ProcAID: Process Anomaly-based Intrusion Detection

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ShmooCon
March 24th, 2022

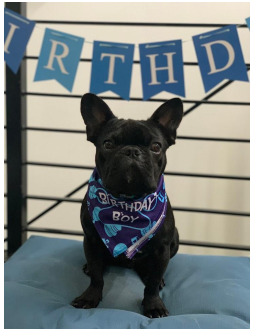
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Introduction

- Graduate Student at GW
  - MS in Cybersecurity in Computer Science
  - GraphLab: DARPA CHASE Project
- Active Duty Coast Guard Officer

GW SCHOOL OF ENGINEERING & APPLIED SCIENCE

DARPA DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



Agenda

- Motivation and Challenges
- Methodology
- Results
- Future Work
- Implications and Conclusion
- Questions

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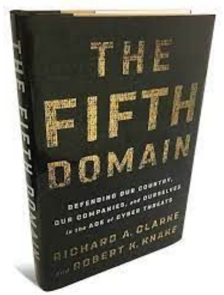
Motivation

- Advanced Persistent Threat (APT) success in current landscape
    - Nation-state actors
    - Well-funded and well-staffed
- Offensive preference in infosec

Challenges

- First intrusion detection model, invented by Dorothy Denning
    - Definition: any deviation in normal operations on a system
- State of intrusion detection
    - Signature-based vs. Anomaly-based
- APTs have breached the capabilities of current assets



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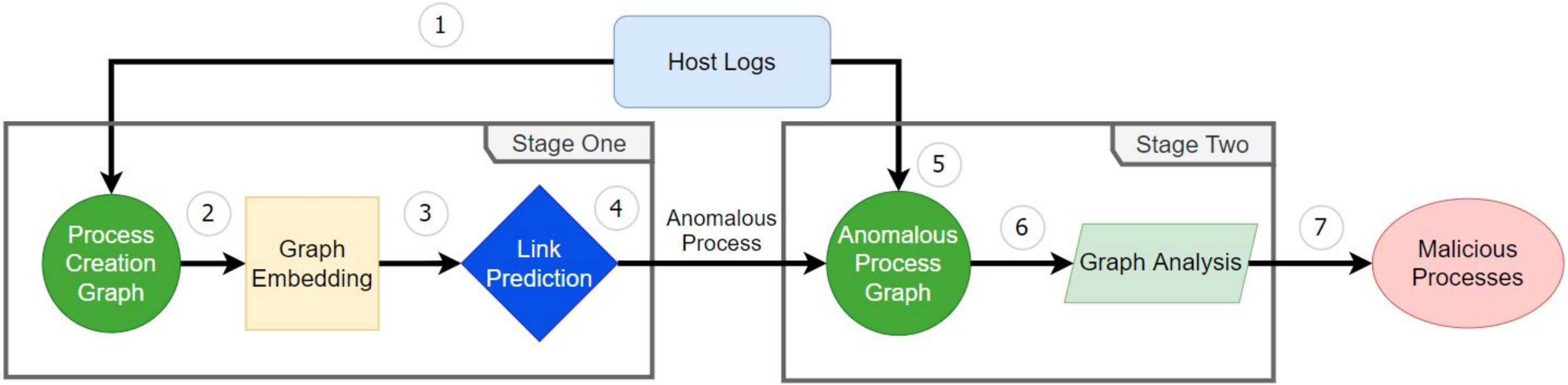
ProcAID Methodology

<u>Stage One:</u> Unsupervised Anomaly Detection via Link Prediction

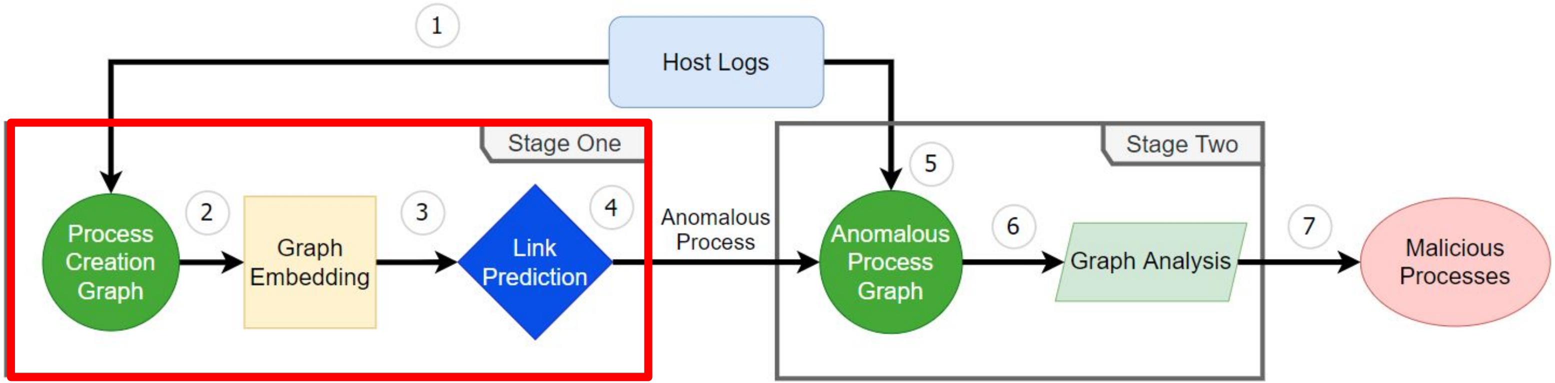
<u>Stage Two:</u> Inverse Graph Leadership and Inverse Graph Density Analysis



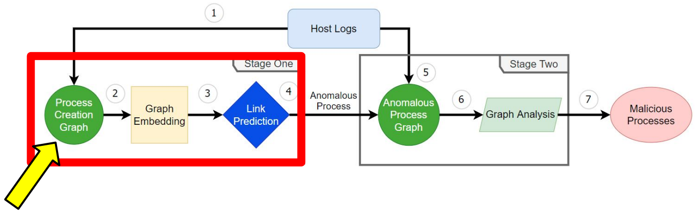
ProcAID Stage One

- **Goal:** Find anomalous process creations
- Key Characteristics:
  - Node2Vec Embedding
  - Logistic Regression

- **Method:** Model user and process interactions
  - Process tree analysis and evaluation
  - Creation of relationships between features

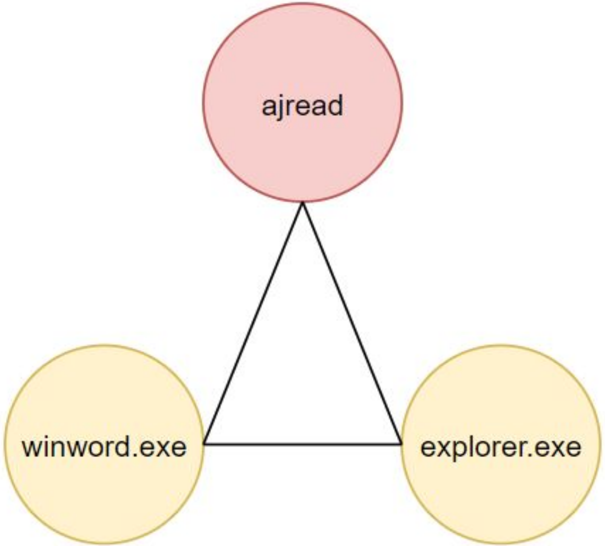


Stage One: Graph Creation

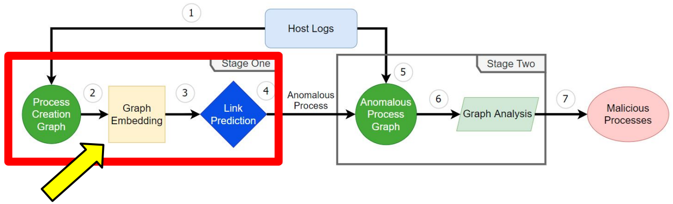


- Form two Process Creation Graphs (train and test) with host logs
- Graph Schema
  - Nodes: User, Process Path, or Parent Process Path
  - Edges: Executions/interactions

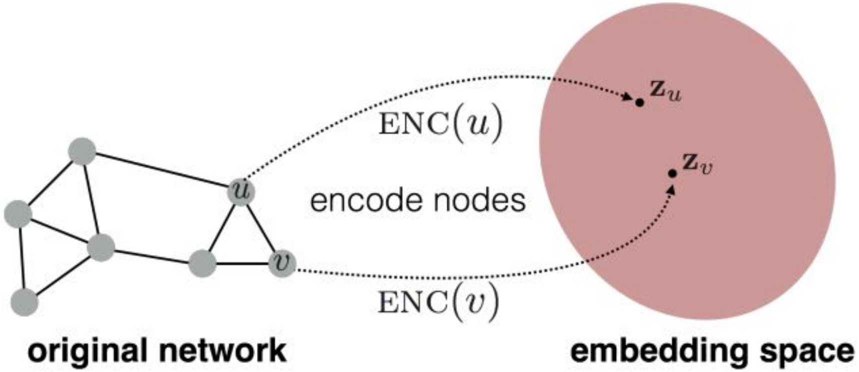
Example: User "ajread" spawns "winword.exe" from "explorer.exe"



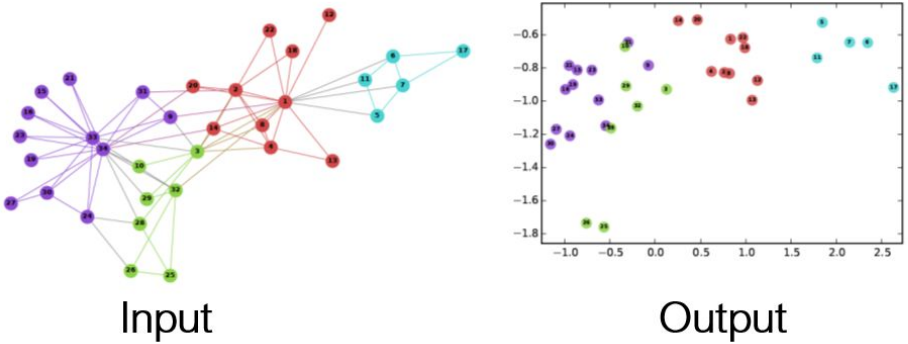
Stage One: Graph Embedding



- Learn information from Process Creation Graphs through embedding
- *node2vec: Scalable feature learning for networks*[1]
  - Second order bias parameters
  - Hadamard embedding of edges



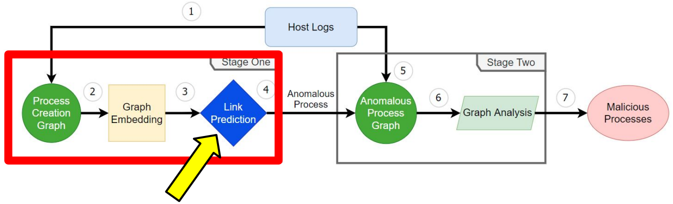
http://snap.stanford.edu/proj/embeddings-www/files/nrltutorial-part1-embeddings.pdf



http://snap.stanford.edu/proj/embeddings-www/files/nrltutorial-part1-embeddings.pdf

[1]A. Grover and J. Leskovec, “node2vec: Scalable feature learning for networks,” in Proceedings of the 22nd ACM SIGKDD international conference on Knowledge discovery and data mining, pp. 855–864, 2016.

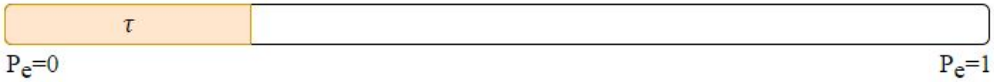
Stage One: Link Prediction



- Predict existence of test graph edges
- ML Algorithm: Logistic Regression
  - Quick training time
  - Well calibrated probabilities
    - *Pe*=0, edge does not exist
    - *Pe*=1, edge does exist

$$p_e = \frac{1}{1 + \exp^{-x*T}}$$

- Prediction Threshold (τ)
  - Edge anomaly if probability less than threshold



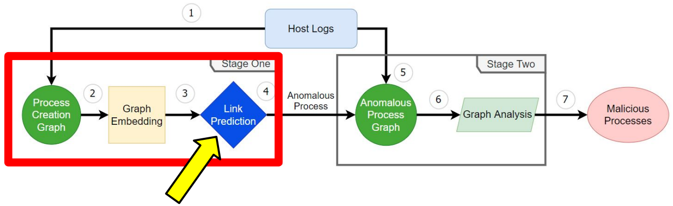
$$e_{anom} = \begin{cases} 1 & p_e < \tau \\ 0 & \text{otherwise} \end{cases}$$

Dataset

- Operationally Transparent Cyber Data Release (OpTC)
- 1000 hosts with multiple days of benign and malicious activity
- Logs formulated into “object” and “action” pairs for analytics

Host	Type of Exploitation	Post-Exploitation Actions
0201	Batch file containing Powershell code	PowerShell Empire, Mimikatz, registry edits
0501	Phishing with Macro-enabled Word Document	DeathStar, PowerShell Empire, Windows Management Instrumentation (WMI) subscriptions, SSH forwarding

Stage One Evaluation Results



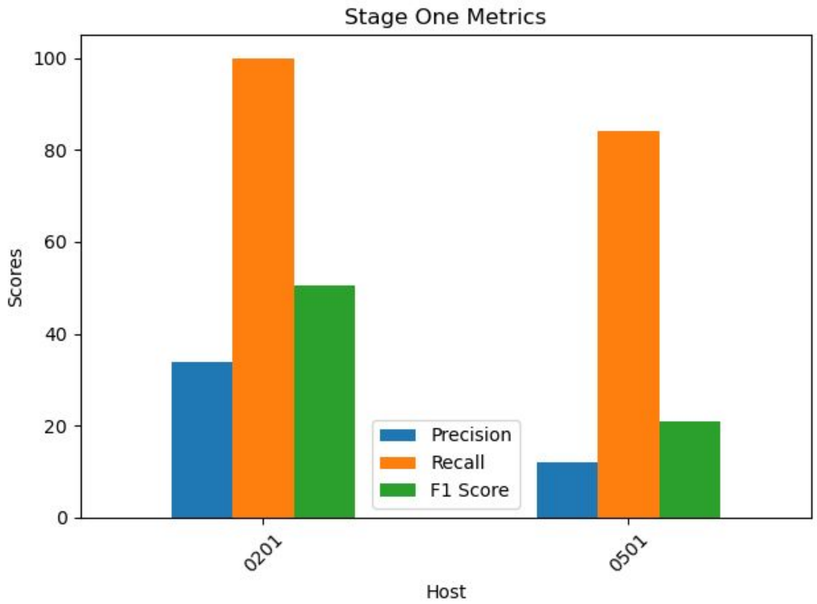
Host 0201

- ProcAID discovers all malicious process creation events
- False positives impact precision

Host 0501

- ProcAID discovers majority of malicious process creation events
- Overwhelmed by false positives

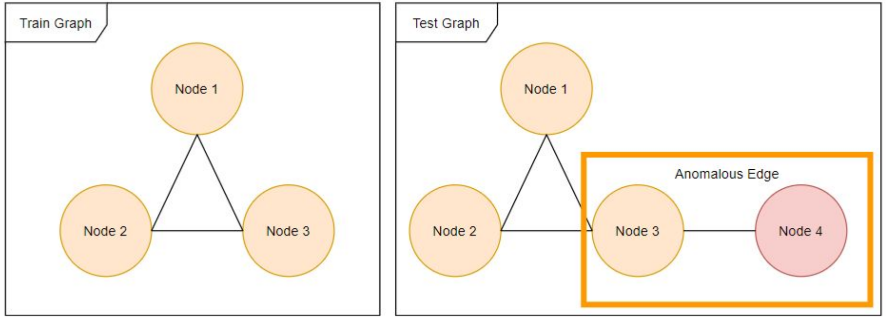
<u>**Conclusion:**</u> Engineer Stage Two to intelligently filter false positives



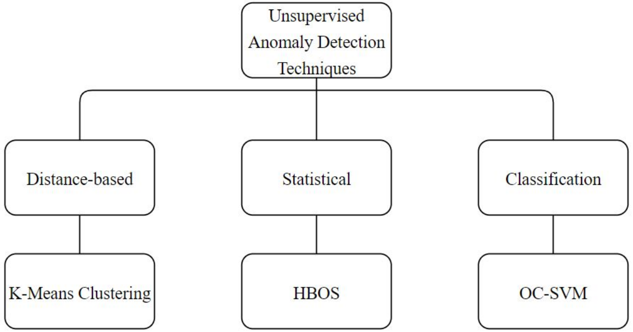
Host	Precision	Recall	F1 Score
0201	33.871	100.00	50.602
0501	11.852	84.211	20.779

Algorithm Comparison

- Independent Variables:
  - Training and Testing Data
  - Features: user, process path, and parent process path
- NewEdge Graph Algorithm
  - Returns new edges found in the Test Graph that are **not** in the Training Graph
    - Key: No threshold

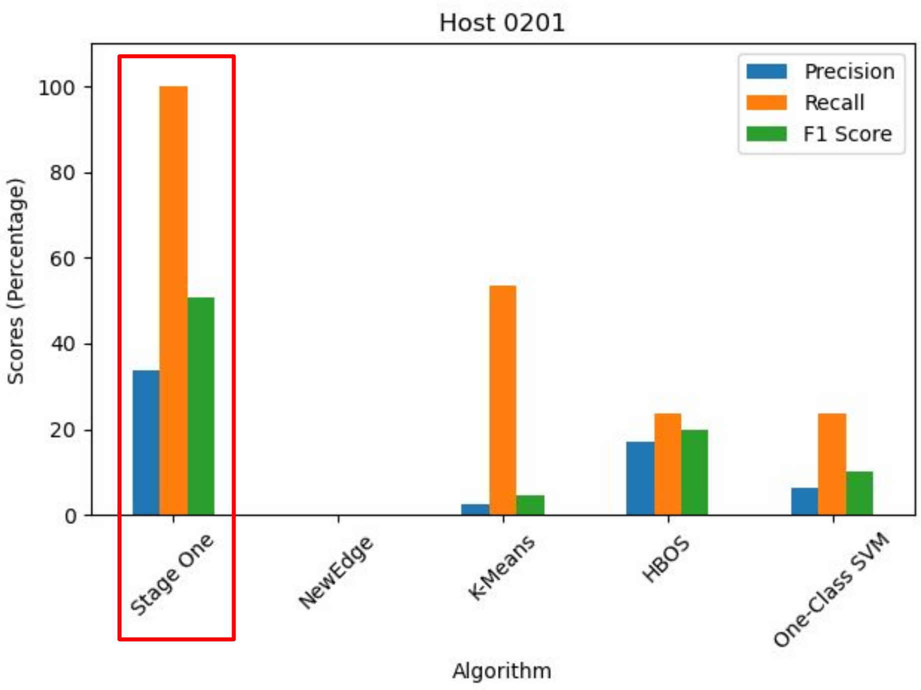


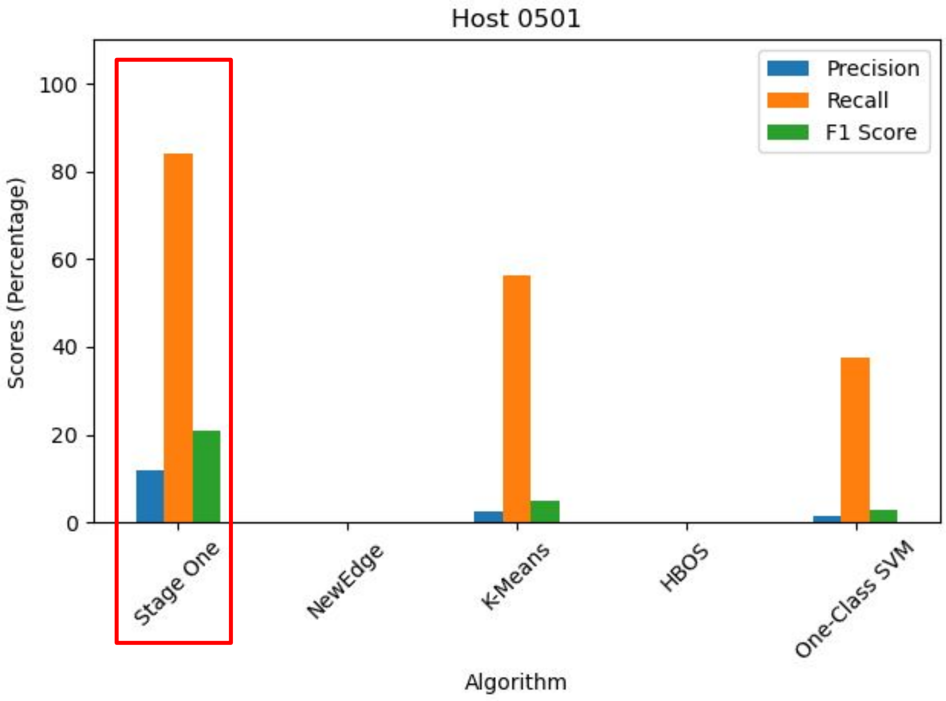
- Unsupervised Algorithms[2]:
  - Distance-based: K-Means Clustering
  - Statistical: Hierarchical Based Outlier Score (HBOS)
  - Classification: One-Class Support Vector Machine (OC-SVM)



[2] F. Falcão, T. Zoppi, C. B. V. Silva, A. Santos, B. Fonseca, A. Ceccarelli, and A. Bondavalli, “Quantitative Comparison of Unsupervised Anomaly Detection Algorithms for Intrusion Detection,” in *Proceedings of the 34th ACM/SIGAPP Symposium on Applied Computing*, pp. 318–327, 2019.

Algorithm Comparison Results (Stage One)

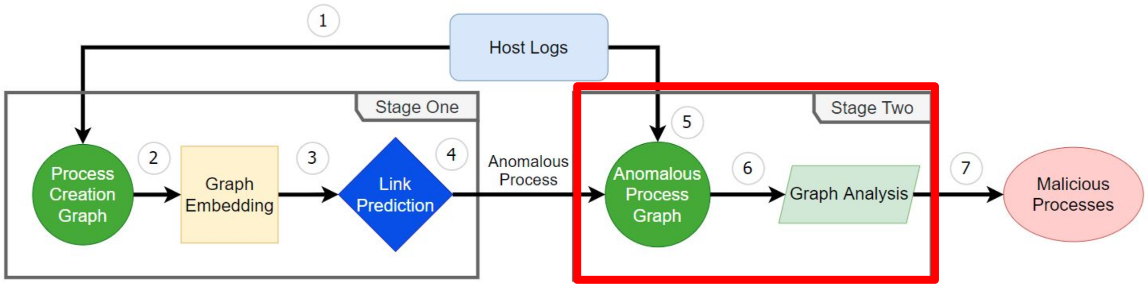




ProcAID: Stage Two

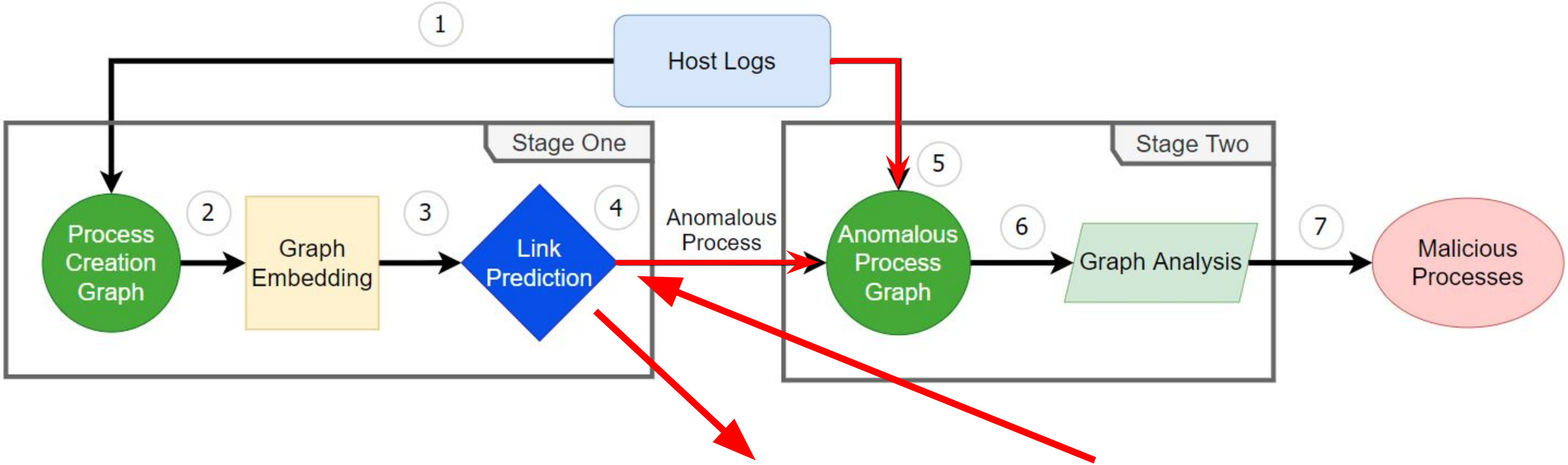
- **<u>Goal:</u>** Scrutinize anomalous process from Stage One

- **<u>Method:</u>** Examine anomalous edges using graph analytics



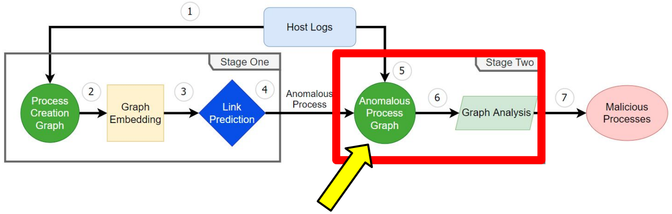
- Substages
  - Data Preparation
    - Format data for Graph Creation
  - Graph Creation
    - Anomalous Process Graph creation
  - Analysis
    - Inverse Graph Leadership
    - Inverse Graph Density

Stage Two: Example



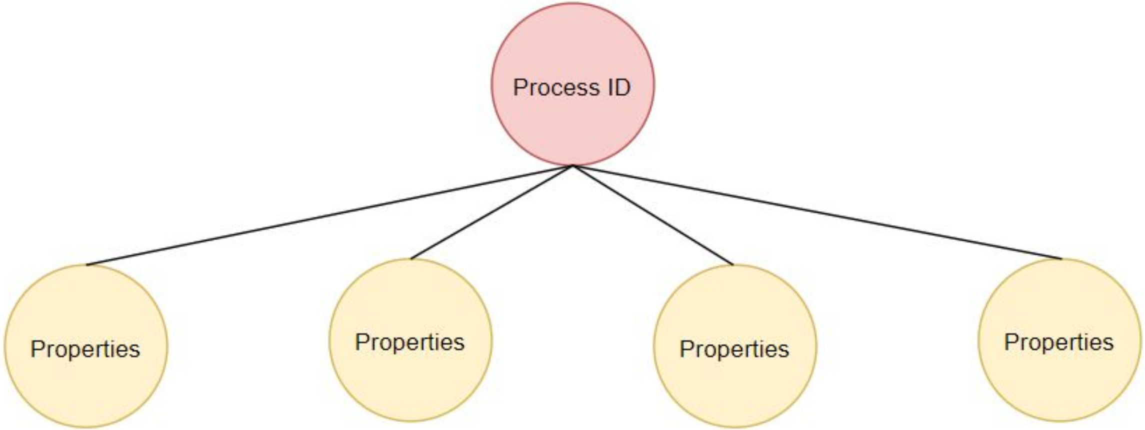
ajread—winword.exe → PID: 926

Stage Two: Graph Creation



- **<u>Purpose:</u>** Model process entire interaction with host

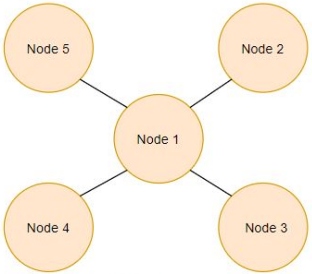
- Graph Schema
  - Nodes: PID, Parent PID, Registry Values, Registry Keys, Source IP, Destination IP
  - Edges: Interactions



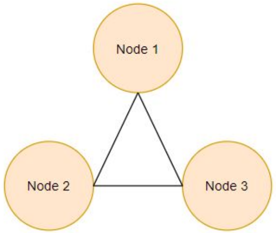
Analysis Background

- Leadership:
  - Measure of the extent of which a graph is dominated by a single node

$$L = \frac{\sum_{i=1}^{n} d_{max} - d_i}{(n-1)(n-2)}$$



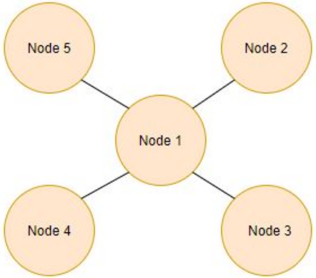
Maximal



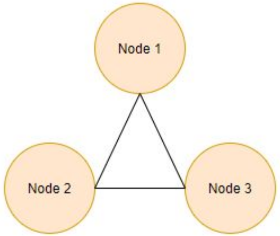
Minimal

- Density
  - Measure of the number of connections between nodes in comparison to the number of possible connections between nodes

$$D = \frac{2m}{n(n-1)}$$

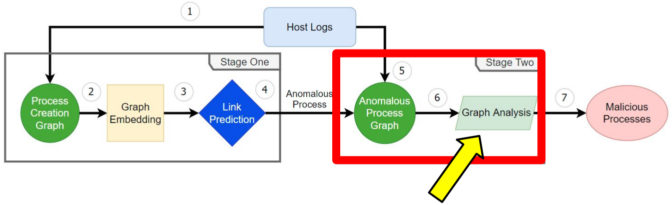


Density=0.40



Density=1.0

Stage Two: Analysis



Assumption 1:

- The Anomalous Process Graph for a malicious process will have a high inverse graph leadership value because process execution will be dominated by multiple objects.

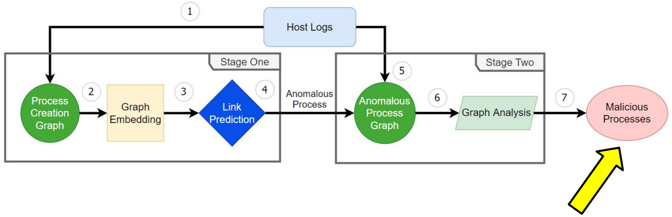
$$L^{-1} = \frac{(n-1)(n-2)}{\sum_{i=1}^{n} d_{max} - d_i}$$

Assumption 2:

- The Anomalous Process Graph for a malicious process will have a high inverse graph density value because objects will interact with a wide range of unique subjects during execution.

$$D^{-1} = \frac{n(n-1)}{2m}$$

Final Maliciousness Score



Assumption 3:

- The total maliciousness score for a malicious process will be higher than the total maliciousness score for a benign process.

$$MalScore_{process} = \sum_{i=0}^{N} [L^{-1}[i] + D^{-1}[i]]$$

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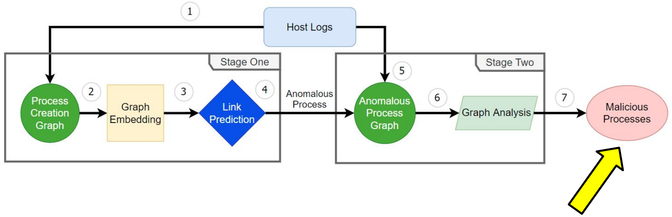


Results for Host 0201

- Placement of malicious activity at the highest percentiles of the results
  - Assumption 3 is affirmed
- Effectively filters false positives from Stage One
- Average Run Time: 30.966 sec
  - Stage One : ~5 sec

Threshold	Precision	Recall
Top 1	1.000	0.500
Top 5	0.800	0.800
Top 10	0.600	0.857
Top 15	0.467	1.000
Top 20	0.400	1.000

Table 4.8: Top-K Comparison for Host 0201

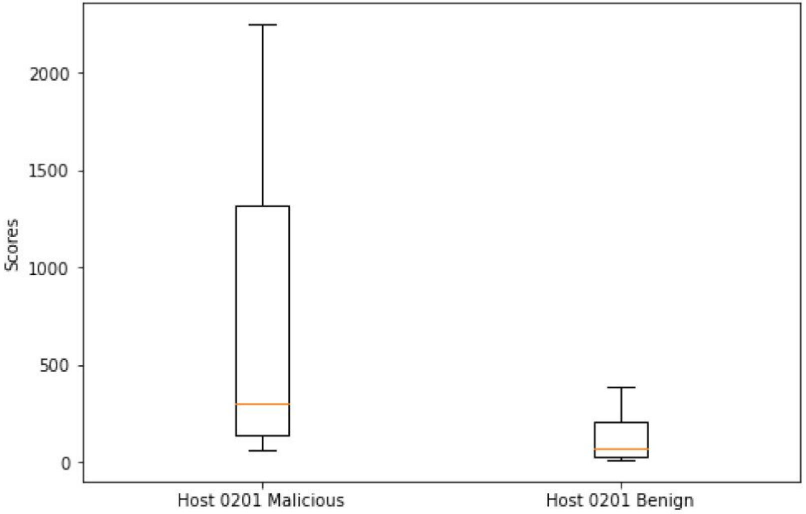
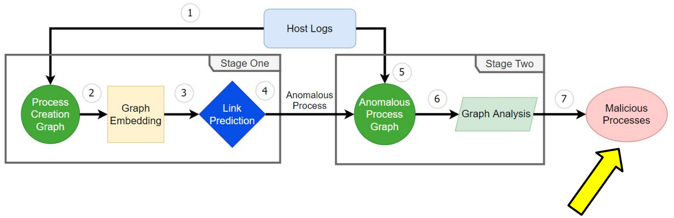


Figure 4.9: Box and Whisker Plot for Scores on Host 0201



Results for Host 0501

- Increased number of false positives impact results
- Placement of malicious activity at higher percentiles of results
  - Assumption 3 is affirmed
- Average Run Time: 268.23 sec
  - Stage One: ~5 sec

Threshold	Precision	Recall
Top 1	0.000	0.000
Top 5	0.800	1.000
Top 10	0.400	1.000
Top 15	0.267	1.000
Top 20	0.200	1.000

Table 4.10: Top-K Comparison for Host 0501

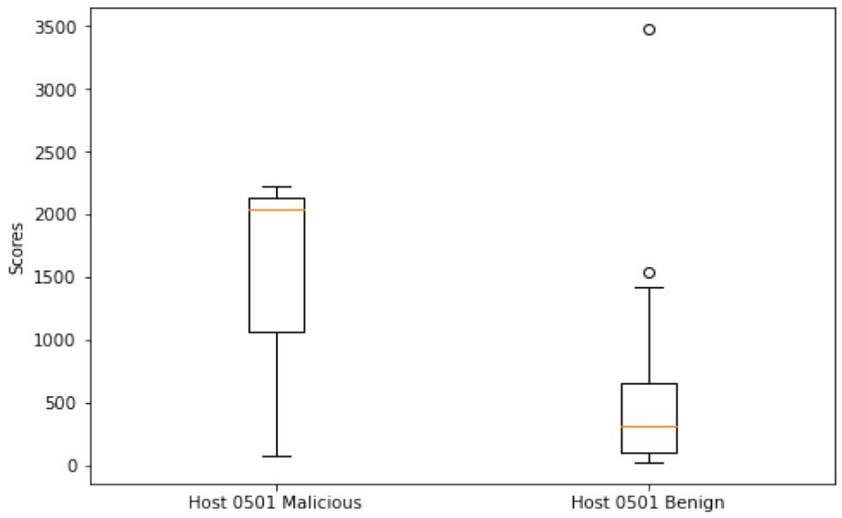
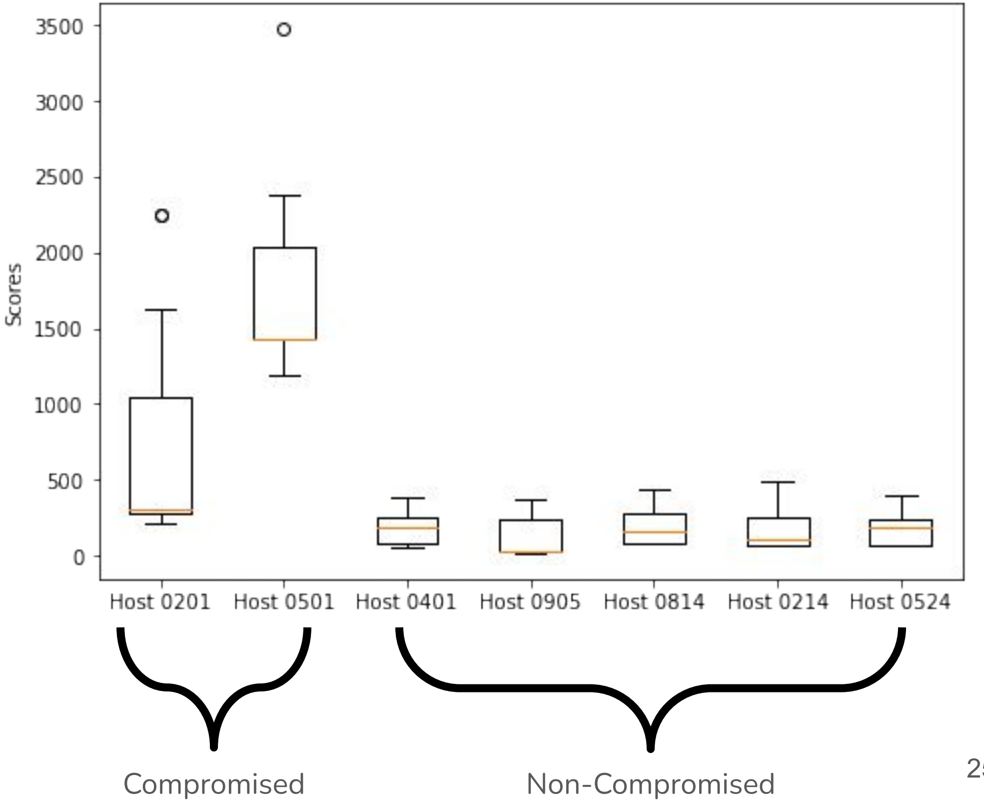


Figure 4.10: Box and Whisker Plot for Scores on Host 0501

ProcAID Results Across Multiple Hosts

- Enterprise Implementation
- Scores reflect both malicious and benign processes
- Compromised hosts show clear increased mean and standard deviation



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Future Work

- Training and testing time analysis
- Graph embedding techniques other than Node2Vec
    - Other techniques could address the offline/online issue
- Datasets
    - Any verbose dataset with Windows Security Event ID 4688 or similar
    - Real world vs. Academic Datasets
- Full enterprise implementation
    - Placement of users and administrators based on process creation activity in Stage One

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Implications and Conclusions

Implications

- ProcAID application is simple and vast in the cybersecurity space
  - No rule creation, no supervision
  - Offline solution
  - Training required

Conclusion

- Fusion of unsupervised link prediction, inverse graph leadership, and inverse graph density
- Efficient and effective host-based anomaly detection system for combatting APTs
- Applications of graph theory in information security

Publication

- https://www.proquest.com/dissertations-theses/procaid-process-anomaly-based-intrusion-detection/docview/2604788938/se-2

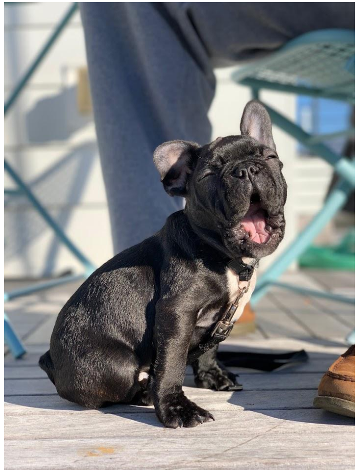
Social Media

read.austin@gmail.com

ajread4@github.com

twitter.com/ajread3

Questions?



Supplemental Slides

ProcAID Algorithm

- Ingests all host logs
- Returns anomalies with maliciousness scores
- Implemented in Python
  - NetworkX
  - SKLearn
- Stage One
  - Lines 1-4
- Stage Two
  - Lines 6-20

Algorithm 1 ProcAID Algorithm

```
Input: HostLogs
Output: Anom,MalScore
 1: //Stage One
 2: ProcGraphTrain=CreateGraph(CreateProcTrain)
 3: ProcGraphTest=CreateGraph(CreateProcTest)
 4: ProcAnomalies=GraphAnomaly(ProcGraphTrain,ProcGraphTest,Thres)
 5: //Stage Two
 6: MalEdgeCollection=FindLogs(ProcAnomalies)
 7: for edge in MalEdgeCollection do
 8:   for parentproc in edge do
 9:     ParentProcData=SplitTime(parentproc,Time)
10:     EvaluationGraph=CreateAnomalyGraph(ParentProcData)
11:     EdgeDataParentProc=LeadershipDensity(EvaluationGraph)
12:   end for
13:   for proc in edge do
14:     ProcData=SplitTime(proc,Time)
15:     EvaluationGraph=CreateAnomalyGraph(ProcData)
16:     EdgeDataProc=LeadershipDensity(EvaluationGraph)
17:   end for
18:   Anom, MalScore=CombineData(EdgeDataParentProc,EdgeDataProc)
19: end for
20: return Anom, MalScore
```

ProcAID Specifications

1. Node2Vec
   a. Number of walks: 100
   b. Walk length: 5
   c. P: 0.125
   d. Q: 2.0
2. Stage One Output:
   a. Host 0201: 15 Edges, Host 0501: 48 Edges
3. Graph Sizes
   a. Process Creation (Train/Test): ~100 Nodes and ~300 Edges
   b. Anomalous Process: ~3000-7000 Nodes and ~9k-16k Edges

Introduction

- MS in Cybersecurity in Computer Science
  - Machine Learning Course

- DARPA CHASE Research Assistantship
  - “The CHASE program seeks to develop automated tools to detect and characterize novel attack vectors, collect the right contextual data, and disseminate protective measures both within and across enterprises.”

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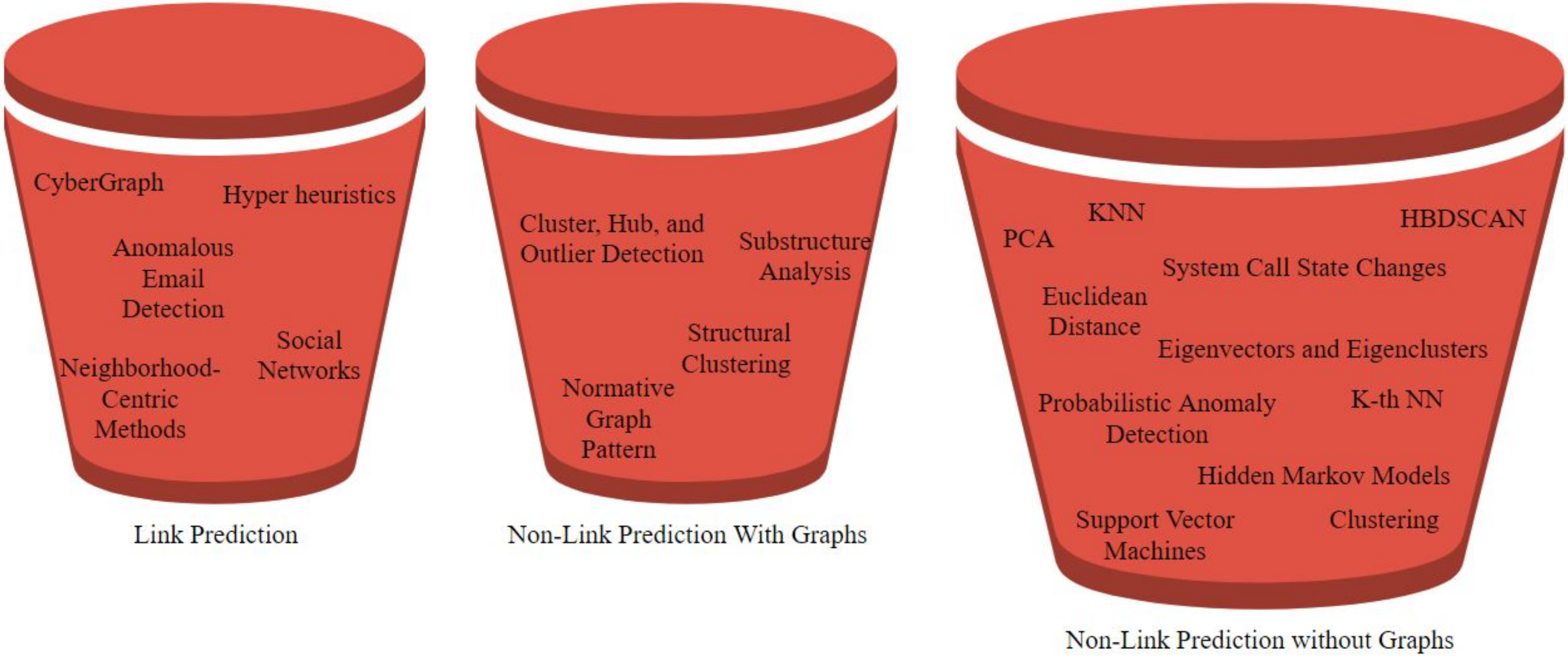
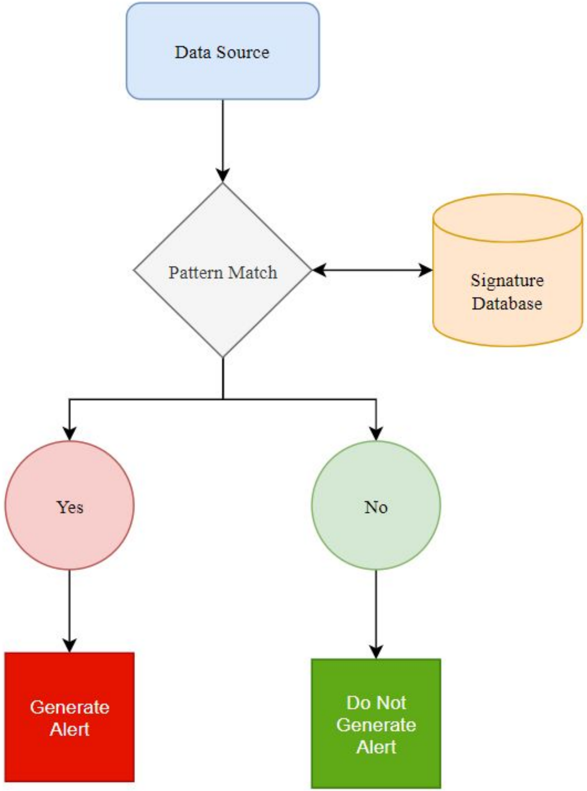
Prior Work in Anomaly Detection



Signature-based Detection Challenges

- Focus on pattern/signature matching in database
- Un-intelligent system
- Principal failure:
  - To detect unknown attacks
  - To detect patterns in behavior
- Common APT characteristics:
  - “Live off the land”
  - Zero-Days
  - Blend-in with the environment
  - Intelligent exploitation



Stage One: Link Prediction Threshold Optimization

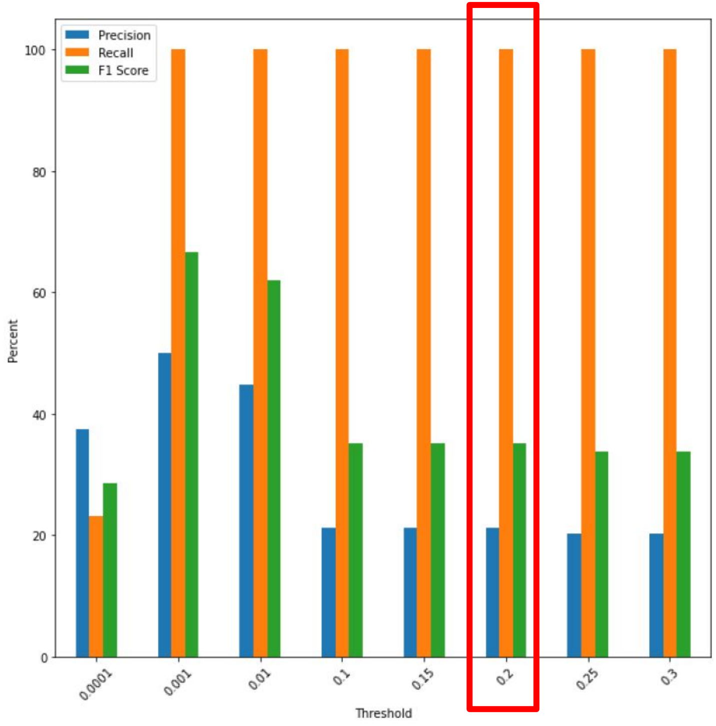


Figure 4.7: Host 0201 τ Evaluation

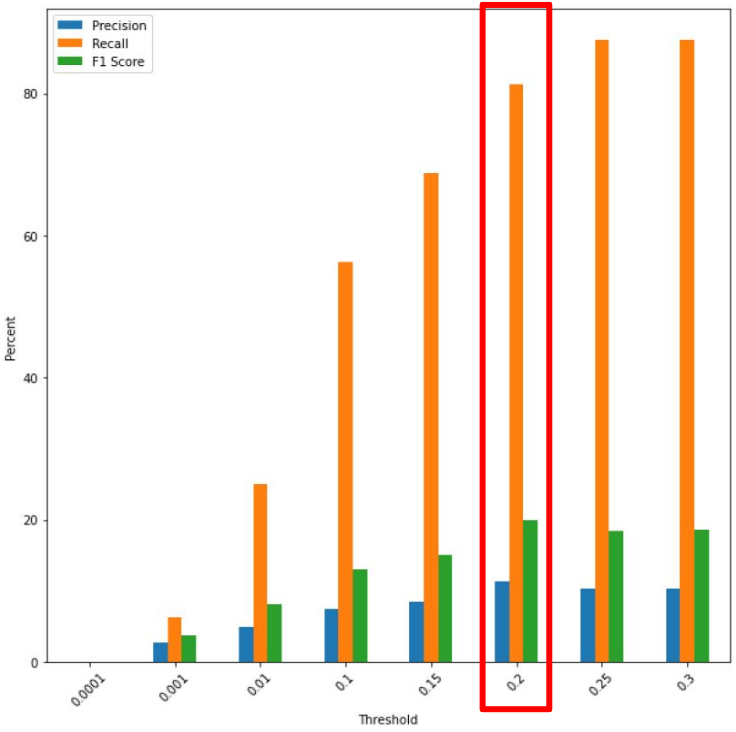


Figure 4.8: Host 0501 τ Evaluation

τ=0.20

P_e=0 P_e=1

Stage One: Random Walk Optimization

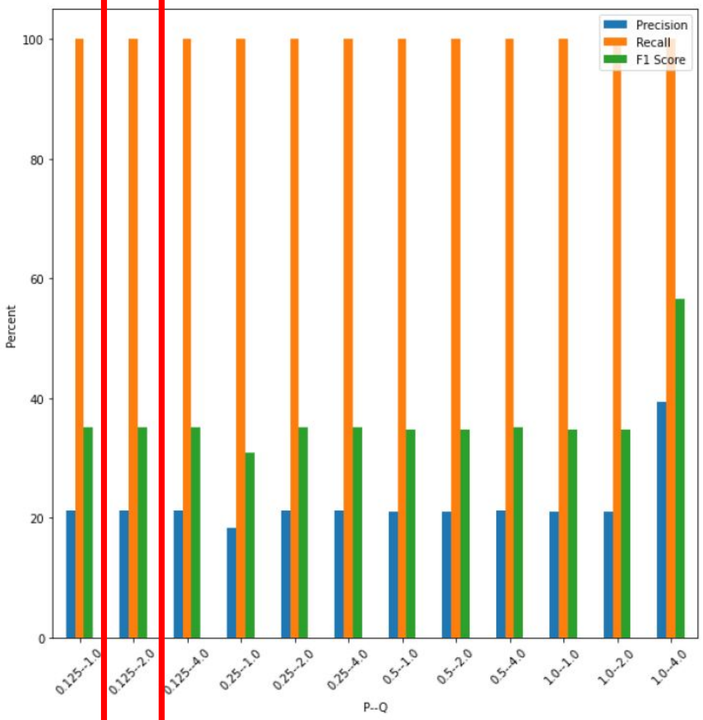


Figure 4.5: Host 0201 Random Walk Evaluation

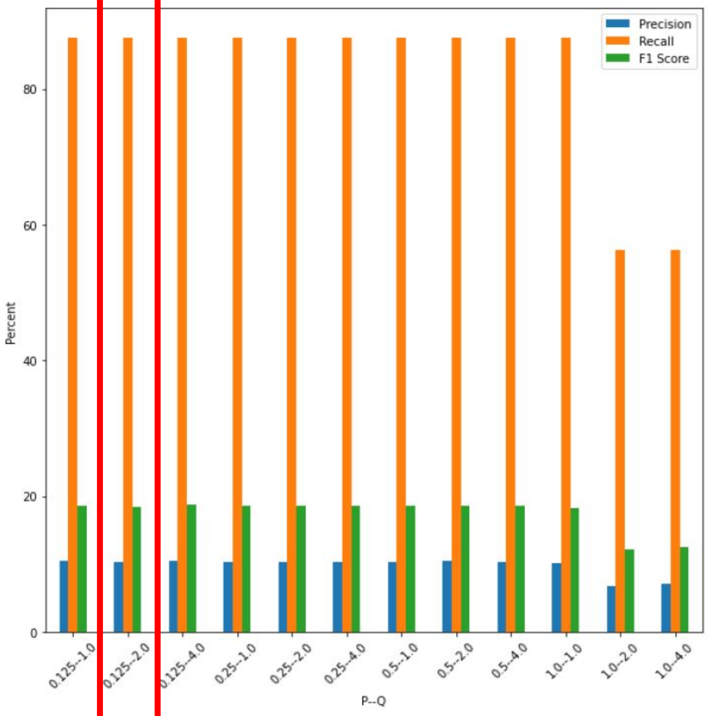
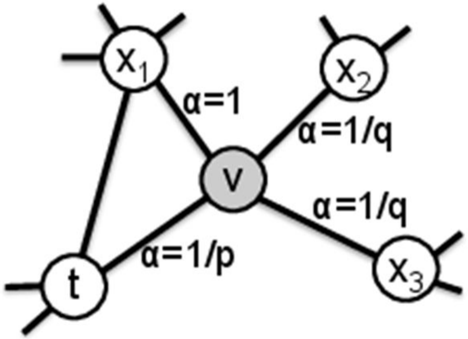
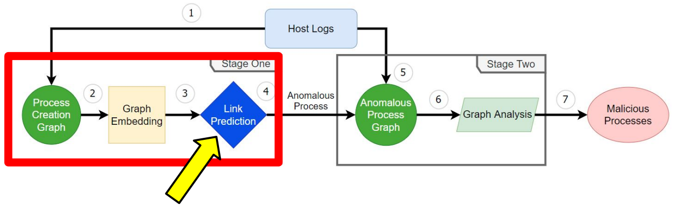


Figure 4.6: Host 0501 Random Walk Evaluation



Stage One Evaluation Metrics



- Metrics:
  - True Positive: edge **found in** Process Creation Graph that is present **in** Red Team notes
  - False Positive: edge **found in** Process Creation graph that is **not in** Red Team notes
  - False Negative: edge **not found in** Process Creation graph that is **in** Red Team notes
  - True Negative: edge **not found in** Process Creation graph that is **not in** Red team notes
- Important: Red Team notes do not track all Red Team activity

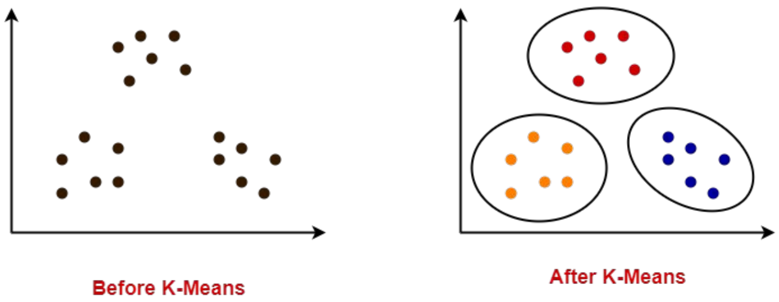
$$Precision = \frac{TruePositive}{TruePositive + FalsePositive} = \frac{RedTeam_{edge}}{RedTeam_{edge} + RedTeam'_{edge}}$$

$$Recall = \frac{TruePositive}{TruePositive + FalseNegative} = \frac{RedTeam_{edge}}{RedTeam_{edge} + RedTeam_{edge'}}$$

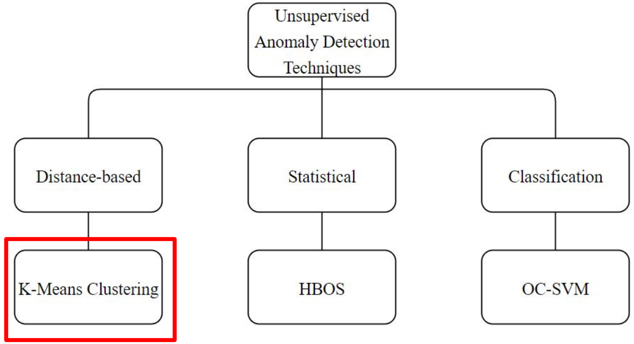
$$F1_{Score} = 2\frac{Recall * Precision}{Recall + Precision}$$

Algorithm Comparison: K-Means Clustering

- Algorithm
  - Iterative assignment of data points to clusters



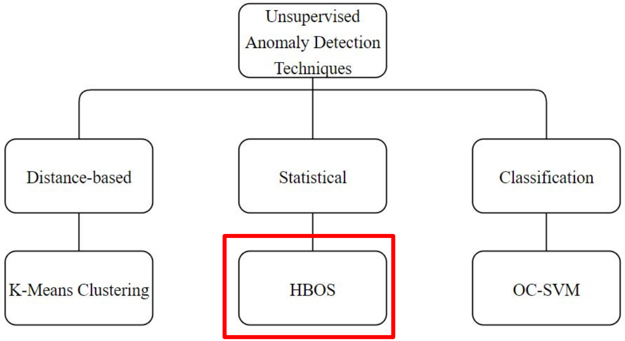
https://www.gatevidyalay.com/tag/k-means-clustering/



- Anomaly Definition:
  - Data with large distance to assigned centroid

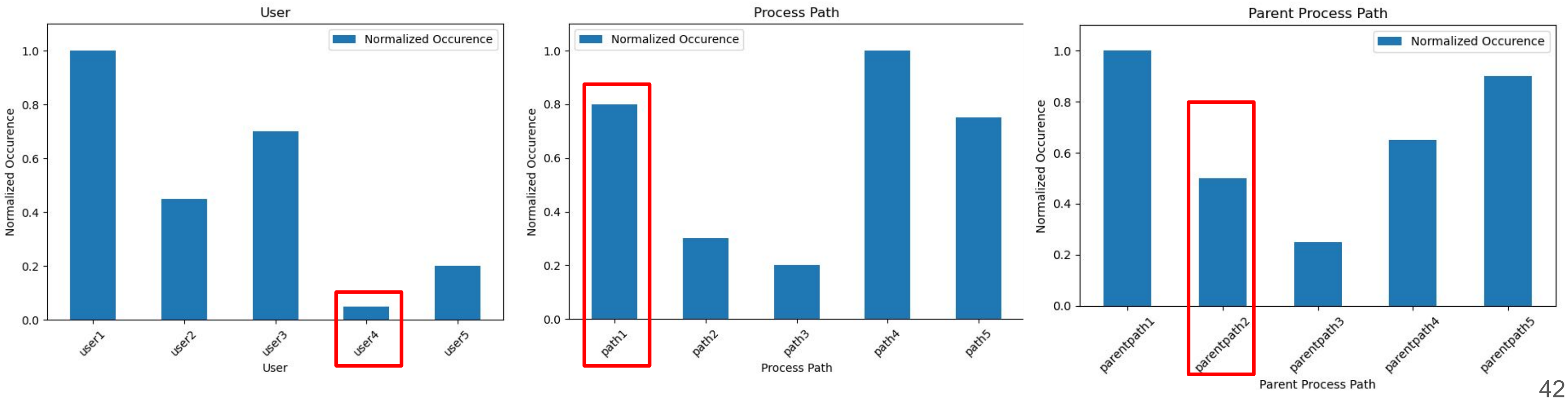
$$e_{anom} = \begin{cases} 1 & e_{euclid} \in \tau_d \\ 0 & \text{otherwise} \end{cases}$$

Algorithm Comparison: HBOS

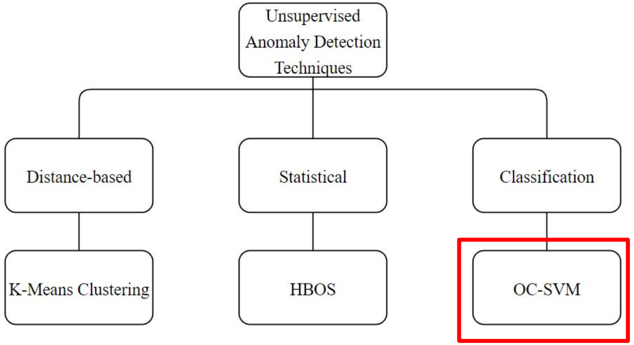


- Algorithm
  - Frequency calculation of features
  - Logarithmic sum of histograms creates score
- Anomaly Definition:
  - Highest scores represent the most anomalous activity

$$HBOS_{instance} = \sum_{i=0}^{d} \log \frac{1}{hist_i(instance)}$$

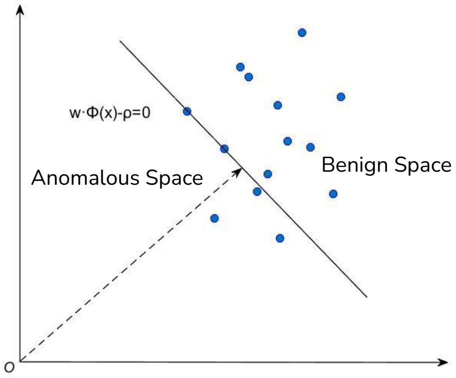


Algorithm Comparison: OC SVM



- Algorithm:
  - Learns a decision boundary to group input data

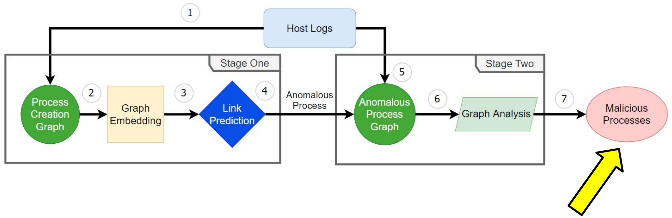
$$g(x) = \omega^T \phi(x) - \rho$$



- Anomaly Definition:
  - Any data point below the learned linear boundary is an anomaly
  - No threshold

$$label = \begin{cases} anomalous & \text{if } g(x) < 0 \\ benign & \text{if } g(x) > 0 \end{cases}$$

Example Results



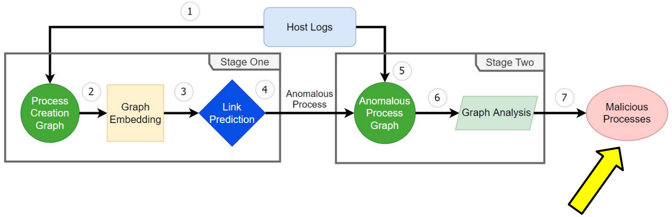
Host 0201

[('powershell.exe--SYSTEMIACOM\\zleazer--4632', **2252**),
('powershell.exe--SYSTEMIACOM\\zleazer--2952', **1632**),
('ping.exe--powershell.exe--2952', **1268**),
('explorer.exe--cmd.exe--2600', **383**),
('cmd.exe--SYSTEMIACOM\\zleazer--1284', **373**)]

Host 0501

[('backgroundtaskhost.exe--SYSTEMIACOM\\sysadmin--652', **3479**),
('powershell.exe--SYSTEMIACOM\\bantonio--2804', **2387**),
('powershell.exe--netstat.exe--1748', **2221**),
('powershell.exe--SYSTEMIACOM\\bantonio--648', **2041**),
('schtasks.exe--powershell.exe--648', **2041**)]

Results for Host 0201



- Placement of malicious activity at the highest percentiles of the results
    - Assumption 3 is affirmed
- Effectively filters false positives from Stage One
- Processes:
    - 4632, 2952, 1284
- Average Run Time: 30.966 sec

Threshold	Precision	Recall
Top 1	1.000	0.500
Top 5	0.800	0.800
Top 10	0.600	0.857
Top 15	0.467	1.000
Top 20	0.400	1.000

Table 4.8: Top-K Comparison for Host 0201

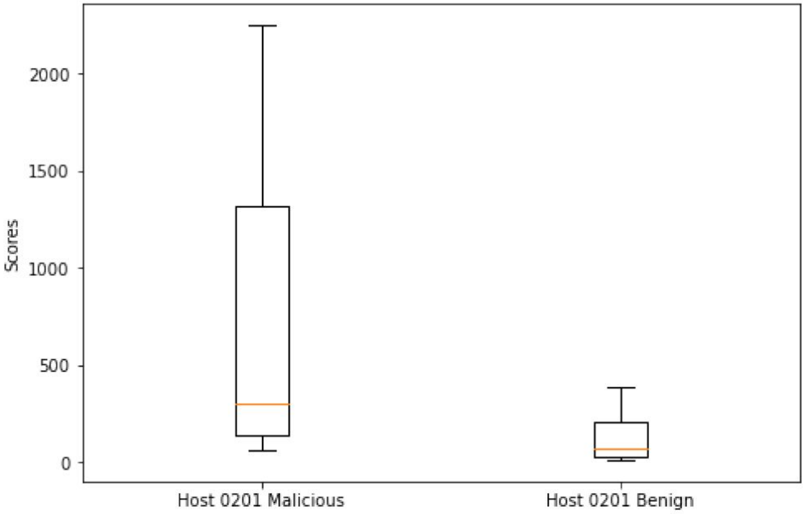
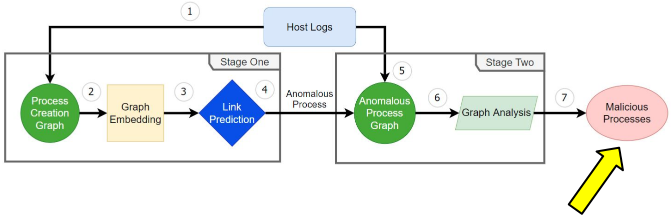


Figure 4.9: Box and Whisker Plot for Scores on Host 0201



Results for Host 0501

- Increased number of false positives impact results
- Placement of malicious activity at higher percentiles of results
    - Assumption 3 is affirmed
- Processes:
    - 2804 (5076), 1748, 648
- Average Run Time: 268.23 sec

Threshold	Precision	Recall
Top 1	0.000	0.000
Top 5	0.800	1.000
Top 10	0.400	1.000
Top 15	0.267	1.000
Top 20	0.200	1.000

Table 4.10: Top-K Comparison for Host 0501

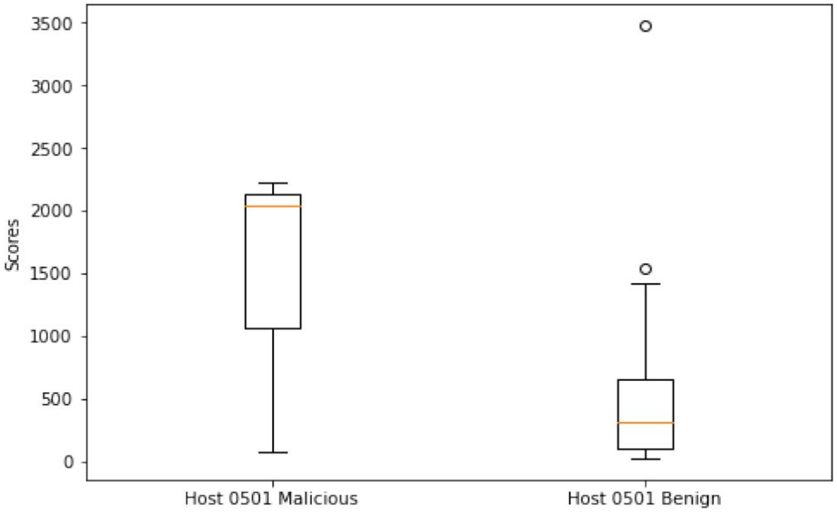


Figure 4.10: Box and Whisker Plot for Scores on Host 0501