FRAPpuccino: Fault-detection through Runtime Analysis of Provenance

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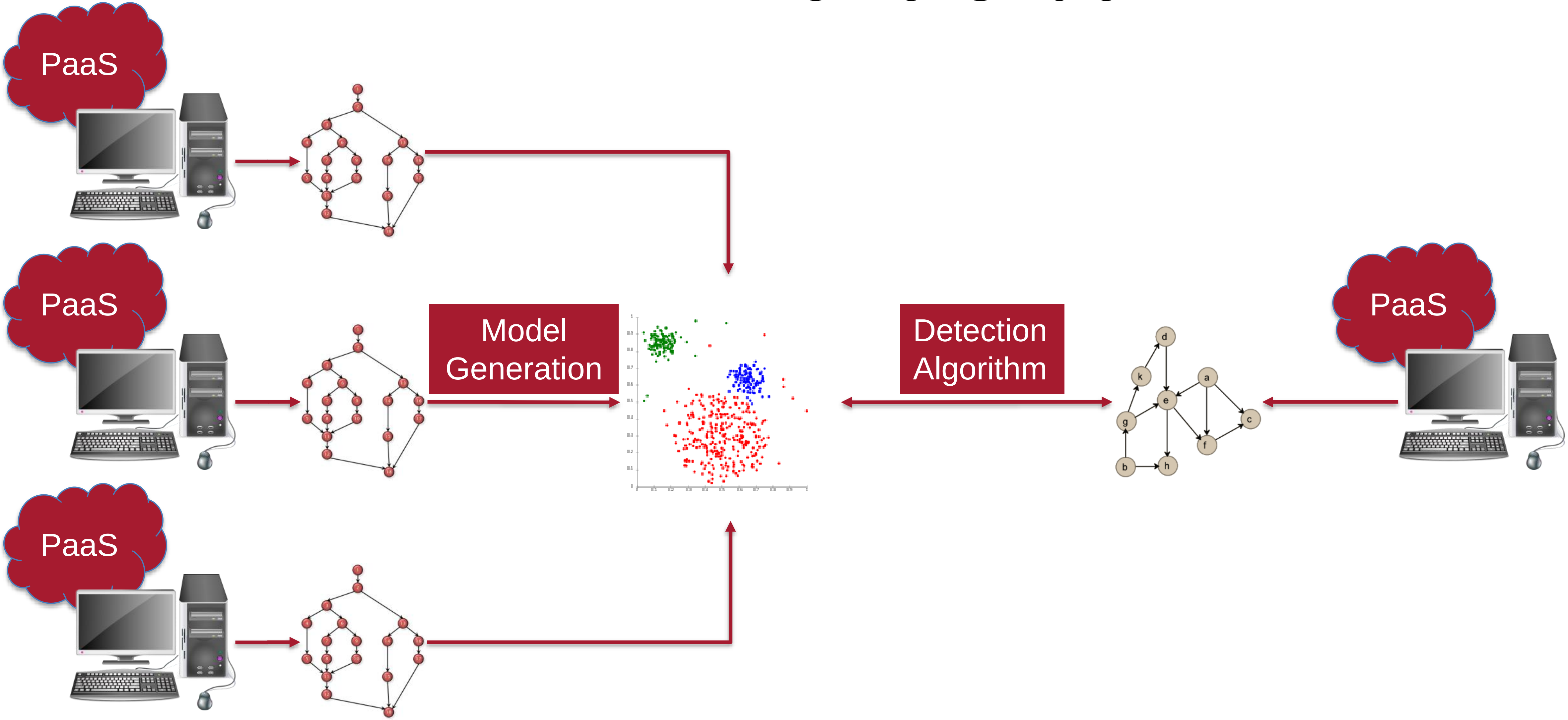
Motivations

- PaaS clouds are popular and the market continues to grow (~30% annually)
  - But cloud security remains **challenging**.
- Cloud applications can serve millions of users
  - Run-time faults can render the service **unavailable**.
- It would be nice to have an automated detection system with <u>high accuracy</u> and <u>no application annotation</u> effort.

FRAP in One Slide

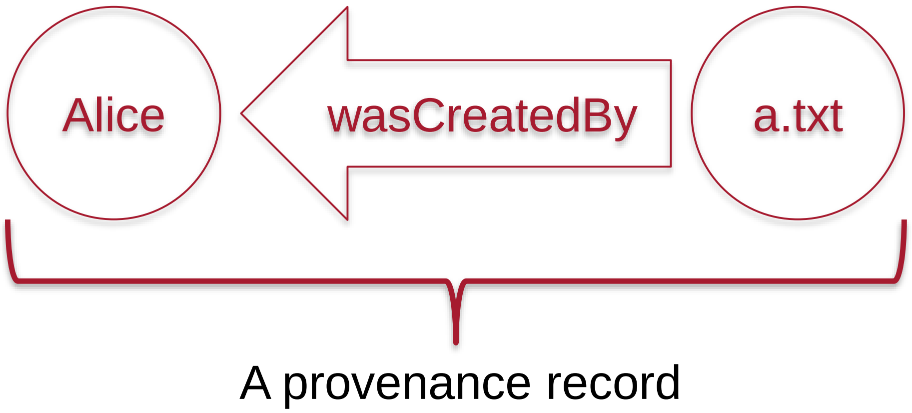


Outline

- Background: what is provenance?
- Model generation
- Detection algorithm
- Experimental results
- Conclusions
- Discussion Topics

Provenance (1)

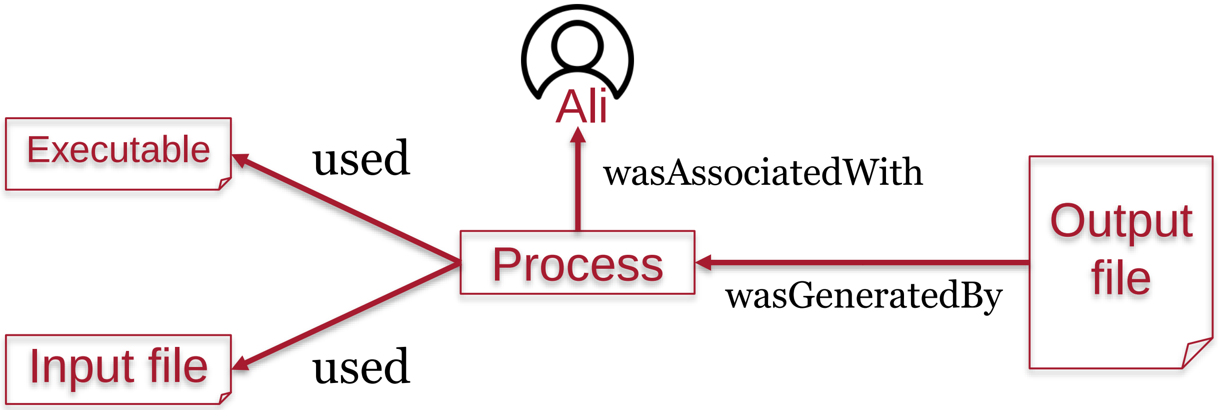
- Provenance tracks the chronology of objects/resources.
- Whole-system provenance records a program's activities on the host system.
  - Example: Alice creates a file `a.txt`.



Provenance (2)

Interactions between a program and its host OS naturally form a DAG.

W3C PROV Data Model Type	DAG Representation	Example
Entity/Activity	Node	Kernel data objects (e.g., files, packets) Inode attributes, network addresses, etc.
Relationship	Edge	Processes manipulate entities
Agent	Node	Users and groups that enact activities



Model Generation

- Determine the size of provenance data that captures program behavior → **dynamic sliding window**
- Generate a **feature vector** from each provenance DAG.
- Clustering FVs to create a program model
  - **Centroid** of each cluster
  - Cluster **radii**
  - **Membership** of each cluster
- Isolated FVs are discarded

Dynamic Sliding Window

- A subset of unbounded provenance data can describe normal program behavior
- *Dynamic*: determine the window size based on the provenance records during program run
- *Sliding*: continuously monitor different subsets of provenance data during detection

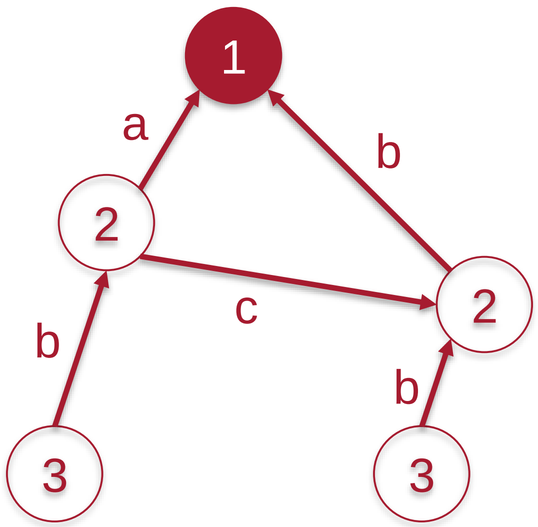
Feature Vector

- Projection of a DAG as a point into an *n*-dimensional space
- Contains counts of DAG labels
- Labels encode program interactions with the system

Generating Feature Vector: 1st Iteration

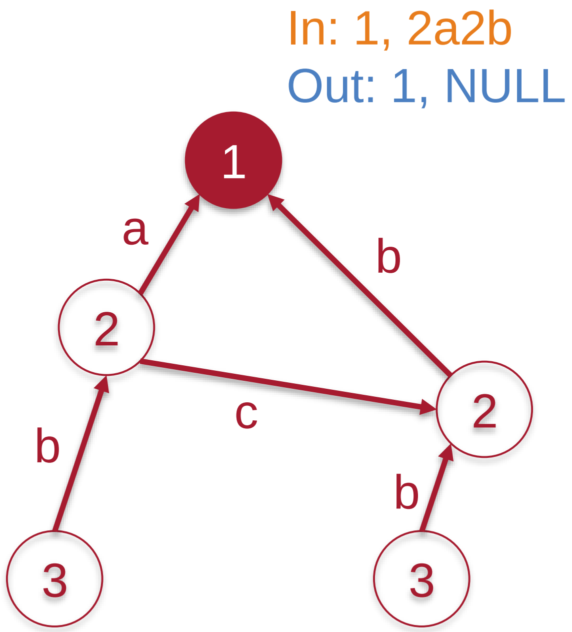
Label String	New Label
1, 2a2b	4

In: 1, 2a2b

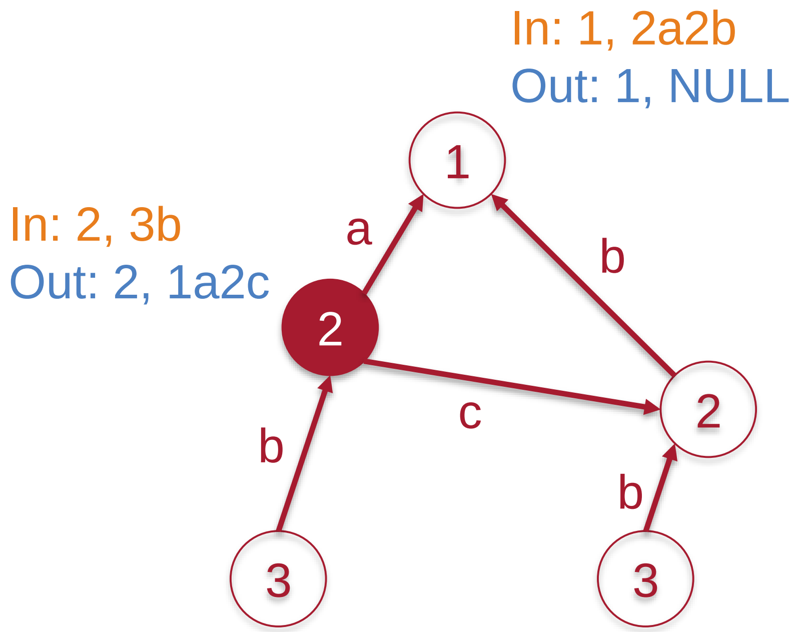


Generating Feature Vector: 1st Iteration

Label String	New Label
1, 2a2b	4
1, NULL	5
4, 5	6

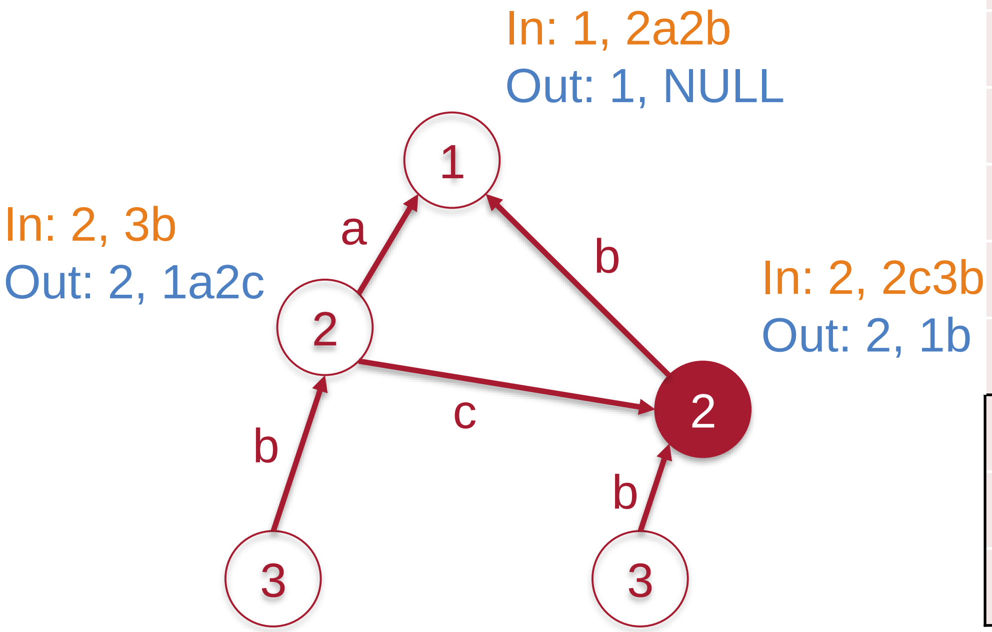


Generating Feature Vector: 1st Iteration



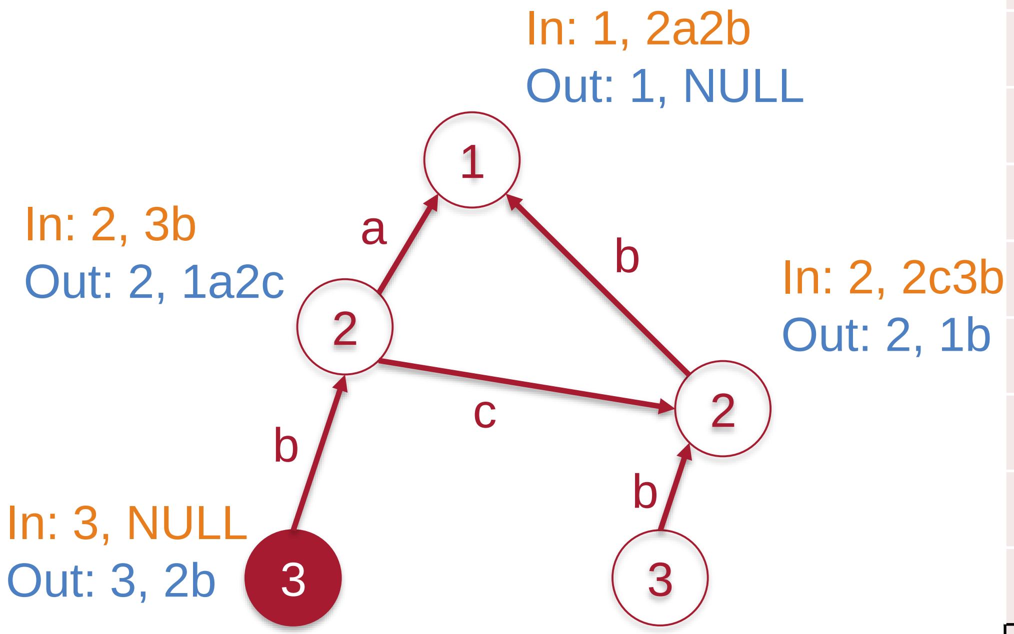
Label String	New Label
1, 2a2b	4
1, NULL	5
4, 5	6
2, 3b	7
2, 1a2c	8
7, 8	9

Generating Feature Vector: 1st Iteration



Label String	New Label
1, 2a2b	4
1, NULL	5
4, 5	6
2, 3b	7
2, 1a2c	8
7, 8	9
2, 2c3b	10
2, 1b	11
10, 11	12

Generating Feature Vector: 1st Iteration



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2, 1a2c	8
7, 8	9
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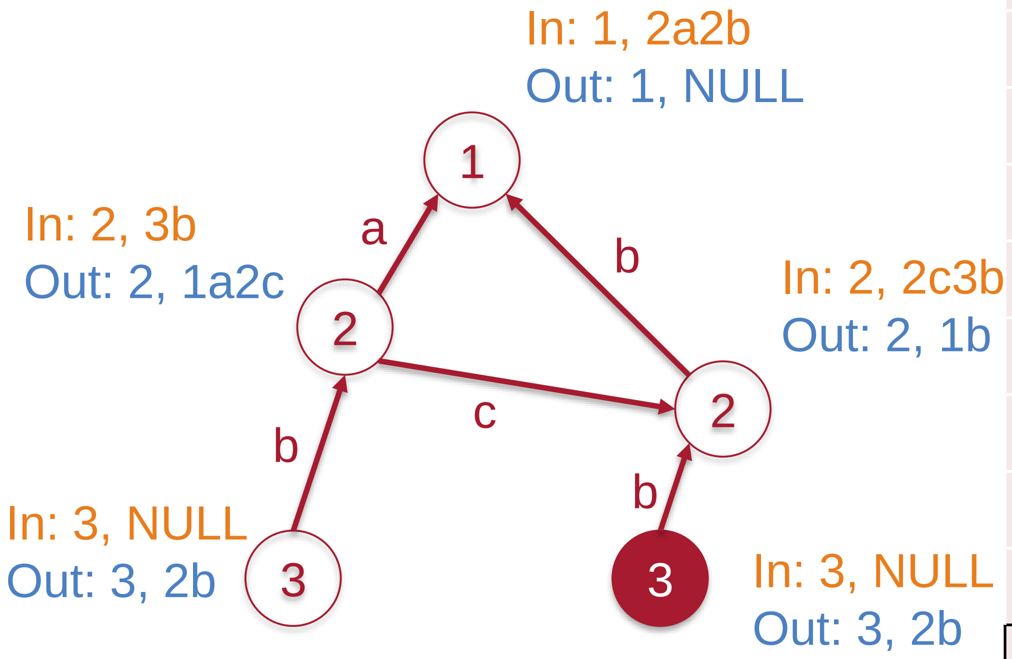
2, 1b	11
10, 11	12
3, NULL	13
3, 2b	14
13, 14	15

Generating Feature Vector: 1st Iteration



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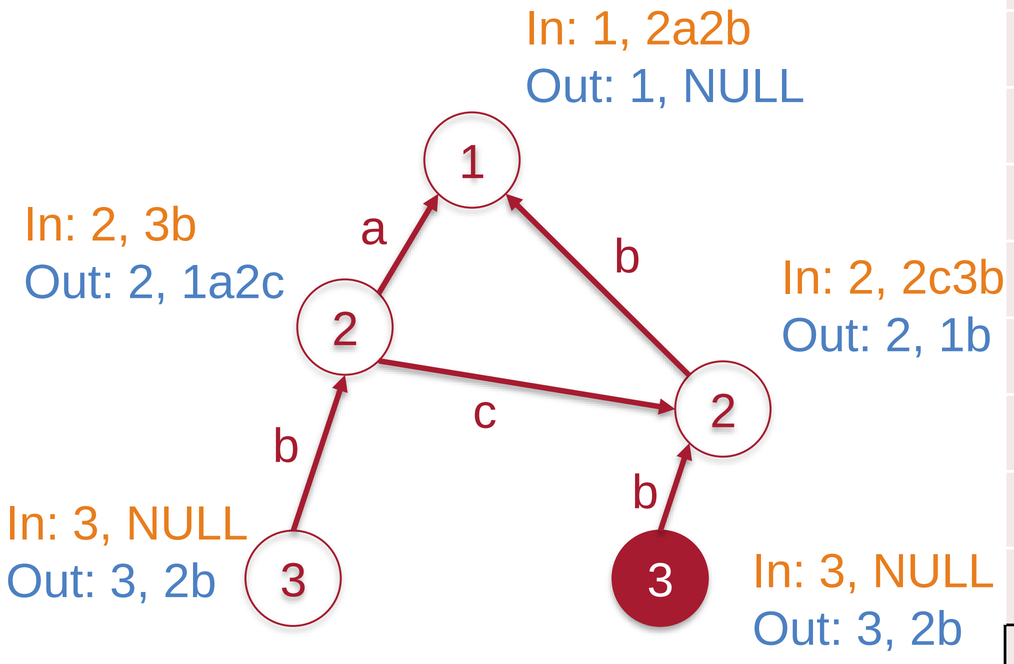
Generating Feature Vector: 1^{st} Iteration



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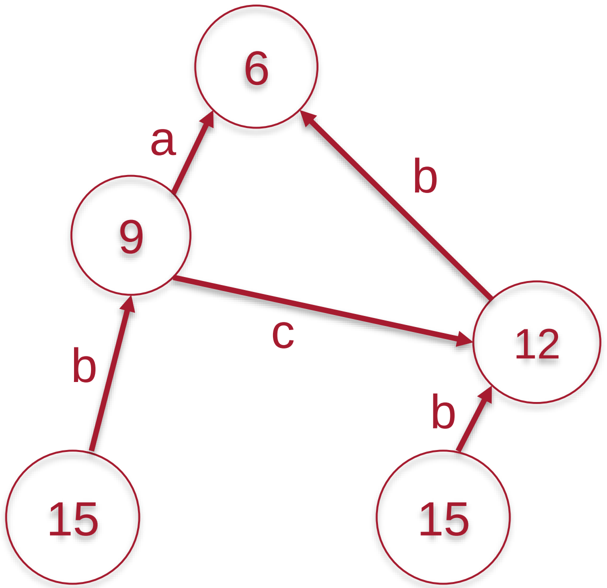
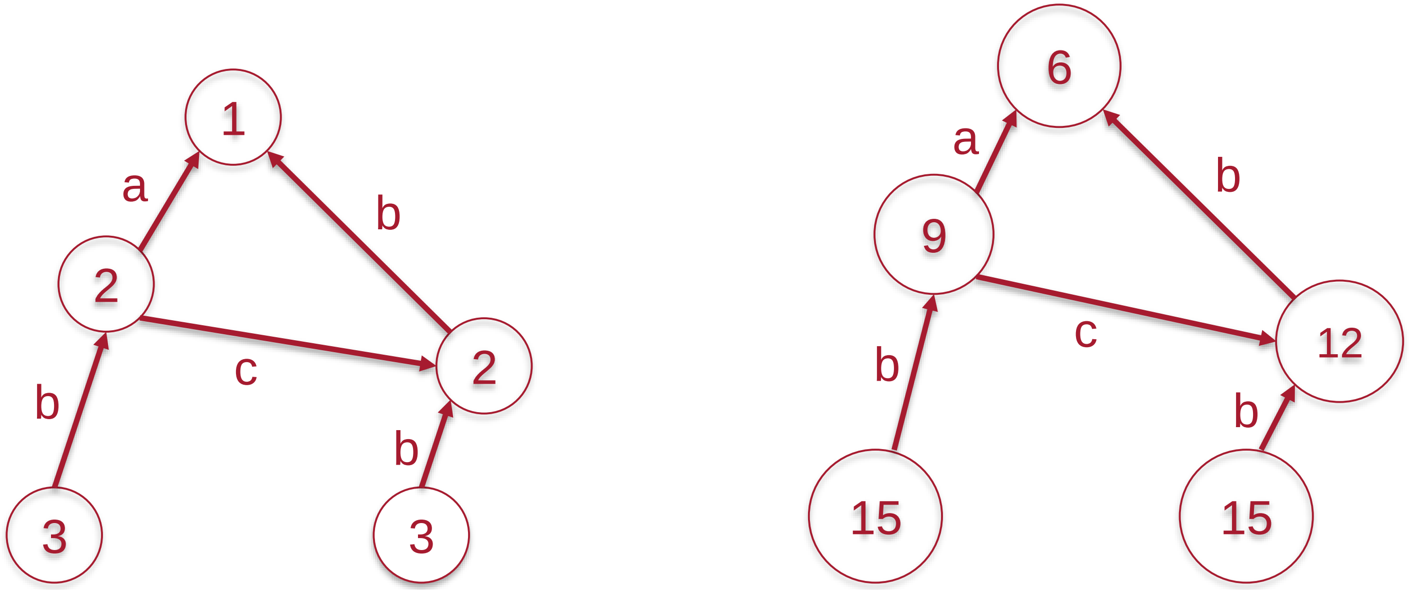


Feature Vector After 1st Iteration

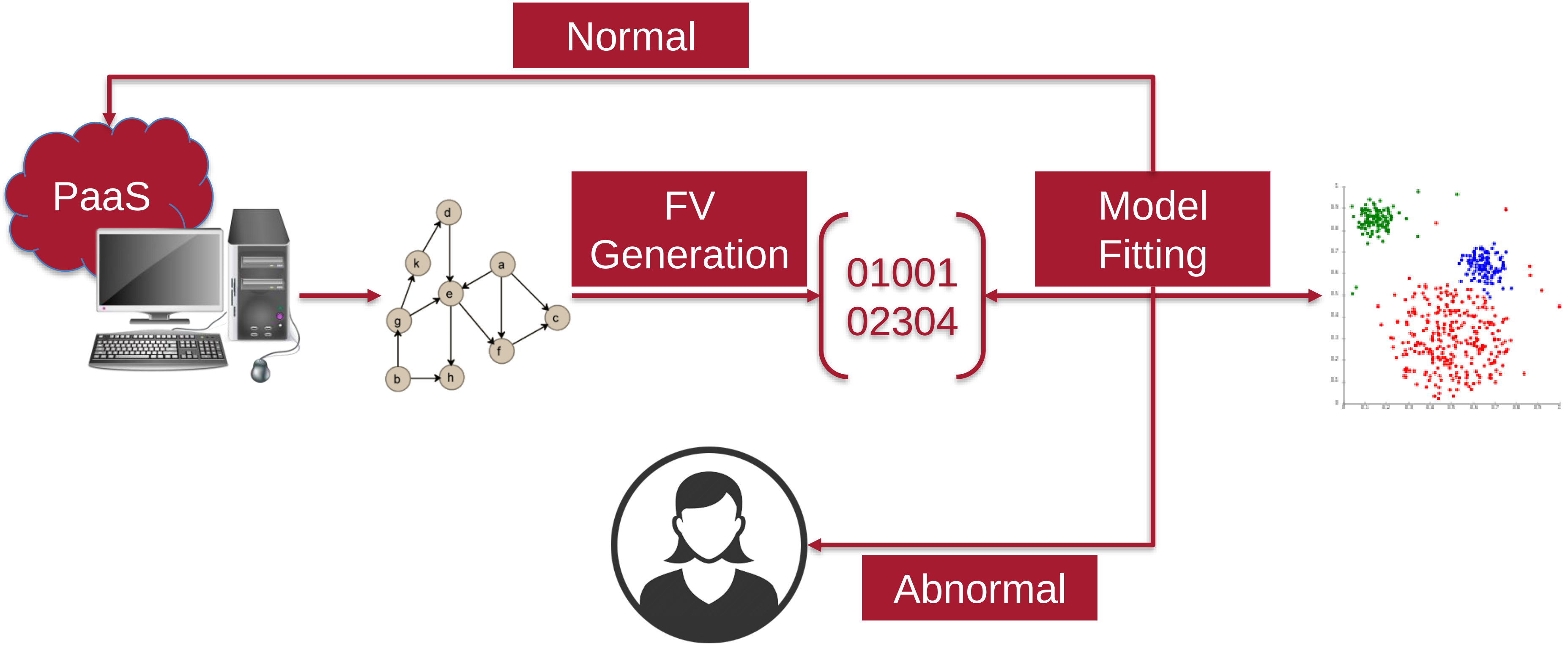


$$\begin{bmatrix} 1 & 2 & 2 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 2 \end{bmatrix}$$

Clustering FVs

- K-means clustering of all feature vectors
  - Determine K by clustering pairwise distances
  - Counts are transformed to probability distributions if needed
- Experiment with distance metrics
  - Kullback-Leibler with back-off probability
  - Hellinger
  - Euclidean

Detection Algorithm (1)



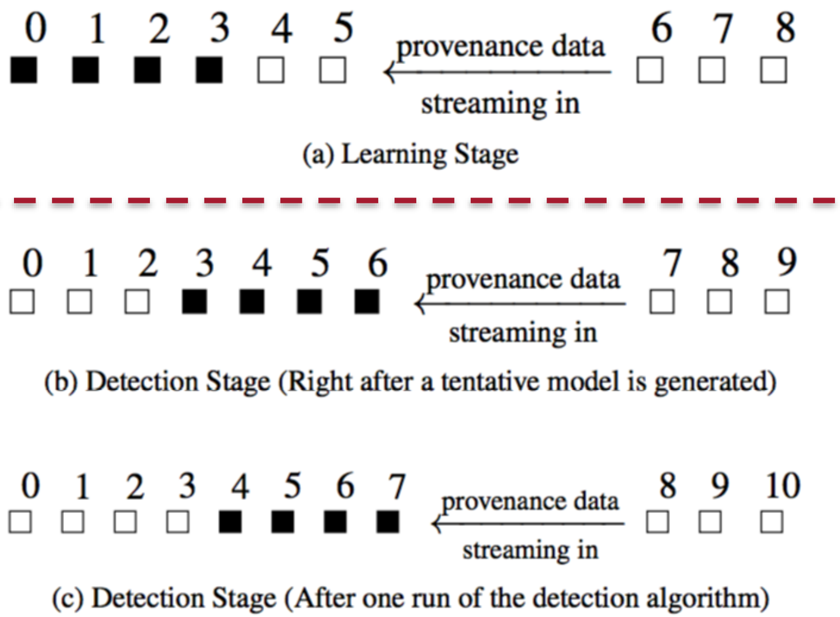
Detection Algorithm (2)

- Continuously monitor a running instance using the dynamic sliding window
- Only store and analyze provenance data within the window

Example Detection Algorithm (Window Size = 4)

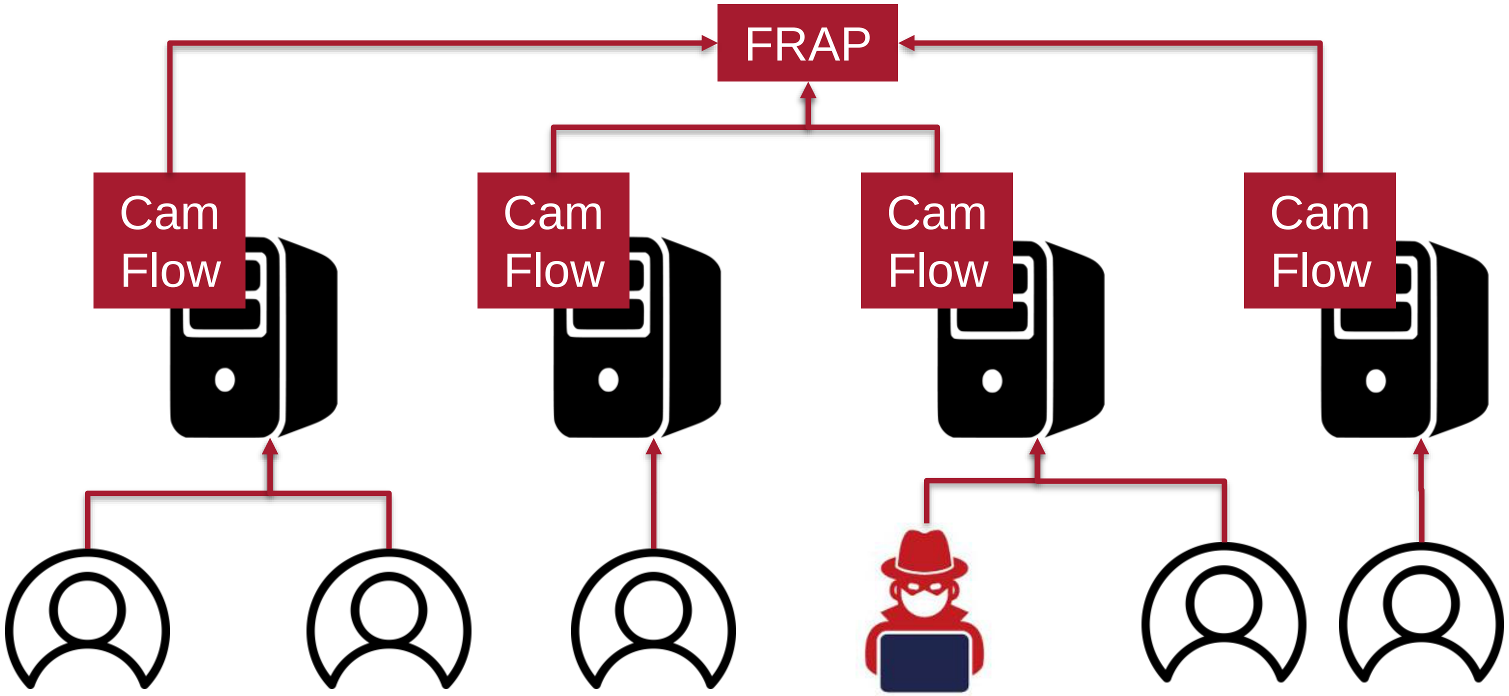
Learning the Model

Using the Model



Experiment Setup

- Ruby server out-of-memory crash
- Faulty server code causes out-of-memory crash when a client requests a particular URL.
- FRAP monitors many instances of a Ruby Server, modeling its normal behavior.



Experimental Results

Distance Metrics	Isolate Bad Instance During Model Generation?	Captured Bad Instance During Continuous Detection?
Kullback-Leibler	✓	✓
Hellinger	✗	✗
Euclidean	✓	✓

- Experiment uses 10 server instances accepting client requests
- 1 instance crashes during model generation
- The same instance crashes again during detection

Conclusions

- Security is still a major concern of the PaaS clouds.
- Provenance provides an alternative approach to detecting faults/intrusions.
- Preliminary experiments show promising results of such an approach.
- Multiple exciting future directions exist.
  - Incorporating more machine learning algorithms?
  - Provenance database of known vulnerabilities?
  - Differential provenance?

Discussion Topics

- What if provenance data are not trustworthy? Can we integrate detection of provenance data tampering?
- How can we use provenance to provide meaningful information to the users when an intrusion is detected?
- What are the pros and cons of FRAP compared to other behavioral-based detection systems and to the cloud IDS’s at large?