Survivor: A Fine-Grained Intrusion Response and Recovery Approach for Commodity Operating Systems

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Agenda

Problem Statement

Approach and Prototype

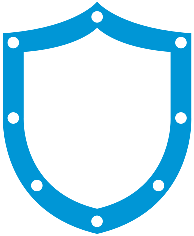
Evaluation

Conclusion

Preventive Security is not Sufficient

Examples of preventive security mechanisms

- Access control
- Cryptography
- Firewalls



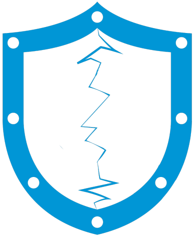
Preventive Security is not Sufficient

Examples of preventive security mechanisms

- Access control
- Cryptography
- Firewalls

Attackers will eventually bypass our security policy

- (Unknown) vulnerability
- System not updated
- Misconfiguration



Preventive Security is not Sufficient

Examples of preventive security mechanisms

- Access control
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- Firewalls

Operating systems should not only prevent but **detect** and **survive** intrusions

- System not updated
- Misconfiguration

Commodity Operating Systems Can Detect but Cannot Survive Intrusions

Intrusion Detection Systems[1] exist in commodity OSs

e.g., Antivirus software share many aspects of host-based IDSs[2]

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What can we do after a system has been compromised?

Eventually we want to patch the system

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What can we do after a system has been compromised?

Eventually we want to patch the system

What should we do while waiting for the patches?

Deliver service despite the attacker's presence

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Related Work: Survivability, Recovery, and Response

Intrusion Survivability[3]

- Trade-off between the availability and the security risk
- Limitations: lack of focus on **commodity OSs**

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- Trade-off between the availability and the security risk
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Intrusion Recovery[4]

- Restore the system in a safe state when an intrusion is detected
- Limitations: the system is **still vulnerable** and can be **reinfected**

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Intrusion Response[5]

- Limit the impact of an intrusion on the system
- Limitations: **coarse-grained responses** and **few host-based solutions**

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Intrusion Survivability[3]

- Trade-off between the availability and the security risk
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Intrusion Recovery[4]

Existing approaches do not allow commodity OSs to **survive** intrusions while maintaining the **availability** of the services

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Problem Addressed

How to design an OS so that it can **survive** ongoing intrusions by making a **trade-off** between **availability** and **security risk**?

Prevent

Detect

Survive

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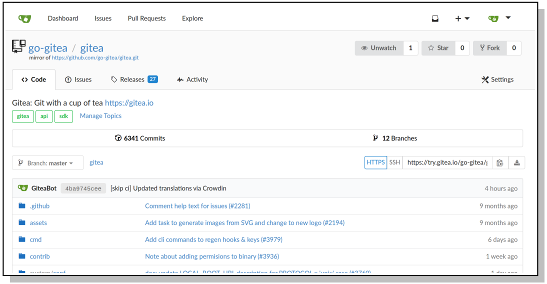
Running Example



Service: Gitea, a Git Self-Hosting Server

Open source clone of Github (git repositories, bug tracking,…)

Intrusion: Ransomware

It compromises data availability

Approach Overview

Illustrative Example

Running Example

Gitea infected with some ransomware

When Detected

- Recovery: We restore the service and the encrypted files to a previous state
- Apply restrictions: We remove the ability to write on the file system

Positive Impact

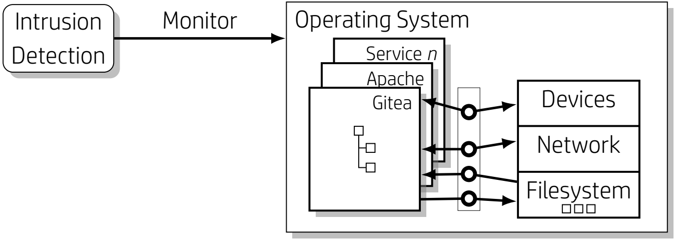
If the ransomware reinfects the service $\rightarrow$ cannot compromise the files

Degraded Mode

Users can no longer push to repositories $\rightarrow$ trade-off between availability and security risk

Approach Overview

During the normal operation of the system



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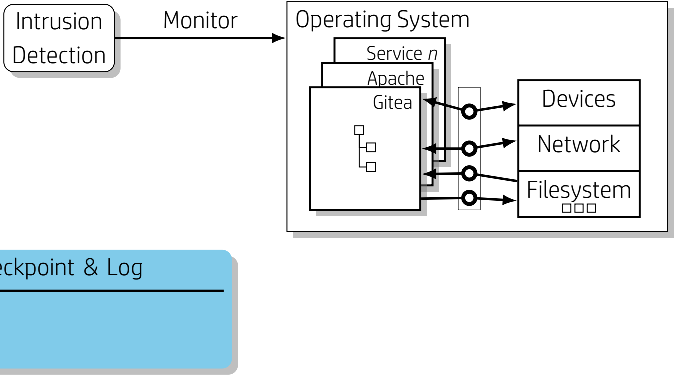

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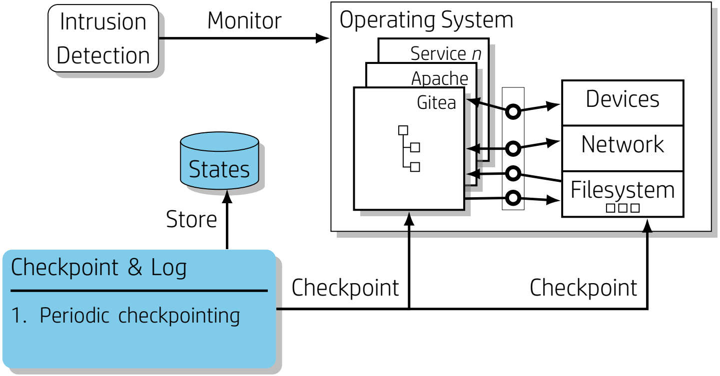

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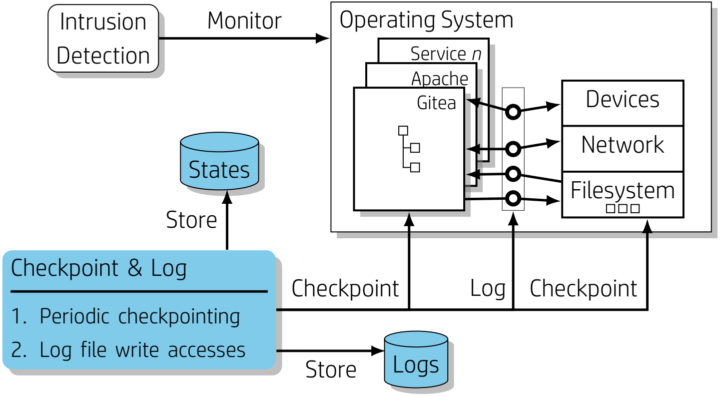

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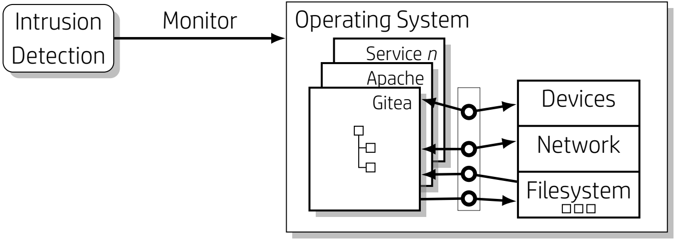
How our approach allows the system to survive intrusions after their detection?



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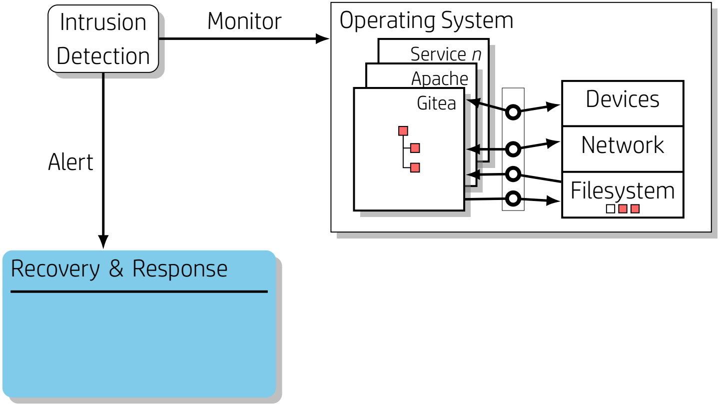

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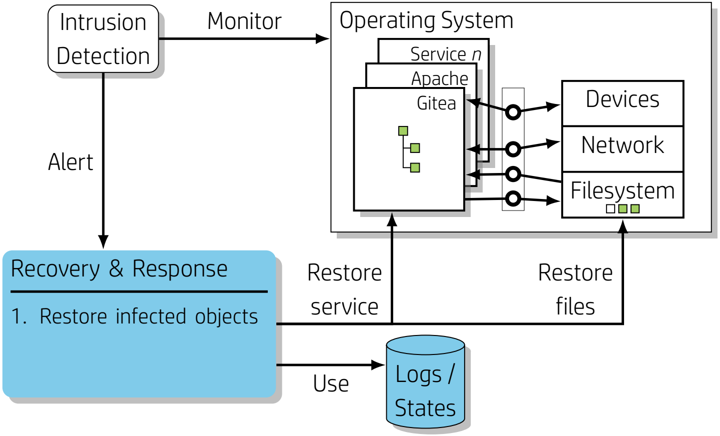

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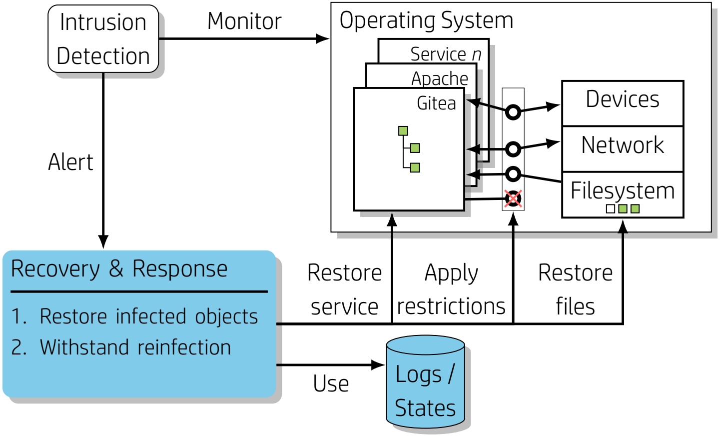

Remove privileges and decrease resource quotas

Per-service responses to prevent attackers to achieve their goals

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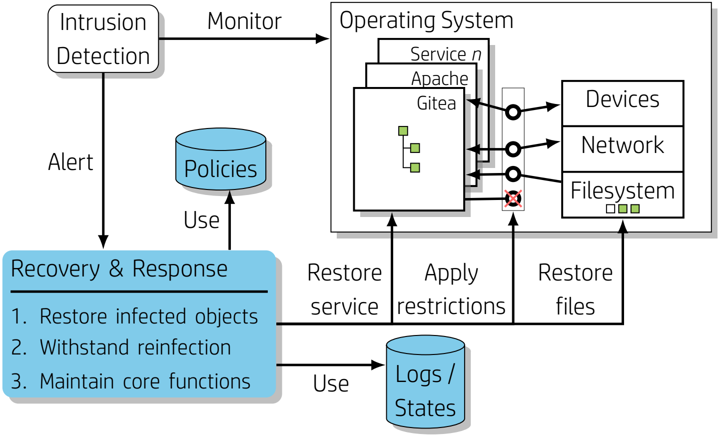

Potential Degraded Mode

The degraded mode maintains core functions **while waiting for patches**

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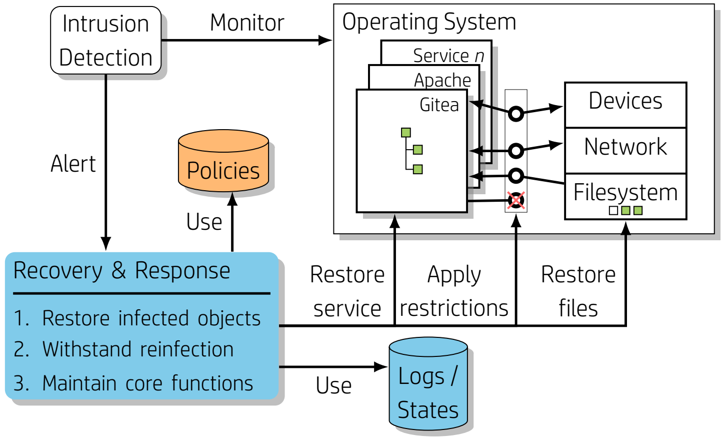

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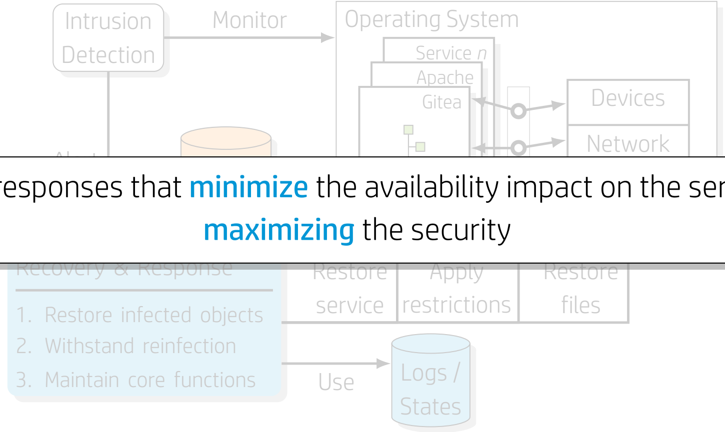
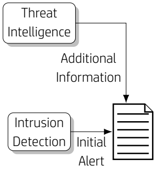


We select responses that **minimize** the availability impact on the service while **maximizing** the security

Cost-Sensitive Response Selection

understand the intrusion - find possible responses - select a response



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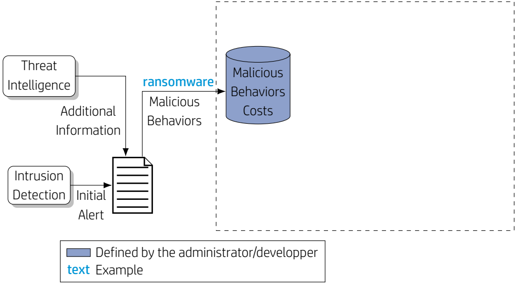


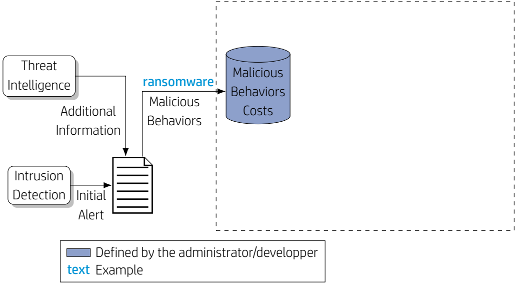
Malicious behaviors
- Availability violation
- Consume system resources
- Crack passwords
- Mine for cryptocurrency
- Compromise data availability
- Compromise access to information assets
- Command and Control
- Determine C2 server
- Generate C2 domain name(s)
- Receive data from C2 server
- Control malware via remote command
- Update configuration
- ...

Example of malicious behaviors

Costs

very low, low, moderate, high, very high, critical

Cost-Sensitive Response Selection



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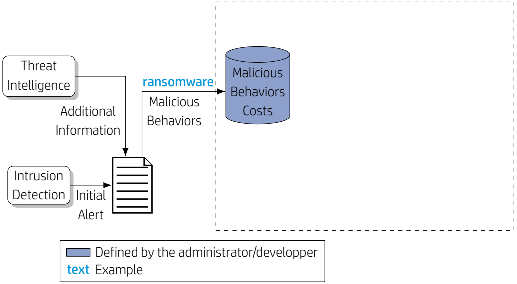
  - ...

Example of a non-exhaustive malicious behavior hierarchy (Source: MAEC of the STIX project)

Costs

very low, low, moderate, high, very high, critical

Cost-Sensitive Response Selection



Malicious behaviors

- Availability violation=**moderate**
  - Consume system resources
    - Crack passwords
    - Mine for cryptocurrency
  - Compromise data availability
    - Compromise access to information assets
  - …
- Command and Control
  - Determine C2 server
    - Generate C2 domain name(s)
  - Receive data from C2 server
    - Control malware via remote command
    - Update configuration
  - …
- …

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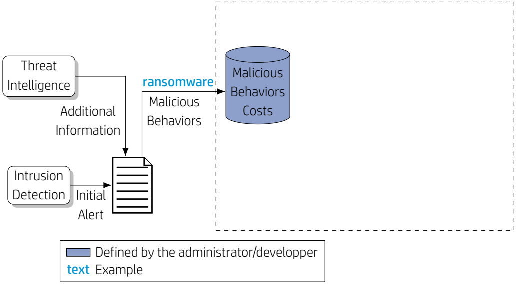

Malicious behaviors
- Availability violation=**moderate**
  - Consume system resources=**moderate**
    - Crack passwords=**moderate**
    - Mine for cryptocurrency=**moderate**
  - Compromise data availability=**moderate**
    - Compromise access to information assets=**moderate**
  - ...
- Command and Control
  - Determine C2 server
    - Generate C2 domain name(s)
  - Receive data from C2 server
    - Control malware via remote command
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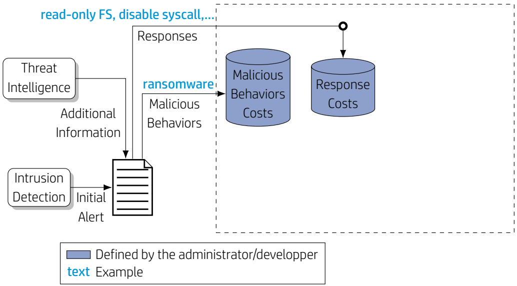

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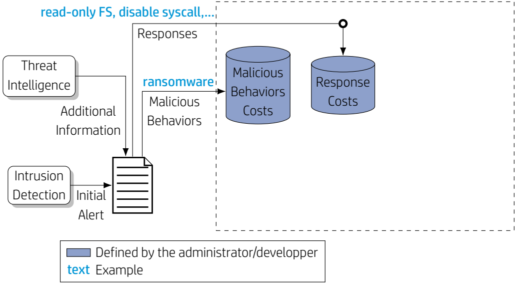
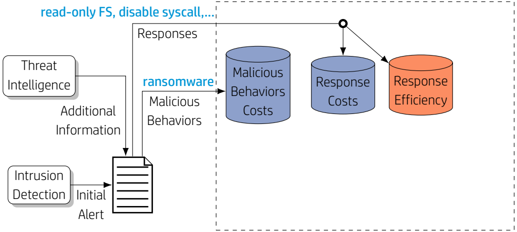


- Per-service responses
  - File system
    - Read-only file system
      - Read-only path
    - Inaccessible path
  - System calls
    - Blacklist any system call
      - Blacklist a list or a category of system calls
  - Network
    - Disable network
      - Blacklist IP addresses
      - Blacklist ports
      - ...
  - Resources
    - CPU quota
    - ...
  - ...

Example of a non-exhaustive per-service response hierarchy

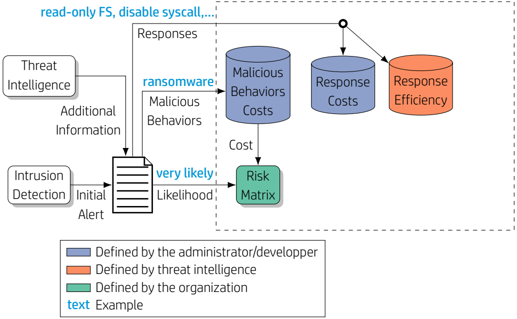
Responses may be provided via the exchange format STIX (e.g., the course of action field)

Cost-Sensitive Response Selection



Defined by the administrator/developper
Defined by threat intelligence
text Example

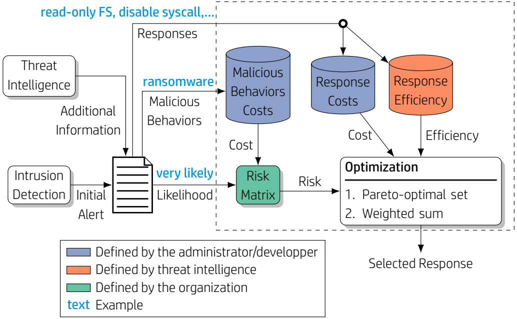
Cost-Sensitive Response Selection



Risk Matrix

Confidence (Likelihood)	Malicious Behavior Cost: Very low 0 – 0.2	Low 0.2 – 0.4	Moderate 0.4 – 0.6	High 0.6 – 0.8	Very high 0.8 – 1
Very likely 0.8 – 1	L	M	H	H	H
Likely 0.6 – 0.8	L	M	M	H	H
Probable 0.4 – 0.6	L	L	M	M	H
Unlikely 0.2 – 0.4	L	L	L	M	M
Very unlikely 0 – 0.2	L	L	L	L	L

Cost-Sensitive Response Selection



Cost vs Efficiency

It prioritizes efficiency if the risk is high, and cost if the risk is low

$$\max\left(Risk \times Efficiency + (1 - Risk) \times (1 - Cost)\right)$$

Cost-Sensitive Response Selection

read-only FS, disable syscall,...

Responses

Cost vs Efficiency

It prioritizes efficiency if the risk is high, and cost if the risk is low

We rely on:

- Possible responses
- Malicious behaviors
- Likelihood

We assign:

- Response costs
- Malicious behavior costs
- Risk matrix

We select responses based on:

- Response cost
- Risk
- Response efficiency

$$\max\left(Risk \times Efficiency + (1 - Risk) \times (1 - Cost)\right)$$

Prototype Implementation for Linux-Based Systems

Projects Used or Modified

Project	What does it do? What is it?	Why do we use/modify it?	Lines of C code added
systemd	system and service manager	Orchestration	2639
CRIU	checkpoint & restore processes	Restoration	383
snapper	manage snapshots of file systems	Restoration	0
Linux kernel		Logging & Responses	460
cgroups	set of processes bound to a set of limits		
seccomp	filter system calls		
namespaces	partition kernel resources		
audit	record security relevant events		
[...]			

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Evaluation Setup

What Do We Evaluate?

- Responses effectiveness
- Cost-sensitive response selection
- Availability cost and performance impact
- Stability of degraded services

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Malware and Attacks

- Different types of malicious behaviors (botnet, ransomware, cryptominer,…)
- Linux.BitCoinMiner, Linux.Rex.1, Hakai, Linux.Encoder.1, GoAhead Exploit

Performance Evaluation Setup

- Various types of services (Apache, nginx, mariadb, beanstalkd, mosquitto, gitea)
- Both synthetic and real-world benchmarks using Phoronix test suite

Security Evaluation

Restoration and Responses Effectiveness

Attack Scenario	Malicious Behavior	Per-service Response Policy
Linux.BitCoinMiner	Mine for cryptocurrency	Ban mining pool IPs
Linux.BitCoinMiner	Mine for cryptocurrency	Reduce CPU quota
Linux.Rex.1	Join P2P botnet	Ban bootstrapping IPs
Hakai	Communicate with C&C	Ban C&C servers' IPs
Linux.Encoder.1	Encrypt data	Read-only filesystem
GoAhead exploit	Open reverse shell	Forbid connect syscall
GoAhead exploit	Data theft	Render paths inaccessible

Results

- The service is restored
- The service can withstand the reinfection

Security Evaluation

Cost-Sensitive Response Selection

Goal

Evaluate the impact of the IDS accuracy when selecting responses

$\rightarrow$ accurate likelihood (1), inaccurate likelihood (2), false positive (3)

Scenario

Survive ransomware that compromised Gitea

Results

- High risk: read-only filesystem (1, 3)
  - Ransomware failed to reinfect
  - Gitea still usable (can access all repositories, clone them, log in)
- Low risk: read-only paths of important git repositories (2)
  - Ransomware could not encrypt important repositories
  - Gitea still usable (can access important repositories, clone them)

Performance Evaluation

Availability Cost

- less than 300 ms to checkpoint
- less than 325 ms to restore

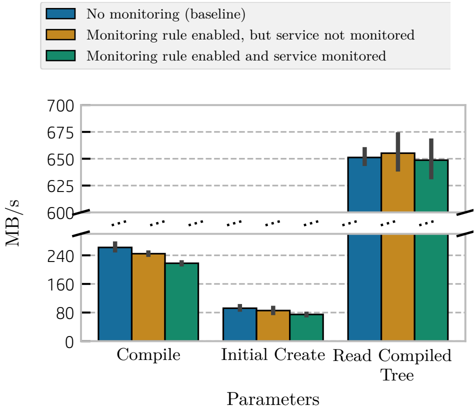
Performance Evaluation

Availability Cost

- less than 300 ms to checkpoint
- less than 325 ms to restore

Monitoring Cost

- Overhead present only on applications that write to the file system



(a) MB/s score with the Compilebench benchmark (more is better)

Performance Evaluation

Availability Cost

- less than 300 ms to checkpoint
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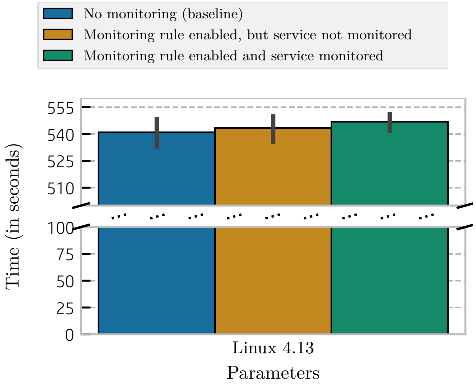
Monitoring Cost

- Overhead present only on applications that write to the file system
- Small overhead in general (0.6 % - 4.5 %)



(b) Time (in seconds) to build the Linux kernel (less is better)

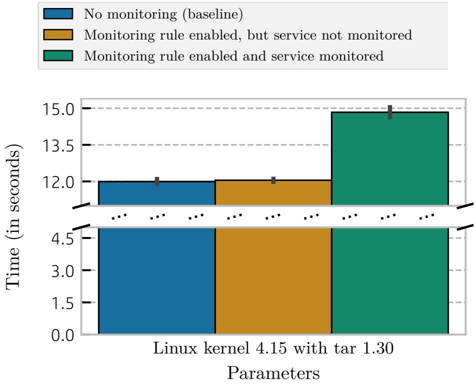
Performance Evaluation

Availability Cost

- less than 300 ms to checkpoint
- less than 325 ms to restore

Monitoring Cost

- Overhead present only on applications that write to the file system
- Small overhead in general (0.6 % - 4.5 %)
- Worst case (28.7 % overhead): writing small files asynchronously in burst



(c) Time (in seconds) to extract the archive (.tar.gz) of the Linux kernel source code (less is better)

Performance Evaluation

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- e.g., SHELF[6] has 8 % and 67 % overhead

[6] Xiong, Jia, and Liu, "SHELF: Preserving Business Continuity and Availability in an Intrusion Recovery System".

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Scientific Contributions and Future Work

Operating systems should not only **prevent** but **detect** and **survive** intrusions

What were the challenges?

- Survive while waiting for the patches
- Maintain availability while maximizing security
- Realistic use cases

Future work

- Checkpointing limitations
- Models input

ACSAC'19

Ronny Chevalier, David Plaquin, Chris Dalton, and Guillaume Hiet. "Survivor: A Fine-Grained Intrusion Response and Recovery Approach for Commodity Operating Systems". Dec. 2019

Thanks for your attention!

Questions?

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