PalanTir: Optimizing Attack Provenance with Hardware-enhanced System Observability

Jun Zeng[*], ***Chuqi Zhang***[*], *and Zhenkai Liang*

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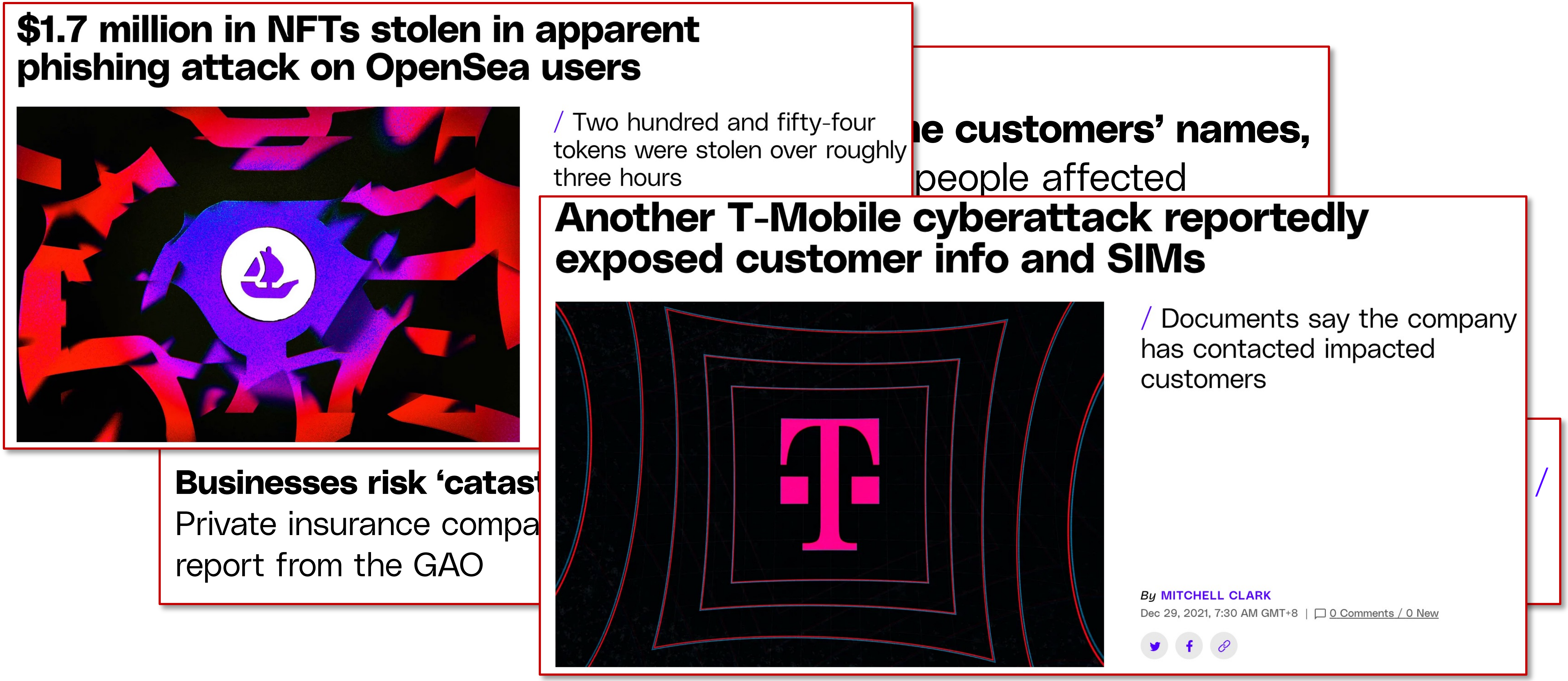
Los Angeles, U.S.A.

NUS
National University
of Singapore

Advanced Cyber Attacks in Enterprises



$1.7 million in NFTs stolen in apparent phishing attack on OpenSea users

/ Two hundred and fifty-four tokens were stolen over roughly three hours

e customers' names,

people affected

Another T-Mobile cyberattack reportedly exposed customer info and SIMs

/ Documents say the company has contacted impacted customers

By MITCHELL CLARK
Dec 29, 2021, 7:30 AM GMT+8 | 0 Comments / 0 New

Businesses risk 'catast

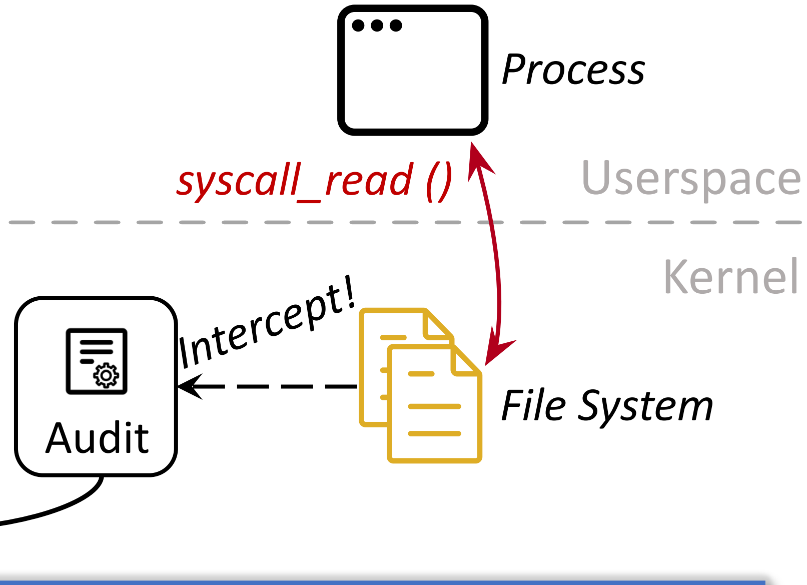
Private insurance compa

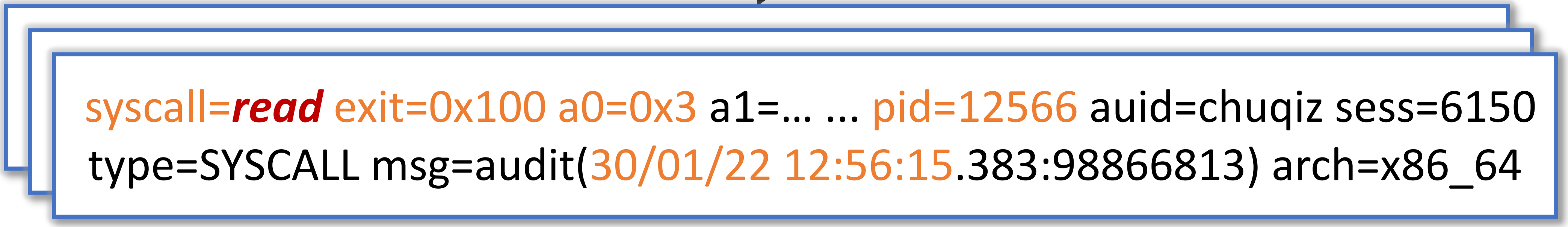
report from the GAO

/

System Auditing:
the Foundation of Attack Investigation

- System auditing records ***OS-level events*** (system entity ***interactions***)
  - e.g., system call





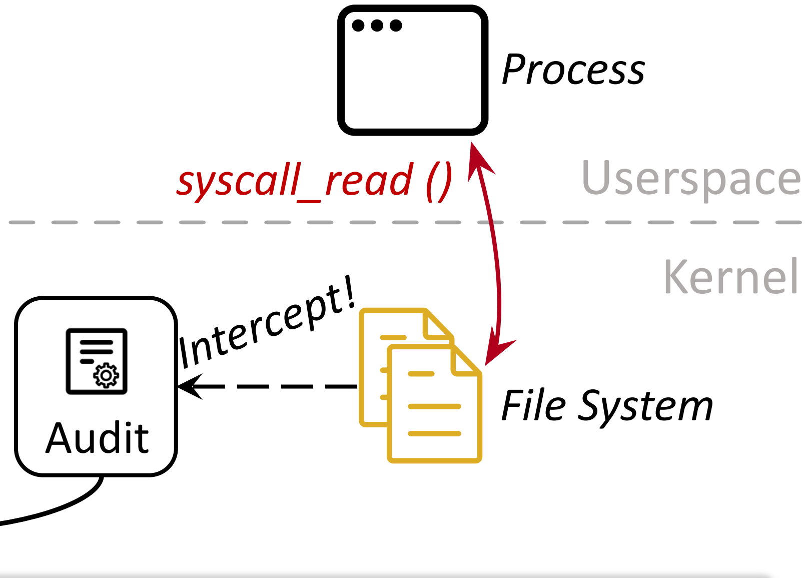
```
syscall=read exit=0x100 a0=0x3 a1=… ... pid=12566 auid=chuqiz sess=6150
type=SYSCALL msg=audit(30/01/22 12:56:15.383:98866813) arch=x86_64
```

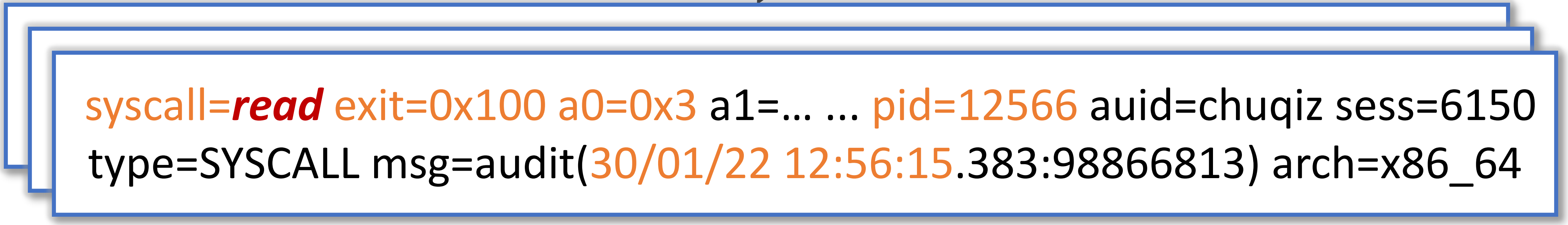
System Auditing: the Foundation of Attack Investigation

- System auditing records ***OS-level events*** (system entity ***interactions***)
  - e.g., system call
- Audit logs can be used for:

✓ ***Root cause analysis***

✓ ***Ramification discovery***





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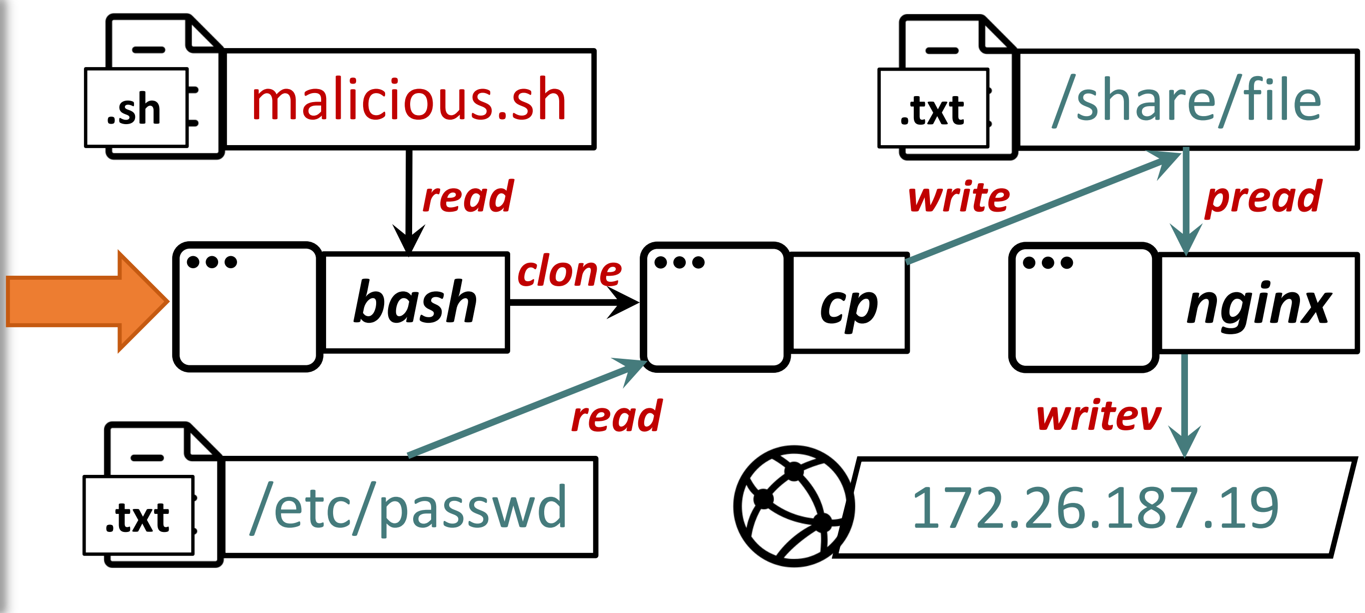
Provenance Graph from Audit Logs

```
…
1. bash, read, malicious.sh
2. bash, clone, cp
3. cp, read, /etc/passwd
4. cp, write, /share/file
5. nginx, pread, /share/file
6. nginx, writev, 172.26.187.19
…
```



✓ ***Provenance Graph*** constructs the ***overall attack scenario*** by ***combining*** historic audit logs***!***

Provenance Graph from Audit Logs

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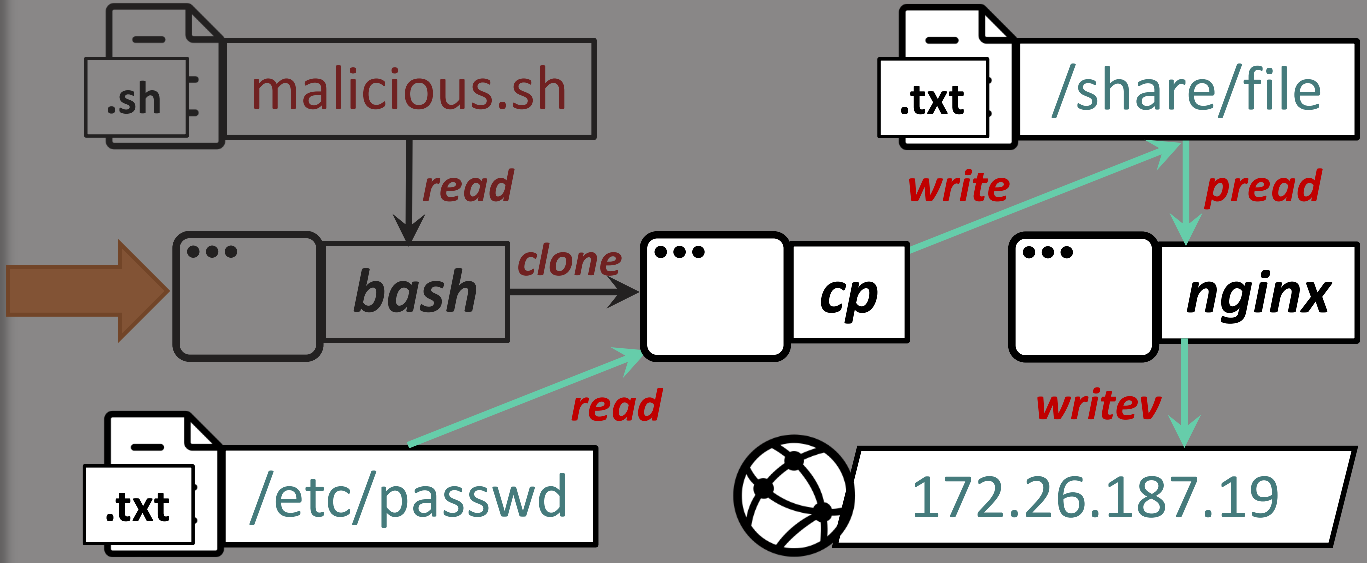


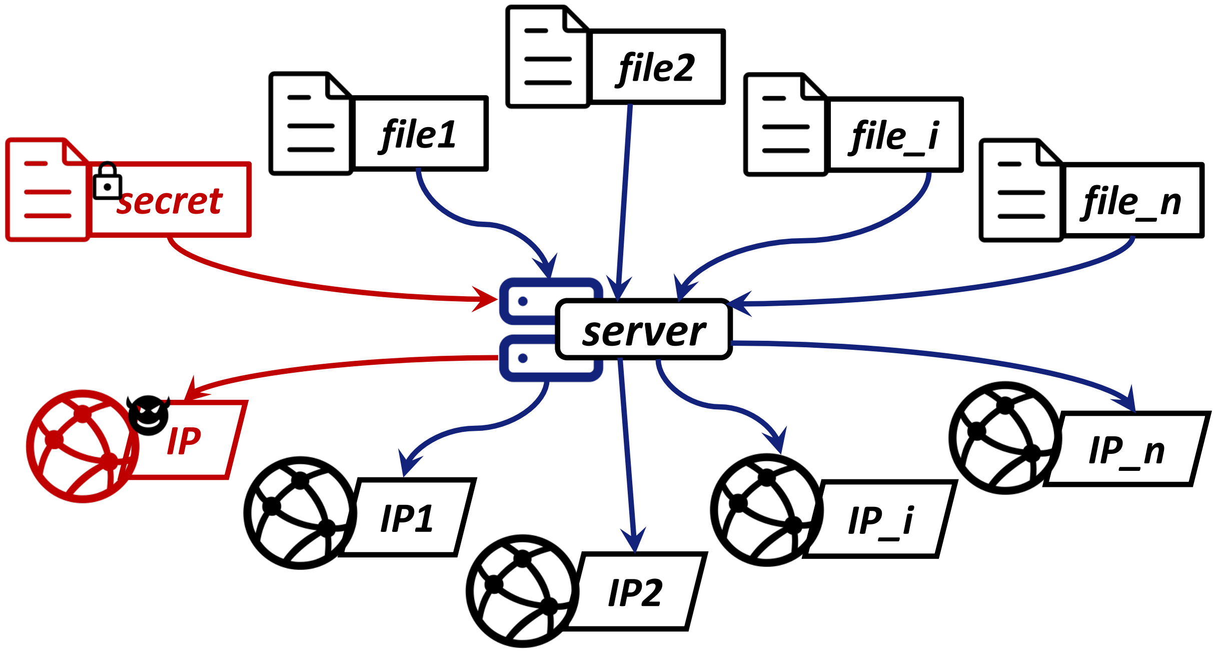
✓***Provenance Graph*** constructs the ***overall attack scenario***
by ***combining*** historic audit logs***!***

Challenges of Provenance Tracking

*Simplified code for a **web server** program*

```
// handle connections
while ((connection_t *) conn) {
    request_t *r = conn->req;
    // handle requested file
    int fd = open(r->req_file);
    read(fd, r->buf, …);
    send(conn->sock_fd, r->buf, …);
}
…
```

Lots of iterations



Challenges of Provenance Tracking

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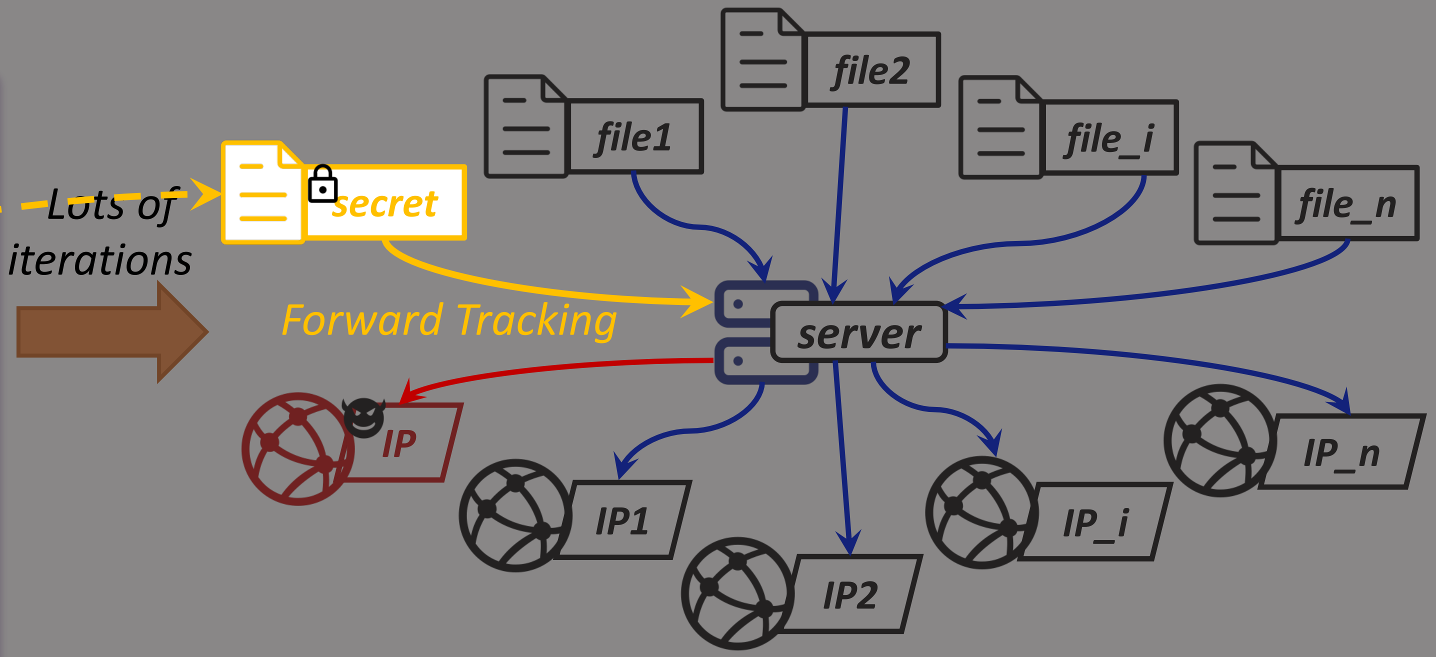

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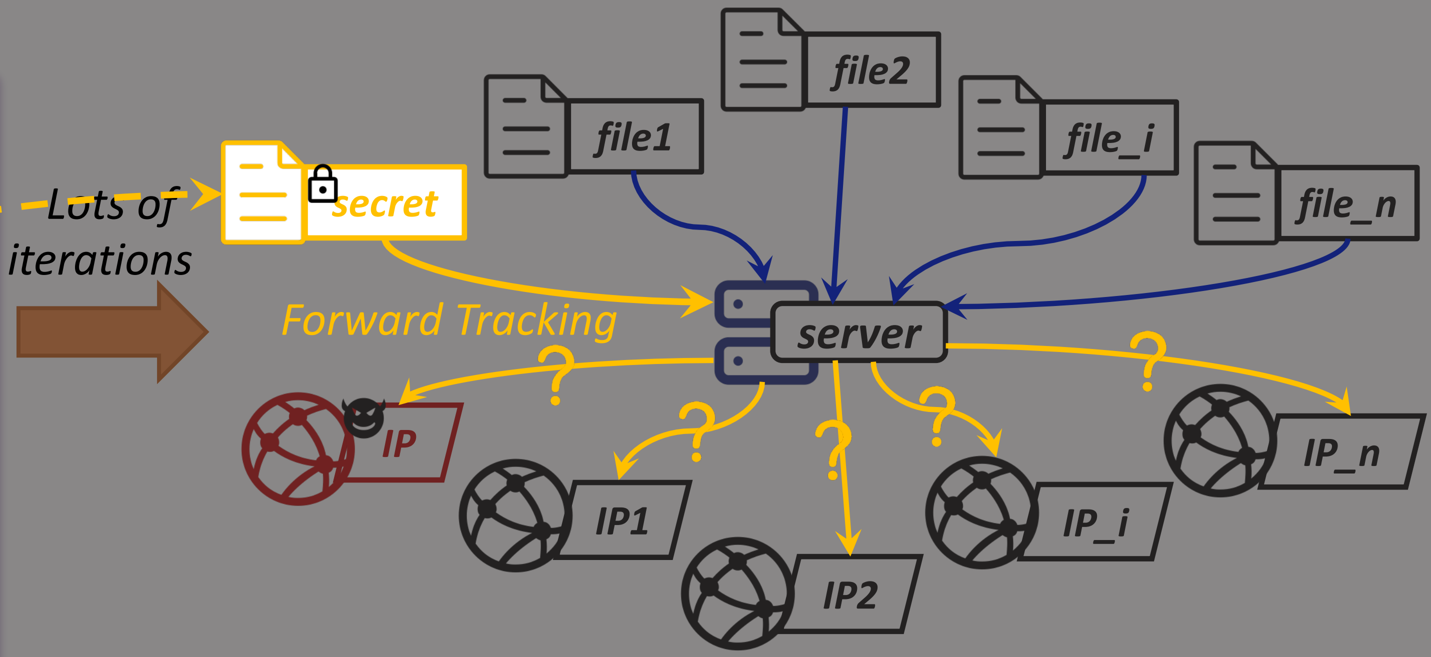

CAN NOT identify** the correct **descendant.

✗ ***No conclusion** of **TRUE provenance.***

Dependency Explosion Problem !

Related Work

- ***Execution Unit Partitioning*** [NDSS'13, Security'16, NDSS'21, …]:
  - Partition program into units by instrumentation or built-in application logs
  - Intrusive to program or error-prone units
- ***Causality Inference*** [ASPLOS'16, NDSS'18, …]:
  - Train a causality model based on dual execution to infer true dependencies
  - Inadequate for high-concurrency programs
- ***Record-and-Replay*** [CCS'17, Security'18, …]:
  - Record non-deterministic program behaviors and replay with taint analysis
  - Fine-grained but intrusive to program, and incur high overhead

Related Work

- ***Execution Unit Partitioning*** [NDSS’13, Security’16, NDSS’21, …]:
  - P
- ***Ca***

💡 ***Ideal Solution:***

- ***Non-intrusive*** to program (i.e., instrumentation free)
- Fine-grained (i.e., ***pinpoint dependency***) provenance

- ***Record-and-Replay*** [CCS’17, Security’18, …]:
  - Record non-deterministic program behaviors and replay with taint analysis
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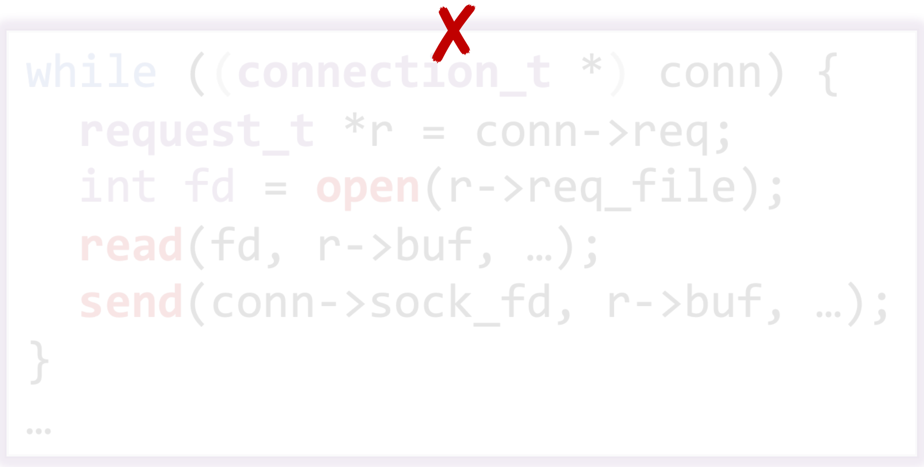
Motivation: Enhance Observability

- Audit log ONLY records OS-level events => ***coarse-grained provenance***
  ✗ ***NO fine-grained provenance*** (program data flow)



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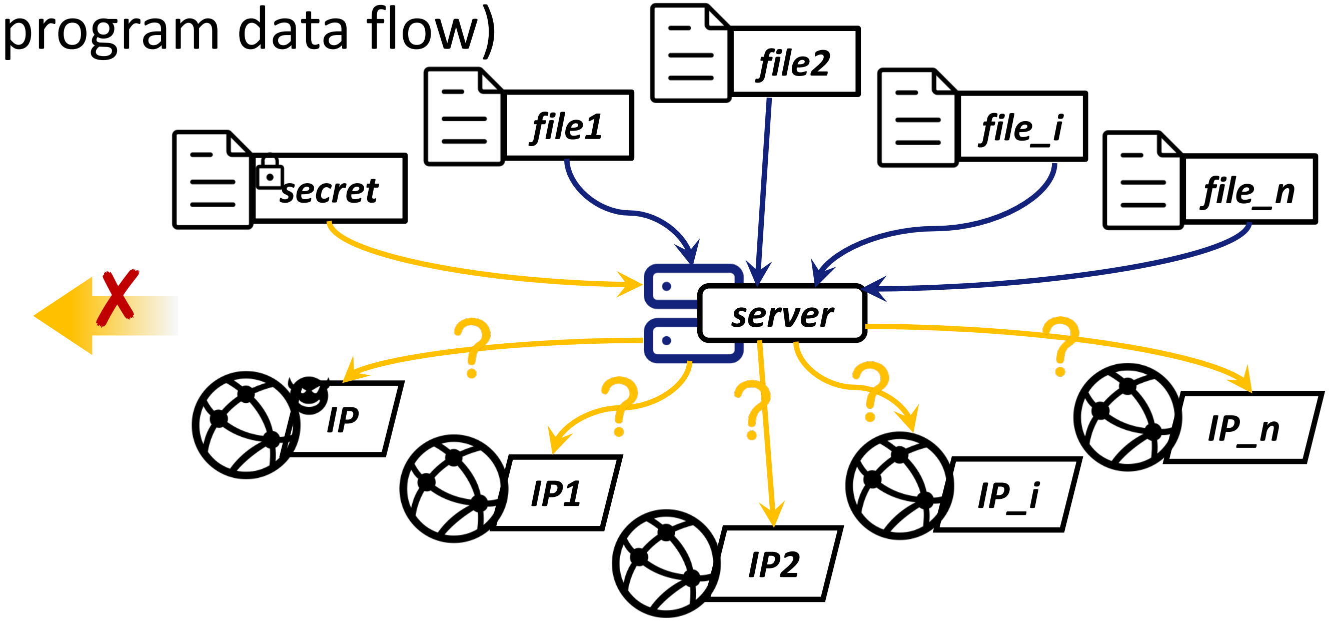

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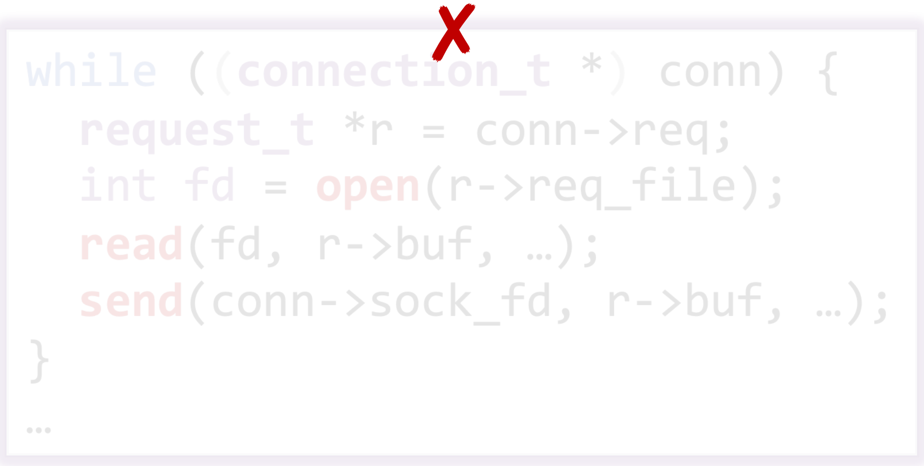

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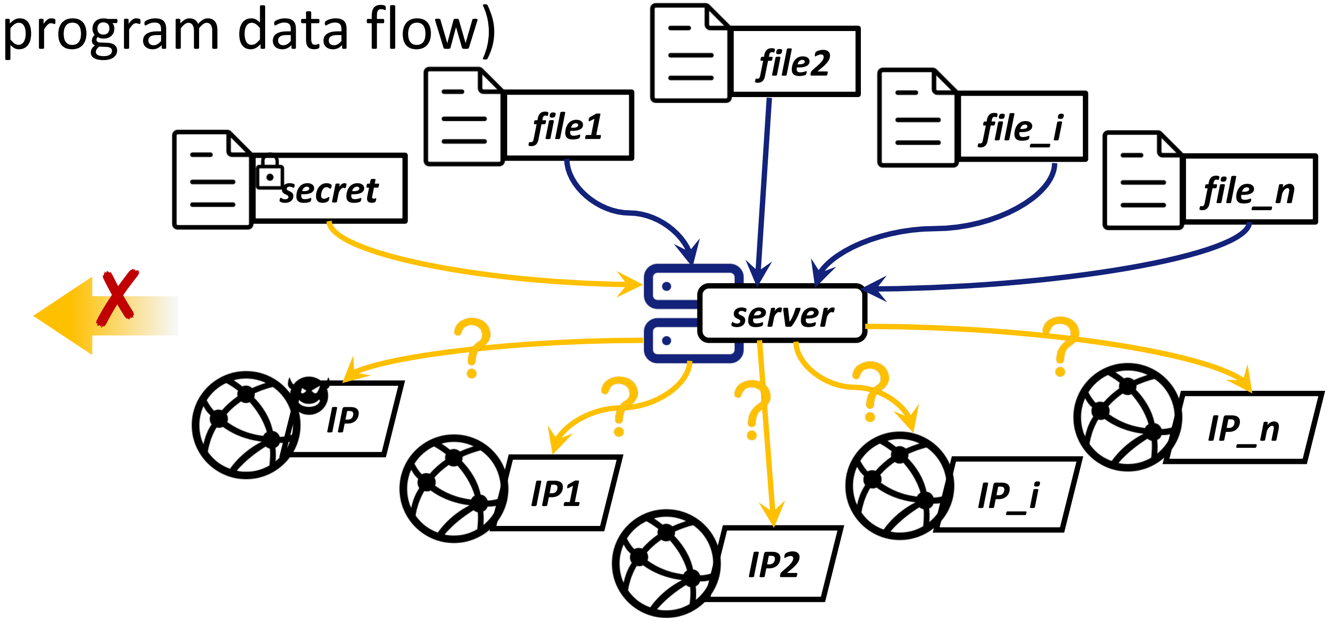

- 💡 *Motivation*: Enhance audit logs with program data flow to achieve ***<u>high system observability</u>***

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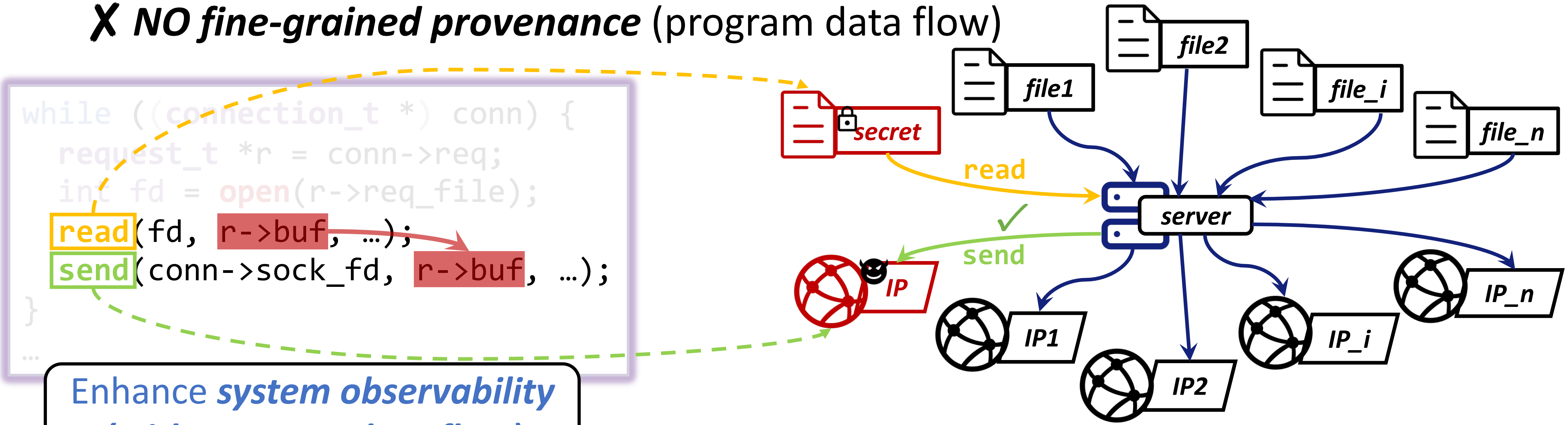

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}
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```

Enhance ***system observability***
(with program data flow)

- 💡 ***Motivation***: Enhance audit logs with program data flow to achieve ***high system observability***

Fine-grained Provenance

- ***Ideal observability:*** Enhance the provenance with ***syscall-to-syscall taints*** (i.e., instruction-level data flow)
- Enhance observability and resolve fine-grained provenance:

```
while ((connection_t *) conn) {
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}
…
```

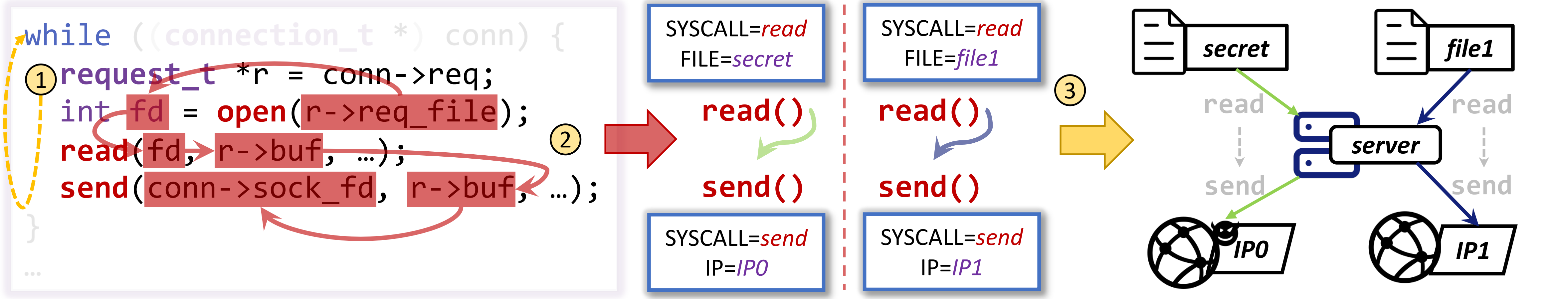
Fine-grained Provenance

- ***Ideal observability:*** Enhance the provenance with ***syscall-to-syscall taints*** (i.e., instruction-level data flow)
- Enhance observability and resolve fine-grained provenance:

① ***Control flow tracing:*** trace runtime execution history

② ***Data flow analysis:*** recover syscall-to-syscall taints

③ ***Optimization:*** incorporate audit logs with the taints



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while ((connection_t *) conn) {
  request_t *r = conn->req;
  int fd = open(r->req_file);
  read(fd, r->buf, …);
  send(conn->sock_fd, r->buf, …);
}
…
```

SYSCALL=*read*
FILE=*secret*

SYSCALL=*send*
IP=*IP0*

SYSCALL=*read*
FILE=*file1*

SYSCALL=*send*
IP=*IP1*

Core Design Ideas for Efficiency

① Control flow tracing

Online program runtime recording

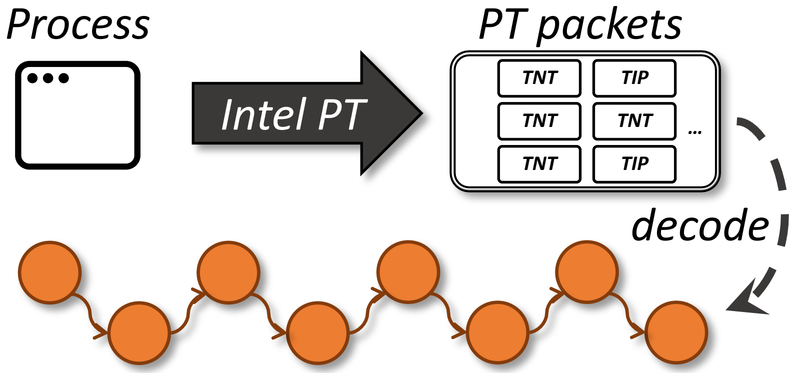
💡 *Insight: Hardware Tracing*

=> Intel® Processor Tracing (PT)

to trace control flow transfer

✓ ***Trivial*** runtime overhead

✓ **Non-intrusive** to program



Execution Trace: A sequence of basic blocks

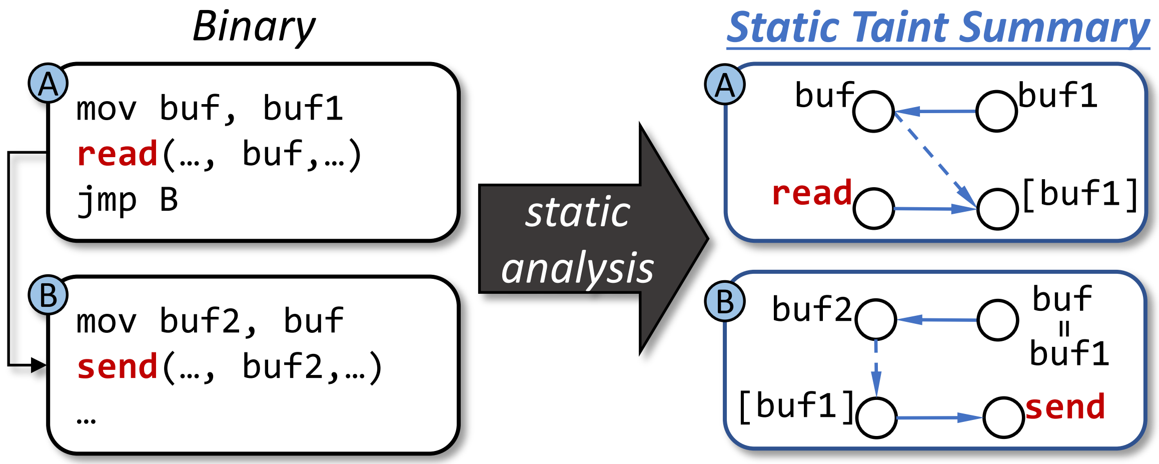
② Data flow analysis

Offline computationally expensive analysis

💡 *Insight: Static Taint Summary*

*=> Pre-summarize **taint propagation logic** per basic block via **static binary analysis***

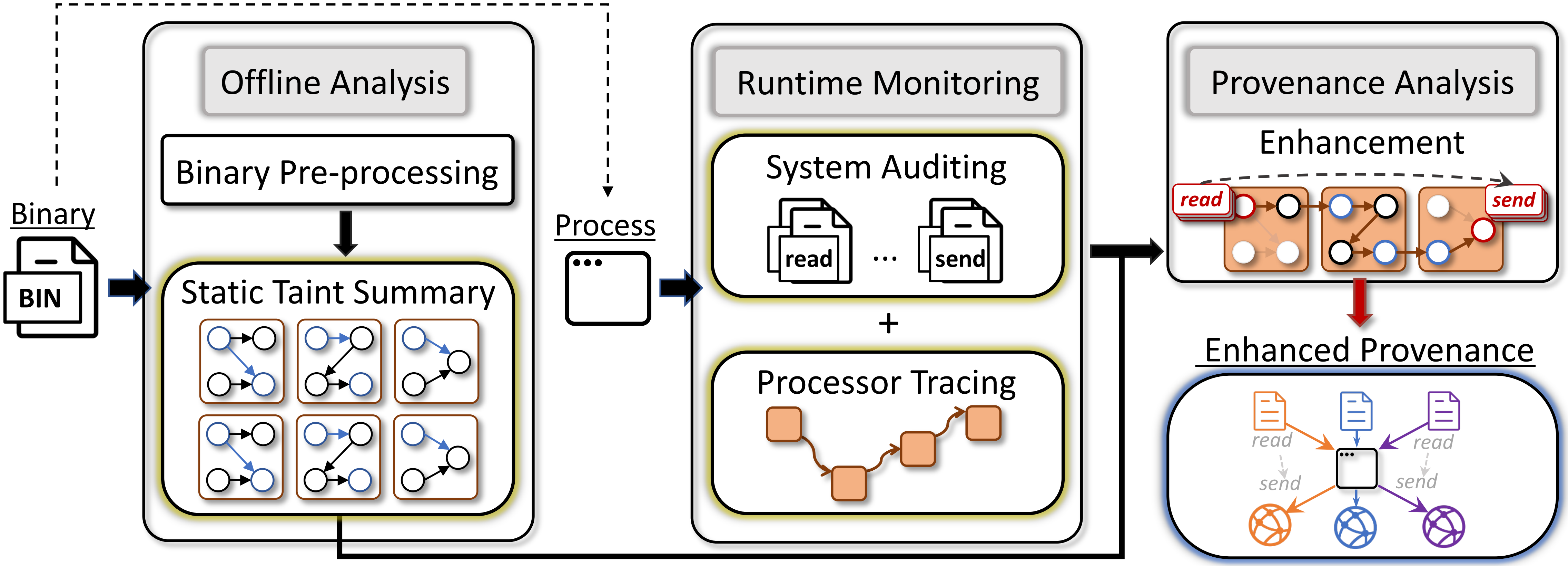
✓ ***Segregate*** offline analysis cost



```
A
mov buf, buf1
read(…, buf,…)
jmp B

B
mov buf2, buf
send(…, buf2,…)
…
```

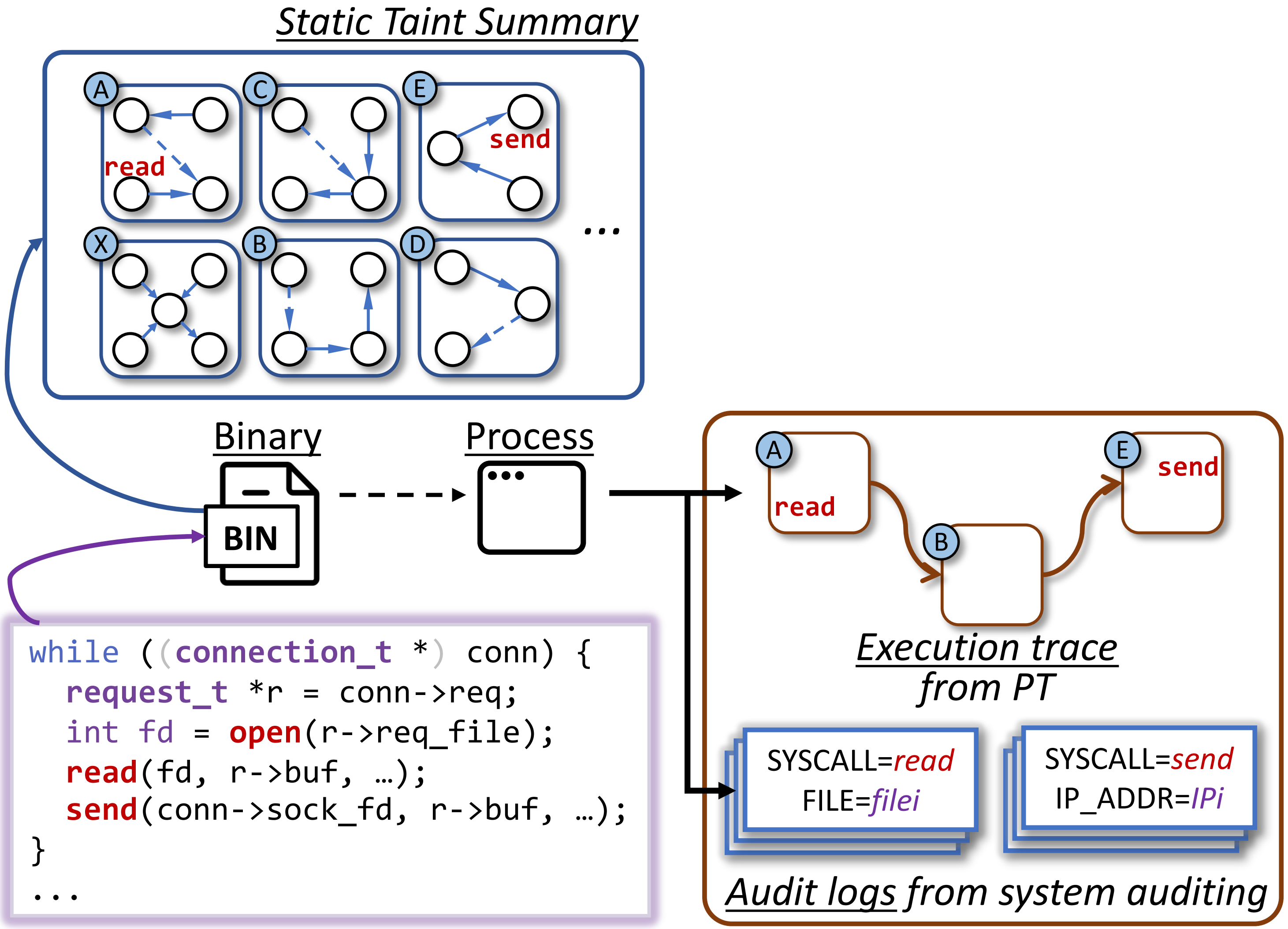
PALANTIR: System Overview



Input: ***Binary*** (***Process*** at runtime)

Output: Observability-enhanced ***provenance graph***

Running Example: Provenance Enhancement



SYSCALL=*read*
FILE=*filei*

SYSCALL=*send*
IP_ADDR=*IPi*

```
while ((connection_t *) conn) {
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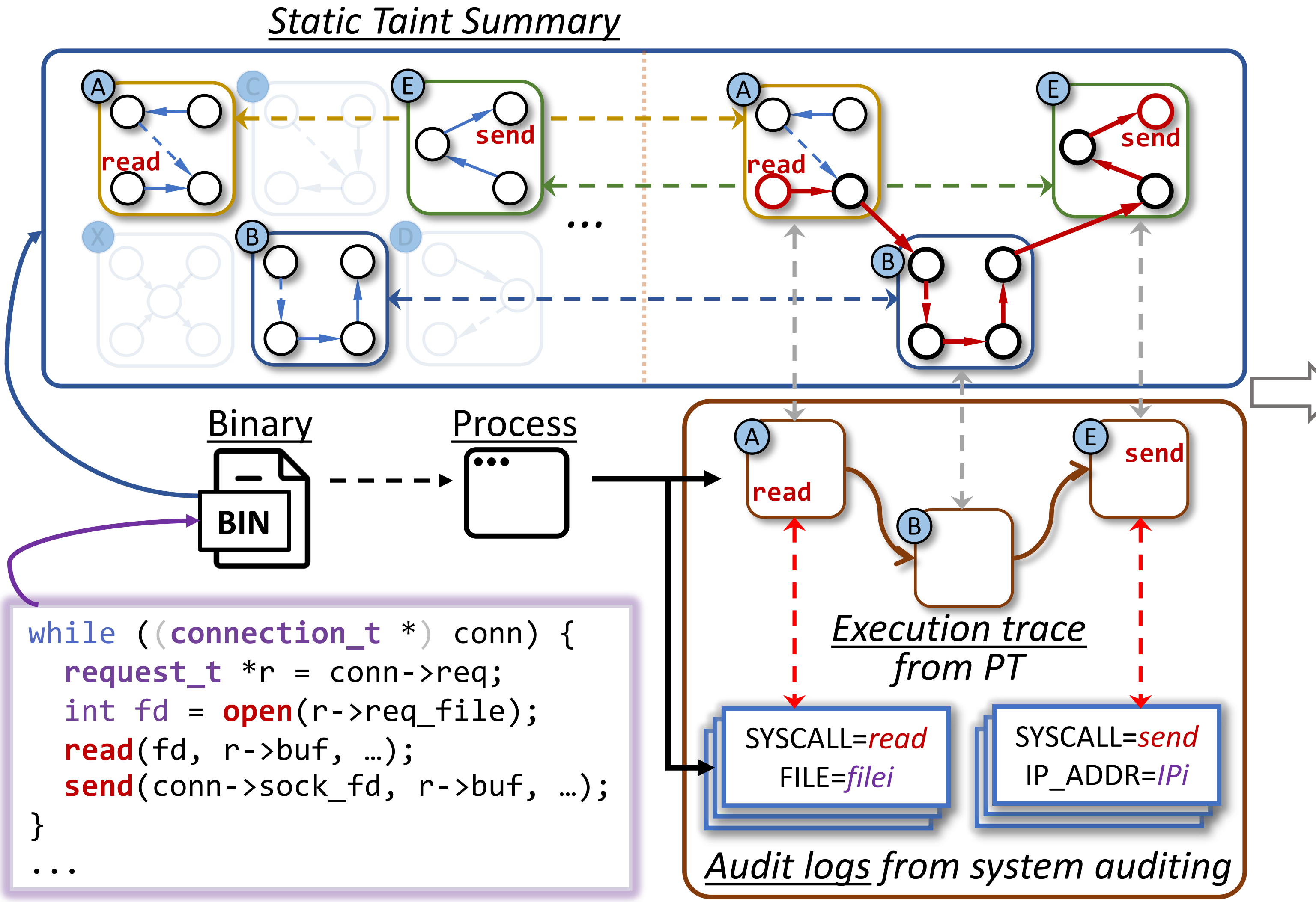
Running Example: Provenance Enhancement



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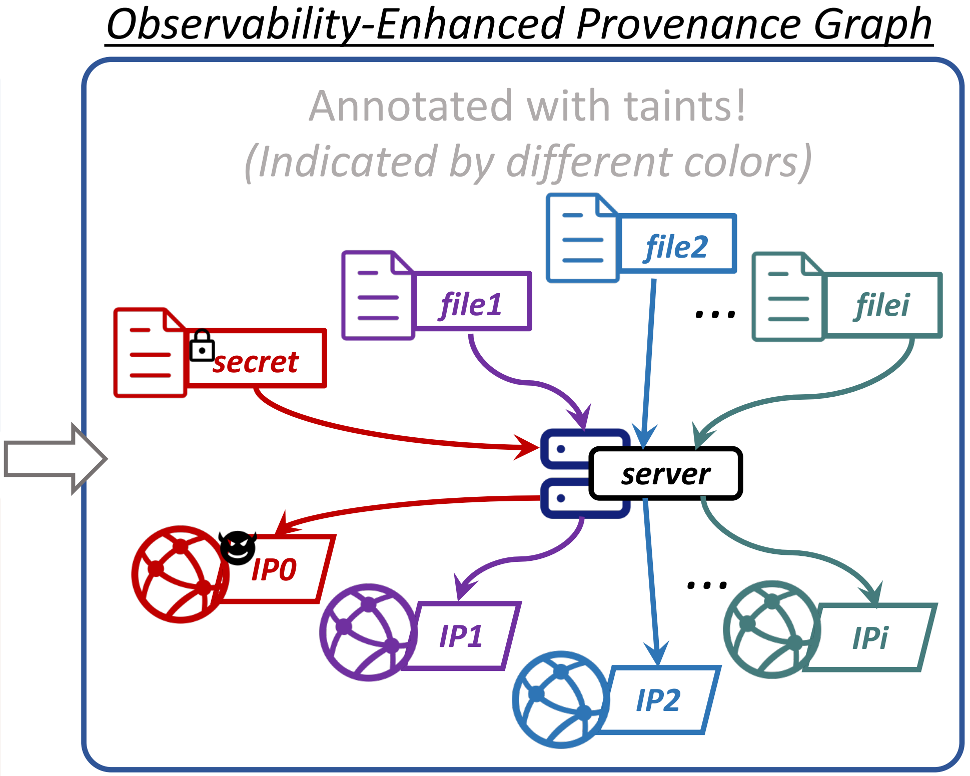

Observability-Enhanced Provenance Graph
Annotated with taints!
(Indicated by different colors)
file2
file1
...
filei
secret
server
IP0
IP1
...
IPi
IP2

✓ ***Fine-grained Provenance*** is ***optimized*** with ***instruction-level Observability***

Evaluation Settings

- ***Evaluation Aspects***
  - ***How efficient*** is PALANTIR at attack investigation?
  - ***What*** is the ***runtime performance*** of PALANTIR?
- ***Evaluation Dataset***
  - ***Four real-world cyber-attacks*** simulated in a testbed:

    Watering-hole, Data Leakage, Insider Threat, and Phishing Email
  - ***SPEC CPU 2006*** benchmarks & real-world ***common programs***

Attack Investigation

- ***Identify true causality*** among system events and dependencies

Attack Scenario	Program	Audit Logs	PT Packets	Instructions	Investigation Time (s)
Watering Hole	Wget	10,256	62,175,669	1,329,321,333	12.05
	Nginx	1,830	401,708	5,160,695	2.86
Data Leakage	Curl	10,309	1,882,471	17,516,456	9.39
	Pure-ftpd	25,562	21,402,396	2,833,740,916	2.85
Insider Threat	Cp	1,814	134,161	1,048,907	0.20
	Lighttpd	4,800	499,995	5,448,715	0.58
Phishing Email	Sendmail	29,433	7,488,895	120,264,352	18.09

✓ PALANTIR achieves a high efficiency in attack investigation

Attack Investigation - Comparison

- ***Compare*** with Dynamic Information Flow Tracking (DIFT)-based system

Attack Scenario	Program	Investigation Time (s)	
		PALANTIR	RTAG
Watering Hole	Wget	12.05	67.93
	Nginx	2.86	37.50
Data Leakage	Curl	9.39	50.03
	Pure-ftpd	2.85	78.16
Insider Threat	Cp	0.20	0.89
	Lighttpd	0.58	12.13
Phishing Email	Sendmail	18.09	238.20

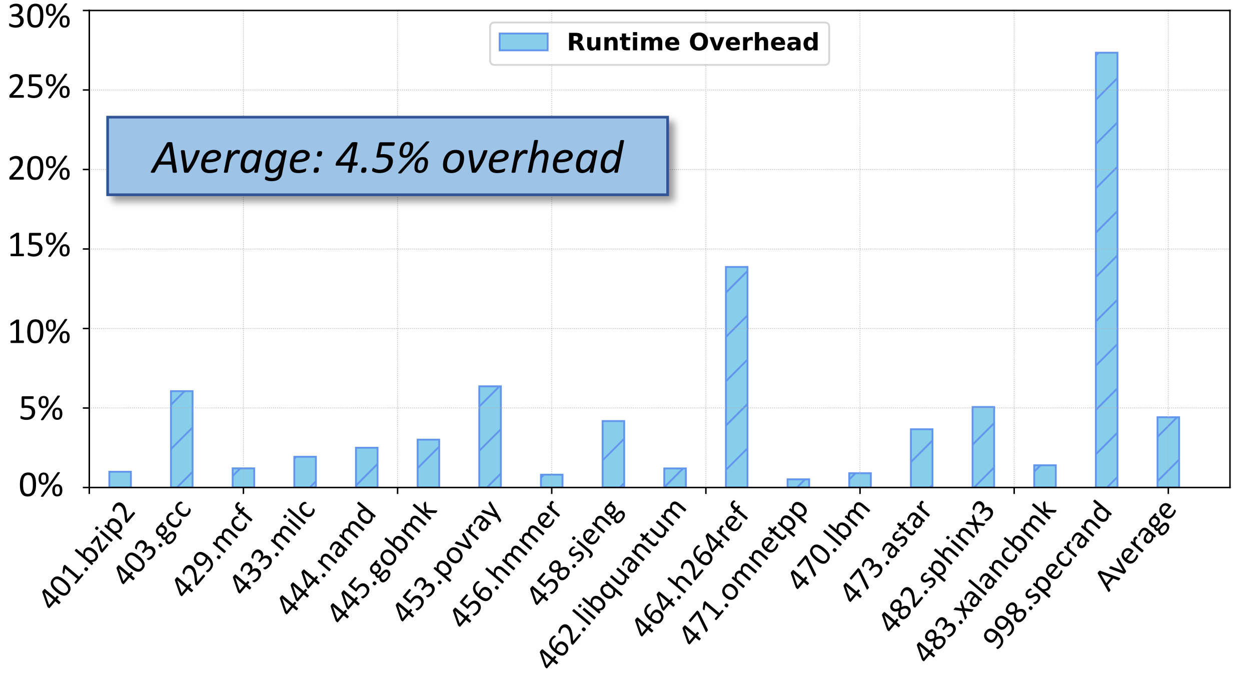
RTAG [Security'18]

- Record-and-replay
- DIFT with libdft

✓ PALANTIR reduces 77%-96% time from DIFT-based provenance tracking

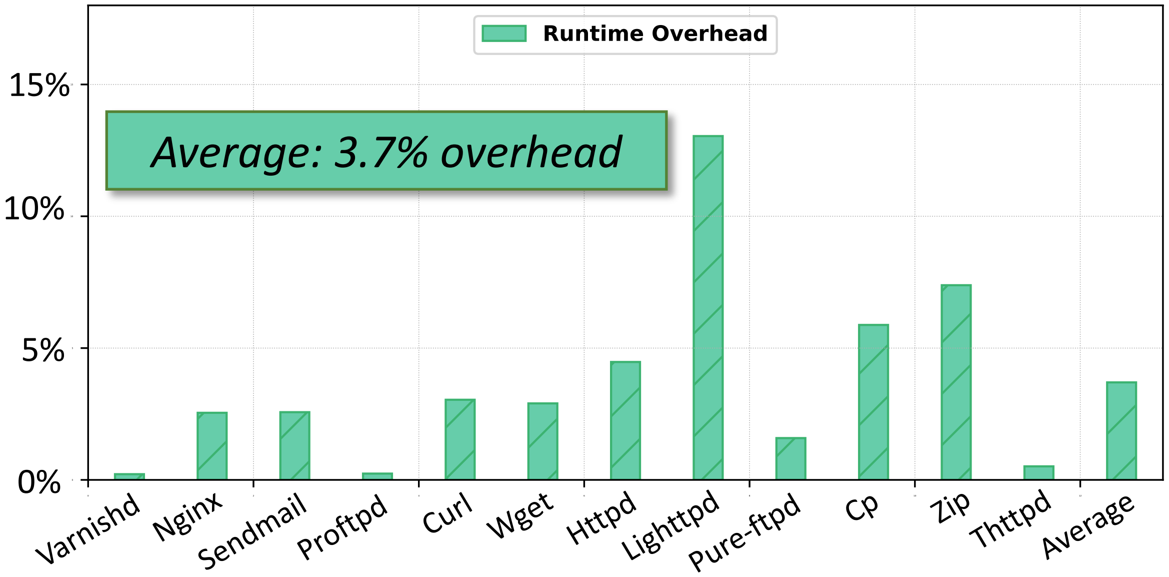
Runtime Performance

*Runtime Overhead on **SPEC CPU 2006 benchmarks***



Average: 4.5% overhead

*Runtime Overhead on **real-world programs***



Average: 3.7% overhead

✓ PALANTIR's hardware PT incurs <5% runtime-overhead for processor tracing

Conclusion

- We propose PALANTIR:
  - Optimize attack provenance by hardware-enhanced system observability
  - Resolve dependency explosion by using instruction-level data flow
- Insights
  - Hardware-assisted approach provides efficient runtime performance
  - Static taint summarization can segregate offline overhead