Practical Whole-System Provenance Capture

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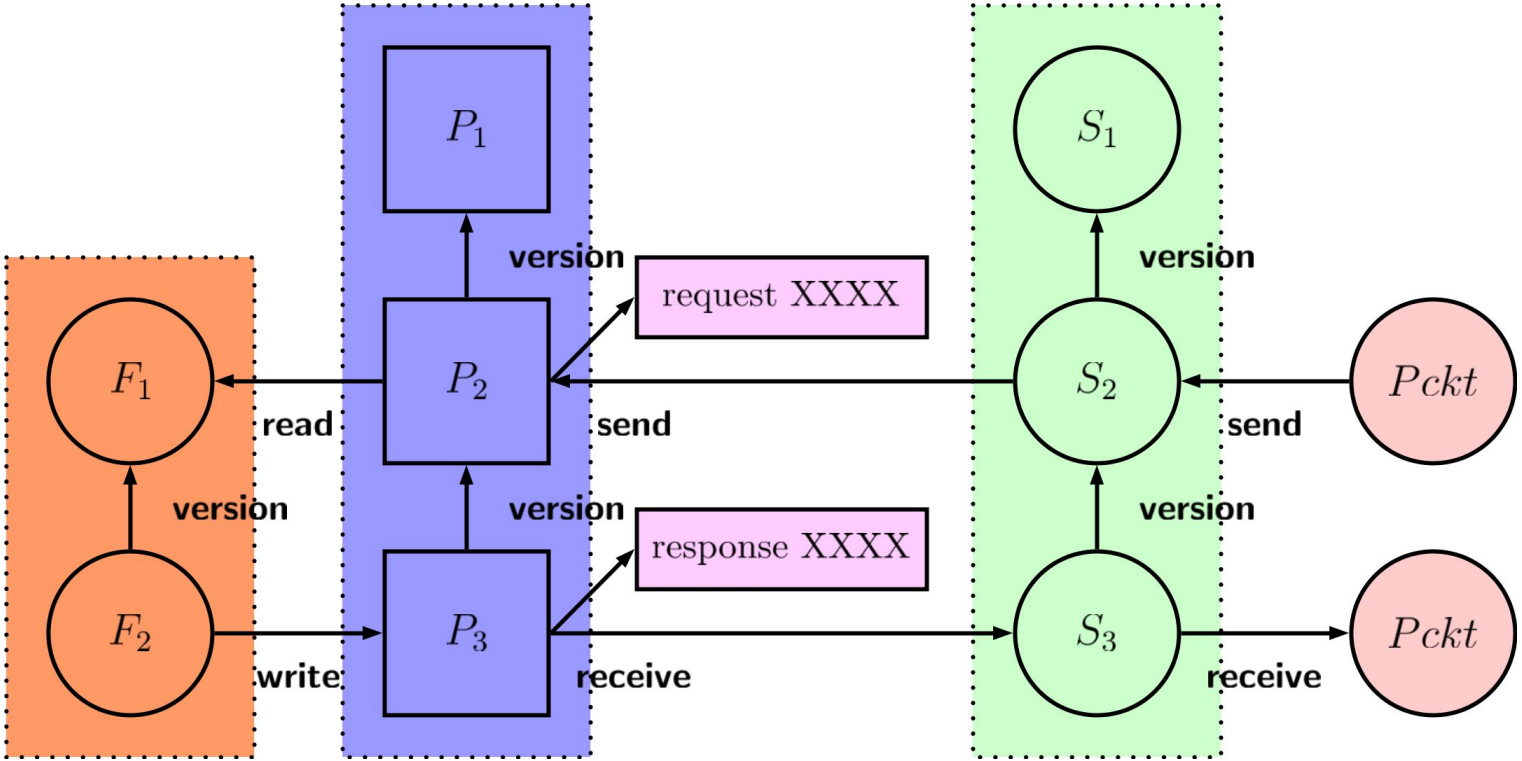
What is provenance?

- From the French “provenir” meaning “coming from”
- **Formal set of documents** describing the origin of an art piece
- **Sequence** of
  - Formal ownership
  - Custody
  - Places of storage
- Used for authentication

What is data-provenance?

- Represent interactions between objects of different types
  - Data-items (**entities**)
  - Processing (**activities**)
  - Individuals and Organisations (**agents**)
- Represented as a **directed acyclic graph** (think information flows)
- Edges represent interactions between objects as dependencies
- It is a representation of **history**
  - Immutable (unless it’s 1984)
  - No dependency to the future

Example


P_1
S_1
version
version
request XXXX
F_1
P_2
S_2
$Pckt$
read
send
send
version
version
version
response XXXX
F_2
P_3
S_3
$Pckt$
write
receive
receive

Why do we care about data-provenance?

- Originally in **reproducibility/repeatability/benefaction**
  - Can I reproduce those results?
  - Can I reproduce the computational environment?
- Application to **retrospective security**
  - Assuming highly trusted agents (think doctor)
  - Critical system (patient life vs access control error)
  - We may still need to understand when things went wrong
- Access control based on origin of data
  - **Provenance-based access control** (PBAC) Sandhu et al. PST'12
- And more…
  - Audit, **intrusion detection**, source of context for search algorithm, fault injection, **compliance auditing** etc…

Provenance in Operating Systems

- How is provenance captured?
  - **Application level :** capture application logic | fine grained
  - **System level :** complete and systematic | coarse grained
  - Both **PASS v2** (Seltzer et al. USENIX ATC 2009)
- How to implement in Linux?
  - Modify FS and SysCall interface? (**PASS** USENIX ATC 2006)
  - Develop a framework akin to LSM? (**LPM** USENIX Sec. 2015 Bates et al.)
  - Modify standard library that interface with sys-calls? (**OPUS**, USENIX TaPP. 2013 Balakrishnan et al.)
- Provenance is useful…
- … but it is not being widely adopted
- Hard to deploy? No accessible out of the box solution?

Building a **practical** capture mechanism

- “Benefaction” problem (Collberg et al. Com. of ACM 2016)
- Maintainability issues, previous implementation hard to port to modern kernel
- Lack of clear separation of concerns between **capture**, **storage** and **query** (SPADE did great there)
- Objectives:
  - Clear focus on **capture**
  - Easy **integration** with other concerns
  - **Self-contained** mechanism
  - **Systematic and ubiquitous** capture

Use-case driven development

- Understanding how people want to use provenance
- We developed features based on **concrete use-cases**
- Based on the litterature…
- … or ongoing research projects
- Focus on **usability**
- We build a capture system…
- … **clear separation of concern** vs holistic approach

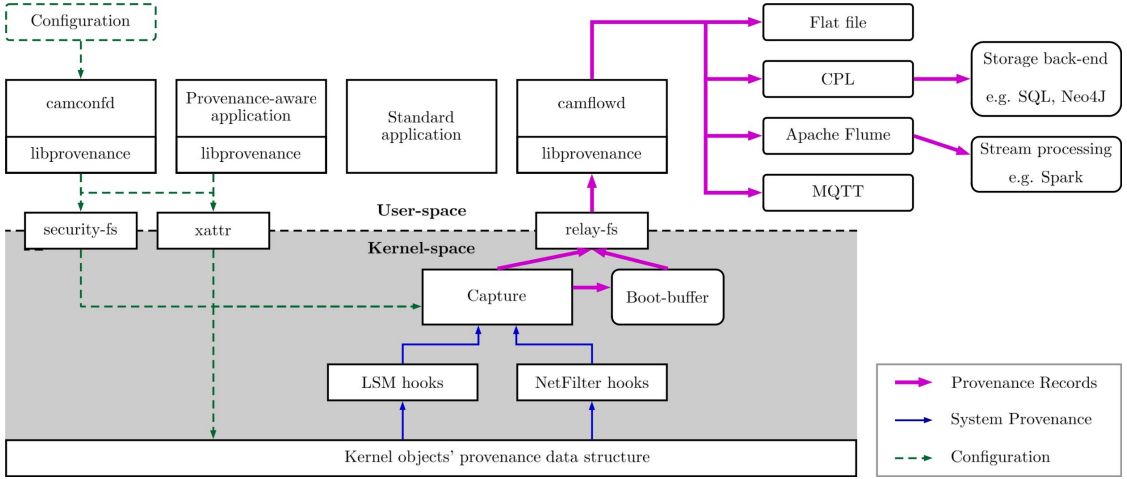
Plan

- Maintainability
- Selective provenance capture
- Embedded capture

- More at the poster session...

Maintainability

- Leverage existing kernel features whenever possible
- Avoid alteration of existing code
- We therefore build upon:
  - **Linux Security Module**
  - to capture system events
  - **NetFilter**
  - to capture network events
  - **RelayFS**
  - to transfer provenance to user space
  - **SecurityFS**
  - to provide a userspace interface for settings



Extent of modification

Existing files modified - total line of code for Prov Capture

System	Headers	C File	Total	LoC
PASS (v2.6.27) pub. 2006	18	69	87	5100
LPM (v2.6.32) pub. 2015	13	61	74	2294
CamFlow (v4.9.5) pub. 2017	8	1	9	2428

When porting CamFlow, only need to worry about internal API changes (more details in the paper)

Selective provenance

- System-provenance guarantee completeness…
- … but generates too much data
- Previous address capture problem …
  - capture everything we can
- … but replace it with a storage and query problem
- Solution **capture only what you need**

Selective provenance

- Define capture target based on
  - **Pathname** (track any transformation to my dataset)
  - **Process** (track the action of this process)
  - **Network** interface (track interaction with server X)
  - **Security ID** (track interaction within this security domain)
  - and more…
- Propagate tracking to derivative data-item
- **Only the relevant information** is being captured
- Significantly **reduce amount of data generated**

Embedding queries in the capture mechanism

- **Data Loss Prevention** (Bates et al. USENIX security 2015)
- Run only a well defined set of queries
- Most information captured is irrelevant to the query…
- … but response time is at best **O(S)** where S is the total graph size
- S increase linearly overtime
- **Take only what you need?** (Bates et al. TaPP 2015)
  - S smaller…
  - … but still increase overtime

Embedding queries in the capture mechanism

- Provenance <-> causality graph
- **Propagate labels** along the graph at capture time
  - Query generally of the type find PATH along X, Y, Z
- Propagation follow query requirements
- Response time **O(1)**
  - Is label(s) present?
- Propagation incurs very small runtime overhead
- Future work **programmable query…**
- Complete provenance graph as **forensic** evidence
  - Response no more dependent on S!
- Framework in development!

Performance overhead

Micro-benchmark

Sys Call	Whole	Selective
stat	100%	28%
open/close	80%	18%
fork	6%	2%
exec	3%	<1%

Macro-benchmark

Prog.	Whole	Selective
unpack	2%	<1%
build	2%	0%
postmark	11%	6%

Selective: cost of allocating/freeing provenance “blob” + recording or not decision

Whole: **Selective** + cost of recording provenance information

More details in the paper

Future work

- Bind with existing storage/query/processing tools
  - Ongoing collaboration with MIT Lincoln team
- Focusing on building provenance applications
  - Do we capture everything we need?
  - Is usability good enough?
- Improving tooling for container support
  - Doable, but requires to dive in
- Providing some (formal?) guarantee of completeness
- Extending user-base and providing support
- Programmable queries
- Submitting a patch for integration in mainline kernel?

Thank you!

Any questions?

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Source, demo and benchmark at:

www.camflow.org