HOLMES:

Real-time APT Detection through Correlation of Suspicious Information Flows

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Advanced Persistent Threat (APT) and its challenges

Targeted cyber attacks on organizations getting more sophisticated and stealthy.

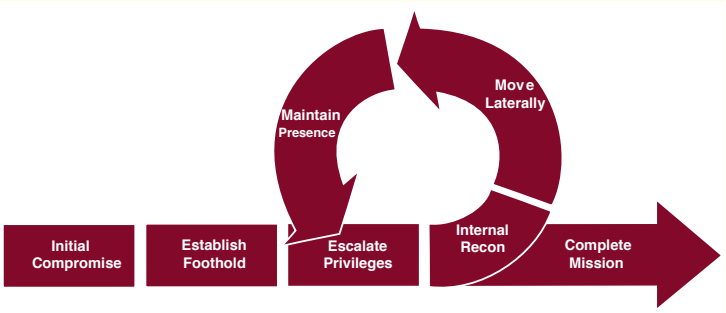
Goal: to steal data, disrupt operations or destroy infrastructure.

- APTs combine many different attack vectors
  - Each appearing in some log sources
    - Firewall, IDS/IPS, Netflow, DNS logs, Identity and access management tools
- Might occur over a long duration
  - Correlating heterogeneous alarms using heuristics like timestamp is not so effective
  - Lacking the full picture (root cause, affected entities, etc.).

Significant manual effort and expertise are needed to piece together numerous alarms emitted by multiple security tools.

Intuition

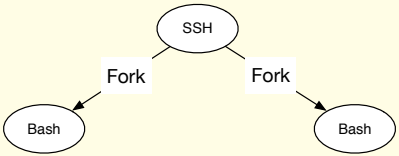
- APT behaviors often conform to the kill-chain [MANDIANT-APT1]

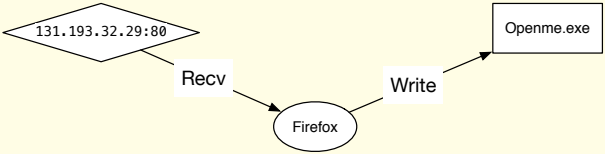


  - Our analysis of over 300 APT whitepapers confirms that most APTs follow this kill-chain
- In particular, high-level steps of APTs need to be causally connected
  - Use connectedness of high-level steps as a basis for campaign detection

Approach

- Use Provenance Graph to enable alert correlation for attack campaign detection
  - vertices: system entities (socket, process, file, memory, etc.), and agents (user, groups, etc.)
  - edges: system calls (causal dependencies or information flow)

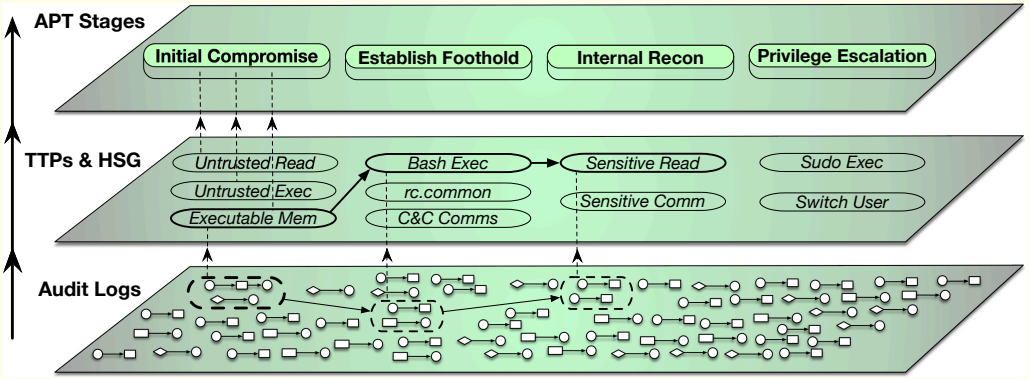




- Leverage the full historical context of a system
- Reason about interrelationships between different events and objects
- *Key challenge*: How to bridge semantic gap between low-level records and high-level activities in killchain?

Bridging the Semantic Gap

Use Tactics, Techniques, and Procedures (TTPs) from MITRE's **ATT&CK** framework as an intermediate layer to bridge low-level audit records to high-level steps



Bridging the Semantic Gap

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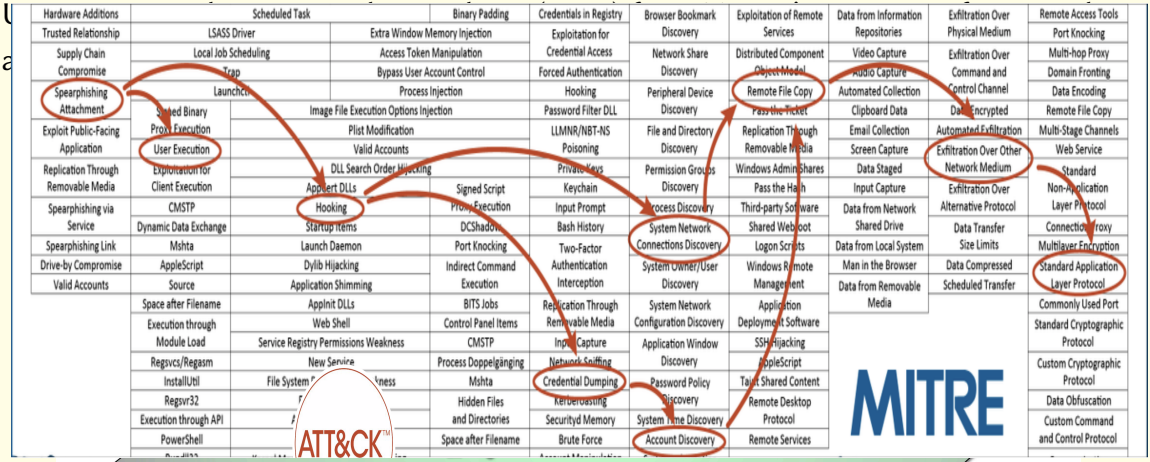
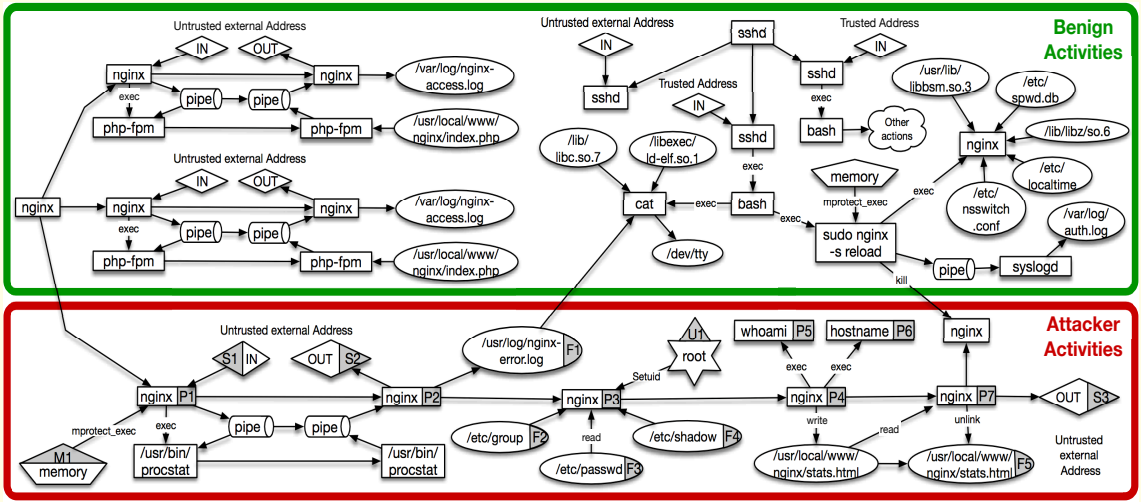


Illustrative Example



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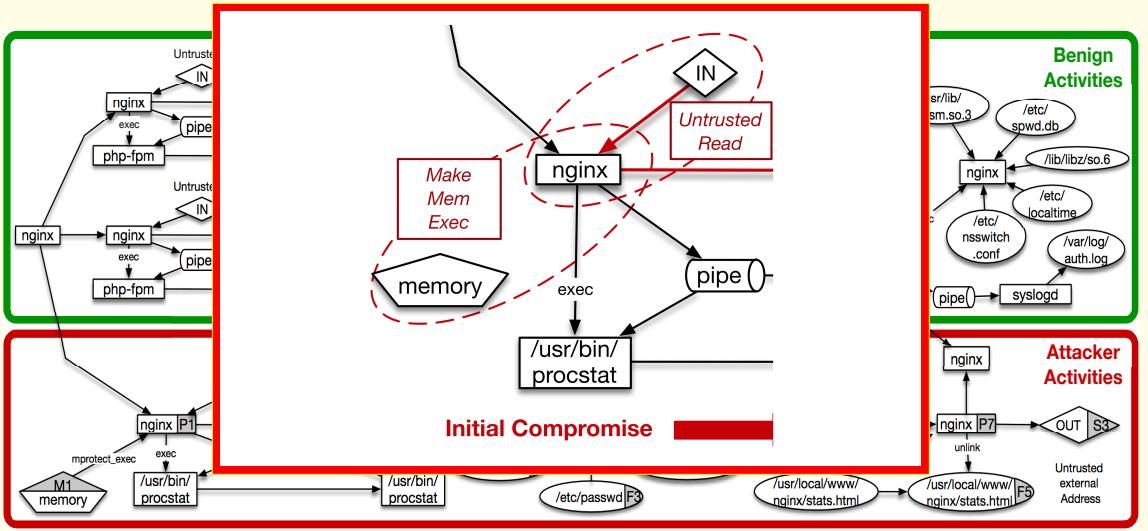

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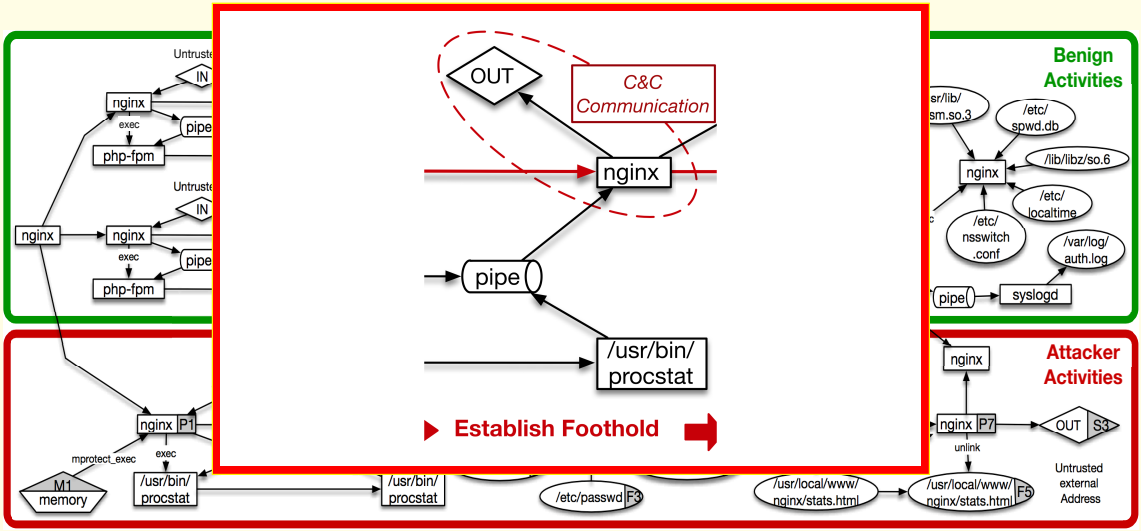

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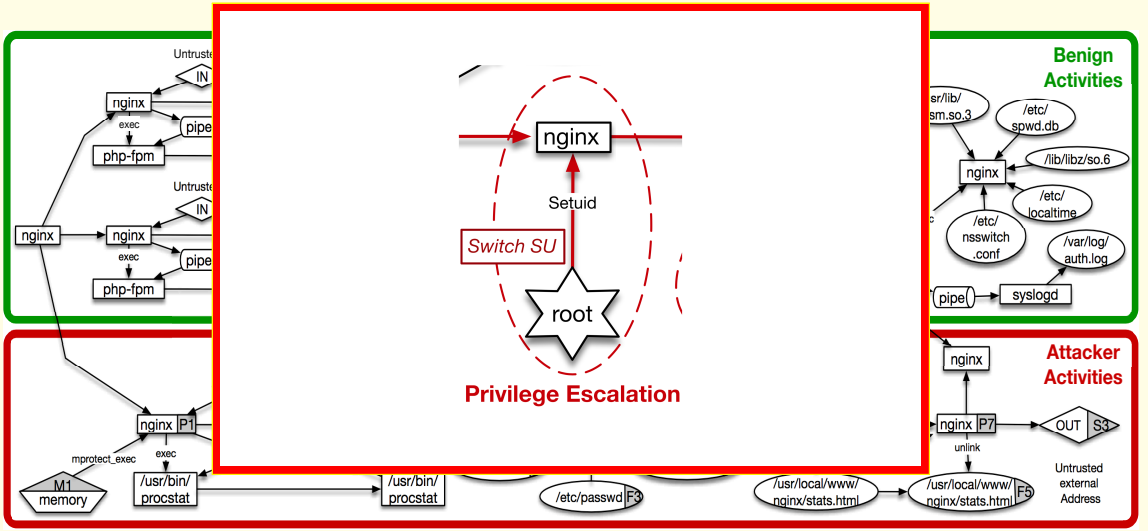

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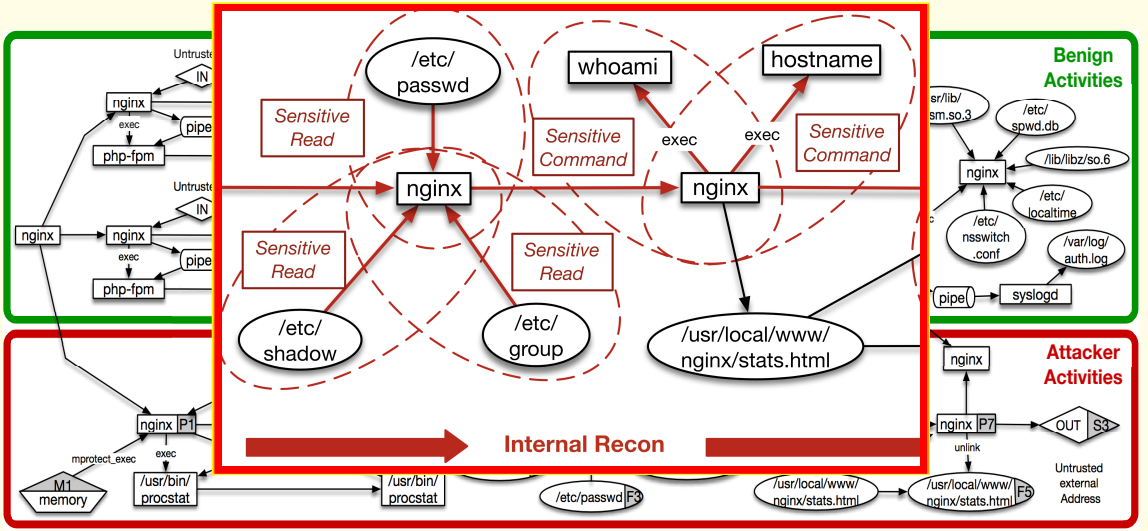

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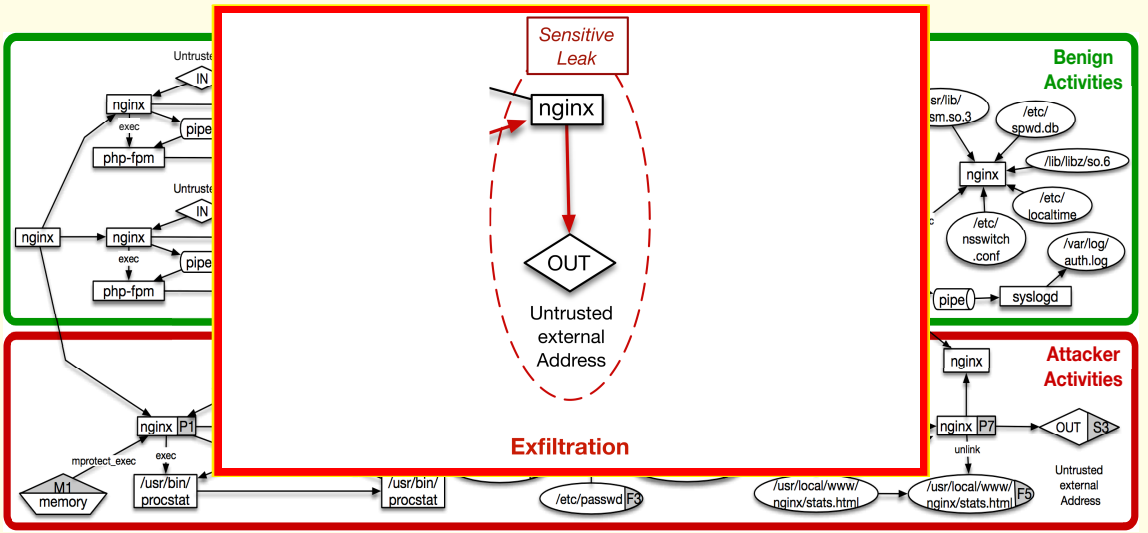

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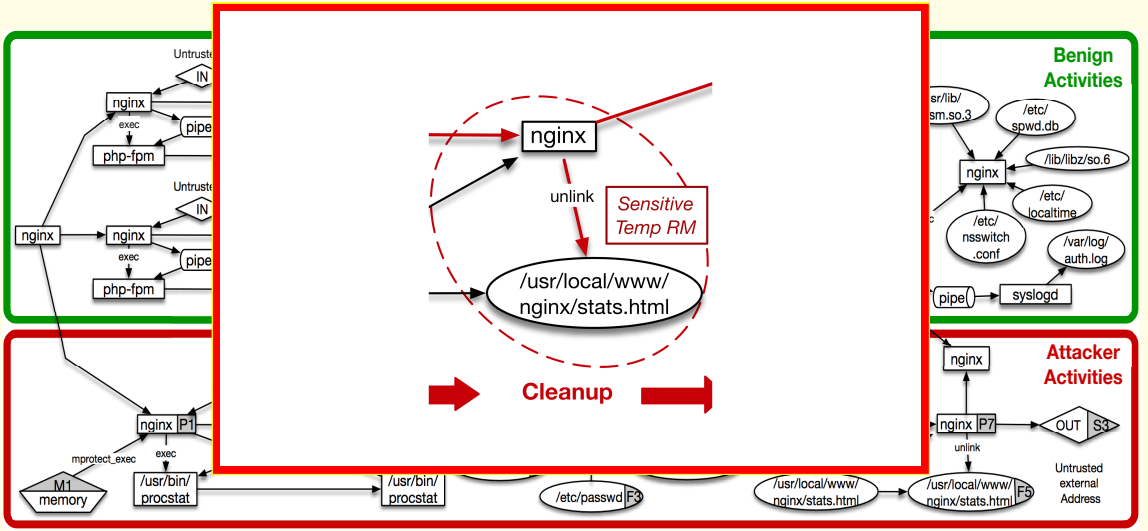

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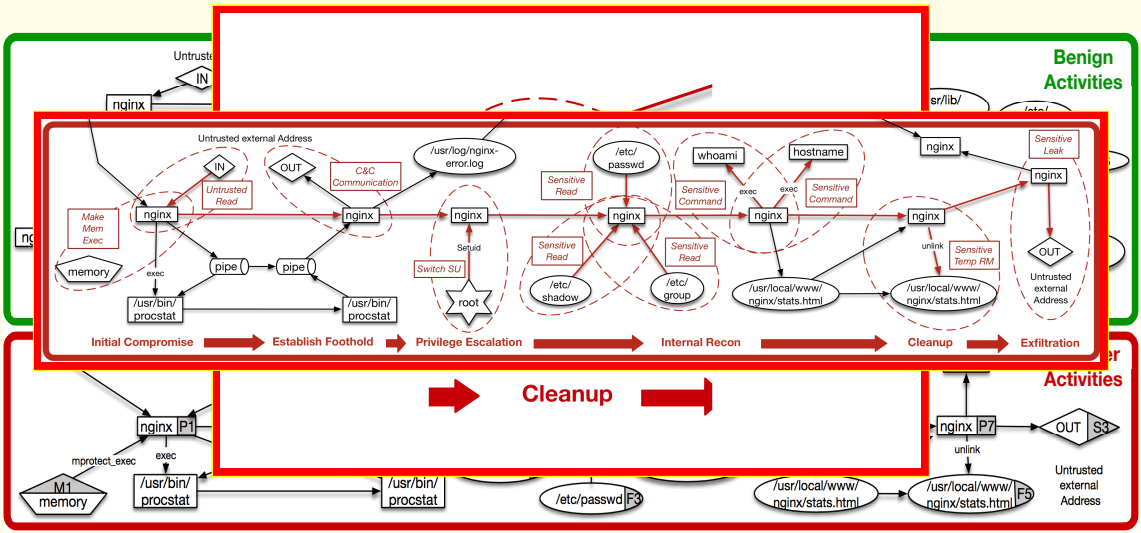
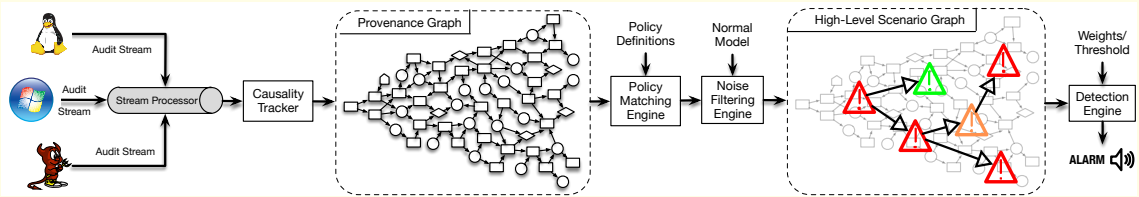


HOLMES Architecture



- Develop TTP specifications over audit logs
- Use specifications to detect TTPs
- Filter noise based on data quantities of benign information flows, measured in bytes transferred
- Construct high-level graph (HSG) that correlates individual alerts/TTPs
- Derive campaign detection signal from graph

Example TTP specifications

APT Stage	TTP	Event Family	Events	Severity	Prerequisites
Initial_Compromise(P)	*Untrusted_Read*(S, P)	READ	FileIoRead (Windows), read/pread/readv/preadv (Linux,BSD)	L	$S.ip \notin$ {Trusted_IP_Addresses}
	Make_Mem_Exec(P, M)	MPROT	VirtualAlloc (Windows), mprotect (Linux,BSD)	M	\$PROT_EXEC\$ $\in M.flags$ $\wedge \exists$ *Untrusted_Read*$(?, P')$: *path_factor*$(P', P) <= path\_thres$
Establish_Foothold(P)	*Shell_Exec*(F, P)	EXEC	ProcessStart (Windows), execve/fexecve (Linux,BSD)	M	$F.path \in$ {Command_Line_Utilities} $\wedge \exists$ *Initial_Compromise*(P') : *path_factor*$(P', P) <= path\_thres$

Severities: L=Low, M=Moderate, H=High, C=Critical

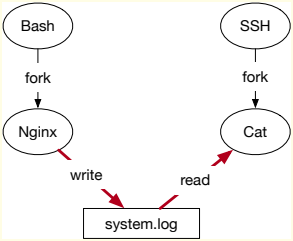
Entity types: P=Process, F=File, S=Socket, M=Memory, U=User.

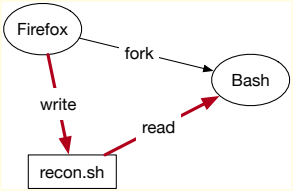
Avoiding spurious dependencies

- Spurious dependencies can result in dependence explosion
- Addressed by asking a key question: *what is the influence that attacker had in creating a dependency?*
- Key notion *Ancestor cover for f*: set of all processes that influence a dependency f.

$$\forall p \in f \ \exists a \in AC(f) \quad a = p \text{ or } a \text{ is an ancestor of } p$$

- *Minimal Ancestor cover for f - corresponds to the minimum number of processes attacker should exploit to influence a dependency f.*





Avoiding spurious dependencies (Cont.)

$$path\_factor(N_1, N_2) = \min_{\forall f : f.src = N_1, f.dst = N_2} AC_{min}(f)$$

- *path_factor* value computed incrementally in real-time

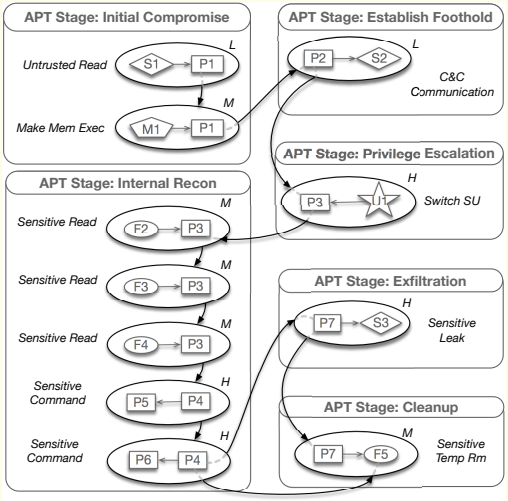
APT Stage	TTP	Event Family	Severity	Prerequisites
Complete_ Mission(P)	*Sensitive_Leak*(P, S)	SEND	H	$S.ip \notin$ {Trusted_IP_Addresses} $\wedge \exists$ *Internal_Reconnaissance*(P') : *path_factor*$(P', P) <=$ *path_thres* $\wedge \exists$ *Initial_Compromise*(P'') : *path_factor*$(P'', P) <=$ *path_thres*

Value of *path_thres* could be set based on the threat an organization is preventing from

- we assume attacker is not willing or capable to compromise more than 3 exploits.

Signal Correlation, HSG, and Threat Tuples

- A TTP is matched and added to the HSG if all its prerequisites are satisfied.
- HSG $\rightarrow$ Threat Tuple: represents various stages of an APT campaign.
- Each element in tuple takes on severity levels $\langle M, L, H, H, -, H, M \rangle$
- HSG provides a compact, visual summary of the campaign at any moment.
  - cyber-analyst can quickly infer the big picture of the attack (scope and magnitude)



HSG Ranking and Prioritization

Severity level transformed to a number based on NIST severity score mappings

Qualitative level	Quantitative Range	Rounded up Average Value
Low	0.1 - 3.9	2.0
Medium	4.0 - 6.9	6.0
High	7.0 - 8.9	8.0
Critical	9.0 - 10.0	10.0

Tuple transformed into numeric value as weighted product

$$\prod_{i=1}^{n}(S_i)^{w_i} \geq \tau \qquad w_i = \frac{(10+i)}{10}$$

Alert raised based on threshold learned from benign activity data

$$\langle C, M, -, H, -, H, M \rangle \rightarrow \langle 10, 6, 1, 8, 1, 8, 6 \rangle \rightarrow 1163881$$

Evaluation Datasets

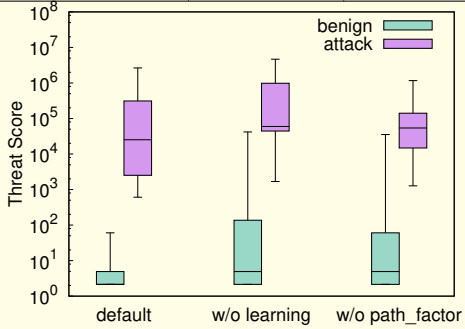
Dataset 1: Using this dataset, we measure the optimal threshold value

Stream No.	Duration	Platform	Scenario No.	Scenario Name	Attack Surface
1	0d1h17m	Ubuntu 14.04 (64bit)	1	Drive-by Download	Firefox 42.0
2	2d5h8m	Ubuntu 12.04 (64bit)	2	Trojan	Firefox 20.0
3	1d7h25m	Ubuntu 12.04 (64bit)	3	Trojan	Firefox 20.0
4	0d1h39m	Windows 7 Pro (64bit)	4	Spyware	Firefox 44.0
5	5d5h17m	Windows 7 Pro (64bit)	5.1	Eternal Blue	Vulnerable SMB
			5.2	RAT	Firefox 44.0
6	2d5h17m	FreeBSD 11.0 (64bit)	6	Web-Shell	Backdoored Nginx
7	8d7h15m	FreeBSD 11.0 (64bit)	7.1	RAT	Backdoored Nginx
			7.2	Password Hijacking	Backdoored Nginx

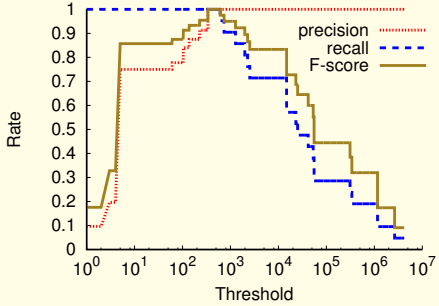
Dataset 2: live detection in a setting that we have no prior knowledge of when or how red-team is conducting the attacks.

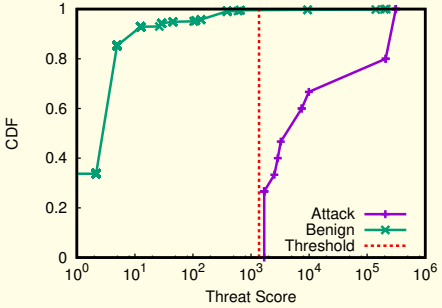
- After this experiment, dataset has been released publicly.

Scenario No.	Threat Tuple	Threat Score	Highest Benign Score in Dataset
1	$\langle C, M, -, H, -, H, M \rangle$	1163881	61
2	$\langle C, M, -, H, -, H, - \rangle$	55342	226
3	$\langle C, M, -, H, -, H, M \rangle$	1163881	338
4	$\langle C, M, -, H, -, -, M \rangle$	41780	5
5.1	$\langle C, L, -, M, -, H, H \rangle$	339504	104
5.2	$\langle C, L, -, -, -, -, M \rangle$	608	
6	$\langle L, L, H, M, -, H, - \rangle$	25162	137
7.1	$\langle C, L, H, H, -, H, M \rangle$	4649220	133
7.2	$\langle M, L, H, H, -, H, M \rangle$	2650614	



Optimal threshold Value and Live Experiment Results





- F-score maximum at [338.25, 608.26] for 6 APT stages
  - Average severity of each APT step = 2.09
- Threshold set for Live experiment (7 APT stages): $2.09^{\sum_{i=1}^{7} w_i} = 2.09^{9.8} = 1378$
- A few false positive: system administrator connecting via SSH

Summary

- Presented a real-time APT detection system that correlates TTPs that might be used to carry out each APT stage.

visualize high-level APT behavior in real time.

- Dependence explosion mitigation by using the concept of minimum ancestral cover
- Benign system activities pruning based on data quantities in the flow of information
- Experiments show high accuracy and performance for **HOLMES**
- Effectiveness evaluated using a live experiment w/o having prior knowledge of attacks.