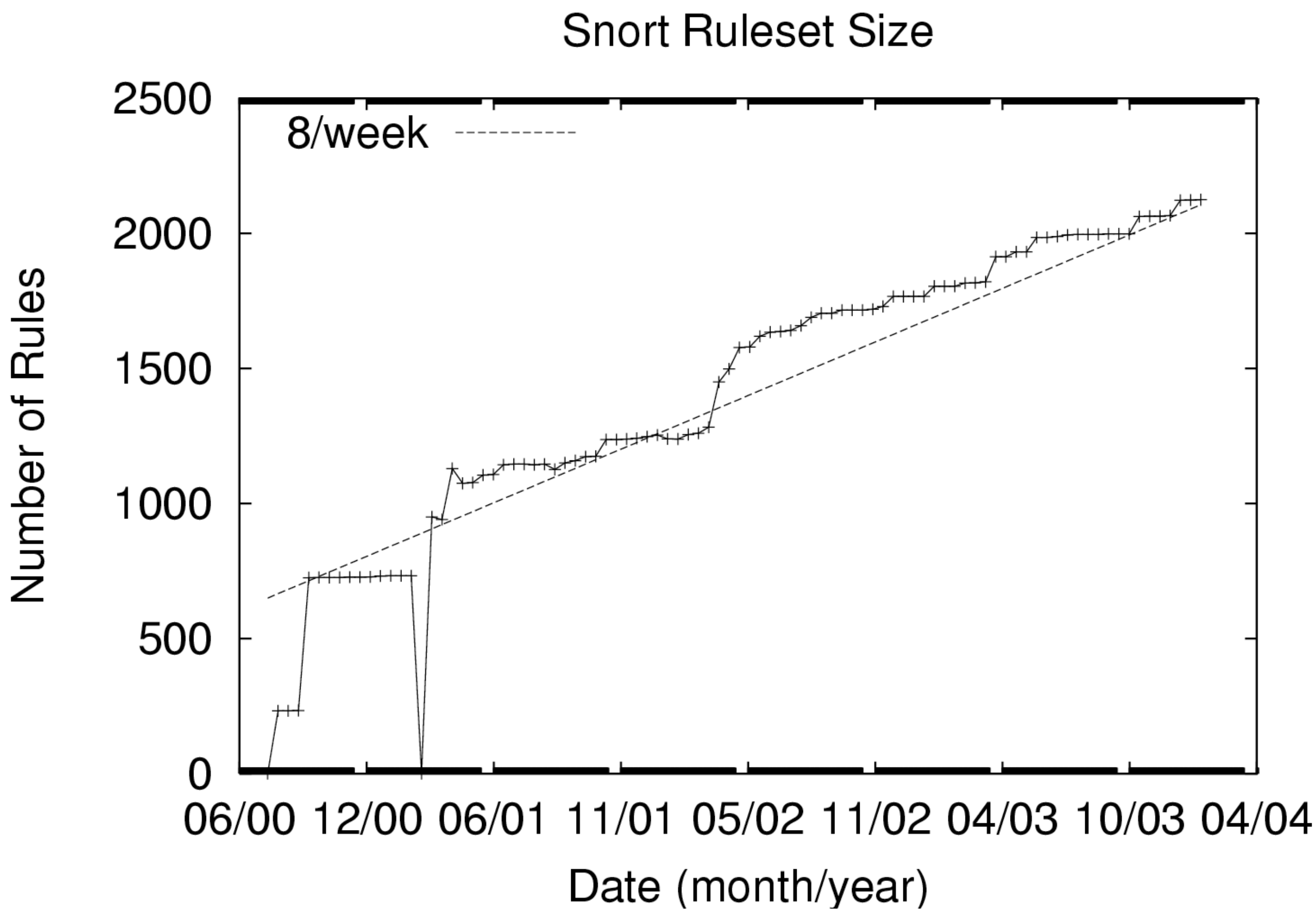
Optimizing Continuous Queries

- Traditional database query optimization:
  - Uses data indexes
  - Minimizes individual query times
- Continuous-query optimization:
  - Executing many queries simultaneously
  - Minimize resource consumption per unit of data input
    - Maximize data throughput

Why is multiple query processing important? Approximately 8 new rules each week



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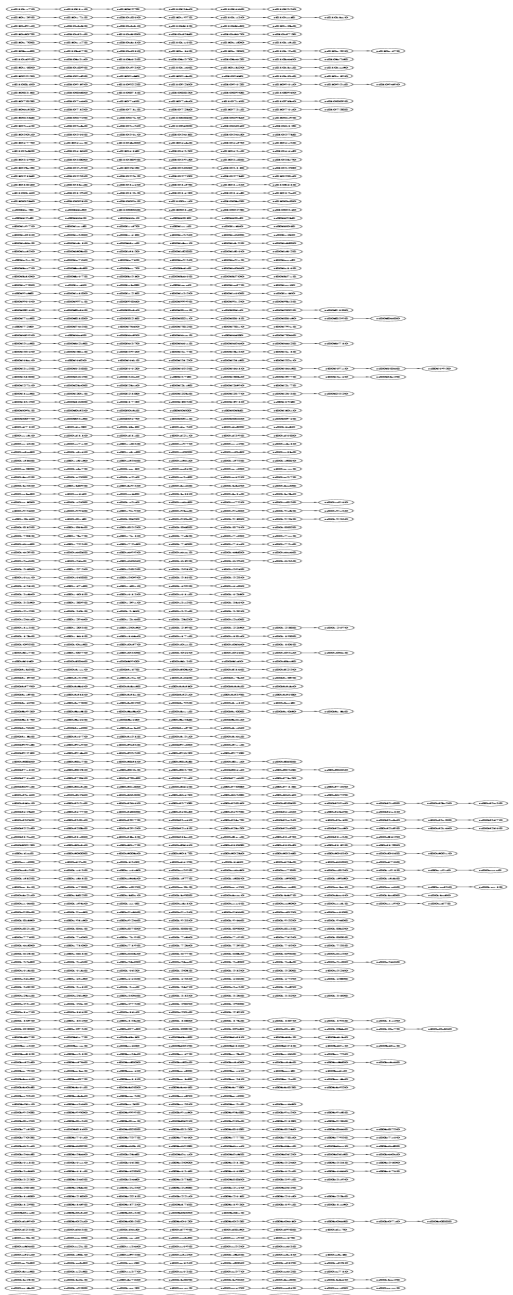
Optimization of 150 Snort Rules



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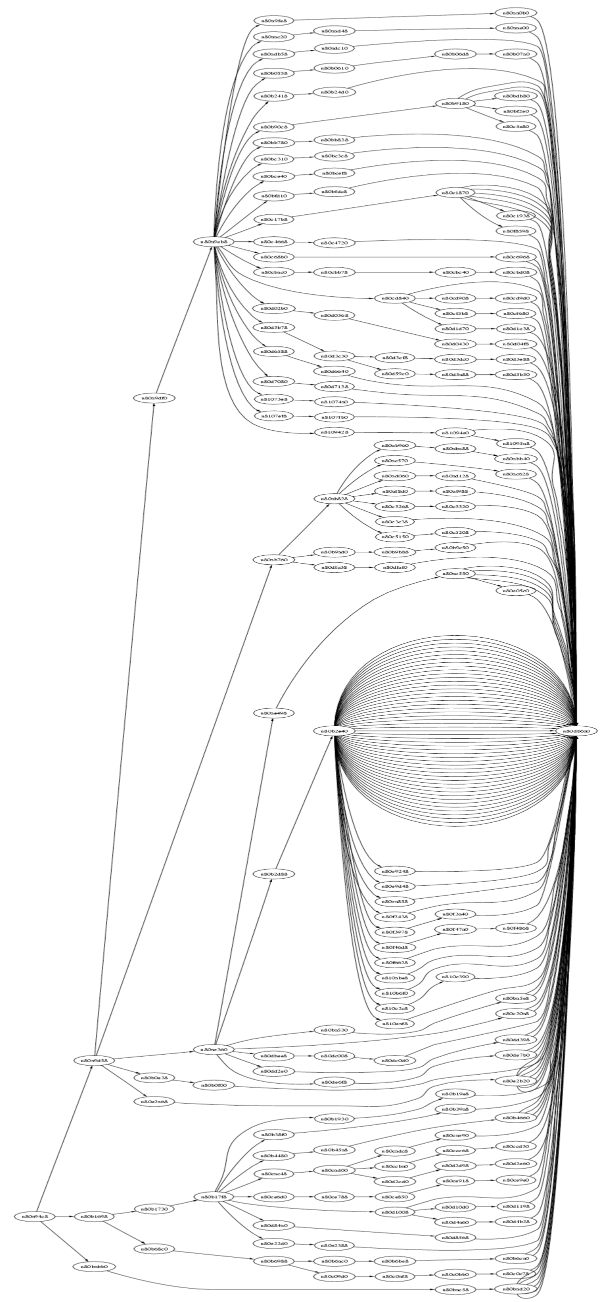
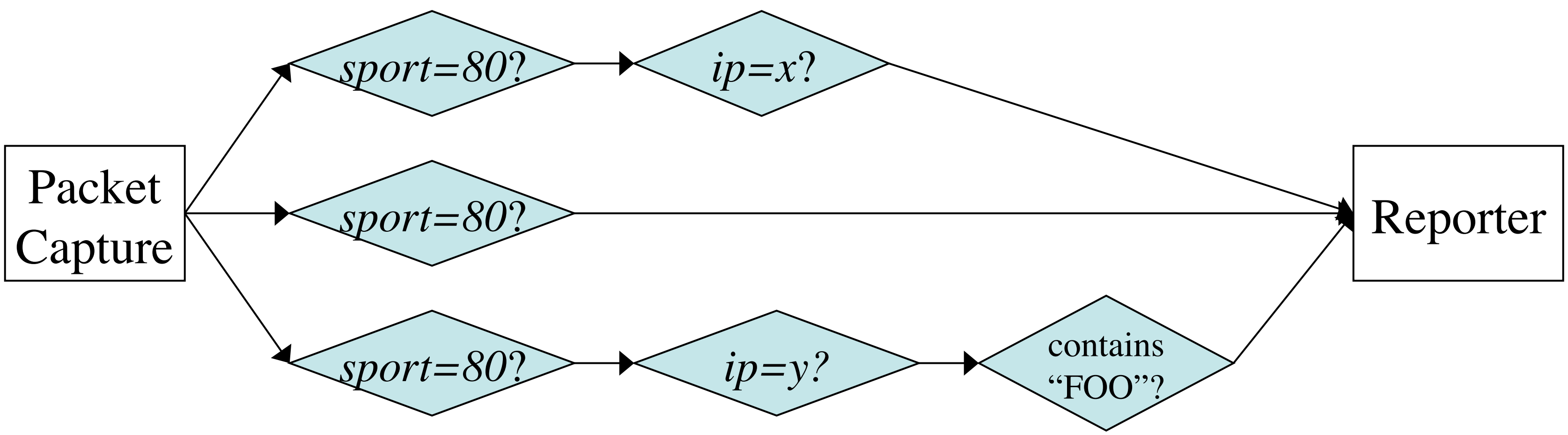


Example Queries

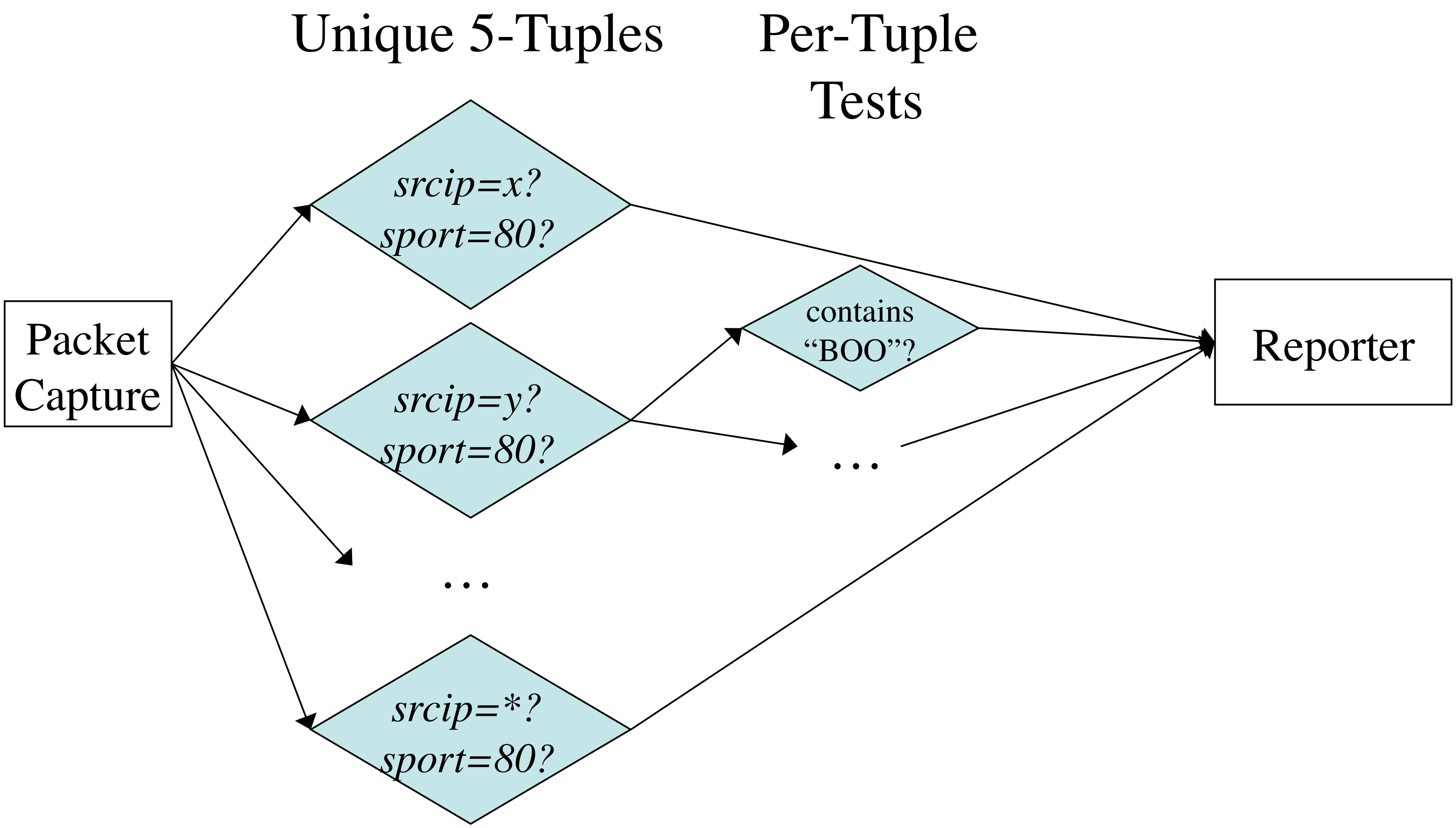
6 Tests in 3 Rules



Snort Approach

[Roesh, LISA 99]

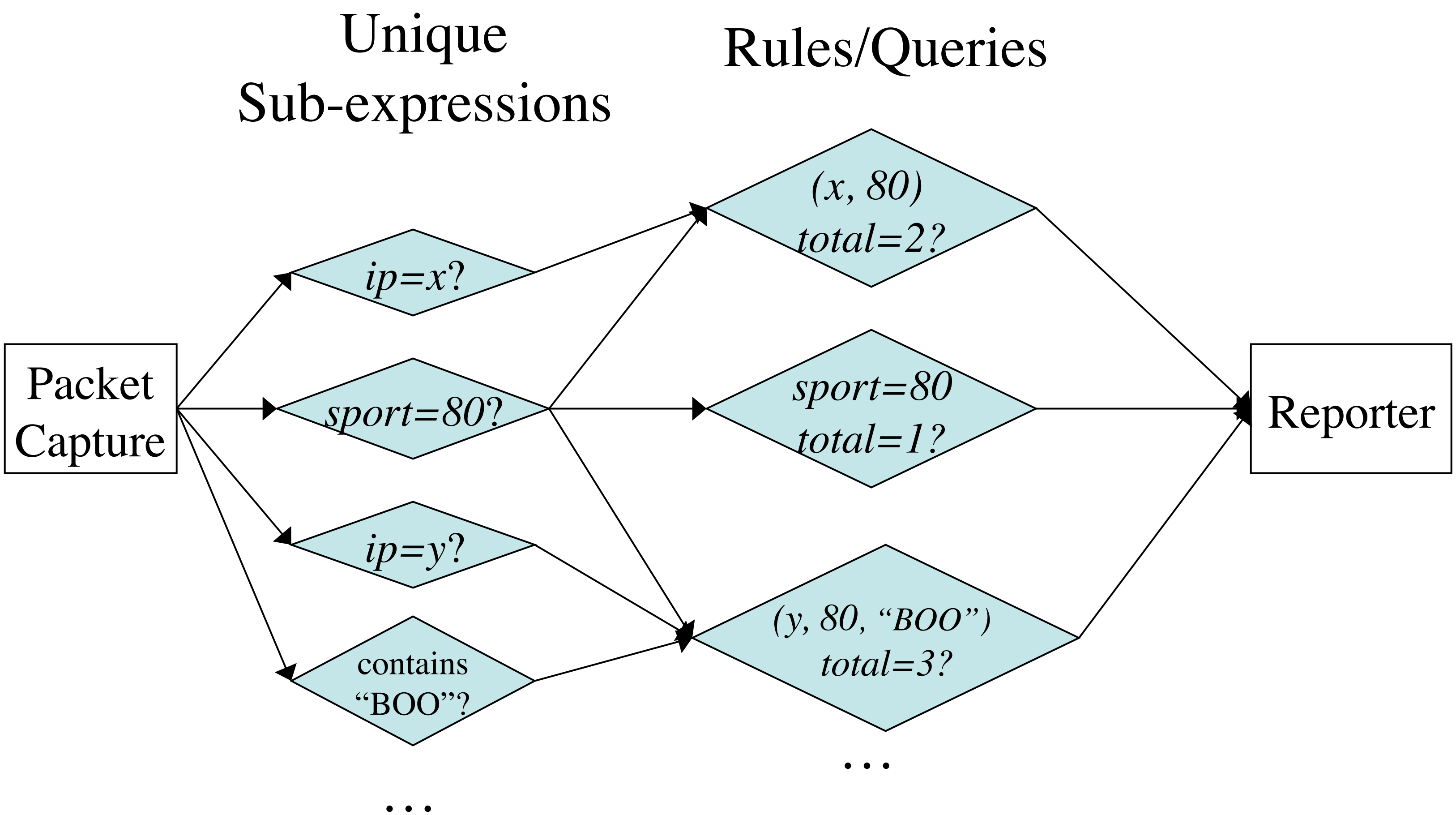
Example: 6-7 Tests



Counting Approach

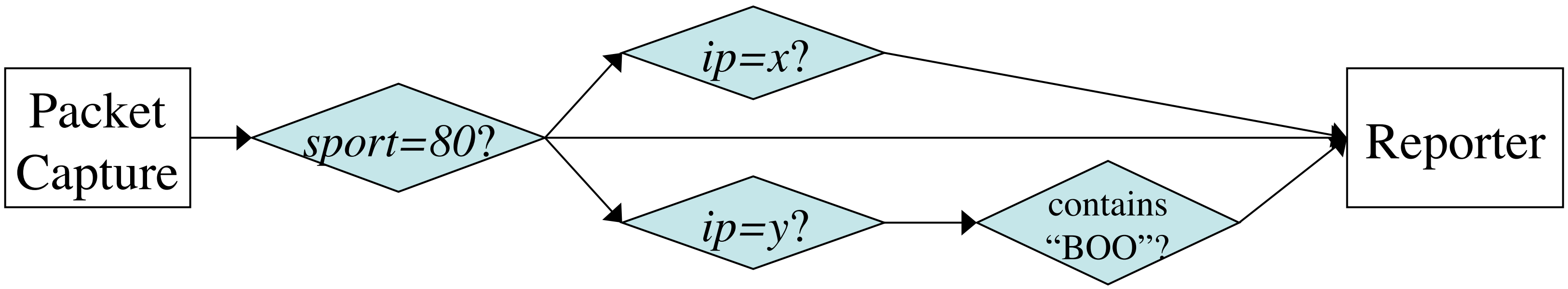
[*Carzaniga & Wolf, SIGCOMM 03*]

Example: 7 Tests



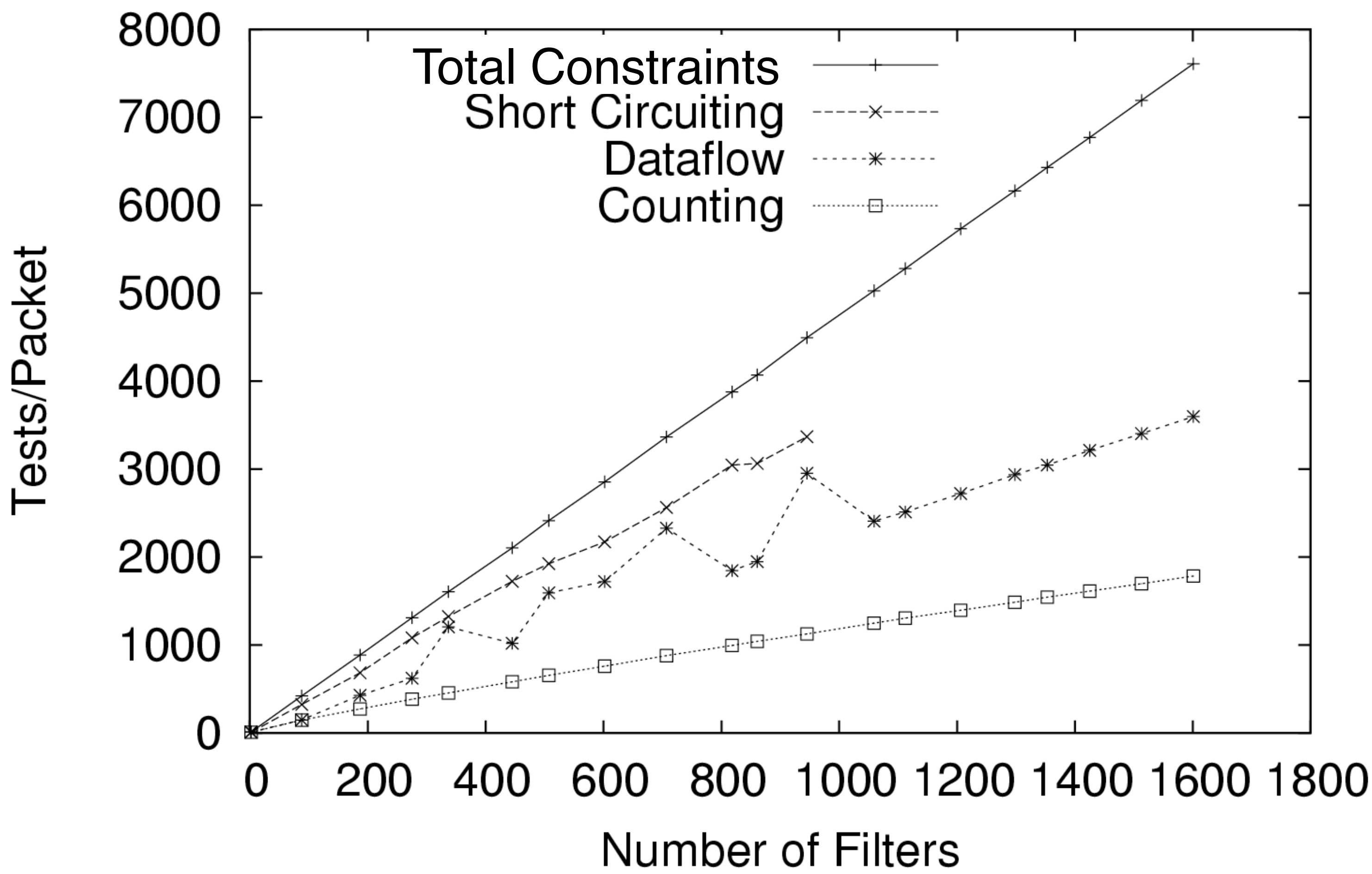
Data-Flow Approach

Example: 1-4 Tests



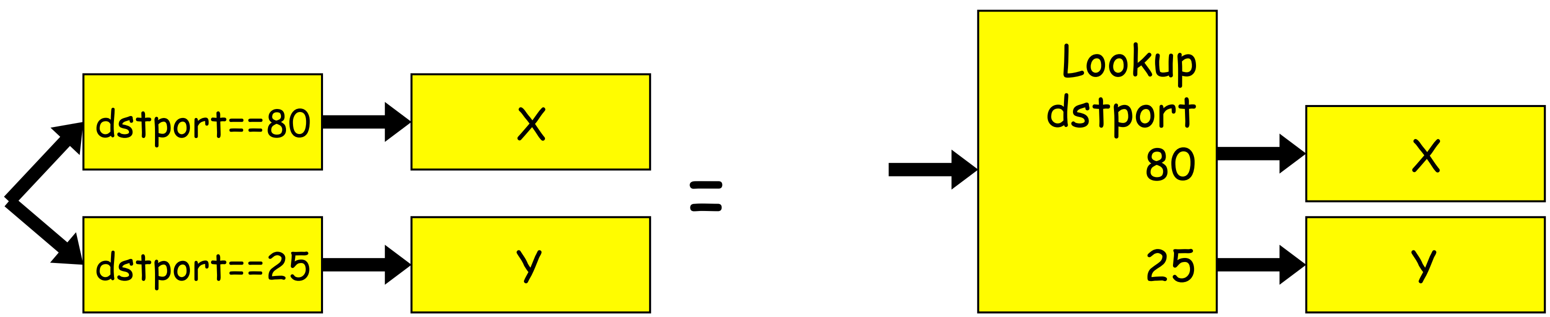
1. Common roots
2. Common leaves
3. Common upstream graphs
4. Common downstream graphs

Performance Comparison

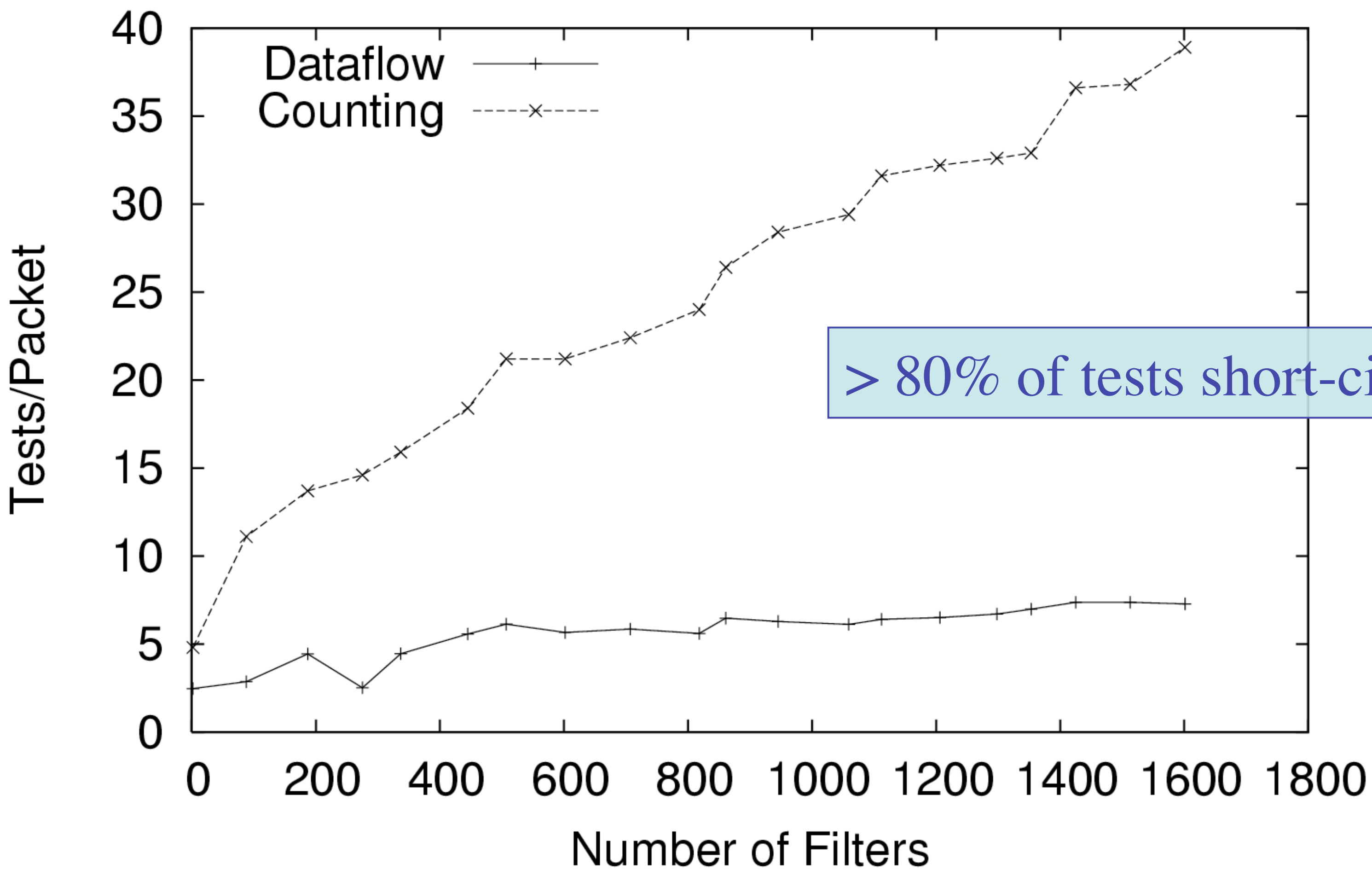


Vector Functions

- Most optimizations in stream analysis have employed a class of algorithms that can be characterized as *vector functions:*
  - $f(x, v) = f(x, v_1), f(x, v_2), \ldots.$
  - Vector version is typically O(1) or O(log n) instead of O(n)
- Examples
  - Set of equality tests becomes a single lookup in a hash-table
  - Set of string matches becomes a single DFA to traverse

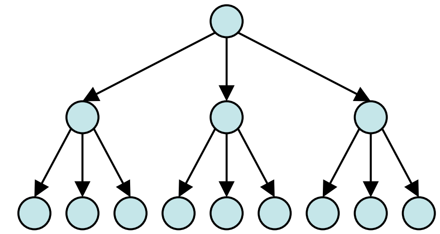


Performance Comparison with Vector Functions



> 80% of tests short-circuited

Analysis: Why was Counting better only without vectors?



- Assume that each test results in p more tests
  - p = *fanout • short-circuiting*
  - $p \leq$ *fanout*
  - $0 \leq$ *short-circuiting* ≤ 1
- Assume data-flow of tests is a balanced tree of depth d
  - d is an integer ≥ 1
- Expected number of evaluations:

  $$1 + p + p^2 + p^3 + \ldots + p^{d-1} \qquad = \qquad (1 - p^d) / (1 - p)$$

- Let u = number of unique tests = Counting's performance

  $$s(1 - p^d) / (1 - p) < u \quad \text{if} \quad (d > 1, p < 1)$$

- For IDS test: $d = 6$
  - With Vectors (u=39): $p < 1.7$ is desired. Actual $p = 1$
  - Without Vectors (u=1782): $p < 4.2$ is desired. Actual $p = 5.8$

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Supported Query Languages

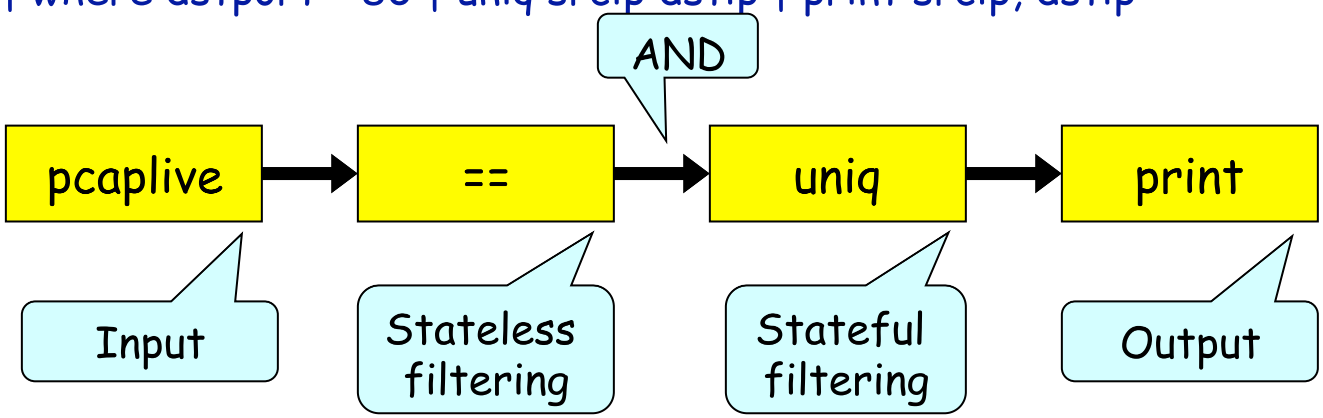
- SQL style:

```
print srcip, dstip from
    (cflow where dstport==80 and uniq(srcip, dstip))
```

  - Misplaced belief that since SQL is well defined, people can just use it
  - Deeply nested queries make you wish you were merely nested in s-expressions

- Unix pipe style:

```
cflow | where dstport==80 | uniq srcip dstip | print srcip, dstip
```



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Supported Query Languages

- Datalog

```
Pairs     :- cflow | uniq(srcip dstip)
SrcCount :- count() group by ipprotocol srcport
DstCount :- count() group by ipprotocol dstport
Pdf       :- filter(count) | pdf
Print     :- sort(-r probability) | print(type ipprotocol port probability)

Pairs | SrcCount | const(-f type src) | Pdf | rename (srcport port) | Print
Pairs | private | DstCount | const(-f type dst) | Pdf | rename (dstport port) | Print
```

  - Clean, allows named subexpressions

Join Models

- DFA module
  - Define a state machine where transitions specified as Booleans on new inputs
- SQL style
  - Example: print running cross-product

```
print a.ipid b.ipid from
    pcapfile(0325@1112-snort.pcap) a, b where a.ipid != b.ipid
```

  - New keyword UNTIL defines when state can be removed
    - "NEW" refers to newly input data for comparison
  - Example: print retransmissions within the same second

```
print expr(b.ts - a.ts) from pcaplive() a until(new.a.ts.sec > a.ts.sec), b until(new)
   where b.ts > a.ts and a.srcip == b.srcip and a.srcport == b.srcport
         and a.seq == b.seq and a.payload != "" and b.payload != ""
```

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Usage Experience

- Online detection & automated response systems
- Ad-hoc queries for forensic analysis and data exploration
- Feature extraction for other software

Conclusions

- Continuous Queries provide a common query syntax, software infrastructure, and optimization framework for traffic analysis
- CQ necessary for streaming applications, sufficient for ad-hoc forensic analysis

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Conclusions

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- Continuous Queries provide a common query syntax, software infrastructure, and optimization framework for traffic analysis
- Two identified strategies for static optimization of multiple queries
  - Remove (Counting) or Reduce (Data-flow) redundant tests
  - Boolean (Data-flow) short-circuiting removes need for some subsequent tests
- Performance Analysis:
  - Counting is preferable when short-circuiting is rare
  - Data-flow out-performs counting when short-circuiting is significant
    - When breadth of graph is reduced with vector functions, actual IDS workload benefits significantly from short-circuiting
- Data-flow approach can also benefit from additional, dynamic reordering of tests to maximize early short-circuiting