SAQL: A Stream-based Query System for Real-Time Abnormal System Behavior Detection

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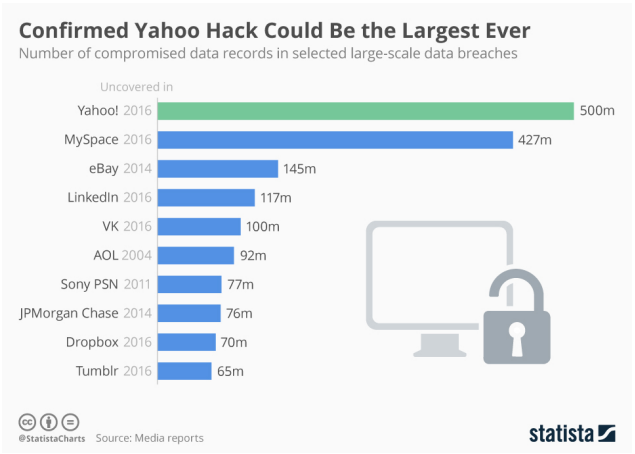
The Equifax Data Breach

Impact of Advanced Persistent Threat (APT) Attack



- Advanced: sophisticated techniques, e.g., exploiting multiple vulnerabilities
- Persistent: adversaries are continuously monitoring and stealing data from the target
- Threat: strong economical or political motives

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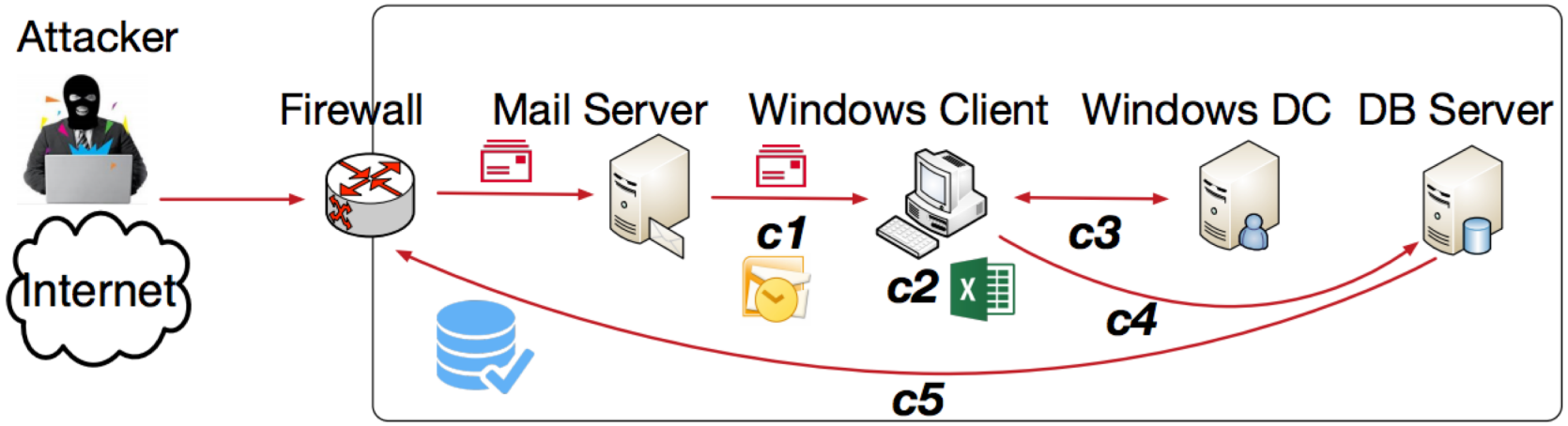
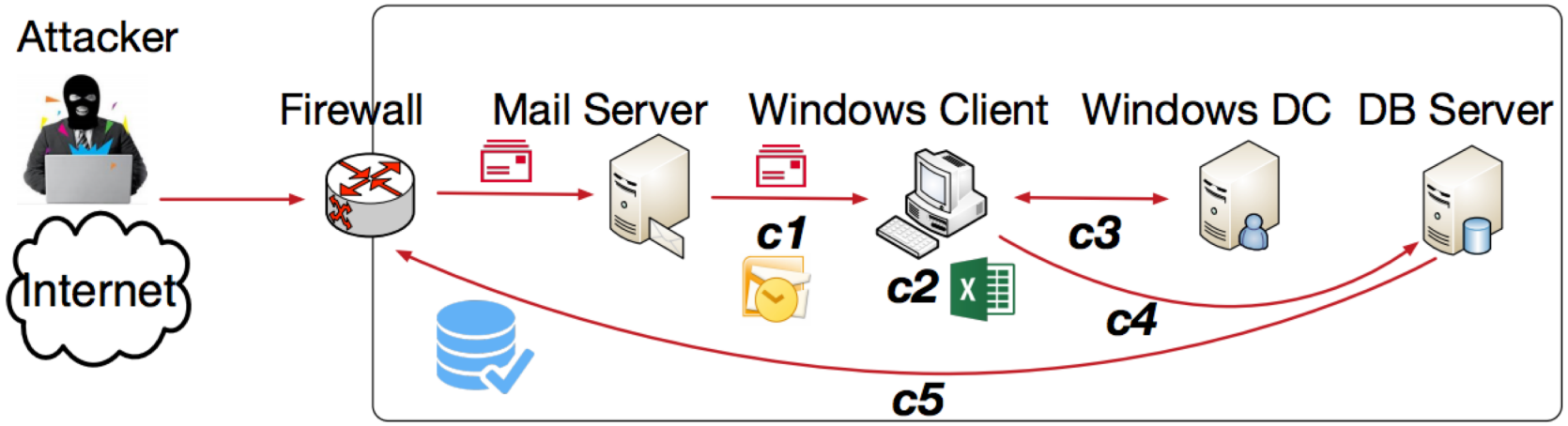
APT Attack: Case Study



- **c1 Initial Compromise**: Attacker sends a crafted e-mail to the victim, which contains an Excel file with a malicious macro embedded
- **c2 Malware Infection**: Victim opens the file and runs the macro, which downloads and executes a malware to open a backdoor
- **c3 Privilege Escalation**: Attacker enters the victim's machine through the backdoor and runs the database cracking tool to obtain database credentials
- **c4 Penetration into Database Server**: Attacker penetrates into the database server and drops another malware to open another backdoor
- **c5 Data Exfiltration**: Attacker dumps the database content and sends the dump back to his host

APT Attack: Case Study



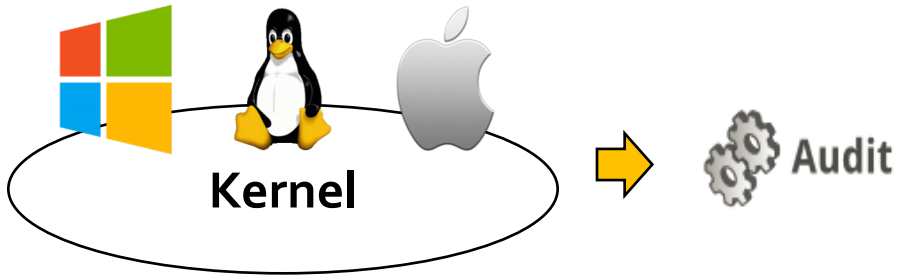
Symantec

FireEye

- Multiple steps exploiting different types of vulnerabilities in the system, exhibiting different abnormal behaviors
  - Known malicious behaviors, e.g., “cmd.exe” starts “gsecdump.exe” (**c3**)
  - Abnormal data transfers, e.g., “sqlservr.exe” transfers large data to external IP, causing large network spikes (**c5**)
  - Abnormal process creations, e.g., “excel.exe” starts “java.exe” (**c2**)

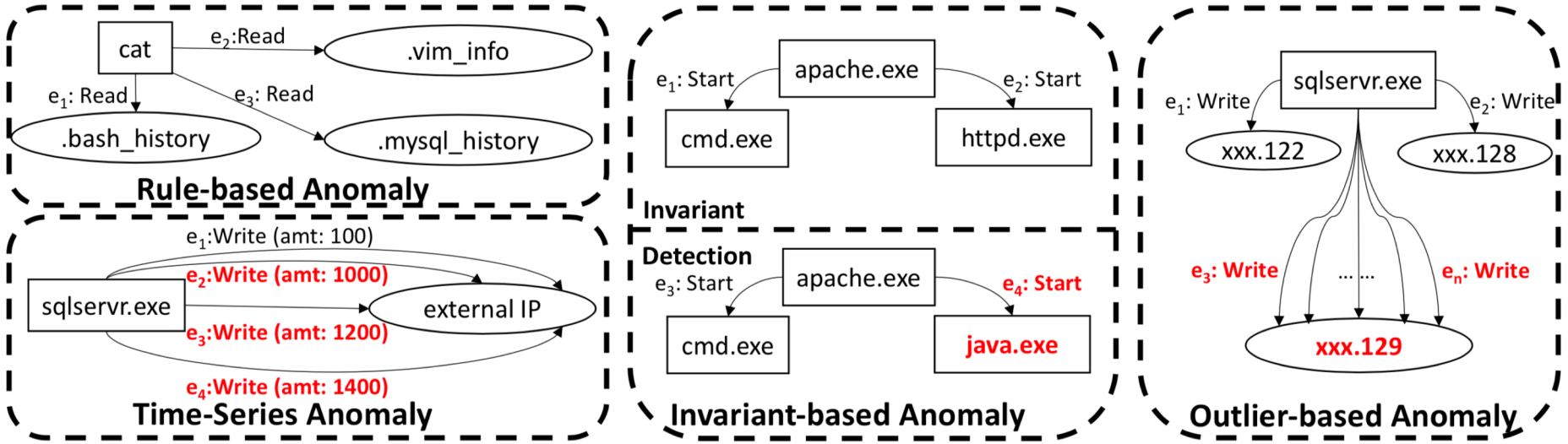
Ubiquitous System Monitoring

- Recording system behaviors from kernel
  - Unified structure of logs: not bound to applications



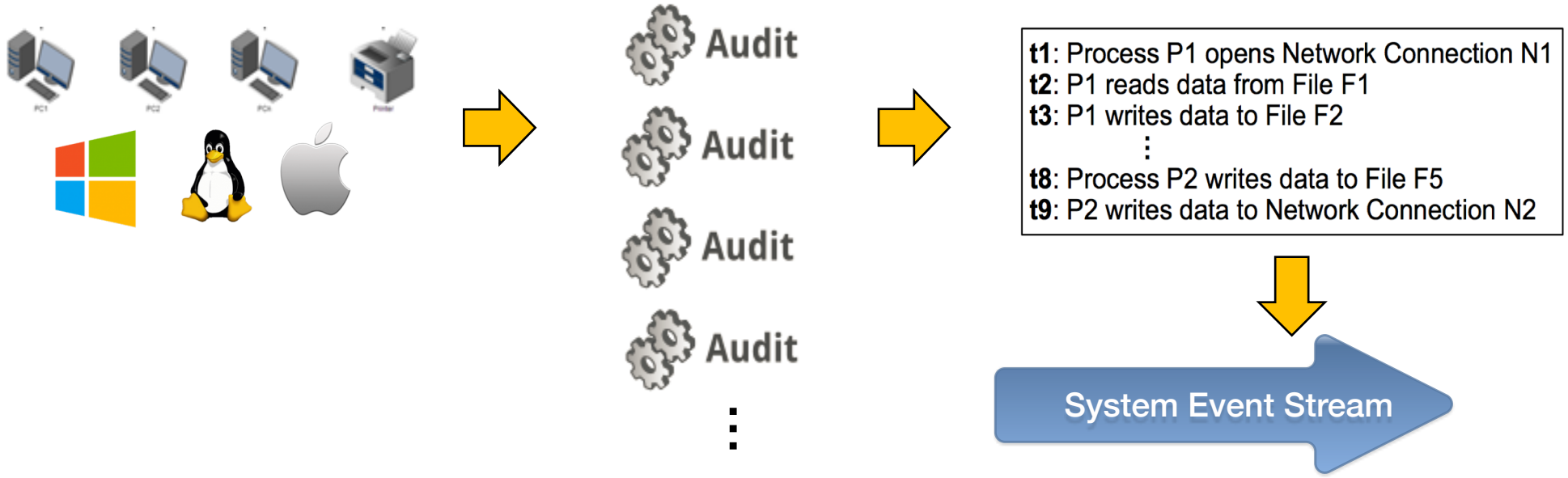
- System activities w.r.t. system resources
  - System resources (system entities): processes, files, network connections
  - System activities (system events): file events, process events, network events
    - Format: <subject, operation, object>, e.g., proc p1 read file f1
- Enabling timely anomaly detection via querying the real-time stream of system monitoring data
  - Continuous queries

Challenge 1: Attack Behavior Specification



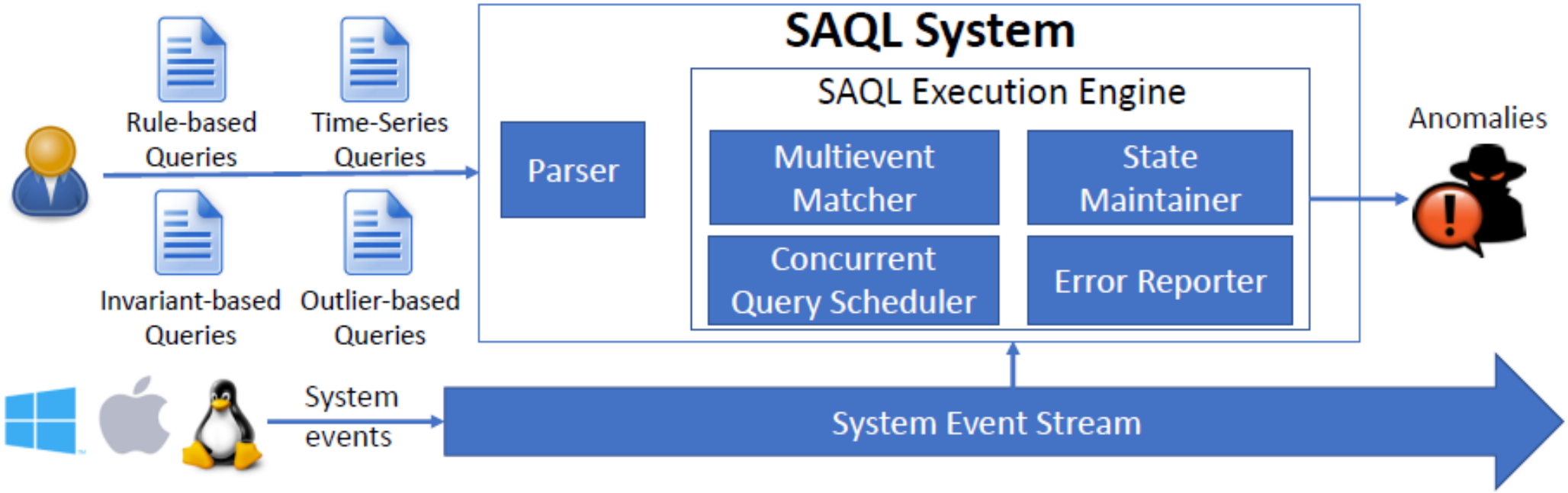
- **Rule-based anomaly**: behavioral rules of system activities and their relationships
- **Time-Series anomaly**: states definition and history states comparison
- **Invariant-based anomaly**: invariant definition, training, and violation checking
- **Outlier-based anomaly**: peer states comparison

Challenge 2: Timely "Big Data" Security Analysis



- System monitoring produces huge amount of system logs per day
  - ~50 GB for 100 hosts per day; throughput ~2500 system events/s (in typical computer science research lab environment)
- Executing multiple concurrent queries incurs considerable overhead

SAQL System



- Novel stream query system for abnormal system behavior detection
  - Build on top of existing mature tools (~50,000 lines of Java code)
    - System-level monitoring tools: auditd, ETW, Dtrace
    - Event stream management: Siddhi

Data Collection

- Data collection agent: system calls as a sequence of system events
  - Windows: Event Tracing for Windows (ETW)
  - Linux: Audit Framework (auditd)
  - Mac: DTrace
- Collect critical attributes for security analysis

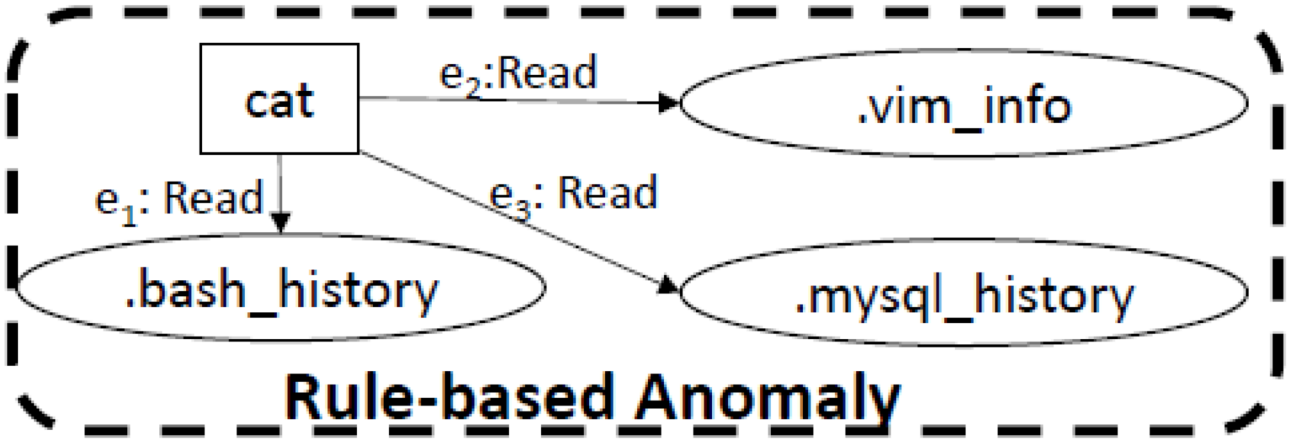
Table 1: Representative attributes of system entities

Entity	Attributes
File	Name, Owner/Group, VolID, DataID, etc.
Process	PID, Name, User, Cmd, Binary Signature, etc.
Network Connection	IP, Port, Protocol

Table 2: Representative attributes of system events

Operation	Read/Write, Execute, Start/End, Rename/Delete
Time/Sequence	Start Time/End Time, Event Sequence
Misc.	Subject ID, Object ID, Failure Code

Rule-based Anomaly: Single-Event




```
1 proc p read file f["%.viminfo" || "%.bash_history" ||
        "%.mysql_history"] as evt
2 return p.exe_name, f.name, evt.agentid, evt.starttime
      , evt.endtime
```

- Event pattern: <subject, operation, object>, attribute constraints, event ID
- Return attributes

Rule-based Anomaly: Multievent

```
1 agentid = XXX // db server
2 proc p1["%cmd.exe"] start proc p2["%osql.exe"] as
      evt1
3 proc p3["%sqlservr.exe"] write file f1["%backup1.dmp"
      ] as evt2
4 proc p4["%sbblv.exe"] read file f1 as evt3
5 proc p4 read || write ip i1[dstip="XXX"] as evt4
6 with evt1 -> evt2 -> evt3 -> evt4
7 return p1, p2, p3, f1, p4, i1, evt1.starttime, evt2.
      starttime, evt3.starttime, evt4.starttime, evt4.
      amount
```

exe_name = “%cmd.exe”

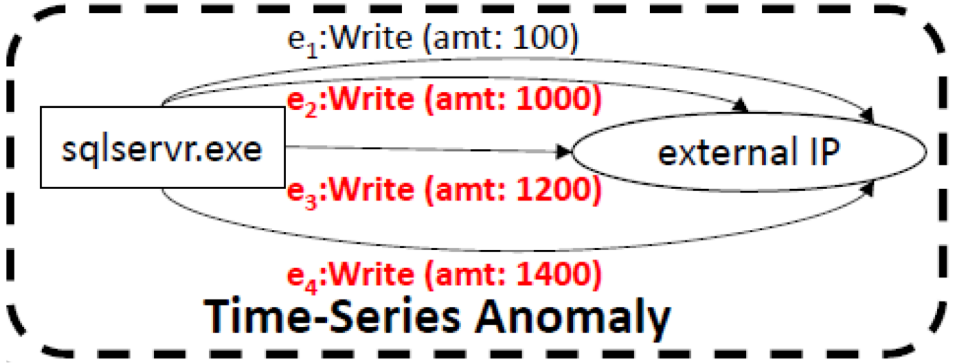
name = “%backup1.dmp”

p1.exe_name, p2.exe_name, p3.exe_name, f1.name, p4.exe_name, i1.dst_ip

- Global constraints: e.g., agent ID
- Event patterns: <subject, operation, object>, attribute constraints, event ID
- Temporal relationships: enforce the event order
- Attribute relationships: e.g., two events linked by the same entity
- Syntax shortcuts: e.g., context-aware attribute inference

Time-Series Anomaly

- Sliding windows
- Aggregation states
- History states access
- Time-series anomaly models (e.g., SMA3)

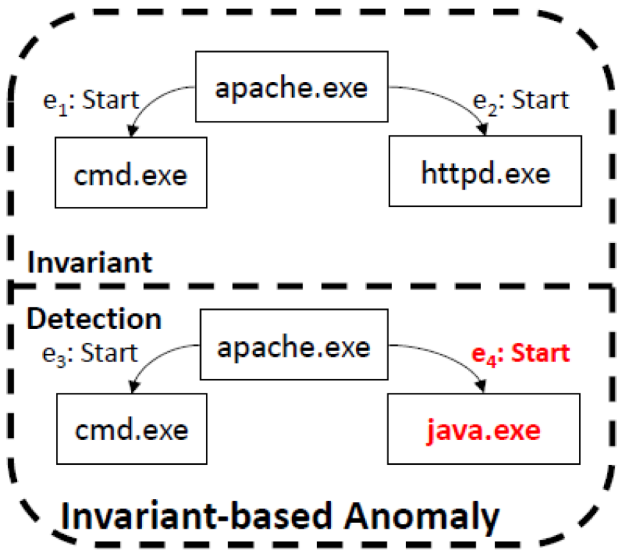


Existing systems lack the explicit support for stateful computation in sliding windows

```
1 agentid = XXX // db server
2 proc p write ip i as evt #time(10 min)
3 state[3] ss {
4   avg_amount := avg(evt.amount)
5 } group by p
6 alert (ss[0].avg_amount > (ss[0].avg_amount + ss[1].
      avg_amount + ss[2].avg_amount) / 3) && (ss[0].
      avg_amount > 10000)
7 return p, ss[0].avg_amount, ss[1].avg_amount, ss[2].
      avg_amount
```

Invariant-based Anomaly

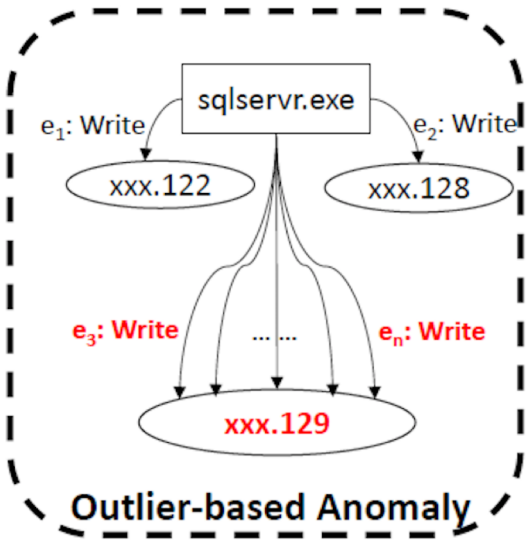
- Invariants definition
- Invariants update
- Offline/online training
- Invariant-based anomaly models




```
1  proc p1["%apache.exe"] start proc p2 as evt #time(10
       s)
2  state ss {
3    set_proc := set(p2.exe_name)
4  } group by p1
5  invariant[10][offline] {
6    a := empty_set
7    a = a union ss.set_proc
8  }
9  alert |ss.set_proc diff a| > 0
10 return p1, ss.set_proc
```

Outlier-based Anomaly

- Cluster definition
- Distance metric
- Clustering method
- Outlier-based anomaly models




```
1 agentid = xxx // db server
2 proc p["%sqlservr.exe"] read || write ip i as evt #
      time(10 min)
3 state ss {
4   amt := sum(evt.amount)
5 } group by i.dstip
6 cluster(points=all(ss.amt), distance="ed", method="
      DBSCAN(100000, 5)")
7 alert cluster.outlier && ss.amt > 1000000
8 return i.dstip, ss.amt
```

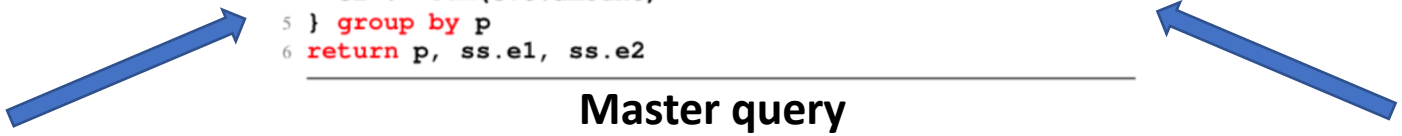
SAQL Execution Engine

```
1 agentid = XXX // db server
2 proc p write ip i as evt #time(10 min)
3 state[3] ss {
4   avg_amount := avg(evt.amount)
5 } group by p
6 alert (ss[0].avg_amount > (ss[0].avg_amount + ss[1].
      avg_amount + ss[2].avg_amount) / 3) && (ss[0].
      avg_amount > 10000)
7 return p, ss[0].avg_amount, ss[1].avg_amount, ss[2].
      avg_amount
```

- **Multievent pattern matching**: match the stream against the event patterns
- **Stateful computation**: compute and maintain states over sliding windows
- **Alert condition checking**: check conditions for triggering alerts
- **Return and filters**: return desired attributes of qualified events

Master-Dependent-Query Scheme

- Challenge: executing multiple concurrent queries incurs considerable overhead
- Key insight: share intermediate execution results among queries (two levels for now: event pattern matching, stateful computation)
  - ➢ Partition concurrent queries into *master-dependent groups*
  - ➢ Only master query has direct access to the stream



```
proc p read || write file f["/etc/passwd" || "%.ssh/
     id_rsa" || "%.bash_history" || "/var/log/wtmp"]
     as evt #time(1 min)
state ss {
  e1 := count(evt.id)
  e2 := sum(evt.amount)
} group by p
return p, ss.e1, ss.e2
```

Master query

```
proc p read || write file f["/etc/passwd" || "%.ssh/
     id_rsa" || "%.bash_history" || "/var/log/wtmp"]
     as evt #time(1 min)
state ss {
  e1 := count(evt.id)
} group by p
return p, ss.e1
```

Dependent query 1

```
proc p read || write file f["/etc/passwd" || "%.ssh/
     id_rsa" || "%.bash_history" || "/var/log/wtmp"]
     as evt #time(1 min)
state ss {
  e2 := sum(evt.amount)
} group by p
return p, ss.e2
```

Dependent query 2

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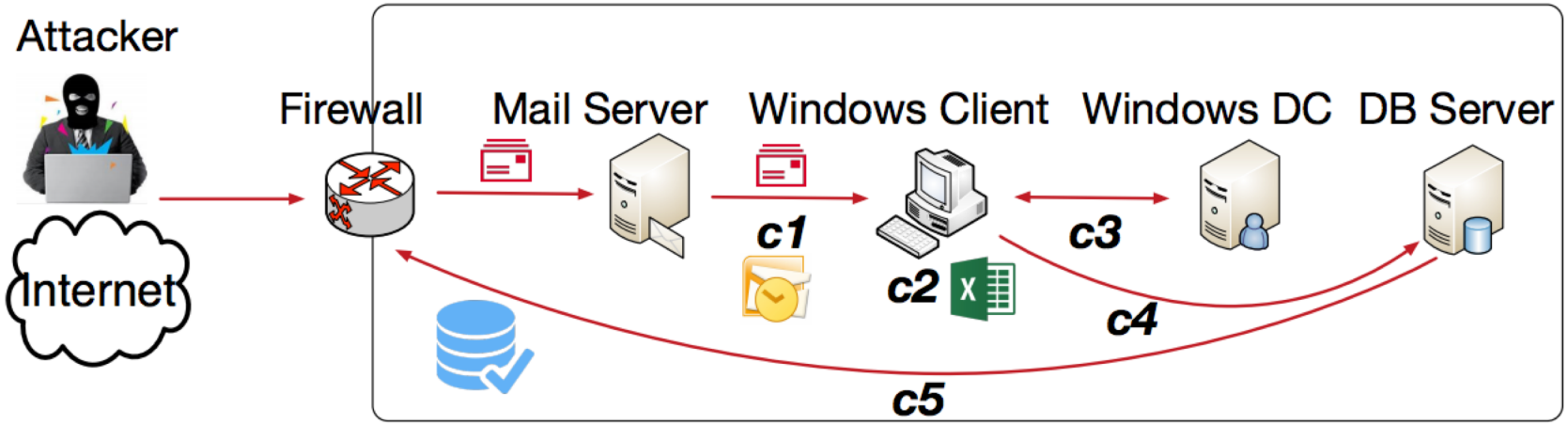
Case Study: Four Major Types of Attacks

- Deploy in NEC Labs of 150 hosts (1.1 TB data; 3.3 billion events; throughput 3750 events/s)
- Deployed server has 12 cores and 128GB of RAM
- 17 queries
  - **APT attack**: *apt-c1, apt-c2, apt-c3, apt-c4, apt-c5, apt-c2-invariant, apt-c5-timeseries, apt-c5-outlier*
  - **SQL injection attack**: *sql-injection*
  - **Bash shellshock command injection attack**: *shellshock*
  - **Suspicious system behaviors**: *dropbox, command-history, password, login-log, sshkey, usb, ipfreq*



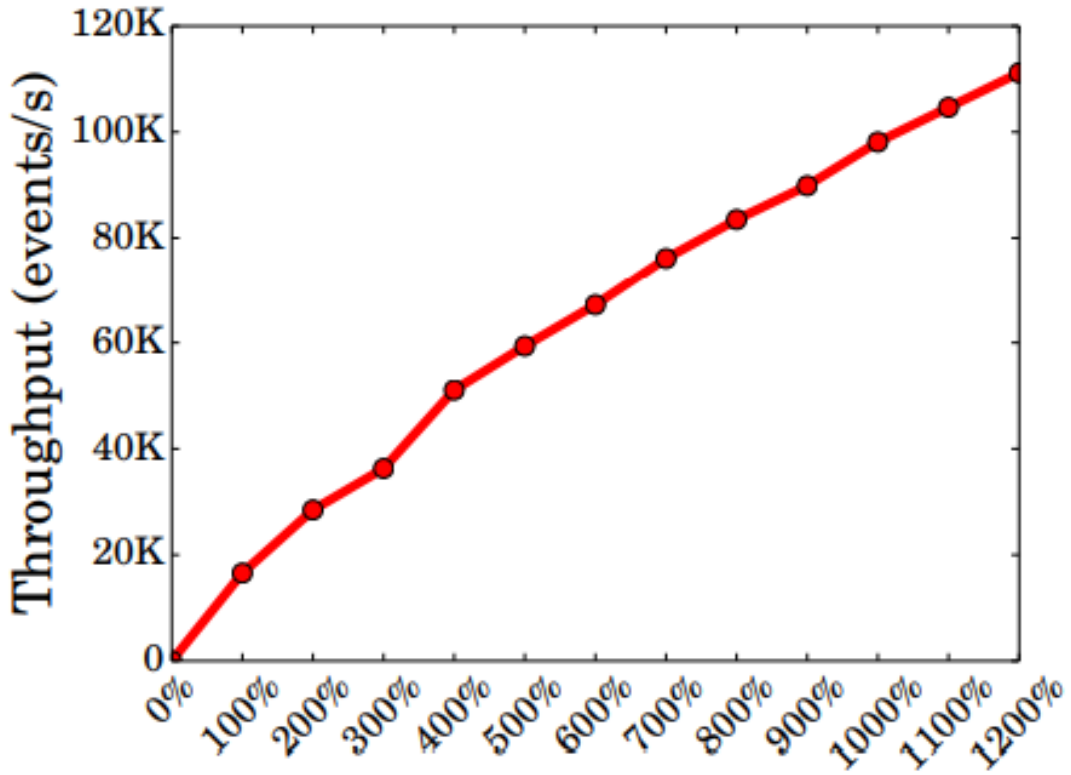
Case Study: Execution Statistics

Table 3: Execution statistics of 17 SAQL queries for four major types of attacks

SAQL Query	Alert Detection Latency	Num. of States	Tot. State Size	Avg. State Size	CPU	Memory
apt-c1	≤1ms	N/A	N/A	N/A	10%	1.7GB
apt-c2	≤1ms	N/A	N/A	N/A	10%	1.8GB
apt-c3	6ms	N/A	N/A	N/A	8%	1.6GB
apt-c4	10ms	N/A	N/A	N/A	10%	1.5GB
apt-c5	3ms	N/A	N/A	N/A	10%	1.6GB
apt-c2-invariant	≤1ms	5	5	1	8%	1.8GB
apt-c5-timeseries	≤1ms	812	3321	4.09	6%	2.2GB
apt-c5-outlier	2ms	812	3321	4.09	8%	2.2GB
shellshock	5ms	3	3	1	8%	2.7GB
sql-injection	1776ms	14	13841	988.6	8%	1.9GB
dropbox	2ms	N/A	N/A	N/A	8%	1.2GB
command-history	≤1ms	N/A	N/A	N/A	10%	2.2GB
password	≤1ms	N/A	N/A	N/A	9%	1.6GB
login-log	≤1ms	N/A	N/A	N/A	10%	2.2GB
sshkey	≤1ms	N/A	N/A	N/A	10%	2.1GB
usb	≤1ms	N/A	N/A	N/A	9%	2.1GB
ipfreq	≤1ms	N/A	N/A	N/A	10%	2.1GB

Low detection latency: <2s

Pressure Test



High system throughput: 110,000 events/s; supporting ~4000 hosts

Performance of Concurrent Query Execution

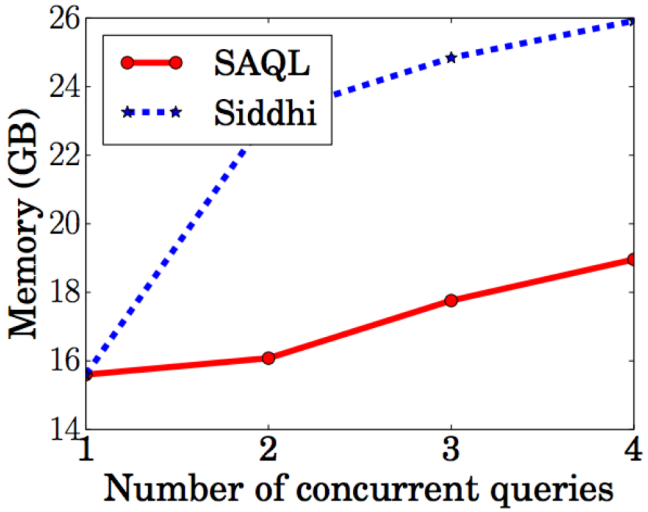
- 64 micro-benchmark queries
  - Four **attack categories**:
    - Sensitive file access: */etc/password, .ssh/id_rsa, .bash_history, /var/log/wtmp*
    - Browsers access files: *chrome, firefox, iexplore, microsoftedge*
    - Processes access networks: *dropbox, sqlservr, apache, outlook*
    - Processes spawn: */bin/bash, /usr/bin/ssh, cmd.exe, java*
  - Four **evaluation categories** for query variations:
    - Event attribute: 1 attribute -> 4 attributes
    - Sliding window: 1 minute -> 4 minute
    - Agent ID: 1 agent -> 4 agents
    - State aggregation: 1 aggregation type -> 4 aggregation types
  - 4 queries for each joint category, 64 = 4 * 4 * 4

Performance of Concurrent Query Execution

- Example micro-benchmark query for joint category “sensitive file accesses & state aggregation”

```
proc p read || write file f["/etc/passwd" || "%.ssh/
     id_rsa" || "%.bash_history" || "/var/log/wtmp"]
     as evt #time(1 min)
state ss {
  e1 := count(evt.id)
  e2 := sum(evt.amount)
  e3 := avg(evt.amount)
  e4 := max(evt.amount)
} group by p
return p, ss.e1, ss.e2, ss.e3, ss.e4
```

- Memory consumption (MB) w.r.t. number of concurrent queries



30% average memory saving for all 64 categories

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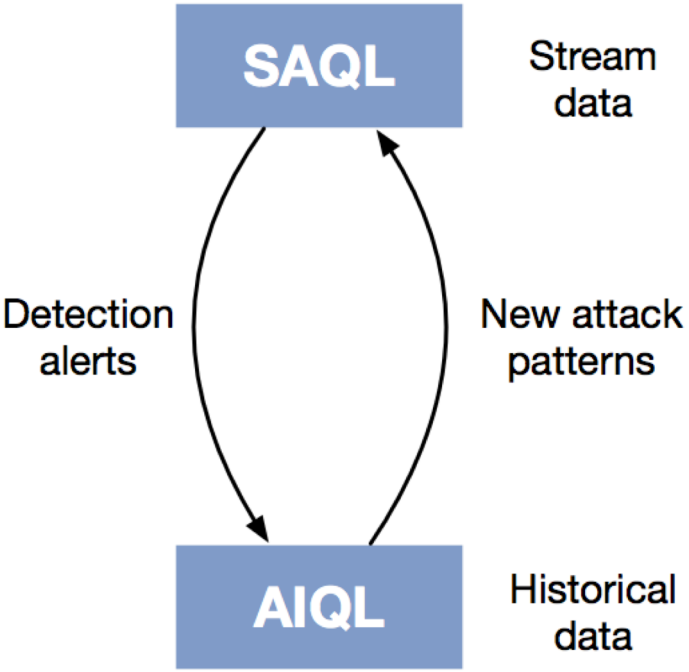
Alert Detection and Investigation

- Historical data is required for alert investigation

- **AIQL (Attack Investigation Query Language) System (*USENIX ATC'18*)**
  - Data stored in relational databases with efficient indexing
  - Compatible query language
  - Leverage domain specifics to speedup the search of complex system event patterns
  - Project website: https://sites.google.com/site/aiqlsystem/

- Together, SAQL and AIQL work seamlessly for defending against APT attacks



Conclusion

- **SAQL (Stream-based Anomaly Query Language) System** : enabling timely anomaly detection via querying the real-time stream of system monitoring data
  - Concisely express four types of anomaly models
  - Efficient stream management and concurrent query execution based on domain specifics
  - Project website: https://sites.google.com/site/saqlsystem/

Q & A

Thank you!

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