# KAIROS: Practical Intrusion Detection and Investigation using Whole-system Provenance (Supplementary Material)

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## 1. Introduction

This document contain materials supplementary to our paper published in the $43^{rd}$ IEEE Symposium on Security and Privacy (S&P'24) [1]. In Section 2 of this document, we report attack descriptions based on the ground truth information provided by the Defense Advanced Research Projects Agency (DARPA) [2–4] and the associated attack summary graphs generated by KAIROS. In Section 3, we report representative false positive samples.

## 2. Attack Reconstruction

**E3-THEIA (Fig. 1).** The attacker leverages a `Firefox` vulnerability to establish a foothold on a victim machine, which enables the attacker to write a malicious payload called `clean` to `/home/admin/` on disk. The attacker then executes the payload with escalated privileges. This new attack process (with root privileges) communicates with the attacker's command-and-control (C&C) server at `161.116.88.72` to download and execute another malicious payload called `profile`, again with root privileges. `profile`, in turn, fetches a third payload called `xdev` from the C&C server and stores the payload in `/var/log/`. `profile` and `xdev` lurk in the victim host to prepare for subsequent attacks. A few days later, the attacker uses `profile` to inject malicious code in the `mail` process and executes `mail` with root privileges. `mail` then performs port scans of all known hosts on the victim's network.

**E3-CADETS (Fig. 2).** The attacker (`81.49.200.166`) connects to a vulnerable `Nginx` server and obtains a shell. Through the shell, the attacker successfully downloads a malicious payload to `/tmp/vUgefal` and executes the payload with root privileges. The elevated process `vUgefal` attempts to move laterally to `154.145.113.18` and `61.167.39.128`. However, only the attempt at infecting `61.167.39.128` is successful. `vUgefal` further plans to inject malicious payload to the `sshd` process. To do so, the attacker downloads the payload to `/var/log/devc`, but the attempted process injection fails.

**E3-ClearScope (Fig. 3).** The attacker exploits a vulnerability in `Firefox` to gain control of a victim host by browsing www.mit.gov.jo. The attacker then loads the payload `shared_files` into the victim's filesystem at `/data/data/org.mozilla.fennec_fire-fox_dev` and runs it with root privileges. The attacker's subsequent attempts to (1) load additional attack modules and (2) inject the attack payload into a process fail. Note that we were unable to find any `execute`- or `fork`-related behaviors in the data. It is unclear whether ClearScope records them in E3. Consequently, malicious activity that leverages such behaviors is not invisible to KAIROS (since it is not included in the data to begin with).

**E5-THEIA (Fig. 4).** The attacker exploits a vulnerability in `Firefox` by browsing www.nhra.com, connecting the victim host to C&C servers (`189.141.204.211` and `208.203.20.42`). The attacker then uses `/run/shm` to escalate privileges and gain access to a list of processes. The attacker finds the `sshd` process and injects malicious code into the process. The compromised `sshd` process writes to a file `/var/log/sshdlog` on the host's filesystem.

**E5-CADETS (Fig. 5).** The attacker sends a malformed `HTTP POST` from `128.55.12.167` to the victim host to trigger the `Nginx`'s backdoor. The `HTTP` request carrying a payload executes shell code, establishing a connection to a C&C server (`4.21.51.250`). The attacker obtains `username` and `hostname` information before unexpectedly losing control. The next day, the attacker sends the malformed `HTTP POST` again and continues the attack from the C&C server (`128.55.12.233`). The attacker exfiltrates the host's environment information such as `hostname`, `passwd`, and `username`, in the subsequent attack.

**E5-ClearScope (Fig. 6).** A user accidentally installs a malicious `appstarter` APK `de.belu.appstarter`, which loads an attack module called `busybox`. This module gives the attacker control from `77.138.117.150`. The attacker then installs the driver `msm_g711tlaw` into the victim host for privilege escalation. The attack exfiltrates `calllog.db`, `calendar.db`, and `mmssms.db` and takes a screenshot. Two days later, the attacker exploits `appstarter` again to try to connect to the C&C server
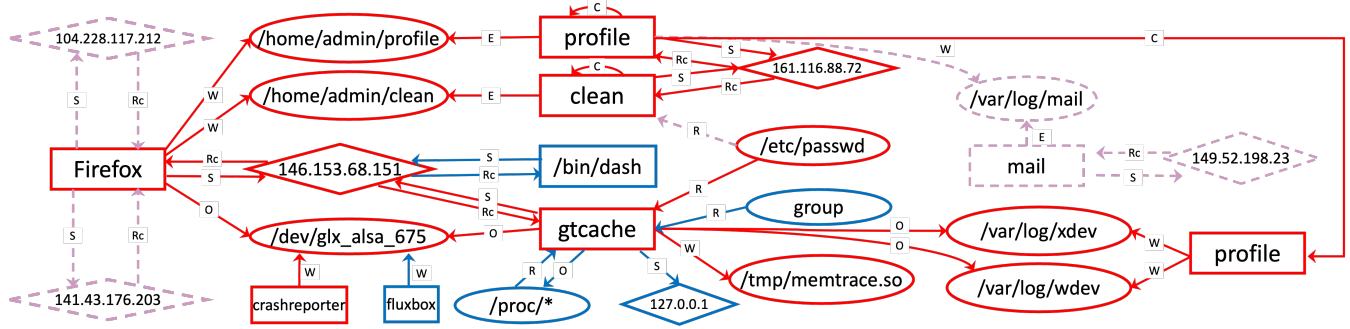
Figure 1. A provenance summary graph from DARPA E3-THEIA that describes attack activity in the motivating example, as automatically generated by KAIROS. Rectangles, ovals, and diamonds represent processes, files, and sockets, respectively. R=Read, W=Write, O=Open, S=Send, Rc=Receive, C=Clone, and E=Execute. We add colors and dashed elements for clarity to highlight the output that KAIROS generates. Solid nodes and edges are extracted by KAIROS from the original provenance graph to reconstruct the attack. Dashed pink nodes and edges are attack-related activities missed by KAIROS, according to the attack ground truth. Blue nodes and edges are activities not explicitly mentioned in the ground truth but included by KAIROS.
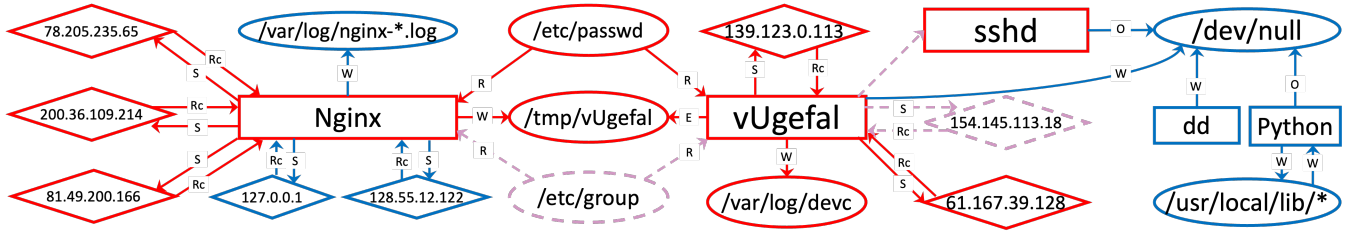


Figure 2. A summary graph that describes attack activity in DARPA's E3-CADETS dataset, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.
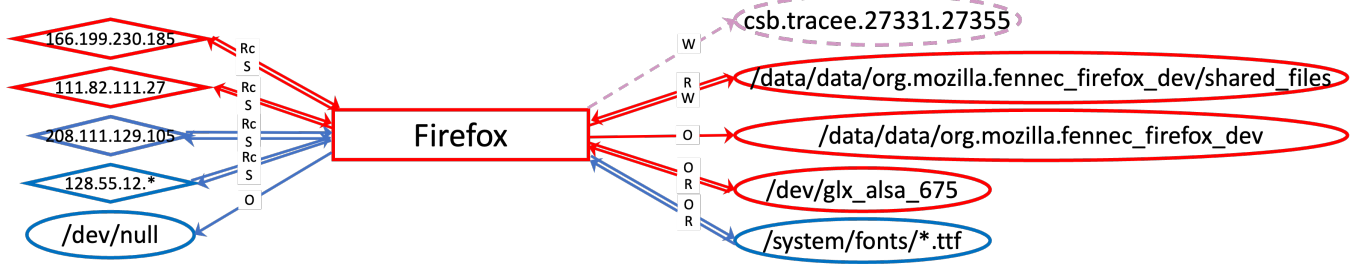


Figure 3. A summary graph that describes attack activity in DARPA's E3-ClearScope dataset, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.

(128.55.12.233) but failed. The ground truth also describes some malicious activity of attack payloads called lockwatch and mozilla. Upon close inspection, we discover that the provenance data related to the malicious activity is corrupted. We remove the corrupted data and omit the malicious activity in Fig. 6.

**OpTC Day 1 (Fig. 7).** The attacker uses a C&C server (132.197.158.98) to connect to the victim host and executes a powershell script runme.bat. The attacker then injects the process lsass to collect the victim's credential and host information. The attacker also scans the network (e.g., using ping and smb) and uses wmiprvse to move laterally to a host at 142.20.57.147. Eventually, the attacker moves to a host at 142.20.58.149 and runs more powershell scripts *.ps1 to collect information.

**OpTC Day 2 (Fig. 8).** The attacker sends a phishing email with a payload (payroll.docx) to the victim. After executing the payload, the attacker uses the elevated powershell to performs network scan and wmiprvse to establish persistence. The attacker uploads plink.exe to forward port 3389 and uses RDP to connect to the host. Finally, the attacker collects and compresses host information into *.zip and runs nx.exe to exfiltrate the files.

**OpTC Day 3 (Fig. 9).** Notepad++ downloads a malicious file update.exe, which runs an attack payload cKfGW.exe. The attacker controls cKfGW.exe through a malicious DNS server (53.192.68.50) to inject system processes and collect and modify host information.
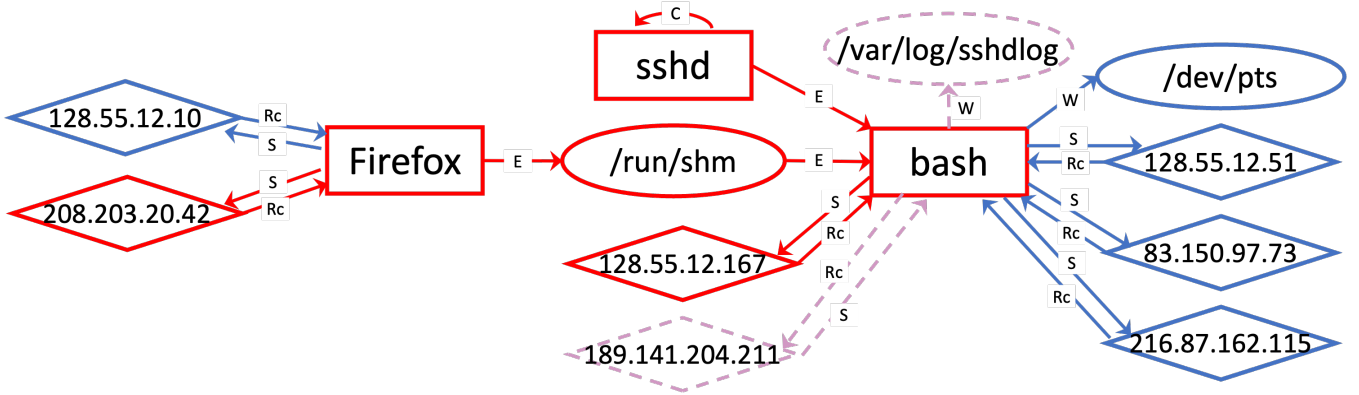
Figure 4. A summary graph that describes attack activity in DARPA's E5-THEIA dataset, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.
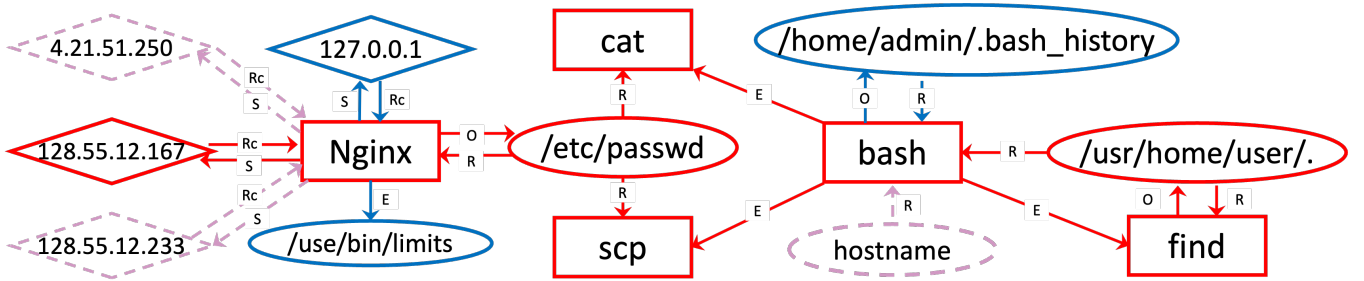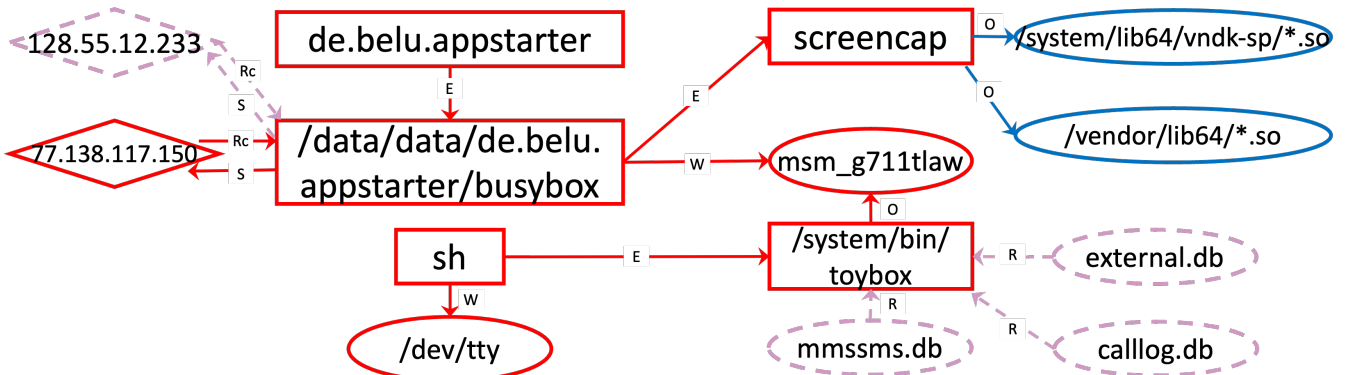


Figure 5. A summary graph that describes attack activity in DARPA's E5-CADETS dataset, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.



Figure 6. A summary graph that describes attack activity in DARPA's E5-ClearScope dataset, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.

## 3. Benign Summary Graph Examples

**E3-CADETS (Fig. 10).** `wget` is a Linux utility used to download files from the Internet. It might connect to any external IP or URL. To determine whether `wget`'s behavior is related to attack activity, sysadmins might either check whether any connected IP is in a blocklist or confirm with the user the identities of the files they download. Any file not recognized by the user might be downloaded by the attacker through a C&C server.

**E3-ClearScope (Fig. 11).** `system_server` is an Android core process used to serve various Android system services, e.g., activity manager service (AMS). Sysadmins can manually identify whether a new legitimate system service triggered KAIROS' intrusion alert.

**E5-THEIA (Fig. 12).** `dbus-daemon` provides one-to-one communication between two applications. `upowerd` is a Linux middleware for power management, which provides its services through `dbus`. Sysadmins can check whether any application using `dbus-daemon` is suspicious.

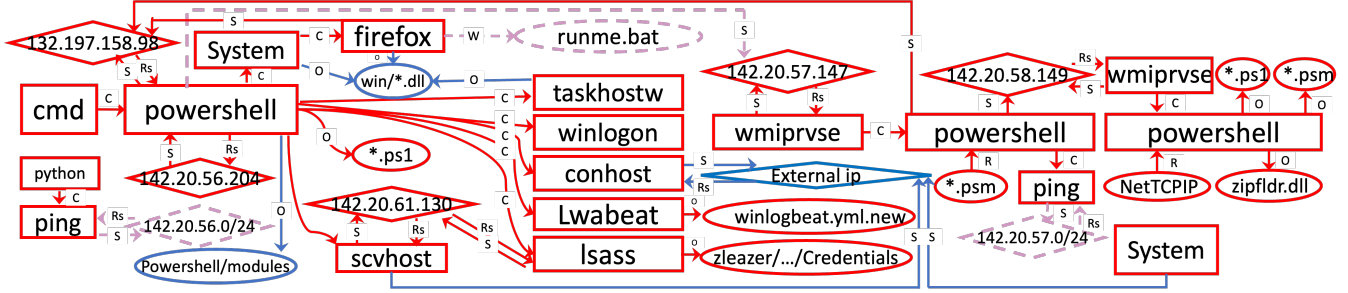**E5-CADETS (Fig. 13).** `scp` is used to securely copy files

Figure 7. A summary graph that describes attack activity in DARPA's OpTC dataset in day 1, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.
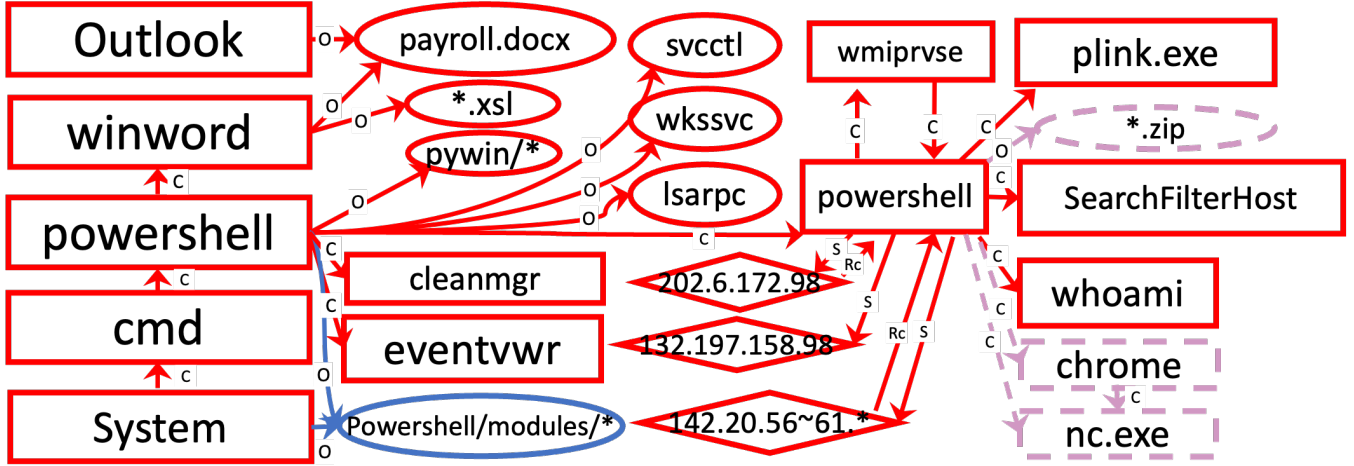


Figure 8. A summary graph that describes attack activity in DARPA's OpTC dataset in day 2, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.

between Linux systems. Unlike `wget`, it serves point-to-point file transfers, so the user should know the identity of the other host. `du` is a Linux utility that collects a host's disk usage. Sysadmins could determine the legitimacy of `scp` and `du` by checking if the user issued the commands. **E5-ClearScope (Fig. 14).** `defcontainer` is a system process associated with APK file installation. Sysadmins might confirm with the user the identities of the APK files they install. Sysadmins should further inspect the installed APK files to ensure that they are from legitimate vendors. **OpTC (Fig. 15).** `Installagent` is Microsoft Windows Store's update agent, which uses the system services `System`, `backgroundTaskHost`, and `svchost`. Sysadmins need to investigate `Installagent` only when suspicious files (e.g., files not in the system path) appear in its activity.

## 4. Availability

KAIROS's code is available online at https://github.com /ProvenanceAnalytics/kairos. StreamSpot's [5] code and its datasets are available online at https://sbustreamspot.github .io/. Unicorn's [6] code is available online at https://github .com/crimson-unicorn. ThreaTrace's [7] code is available online at https://github.com/threaTrace-detector/threaTrace.

DARPA E3 and E5 datasets are available online at https: //github.com/darpa-i2o/Transparent-Computing. DARPA OpTC datasets are available online at https://github.com/F iveDirections/OpTC-data.

## References

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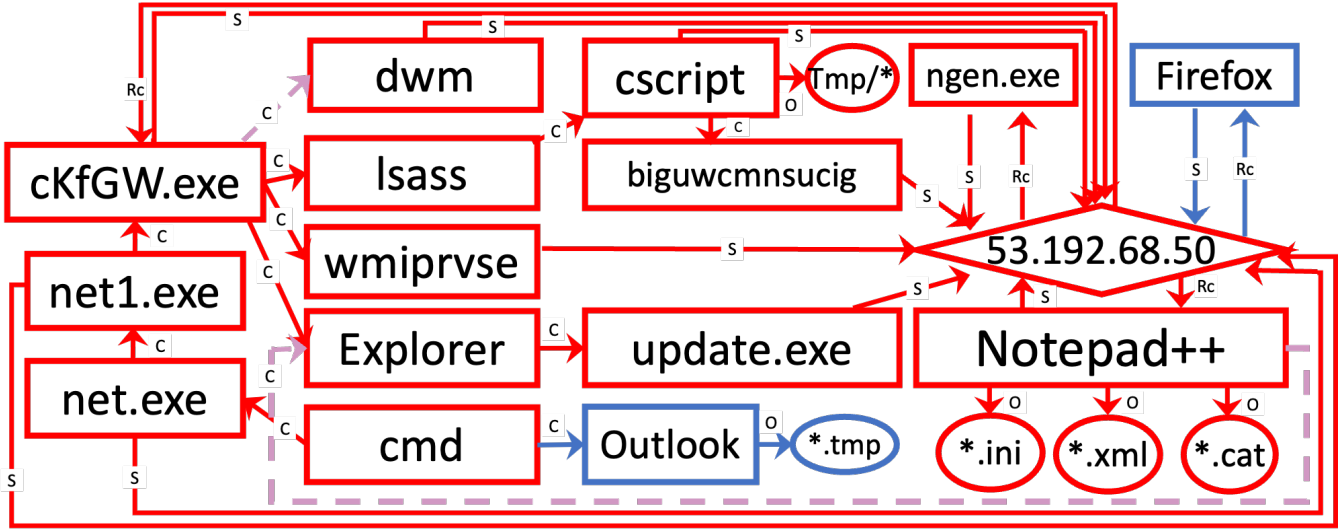
Figure 9. A summary graph that describes attack activity in DARPA's OpTC dataset in day 3, as automatically generated by KAIROS. Colors and dashed elements are added to ease comparison with the ground truth.
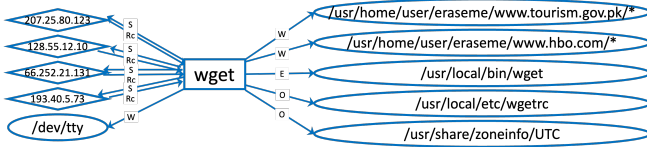


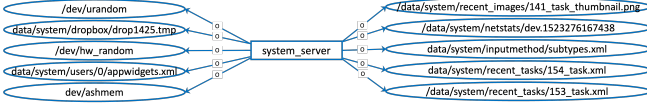Figure 10. A benign summary graph in DARPA's E3-CADETS dataset.



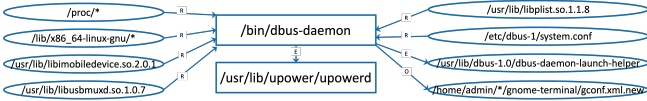Figure 11. A benign summary graph in DARPA's E3-ClearScope.



Figure 12. A benign summary graph in DARPA's E5-THEIA dataset.
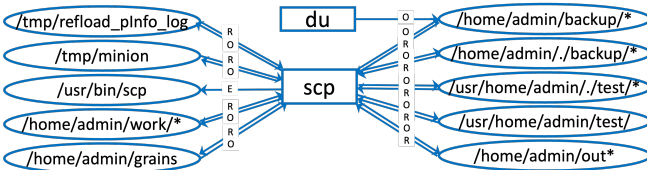


Figure 13. A benign summary graph in DARPA's E5-CADETS dataset.
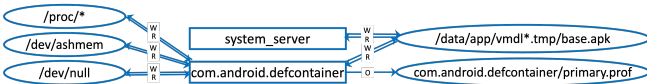


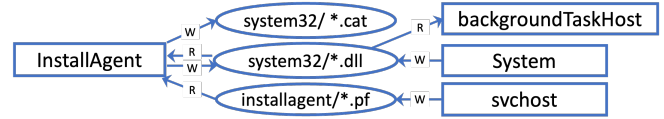Figure 14. A benign summary graph in DARPA's E5-ClearScope.



Figure 15. A benign summary graph in DARPA's OpTC.

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[7] S. Wang, Z. Wang, T. Zhou, X. Yin, D. Han, H. Zhang, H. Sun, X. Shi, and J. Yang, "Threatrace: Detecting and tracing host-based threats in node level through provenance graph learning," *IEEE Transactions on Information Forensics and Security*, 2022.