Lawrence Livermore National Laboratory

Hierarchical Bloom Filters: Accelerating Flow Queries and Analysis

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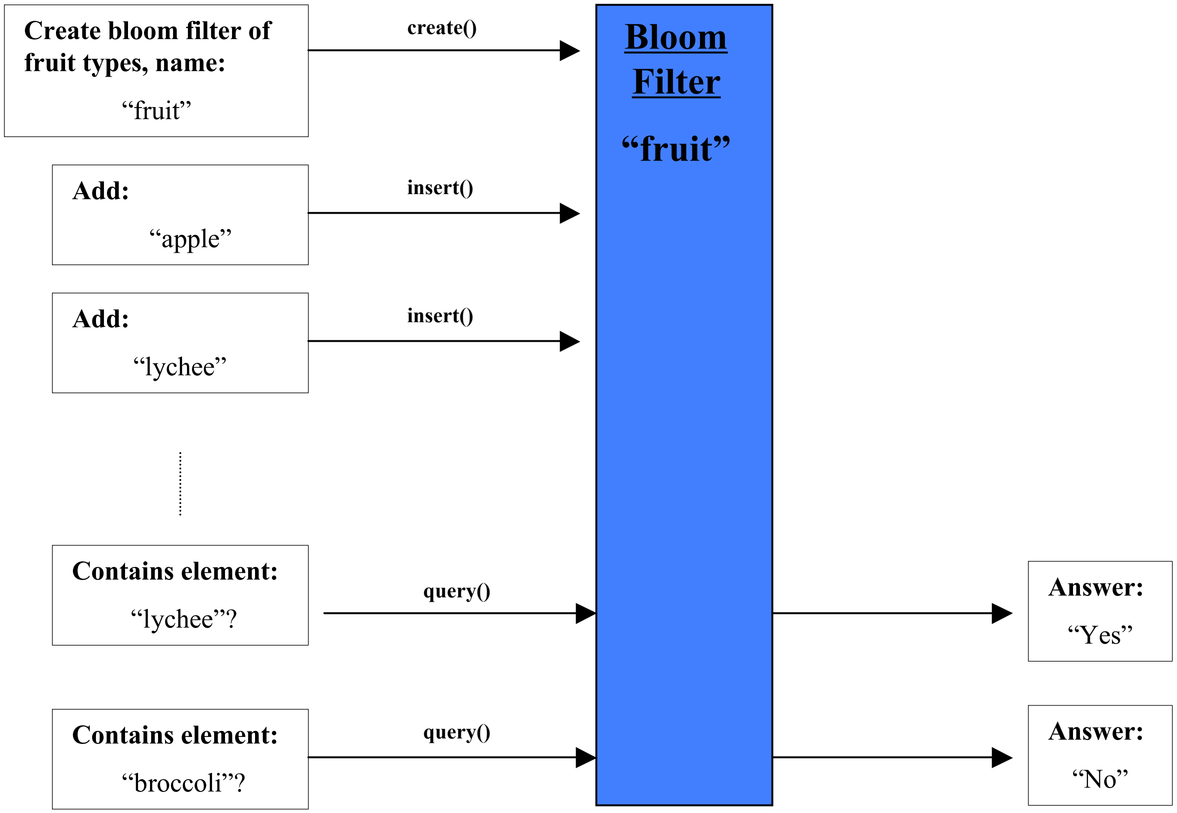
Overview

- Introduction to Bloom Filters
- Overview of CIAC’s Bloom Filter-Based indexing System
- Approach's Applicability for CIAC & other CERTs
- Performance on Actual Flow Data
- Applications of Approach in Conjunction With Analytical Tools
  - Facilitating incident detection and analysis with flow visualization tools.

A Very Brief Introduction to Bloom Filters

Introduction to Bloom Filters

- High-level Functionality – trivial



http://www.eecs.harvard.edu/~michaelm/NEWWORK/postscripts/BloomFilterSurvey.pdf
http://en.wikipedia.org/wiki/Bloom_filter

Introduction to Bloom Filters

- **The Concept**
  - Efficient, probabilistic data structure, providing extremely light-weight string lookups, or “approximate membership queries”.
  - Invented by Burton Bloom in 1970 to optimize spellchecking.
  - Trade-off small probability of **false positives** for massive gains in **space and time efficiency**.
  - Popular for various large-scale network applications (e.g., web caches, query routing).

References:

http://www.eecs.harvard.edu/~michaelm/NEWWORK/postscripts/BloomFilterSurvey.pdf

http://en.wikipedia.org/wiki/Bloom_filter

How Bloom Filters Work

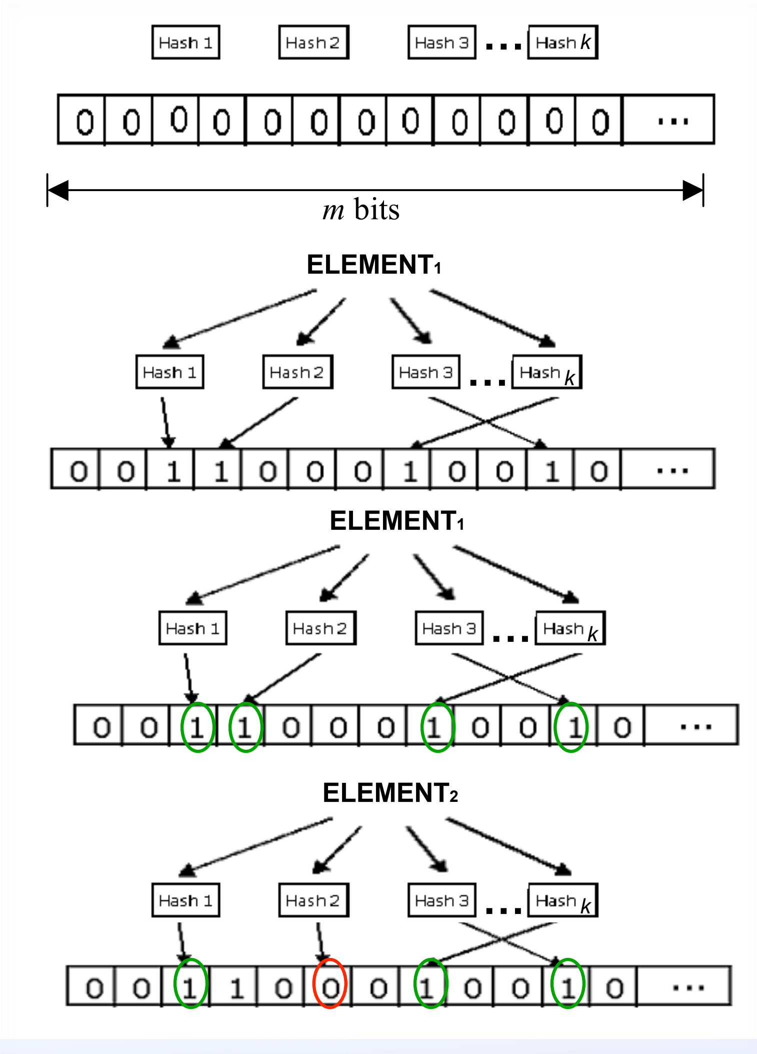
1. <u>Empty</u> bloom filter is a bit array of *m* ‘0’- bits.

2. Introduce *k* different hash functions, each maps key value to one of m array positions.

3. <u>Insert</u> element by feeding it to each hash function, to obtain *k* array positions. Set these bits to ‘1’.

4. <u>Query</u> element (check its existence) by re-feeding into each hash function, and checking corresponding bit positions. If all bits are ‘1’, then element is either in the filter or it’s a <u>false positive</u>.

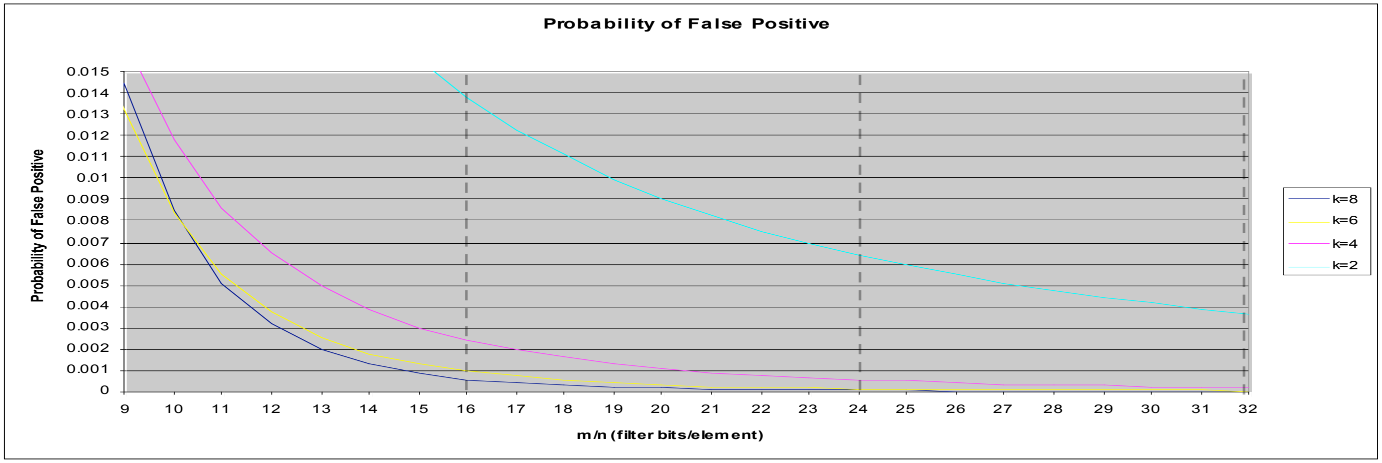
5. If bit positions of hashes of an element contain a ‘0’, then that element is <u>definitely</u> <u>not</u> in filter (no false negatives).



Introduction to Bloom Filters

- False Positives
  - Probability of false positive for a populated bloom filter is:

$$p(FP \approx \left(1 - e^{-kn/m}\right)^k$$



- k - number of hash functions used
- n – number of elements inserted
- m – size of bloom filter (bit array)

Bloom Filters - Summary

- Quick test of element membership:
  - 0 likelihood of false negatives
  - Tunable false positive rates
- Probability of collisions proportional to the number of elements in set & inversely proportional to filter size.
- Enforce maximum false positive threshold by tuning filter size:
  - Often require as little as one byte per element

Functionality

- Significant space and time advantages over many standard, deterministic indexing structures:
  - Self-balancing trees
  - Tries
  - Hash-Tables
  - Arrays, Linked Lists
- Query time is O(k), independent of number of items in set.
- Many open source implementations available.

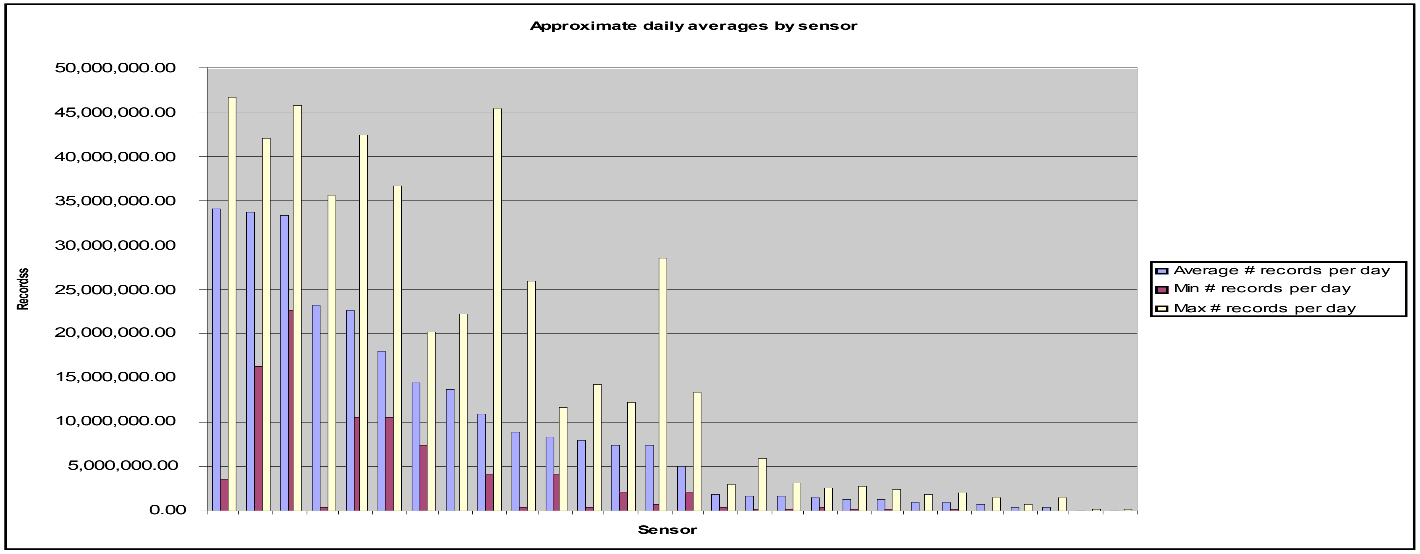
Practicality

Inexpensive, easy to deploy and maintain

Bloom Filters: Operational Viability for CIAC and the CERT Community

CIAC's Flow Collection Review

- CIAC collects massive volumes of biflow data from 29 sensors across the DOE complex:
  - 300-500 million biflows daily (~4600/s)
  - ~14GB/94GB compressed/uncompressed daily



CIAC’s Flow Collection Review

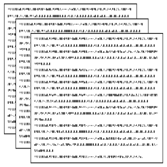
- biflow feed:
  - Session summary
  - Fields:
    - Date/Time & Duration
    - Source/Destination IP and Port
    - Protocol Information
    - Bidirectional Byte and Packet Counts
    - Bidirectional Protocol Options
    - Subset of TCP/ICMP flags

Example Biflow Record

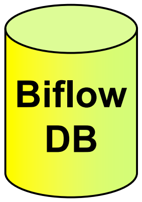
```
1171066191.997532,20070210000951.997532,site3,flo30,6,192168081021,192,168,81,21,IT,010000001008,10,0,1,8,US,53,1024,0,0,0.0000,0,0,54,0,1,0,0,0,0,0,0,60,0,60,0,,,14,00,+14,0,0,0,0
```

CIAC Analysis - Legacy Search Methodologies

- File *grep*
  - Search sensors and hours for range of interest (e.g., “site3, site12, site21 from 10/1/06 through 12/31/06”).
  - Requires reading/decompressing and combing through GBs of data (from disk) for every day searched.

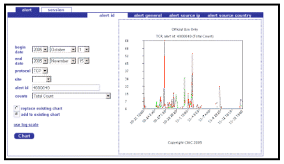


- RDBMS - Oracle
  - SQL+
  - Perl/JDBC
  - Typically limited* to past ~25 days of bi-directional sessions (~15%)



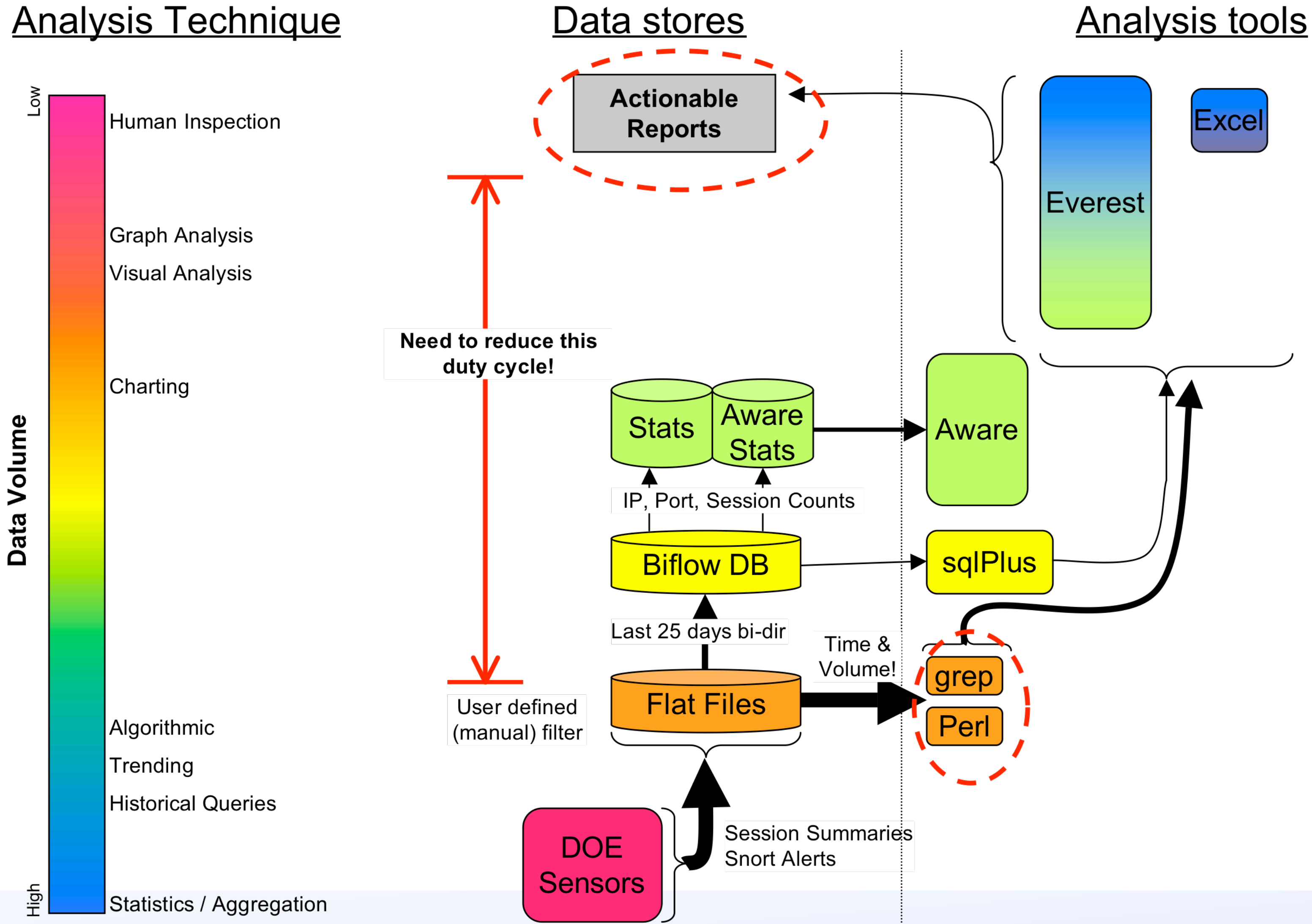
Biflow DB

- AWARE web portal
  - High-level charting and statistics (session counts, etc.)



<u>Many mission-critical searches can take several hours or days to complete</u>

Current CIAC Analysis Data Flow



Watch and Warn Query Needs and Issues

- Rapidly search all flow data over long periods of time:
  - Analysts typically search on IP address:
    - Watch list (suspicious, known-bad, etc.)
    - Nodes of interest
    - Compromised internal nodes
  - Various time (hours, days, months) and space (single site, all sites) scales.
  - Require quick turnaround (minutes) to respond to site requests:
    - e.g. "Have you seen these IPs at my site in the past 3 weeks?"

- IP-based searches often yield relatively small result sets:
  - "Interesting" IP might only have been seen in 30 site-hours, whereas 21,600 hours (~1 DOE-month) might have been searched.

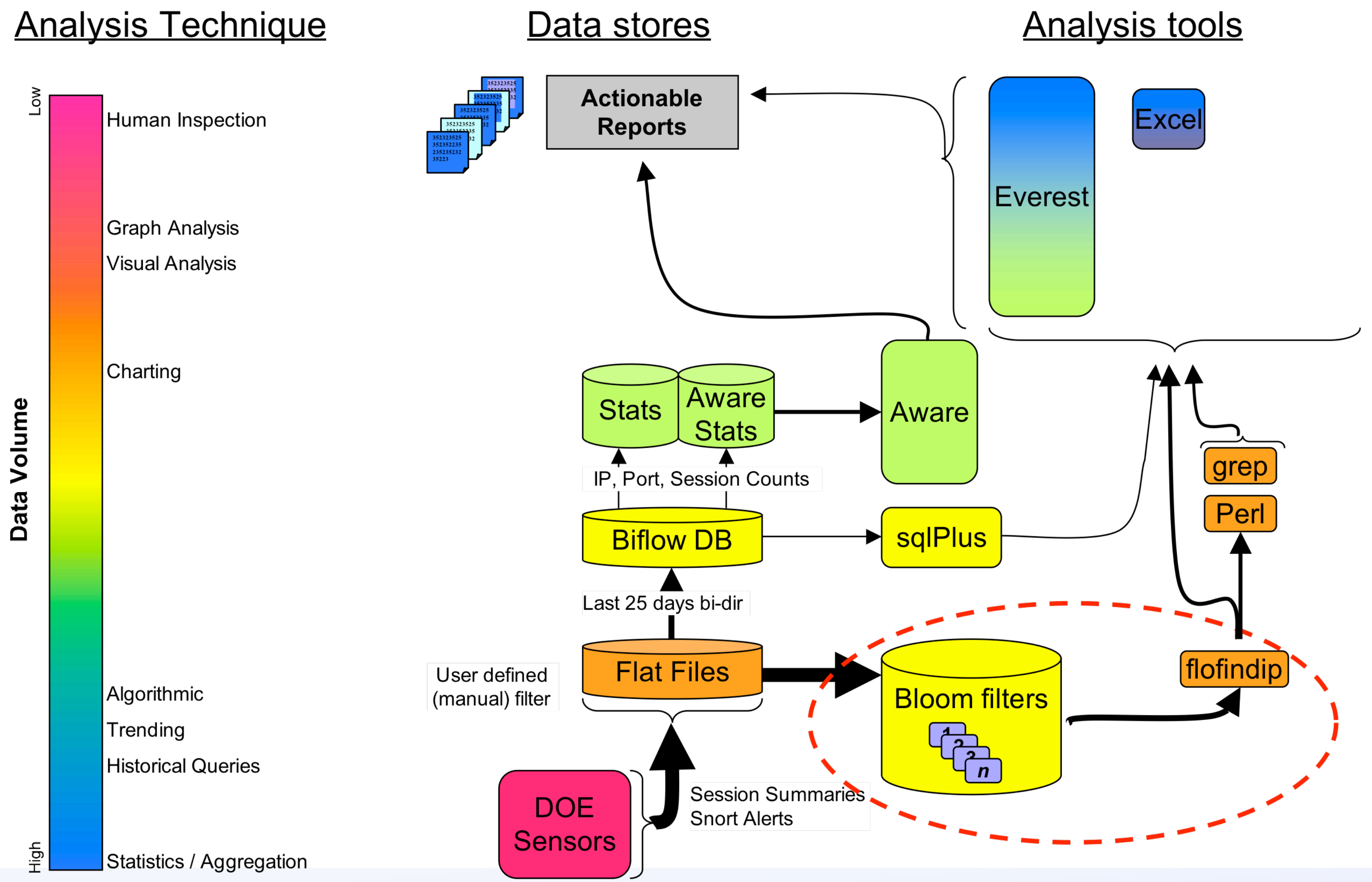
    ➔ 99.9% wasted duty cycle!
  - Need to reduce the search space (raw flow files) through better cataloging of data as it arrives.

Bloomdex:
CIAC’s Bloom Filter-based Indexing System for Network Flow Analysis

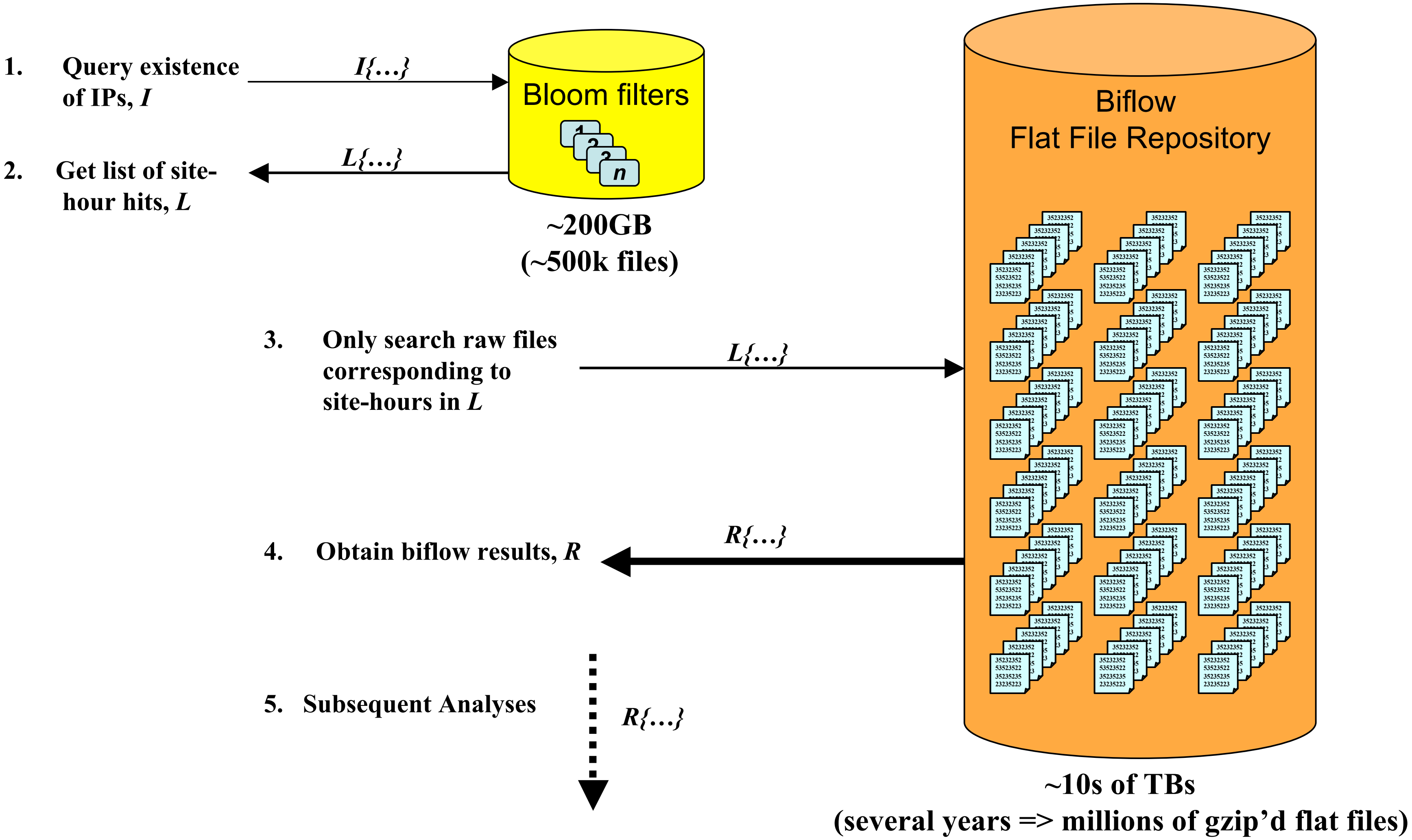
Solution: Bloomdex

- ***Bloomdex***
  - A hybrid hierarchy/file-based Bloom filter system to index CIAC's biflow records.
  - Currently indexed by source or destination IP.
  - Index partitioned by:
    - Site-month (e.g., "SITE8 11/2006")
    - Site-day (e.g., "SITE8 11/5/2006")
    - Site-hour (e.g., "SITE8 11/5/2006 13:00")
  - Uses intuitive directory tree structures and multi-scale bloom filters to accelerate IP-based searches.
  - max(FP rate) ≈ 2×10^{-4} → **3 bytes of storage per unique IP**

Blooomdex - CIAC Analysis Data Flow



Reducing the Biflow Search Space



1. Query existence of IPs, *I*
2. Get list of site-hour hits, *L*
3. Only search raw files corresponding to site-hours in *L*
4. Obtain biflow results, *R*
5. Subsequent Analyses

Bloom filters

~200GB
(~500k files)

Biflow
Flat File Repository

~10s of TBs
(several years => millions of gzip'd flat files)

Bloomdex: Performance Profile

Bloomdex: Comparative Performance Profiles

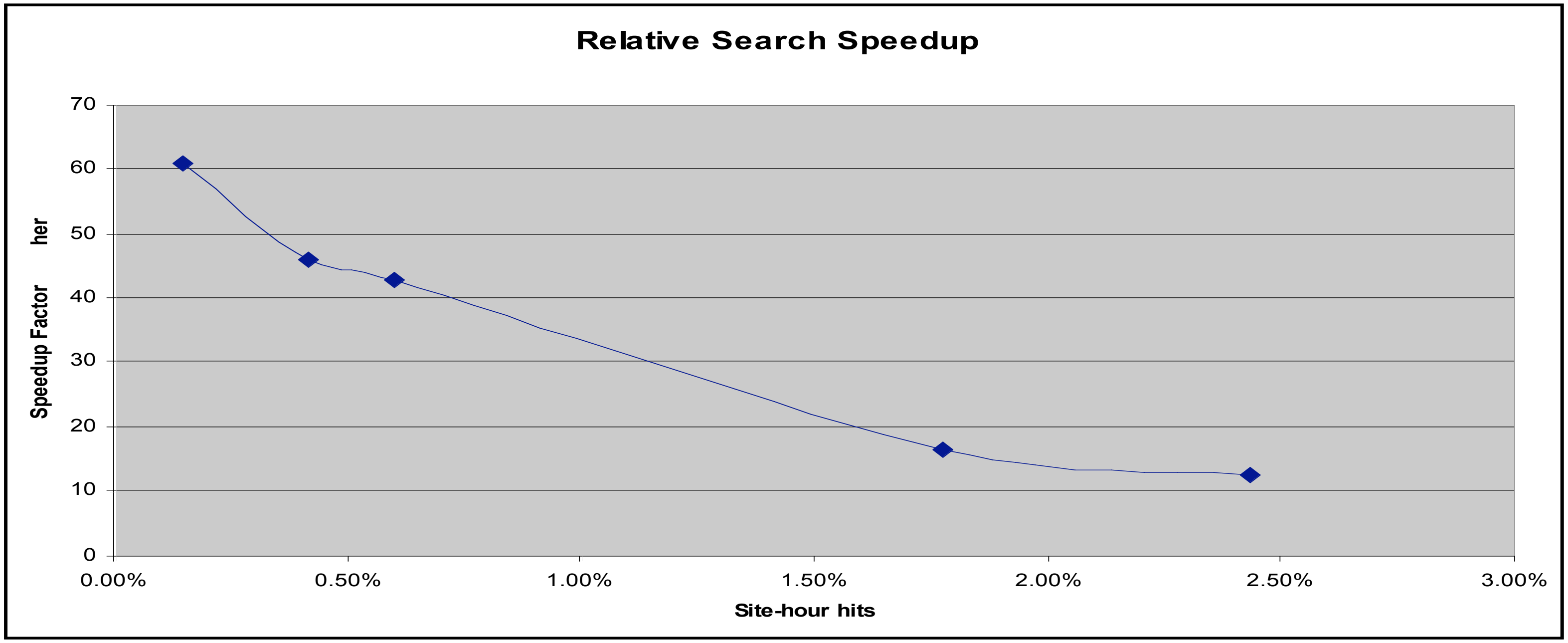
Typical analyst IP-based queries:

IPs searched	Date-range searched	Site-hours searched	Site-hour hits	% Site-hour hits	Session hits	Raw biflow file hits	Search time (conventional)	Search time (bloomdex)	Relative Speedup
8	12/13/06 - 1/9/07	19,140	466	2.43%	10,594	600	**16.29 hours**	**1.3 hours**	**12.5**
13	10/15/06 - 1/17/07	65,888	1,166	1.77%	158,345	1,667	**57.52 hours**	**3.45 hours**	**16.7**
13	1/22/07 - 1/29/07	4,959	31	0.60%	78	39	**4.16 hours**	**5.82 minutes**	**42.9**
4	1/1/07 - 1/2/07	725	3	0.41%	3	3	**21.5 minutes**	**28 seconds**	**46.1**
9	1/23/07 - 1/24/07	725	1	0.14%	1	1	**41.7 minutes**	**41 seconds**	**61**

- Expect >10x speedup
- Strong dependency on site-hour hit ratio
- Future optimizations to search tools could make it even faster

Bloomdex: Performance Profile

- Comparative Performance:



□ **Strong relationship between speedup and site-hour hit ratio**

□ **Ideal for searches on sparsely-occurring IPs**

Bloomdex: Performance Profile

- Bloom filter generation performance:

  - **Average site-day filter generation rate:**
    - ~ 33/hour = 792/day (current incoming rate: 29/day)

  - **Average site-hour filter generation rate:**
    - ~ 390/hour = 9360/day (current incoming rate: 696/day)

<u>Will scale well to 100+ sites (cheaply)</u>

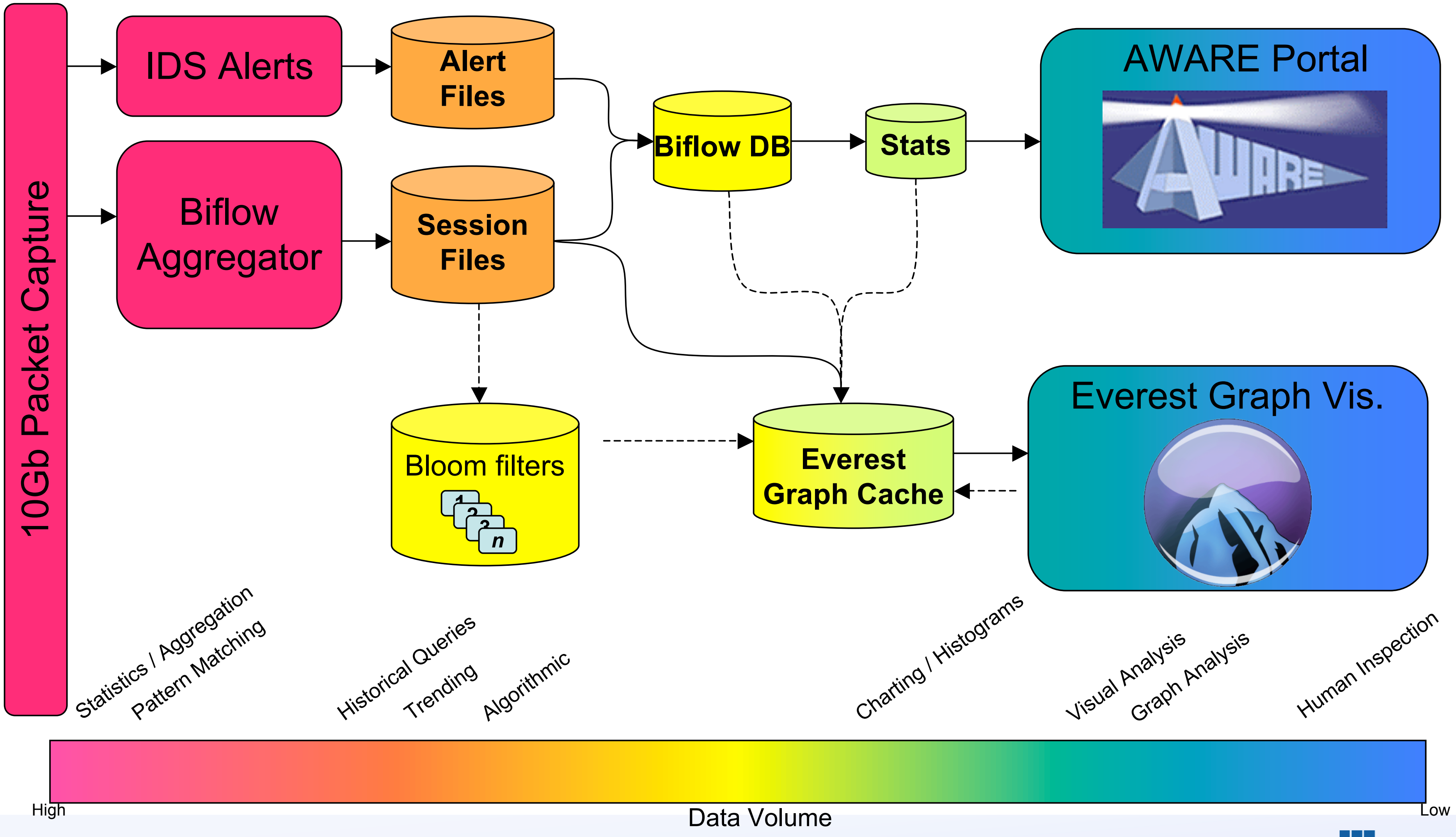
Bloomdex: Status

- **Coverage**
  - 2.5 years of biflow records indexed.
- **Storage footprint**
  - 3 bytes per unique IP at the site-hour, site-day and site-month levels.
  - Bloom filters currently using ~200GB of shared storage.
- **Exploring additional space and performance-based optimizations**
  - Other dimensions (e.g., port, ip-port, srcip-dstip pairs)
  - Counting Bloom filters
  - Different hashing functions
  - Parallelization

Bloomdex:

Analyst Workflow Integration

Analyst Workflow Integration



Facilitating Incident Analysis with Bloomdex and Everest Flow Visualization

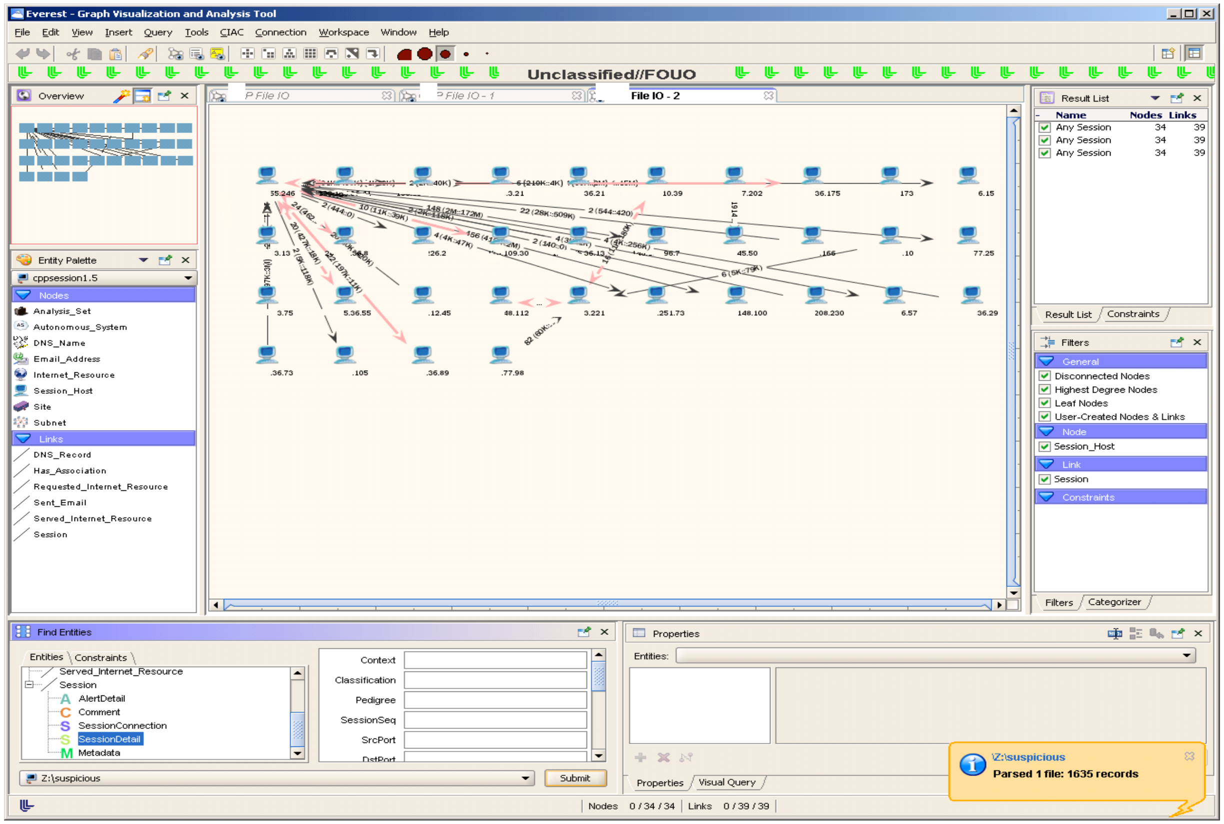
- **Example Use Scenario:**

1. Site reports compromise
   - Supplies <u>4 suspect IPs</u> to CIAC.

2. CIAC queries biflow data for suspect IPs using *Bloomdex* query tool:
   - Search all sensors over a sufficient time range (perhaps a full year).
   - Quickly identify several other sites with hosts exhibiting similar behaviors.
   - <u>Analysis set narrowed down to just 1,635 sessions.</u>

Analysis Using Bloomdex and Everest (2)

3. Launch Everest graph visualization tool, point to *Bloomdex* output file containing result set (1,635 biflow records).
4. Issue general query to generate session graph:



Everest - Graph Visualization and Analysis Tool

Unclassified//FOUO

Result List

Name	Nodes	Links
☑ Any Session	34	39
☑ Any Session	34	39
☑ Any Session	34	39

Filters

General
- ☑ Disconnected Nodes
- ☑ Highest Degree Nodes
- ☑ Leaf Nodes
- ☑ User-Created Nodes & Links

Node
- ☑ Session_Host

Link
- ☑ Session

Constraints

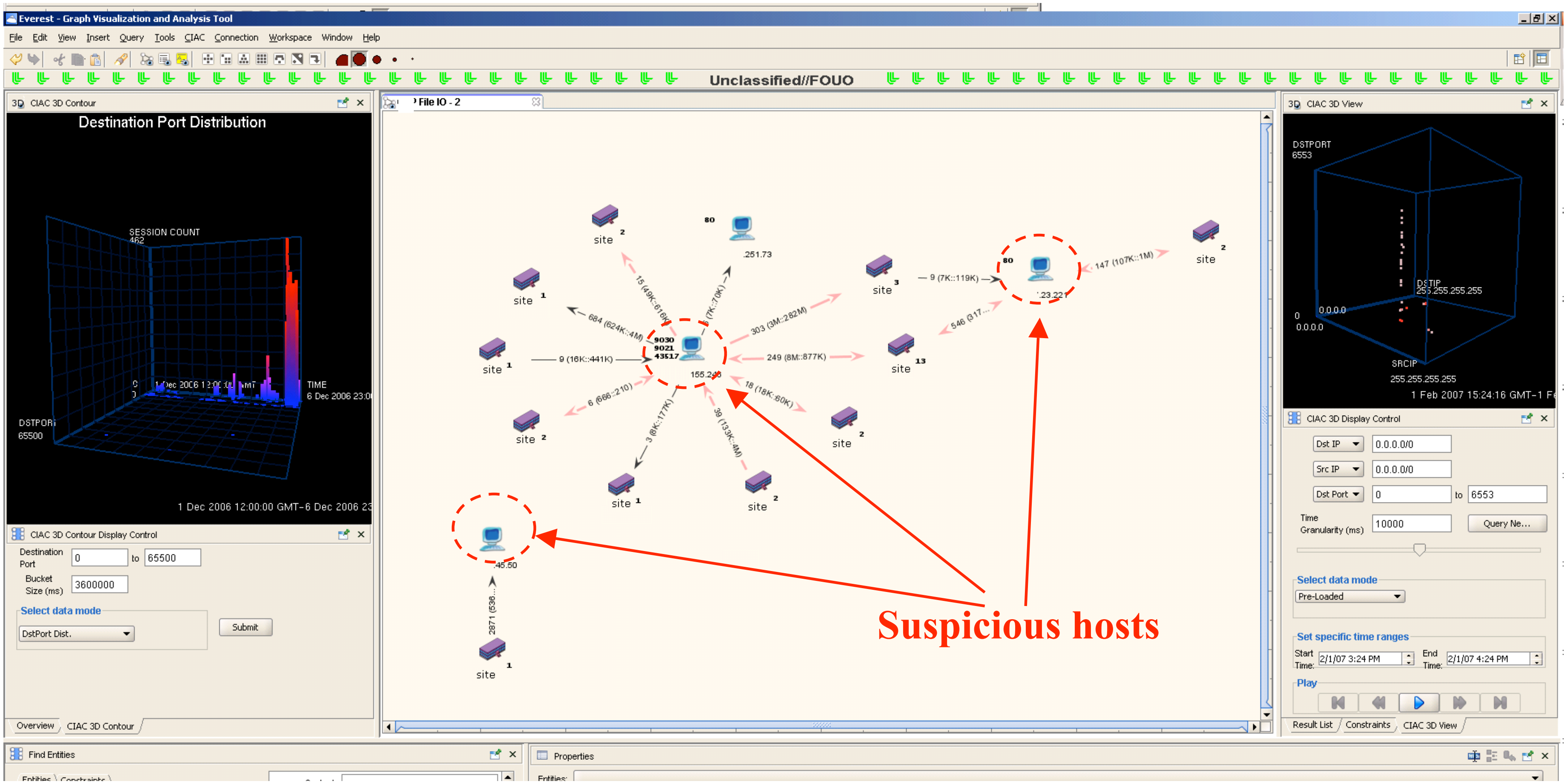
Z:\suspicious

Parsed 1 file: 1635 records

Nodes 0 / 34 / 34 Links 0 / 39 / 39

Analysis Using Bloomdex and Everest (3)

5. Perform drill-down or aggregate analysis



CIAC 3D Contour Display Control

Destination Port: 0 to 65500

Bucket Size (ms): 3600000

Select data mode: DstPort Dist.

Submit

CIAC 3D Display Control

Dst IP: 0.0.0.0/0

Src IP: 0.0.0.0/0

Dst Port: 0 to 6553

Time Granularity (ms): 10000

Query Ne...

Select data mode: Pre-Loaded

Set specific time ranges

Start Time: 2/1/07 3:24 PM

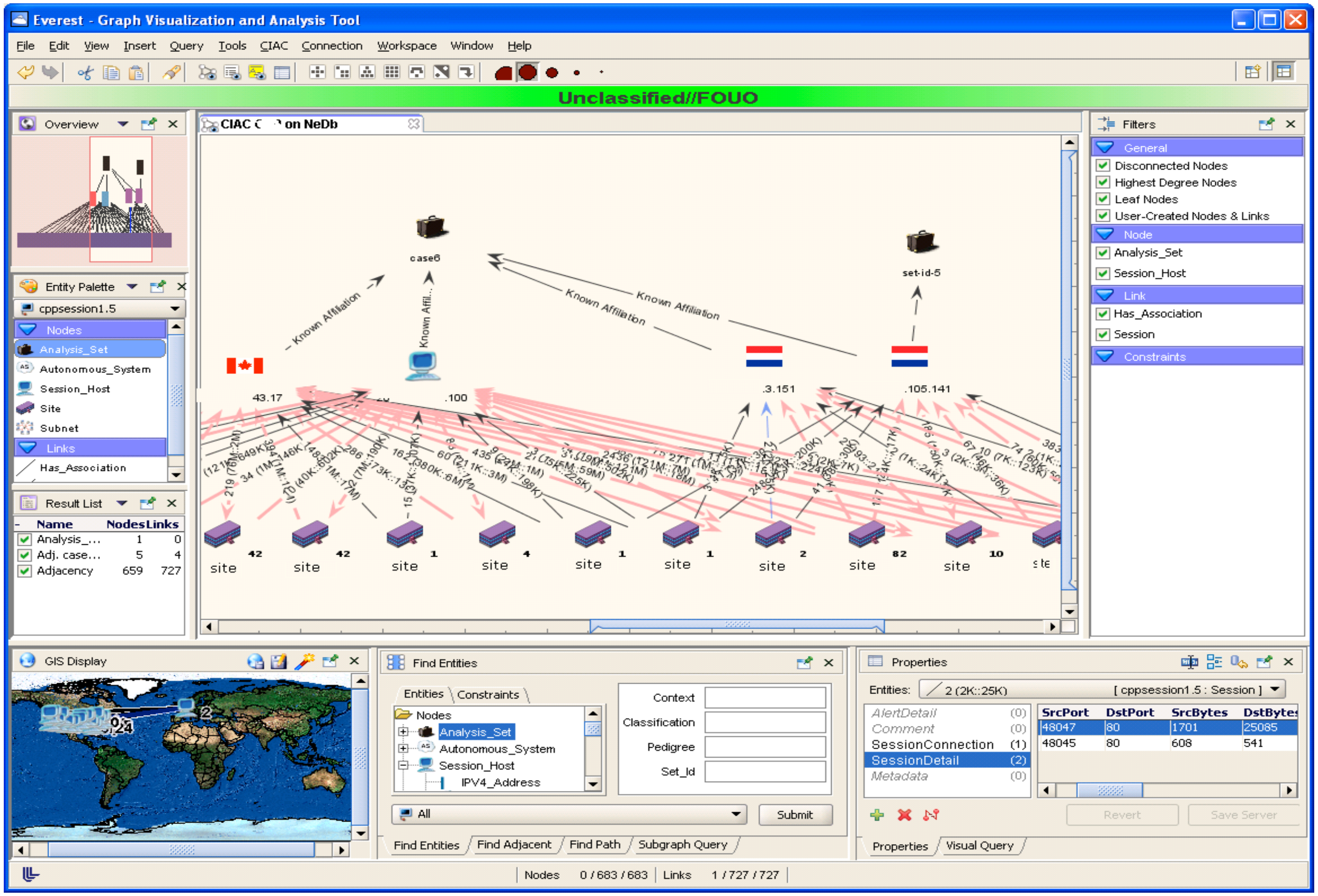
End Time: 2/1/07 4:24 PM

Play

Suspicious hosts

Analysis Using Bloomdex and Everest (4)

6. Perform in-depth or summary analysis



Filters

General
- ☑ Disconnected Nodes
- ☑ Highest Degree Nodes
- ☑ Leaf Nodes
- ☑ User-Created Nodes & Links

Node
- ☑ Analysis_Set
- ☑ Session_Host

Link
- ☑ Has_Association
- ☑ Session

Constraints

Result List

	Name	Nodes	Links
☑	Analysis_...	1	0
☑	Adj. case...	5	4
☑	Adjacency	659	727

Find Entities: Entities / Constraints; Nodes: Analysis_Set, Autonomous_System, Session_Host, IPV4_Address

Context:
Classification:
Pedigree:
Set_Id:

All — Submit

Properties

Entities: 2 (2K::25K) [cppsession1.5 : Session]

AlertDetail	(0)
Comment	(0)
SessionConnection	(1)
SessionDetail	(2)
Metadata	(0)

SrcPort	DstPort	SrcBytes	DstBytes
48047	80	1701	25085
48045	80	608	541

Revert — Save Server

Nodes 0 / 683 / 683 | Links 1 / 727 / 727

Conclusion

- **The *Bloomdex* suite enables significantly faster turnaround times on analyst IP-based queries:**
  - It does this by drastically narrowing the search space through Bloom filter pre-queries.
  - Facilitates use of other analytic tools, such as Everest.
  - Provides significant space savings.
  - **Very straightforward and inexpensive to deploy and maintain.**

- **Future**:
  - Utilize compressed bitmap indexes as an integrated indexing/retrieval solution.

Questions

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