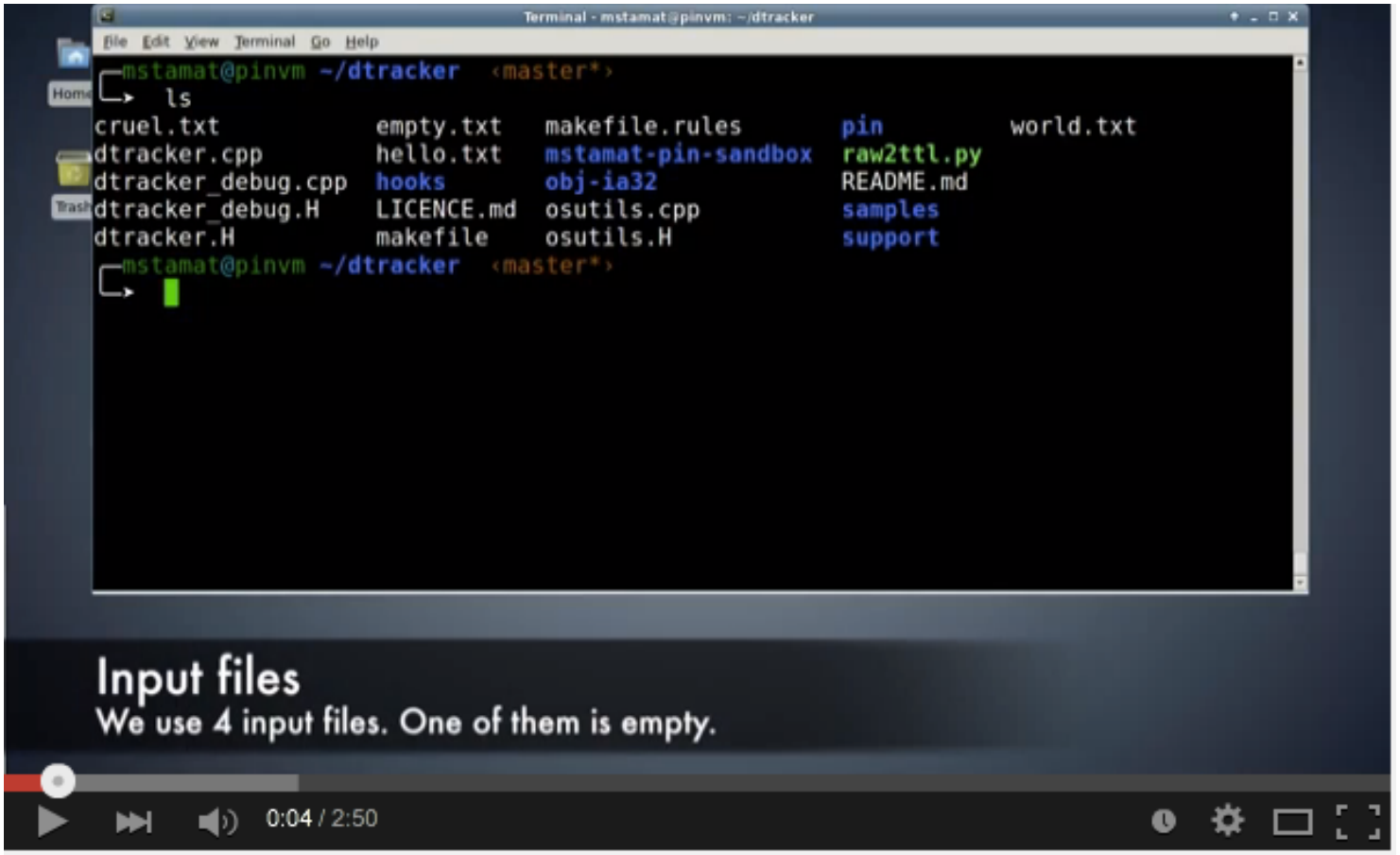
Decoupling Provenance Capture and Analysis from Execution

Manolis Stamatogiannakis (@mstamat)
Paul Groth (@pgroth)
Herbert Bos

usenix
ASSOCIATION

TaPP 2015
July 8-9, 2015, Edinburgh, Scotland



Demo of DataTracker provenance capture tool

Manolis Stamatogiannakis

Subscribe 0

100 views

http://bit.ly/dtracker-demo

Stamatogiannakis, M., Groth, P., & Bos, H. (2014). Looking inside the black-box: Capturing data provenance using dynamic instrumentation. In *Provenance and Annotation of Data and Processes* (pp. 155-167). Springer International Publishing.

VU UNIVERSITY AMSTERDAM

Capturing Provenance

Disclosed Provenance

+ Accuracy
+ High-level semantics
– Intrusive
– Manual Effort

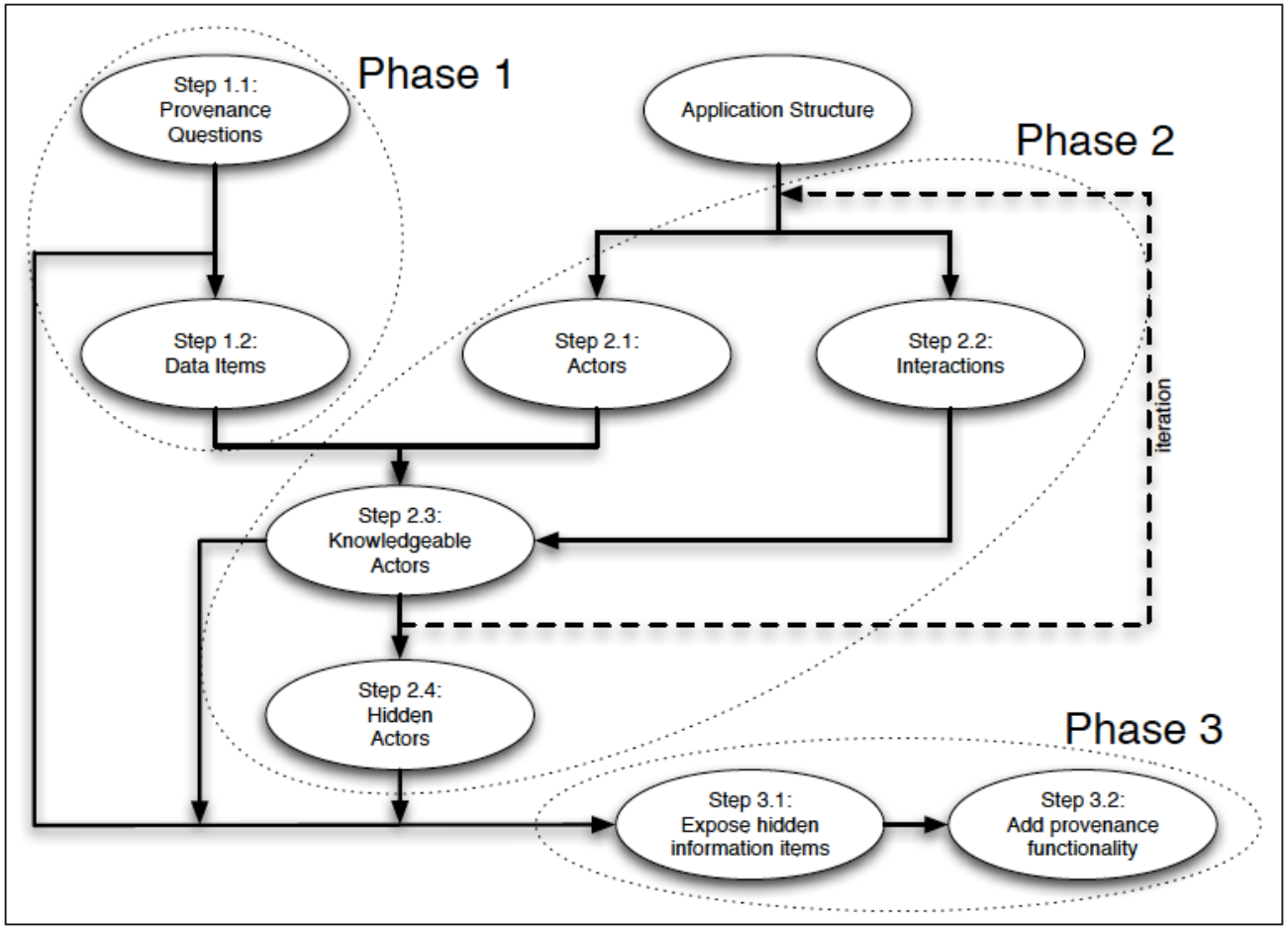
Trio (Widom '09)
CPL (Macko '12)
PrIME (Miles '09)
Taverna (Oinn '06)
VisTrails (Fraire '06)

Observed Provenance

– False positives
– Semantic Gap
+ Non-intrusive
+ Minimal manual effort

ES3 (Frew '08)
Trec (Vahdat '98)
PASSv2 (Holland '08)
DTrace Tool (Gessiou '12)

What to capture?



Miles, Simon, Groth, Paul, Munroe, Steve and Moreau, Luc (2011) PrIMe: a methodology for developing provenance-aware applications. *ACM Transactions on Software Engineering and Methodology*, 20, (3), 8:1-8:42.

Provenance is post hoc.

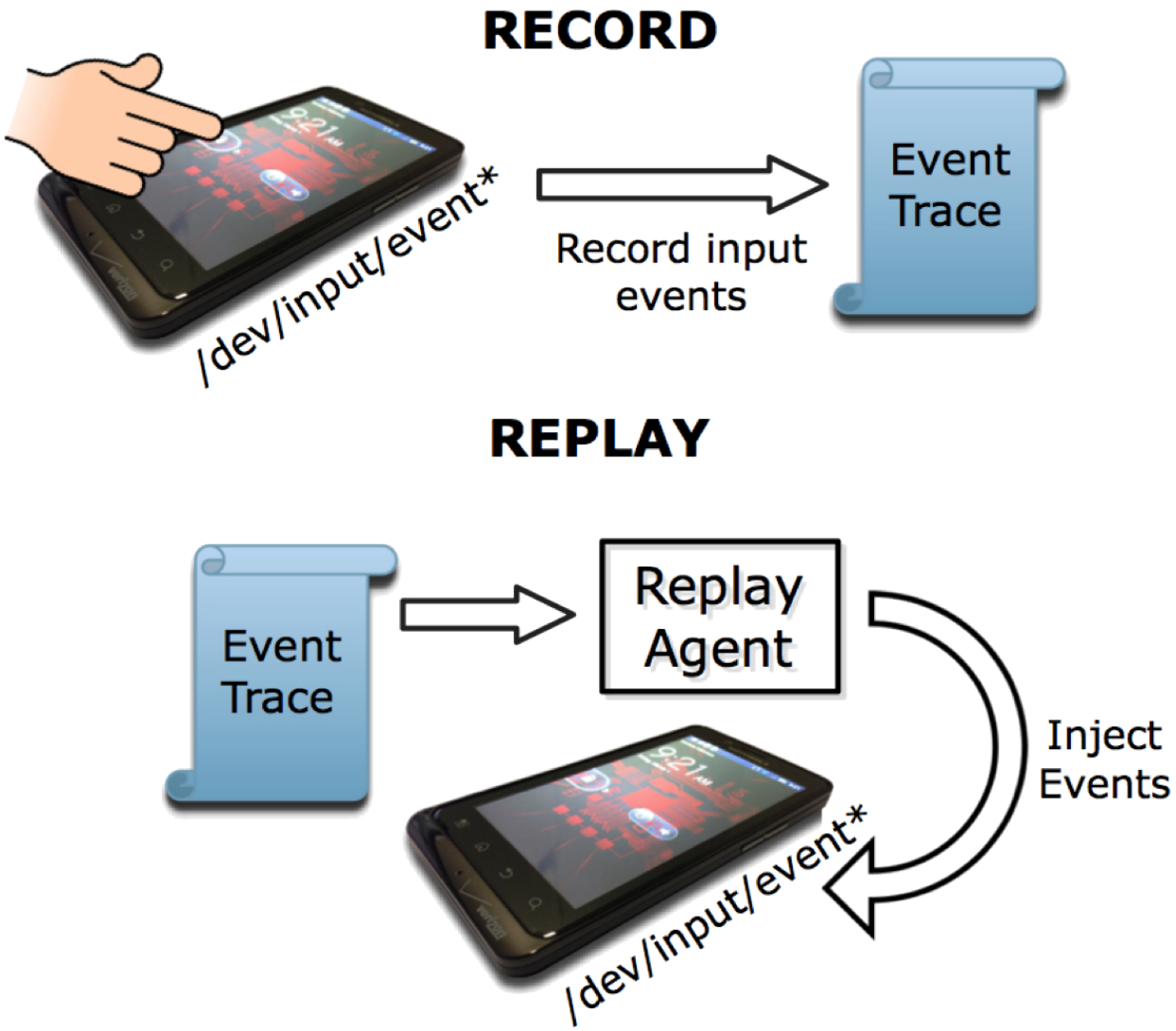
Aim:

Eliminate the need for developers to know what provenance needs to be captured.

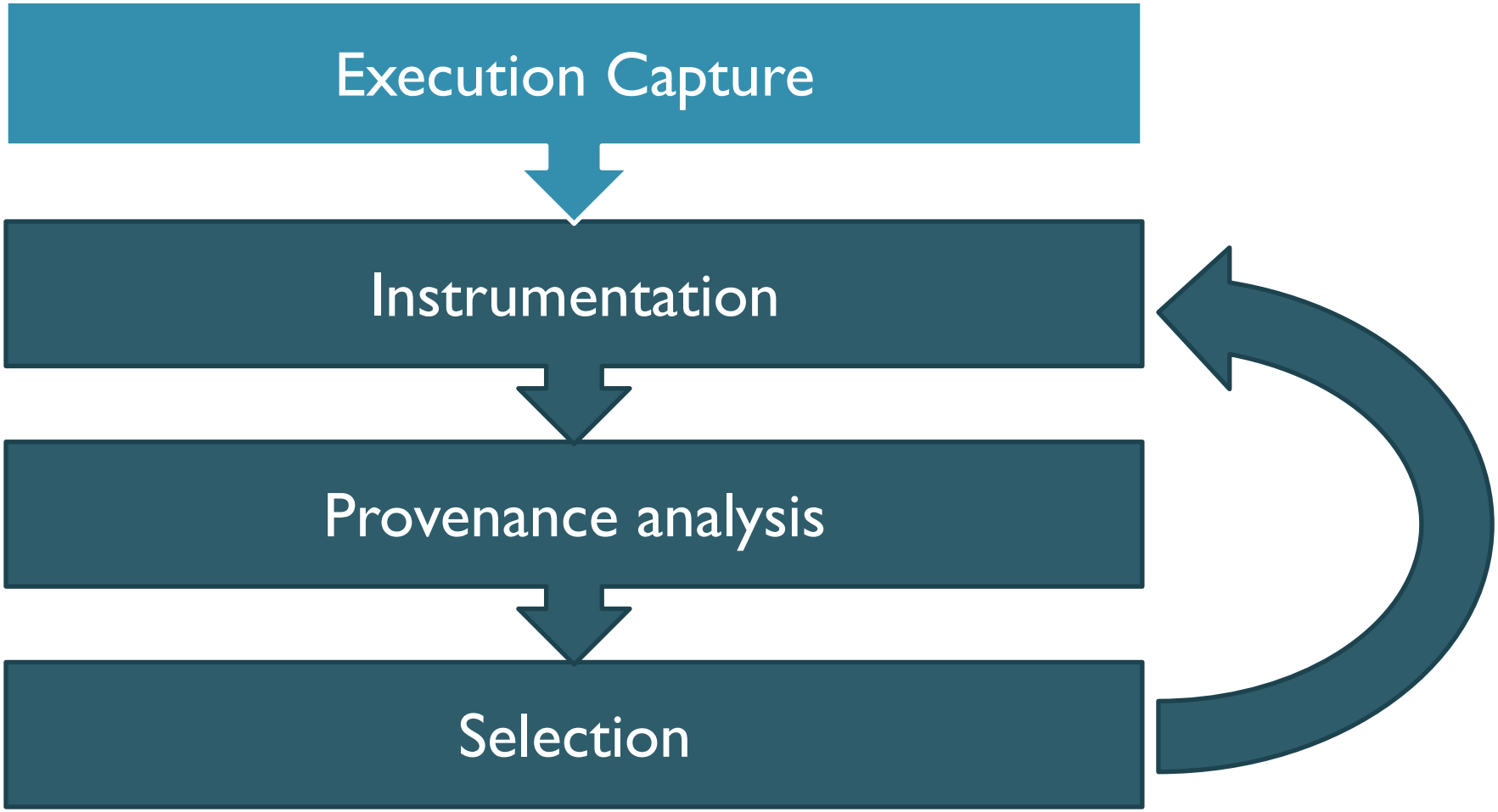
Re-execution

Common tactic in provenance:

- DB: **Reenactment queries (Glavic '14)**
- DistSys: **Chimera (Foster '02), Hadoop (Logothetis '13), DistTape (Zhao '12)**
- Workflows: **Pegasus (Groth '09)**
- PL: **Slicing (Perera '12)**
- OS: **pTrace (Guo '11)**
- Desktop: **Excel (Asuncion '11)**

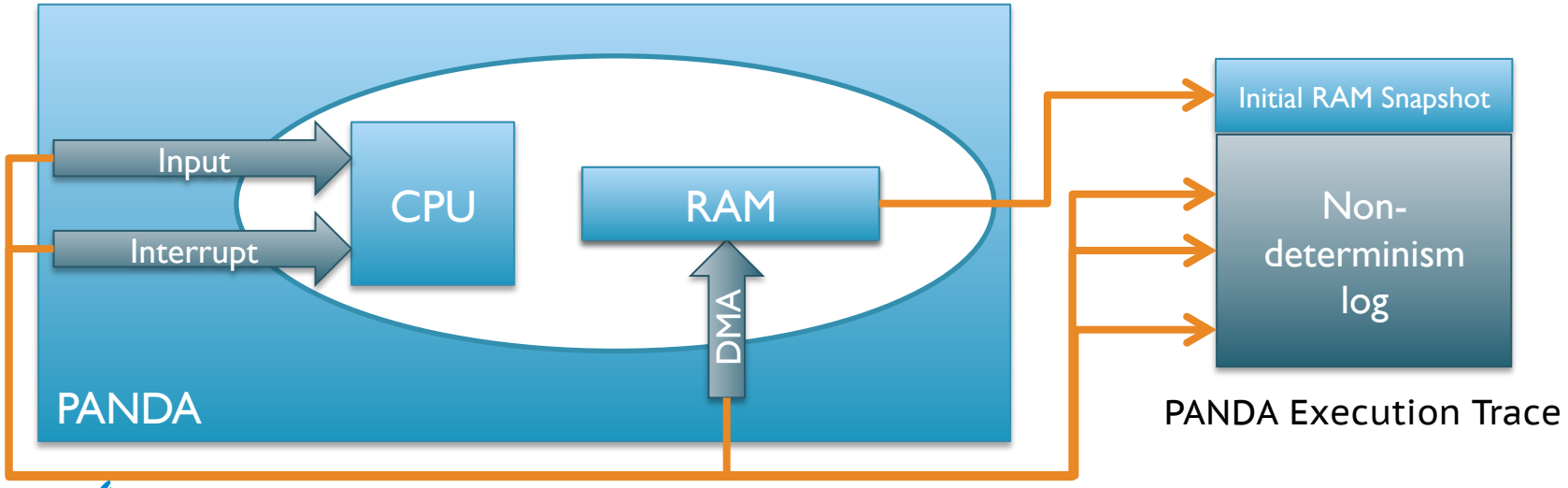

RECORD
/dev/input/event*
Record input events
Event Trace
REPLAY
Event Trace
Replay Agent
Inject Events
/dev/input/event*

Methodology



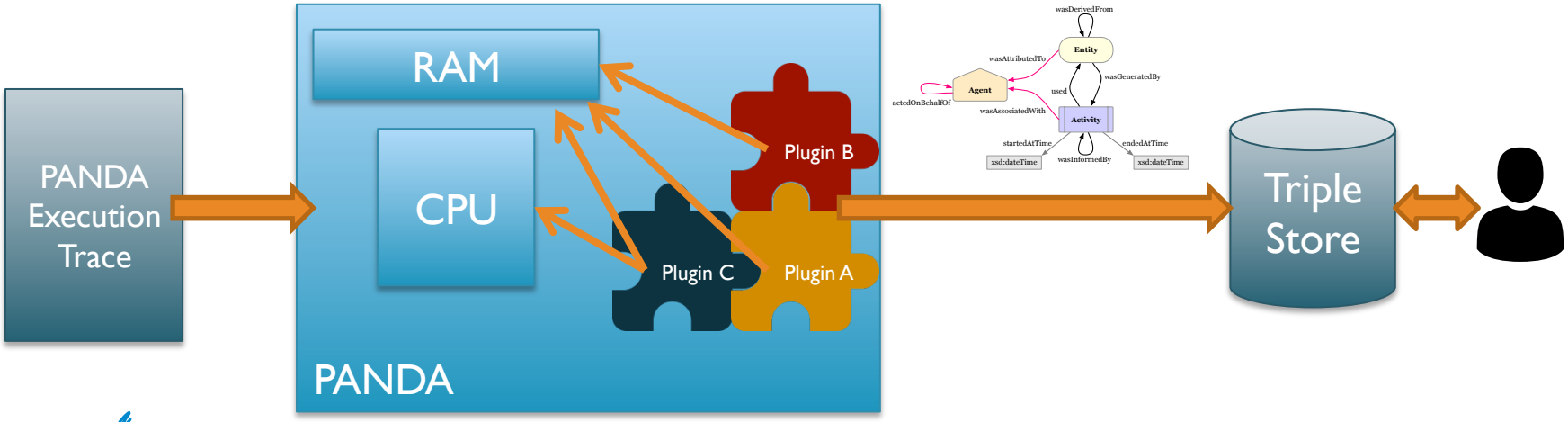
Prototype Implementation (1/2)

- PANDA: an open-source Platform for Architecture-Neutral Dynamic Analysis. **(Dolan-Gavitt et al. '14)**
- Based on QEMU virtualization platform.
- Logs self-contained execution traces.
  - An initial RAM snapshot.
  - Non-deterministic inputs.



Prototype Implementation (2/2)

- Debian Linux guest.
- Analysis plugins
  - Read-only access to the VM state.
  - Invoked per instr., memory access, context switch, etc.
  - Can be combined to implement complex functionality.
  - **OSI Linux**, **PROV-Tracer**, ProcStrMatch.
- Provenance stored PROV/RDF triples, queried with SPARQL.



OS Introspection

- What processes are currently executing?
- Which libraries are used?
- What files are used?

- Possible approaches:
  - ~~Execute code inside the guest-OS.~~
  - Reproduce guest-OS semantics purely from the hardware state (RAM/registers).

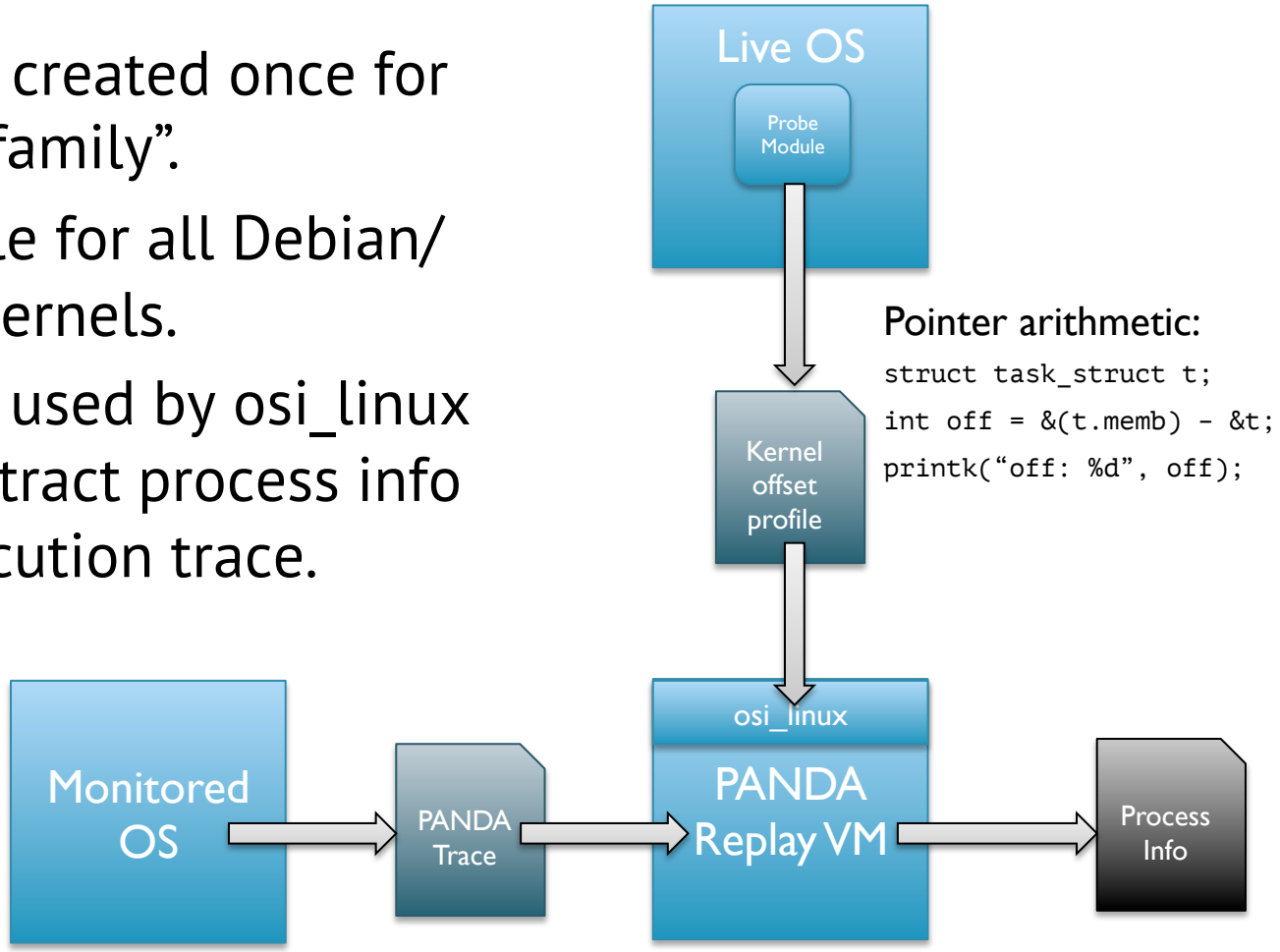
Introspecting Kernel Structures (1/2)

```
struct task_struct {
        volatile long state;    /* -1 unrunnable, 0 runnable, >0 stopped */
        void *stack;
        atomic_t usage;
        unsigned int flags;     /* per process flags, defined below */
        unsigned int ptrace;

#ifdef CONFIG_SMP
        struct llist_node wake_entry;
        int on_cpu;
        struct task_struct *last_wakee;
        unsigned long wakee_flips;
        unsigned long wakee_flip_decay_ts;

        int wake_cpu;
#endif
        int on_rq;

        int prio, static_prio, normal_prio;
        unsigned int rt_priority;
        const struct sched_class *sched_class;
        struct sched_entity se;
        struct sched_rt_entity rt;
#ifdef CONFIG_CGROUP_SCHED
        struct task_group *sched_task_group;
#endif
        struct sched_dl_entity dl;
```

- Kernel structure members are known.
- Their offsets depend on compile-time configuration.
- Each linux vendor supplies a few different kernel configurations.
- Rule of thumb: same vendor/configuration/ version combo → same offsets.

Introspecting Kernel Structures (2/2)

- Offset profile created once for each kernel “family”.
- E.g. one profile for all Debian/amd64/3.2.* kernels.
- The profile is used by osi_linux module to extract process info from the execution trace.



The PROV-Tracer Plugin

- Registers for process creation/destruction events.
- Decodes executed system calls.
- Keeps track of what files are used as input/ output by each process.
- Emits provenance in an intermediate format when a process terminates.

More Analysis Plugins

- ProcStrMatch plugin.
  - Which processes contained string S in their memory?
- Other possible types of analysis:
  - Taint tracking
  - Dynamic slicing

Execution Overhead (1/2)

- QEMU incurs a 5x slowdown.
- PANDA recording imposes an additional 1.1x – 1.2x slowdown.

Virtualization is the dominant overhead factor.

Execution Overhead (2/2)

- QEMU is a suboptimal virtualization option.
- ReVirt – User Mode Linux (**Dunlap et al. '02**)
  - Slowdown: 1.08x rec. + 1.58x virt.
- ReTrace – VMWare (**Xu et al. '07**)
  - Slowdown: 1.05x-2.6x rec. + ??? virt.

Virtualization slowdown is considered acceptable.

Recording overhead is fairly low.

Storage Requirements

- Storage requirements vary with the workload.
- For PANDA (**Dolan-Gavitt et al. '14**):
  - 17-915 instructions per byte.
- In practice: O(10MB/min) uncompressed.
- Different approaches to reduce/manage storage requirements.
  - Compression, HD rotation, VM snapshots.
- 24/7 recording seems within limits of todays' technology.

An Example (1)

```
$ qemu -replay alice.et -panda
  "osi;osi_linux;prov_tracer"
$ ./raw2ttl.py < prov_out.raw > alice.ttl
```

```
<exe://pam-foreground-~3451> prov:endedAtTime 199090196 .
<exe://getent~3451> a prov:Activity .
<exe://getent~3451> rdf:type dt:getent .
<exe://cut~3452> a prov:Activity .
<exe://cut~3452> rdf:type dt:cut .
<file:/etc/nsswitch.conf> a prov:Entity .
<file:/etc/nsswitch.conf> rdfs:label "/etc/nsswitch.conf" .
<file:/etc/nsswitch.conf> rdf:type dt:Unknown .
<exe://getent~3451> prov:used <file:/etc/nsswitch.conf> .
# unused file:3477815296:getent~3451:/etc/passwd:r0:w0:f524288
<exe://getent~3451> prov:startedAtTime 199090196 .
<exe://getent~3451> prov:endedAtTime 200392668 .
<file:FD0_3452> a prov:Entity .
<file:FD0_3452> rdfs:label "FD0_3452"
```

An Example (2

```
SELECT (MIN(?startTime) AS ?s)
       (MAX(?endTime) AS ?e) WHERE
{
  <file:/home/panda/work/camelidae-new.tar>
  prov:wasDerivedFrom ?file .
  FILTER regex(str(?file), "txt")

  ?file prov:wasGeneratedBy ?activity .
  ?activity a dt:Editor .
  ?activity prov:startedAtTime ?startTime .
  ?activity prov:endedAtTime ?endTime .
}
```

```
Results:
s          e
705412095 990055363
```

Example (3)

```
$ export s=705412095 e=990055363
$ qemu -replay alice.et -panda
  "scissors:start=$s,end=$e,name=report.et"
```

```
$ echo '"Llamas are lame"' > search_strings.txt
$ qemu -replay report.et -panda
  "osi;osi_linux;callstack_instr;stringsearch;psstrmatch"
```

Example (4)

```
SELECT (MIN(?st) as ?min) ?vi WHERE
{
    ?vi dt:hasMemText "Llamas are lame".
    ?vi prov:startedAtTime ?st
} GROUP BY ?vi
```

```
Results:
min         vi
705412095 exe://vi~3547
782648505 exe://vi~3557
857809758 exe://vi~3570
963886071 exe://vi~3595
```

Conclusion

- Decouple capture/analysis from execution
- VMs provide a useful indirection mechanism
- Future:
  - More plugins
  - Real world analysis (rrshare.org)
  - Cloud analysis
- Are traces/immutable logs primitive?

Source & Text

- PROV-Tracer source:
  - https://github.com/m000/panda/tree/prov_tracer/
  - Plugins under qemu/panda_plugins.
- Full text of paper:
  - http://workshops.inf.ed.ac.uk/tapp2015/TAPP15_I_3.pdf