PEMU: A PIN Highly Compatible Out-of-VM Dynamic Binary Instrumentation Framework

Junyuan Zeng, Yangchun Fu, Zhiqiang Lin

Department of Computer Science
The University of Texas at Dallas

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Dynamic Binary Instrumentation (DBI)

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- Dynamically inserts extra analysis code into the running binary program to observe how it behaves.

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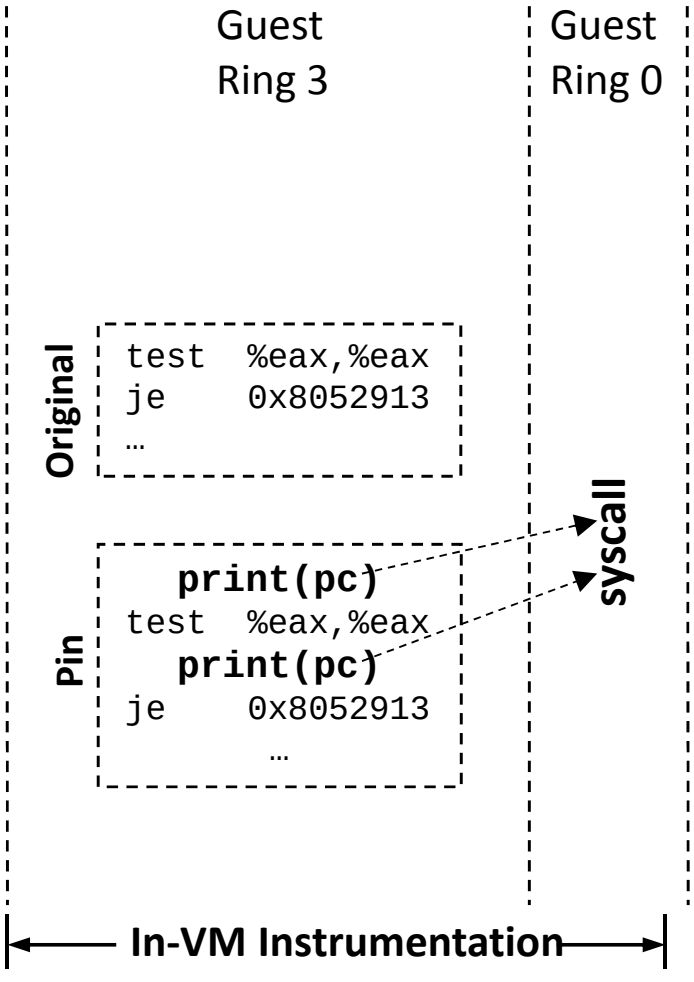
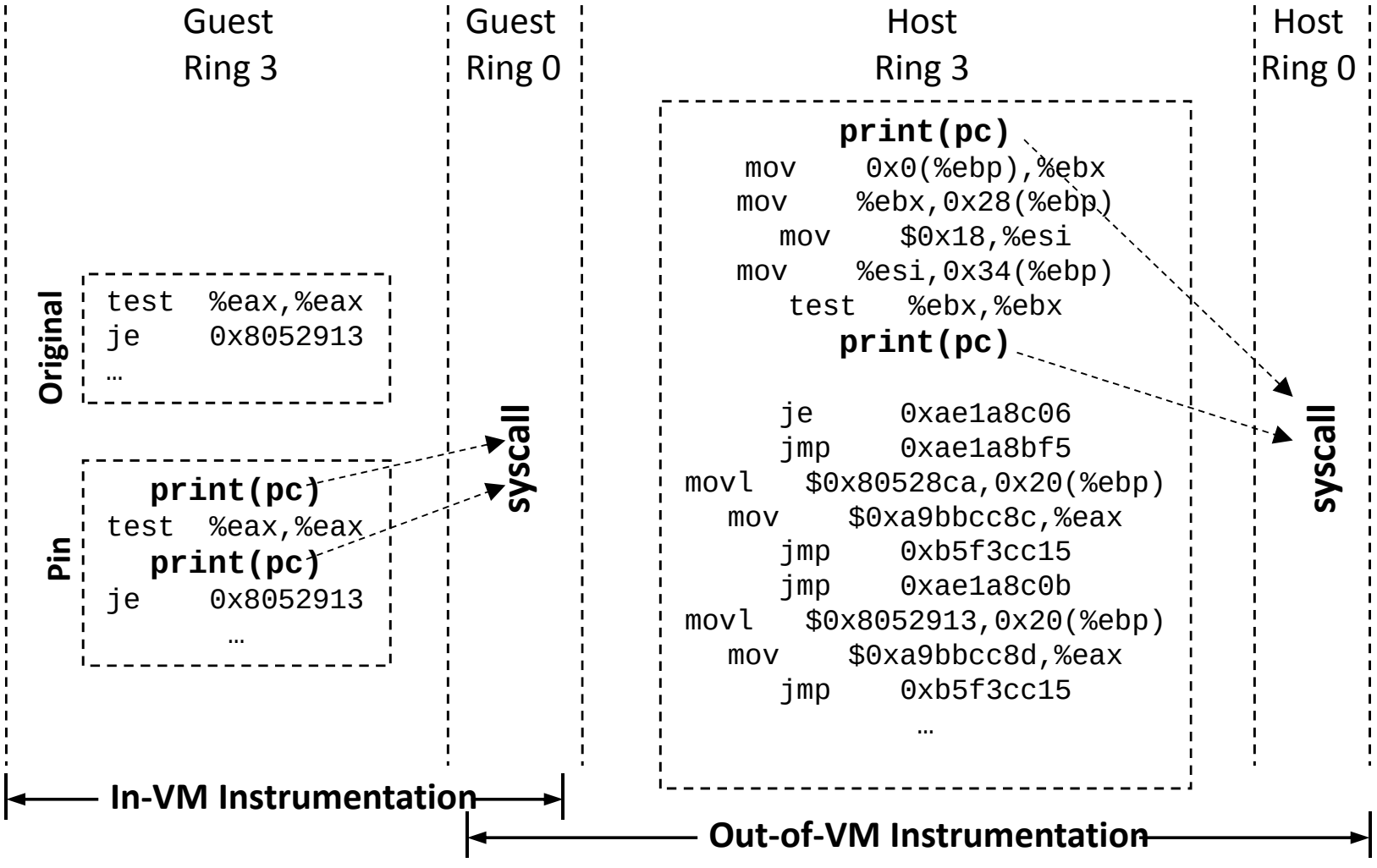
Applications

1. Performance profiling
2. Architecture simulation
3. Program shepherding
4. Program optimization
5. Dynamic taint analysis
6. Reverse engineering
7. Malware analysis
8. ...

In-VM DBI


Guest
Ring 3
Guest
Ring 0
Original
test %eax,%eax
je 0x8052913
…
Pin
print(pc)
test %eax,%eax
print(pc)
je 0x8052913
…
syscall
In-VM Instrumentation

In-VM DBI vs. Out-of-VM DBI



State-of-the-Art

Platforms	Year	Emulator, Simulator, Virtualizer	Kernel Level Instrumentation	User Level Instrumentation	w/ API for instrumentation	Out-of-VM	Guest OS Agnostic	PIN API Compatible	Open Source
EMBRA [WR96]	1996	✓	✓	✓	✗	✓	✗	✗	✗
VMWARE [DBR98]	1998	✓	✓	✓	✗	✓	✗	✗	✗
KERNINST [TM99]	1999	✗	✓	✓	✓	✗	✓	✗	✓
DYNINSTAPI [BH00]	2000	✗	✓	✓	✓	✗	✓	✗	✓
DYNAMO [BDB00]	2000	✗	✓	✓	✗	✗	✓	✗	✗
BOCHS [boc01]	2001	✓	✓	✓	✗	✓	✗	✗	✓
SIMICS [MCE+02]	2002	✓	✓	✓	✗	✓	✗	✗	✗
VALGRIND [NS03, NS07]	2003	✗	✗	✓	✓	✗	✓	✗	✓
STRATA [SKV+03]	2003	✗	✗	✓	✓	✗	✓	✗	✓
DYNAMORIO [BDB00, BZA12]	2004	✗	✗	✓	✓	✗	✓	✗	✓
QEMU [Bel05]	2005	✓	✓	✓	✗	✓	✗	✗	✓
PIN [LCM+05]	2005	✗	✗	✓	✓	✗	✓	✓	✗
NIRVANA [BCdJ+06]	2006	✗	✗	✓	✓	✗	✓	✗	✗
HDTRANS [SSNB06]	2006	✗	✗	✓	✓	✗	✓	✗	✓
VIRTUALBOX [Wat08]	2007	✓	✓	✓	✗	✓	✗	✗	✓
PINOS [BL07]	2007	✓	✓	✓	✓	✗	✗	✓	✗
TEMU [YS]	2010	✓	✓	✓	✓	✓	✓	✗	✓
DYNINST [MB11]	2010	✗	✓	✓	✓	✗	✓	✗	✓
DRK [PFG12]	2013	✗	✓	✓	✓	✗	✓	✗	✓
DECAF [HPY+14]	2014	✓	✓	✓	✓	✓	✗	✗	✓
PEMU	2015	✓	✓	✓	✓	✓	✓	✓	✓

Limitations Among Prior Works

Process Level DBI (e.g., PIN, VALGRIND)

- Process-level DBI such as PIN and VALGRIND provides rich APIs to analyze user level binary code execution, but the analysis code is executed inside the VM (i.e., in-VM) with the same privilege as the instrumented process.
- No kernel level instrumentation
- Limited type of OS (VALGRIND only for Linux)

VM Monitor Level DBI (e.g., QEMU)

- No general DBI APIs

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DRK [PFG12]	2013	✗	✓	✓	✓	✗	✓	✗	✓
DECAF [HPY+14]	2014	✓	✓	✓	✓	✓	✗	✗	✓
PEMU	2015	✓	✓	✓	✓	✓	✓	✓	✓

Introduction of PEMU

PIN + QEMU = PEMU

Objectives

- **Rich APIs**
  - Provide rich and well-defined APIs for DBI
  - PIN-API compatibility
- **Cross-OS**
  - OS agnostic for the introspection
- **Strong Isolation**
  - Out-of-VM Instrumentation to isolate analysis routings with target programs (QEMU)
- **VM Introspection**
  - Support high level guest object introspection

A sample PIN plugin

```
1  static UINT64 icount;
2  FILE *pFile;
3  VOID docount(UINT32 c) { icount += c; }
4  VOID Trace(TRACE trace, VOID *v) {
5     for (BBL bbl = TRACE_BblHead(trace);
6        BBL_Valid(bbl); bbl = BBL_Next(bbl)) {
7        BBL_InsertCall(bbl, IPOINT_BEFORE,
8        (AFUNPTR)docount, IARG_UINT32, BBL_NumIns(bbl),
9        IARG_END);
10    }
11 }
12 VOID Fini(INT32 code, VOID *v) {
13    fprintf(pFile, "Count %lld\n", icount);
14    fclose(pFile);
15 }
16 INT32 Usage(VOID) {
17    return 0;
18 }
19 int main(int argc, char * argv[]) {
20    if(PIN_Init(argc, argv)) return Usage();
21    pFile = fopen("pemu_count", "w");
22    TRACE_AddInstrumentFunction(Trace, 0);
23    PIN_AddFiniFunction(Fini, 0);
24    PIN_StartProgram();
```

Challenges

1. **How to implement PIN API based on QEMU**
   - QEMU does not have abstraction for TRACE, SEC, Function and IMG etc.
   - QEMU basic block has limited size
2. **Semantic gap between guest OS and host OS**
   - How to find the target process or thread
   - PIN plugins may inspect guest OS state, such as `getpid`

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   $\Rightarrow$ Instrumentation Engine
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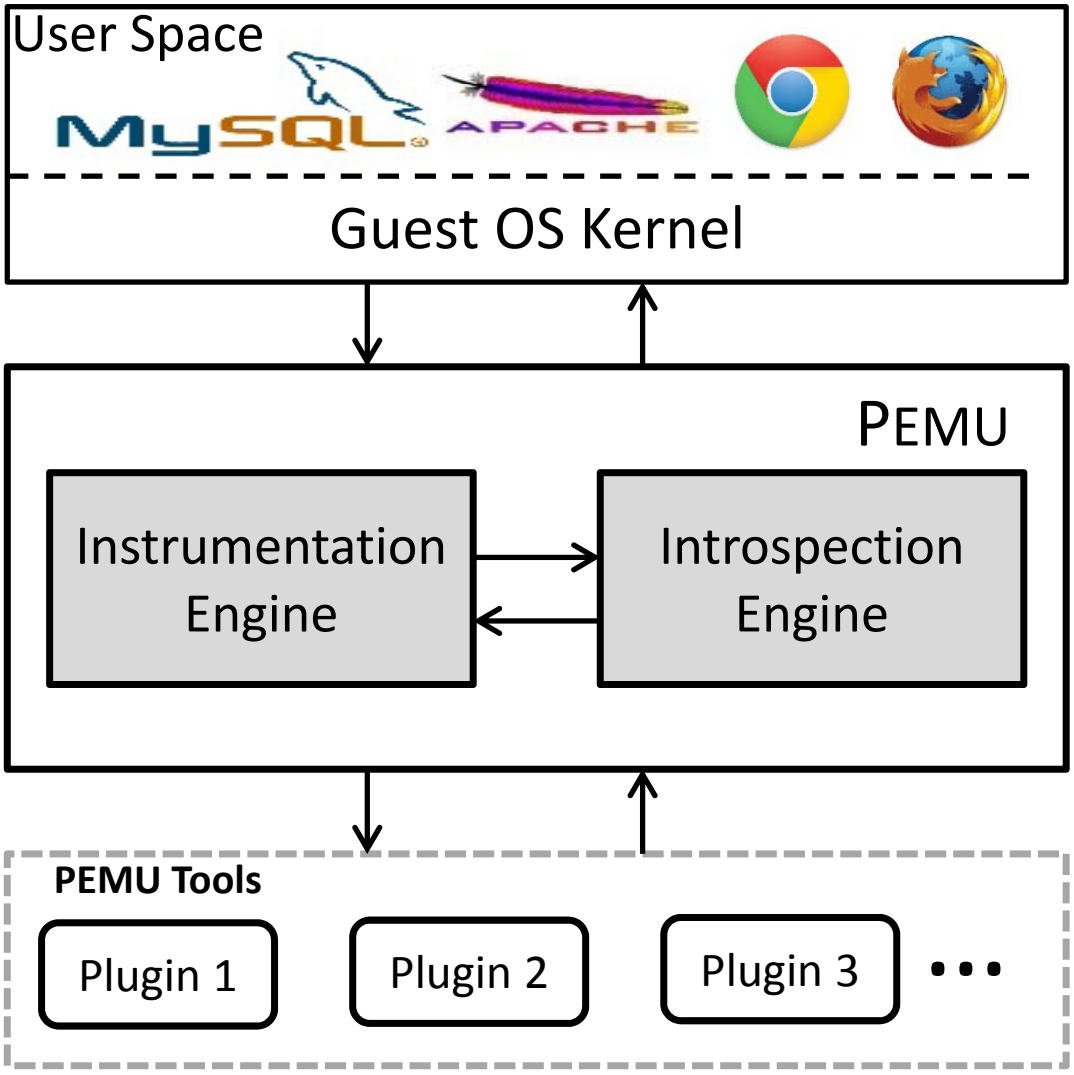
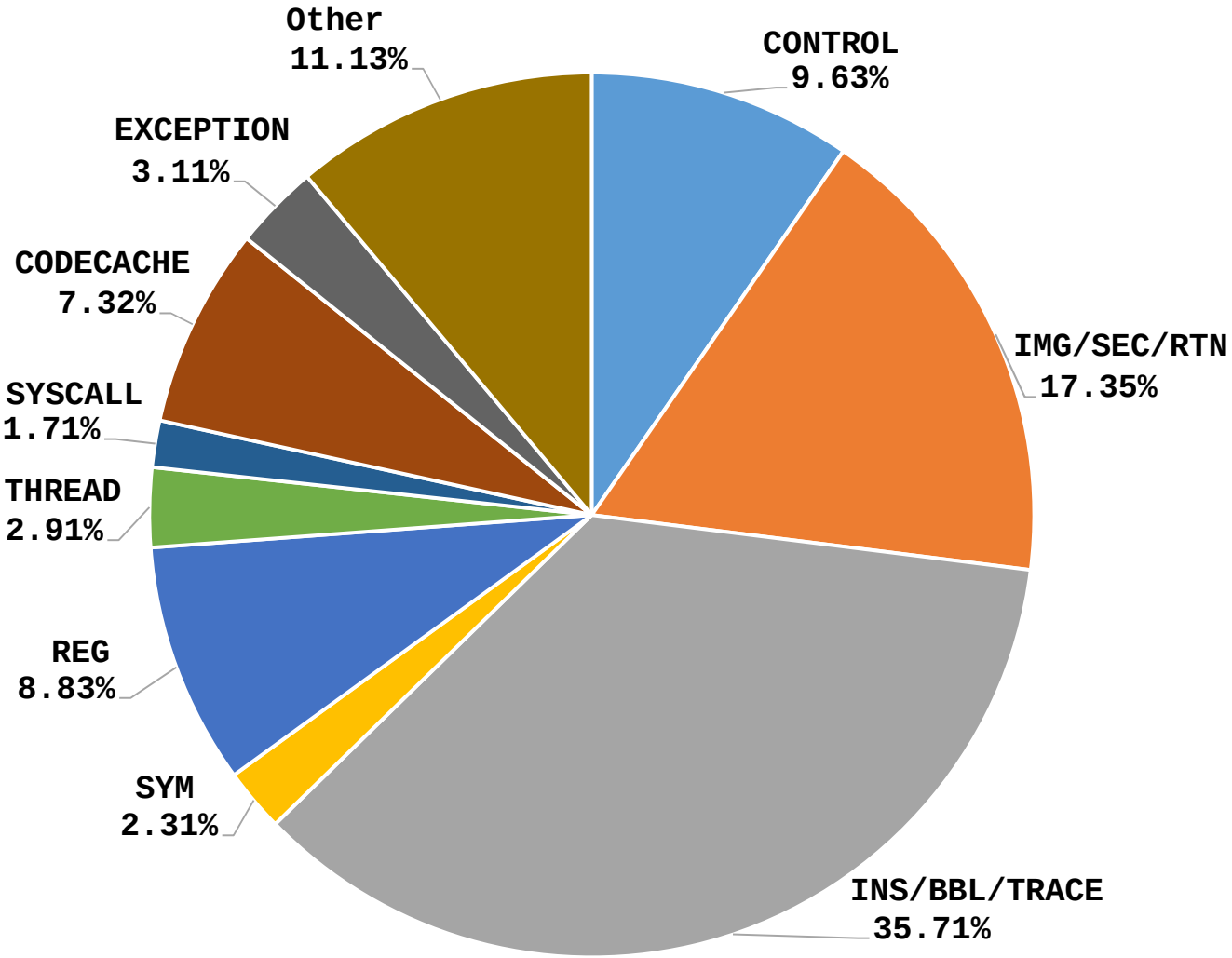
   $\Rightarrow$ Introspection Engine

PEMU Architecture



Instrumentation Engine: PIN APIs



Instrumentation Engine

1. **Trace Instrumentation**: occurs immediately before a code sequence is executed
   - Instruction Level, e.g., `INS_InsertCall(ins, IPOINT_BEFORE,..)`
   - Basic Block Level, e.g., `BBL_InsertCall(bbl, IPOINT_BEFORE,..)`
   - Trace Level, e.g., `TRACE_InsertCall(trace, IPOINT_BEFORE,..)`

2. **Ahead-of-time Instrumentation**: caches the instrumentation before the execution.
   - IMG instrumentation, e.g., `IMG_AddInstrumentFunction`
   - RTN instrumentation, eg.., `RTN_InsertCall`

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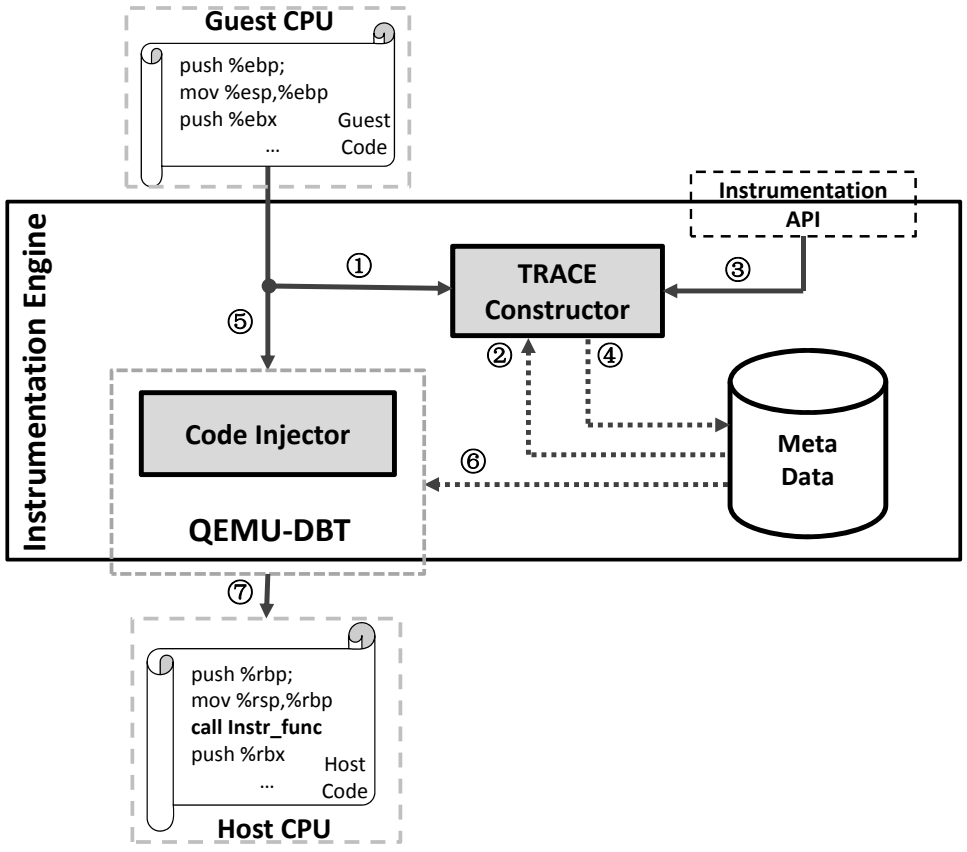
   - Trace Level, e.g., `TRACE_InsertCall(trace, IPOINT_BEFORE,..)`

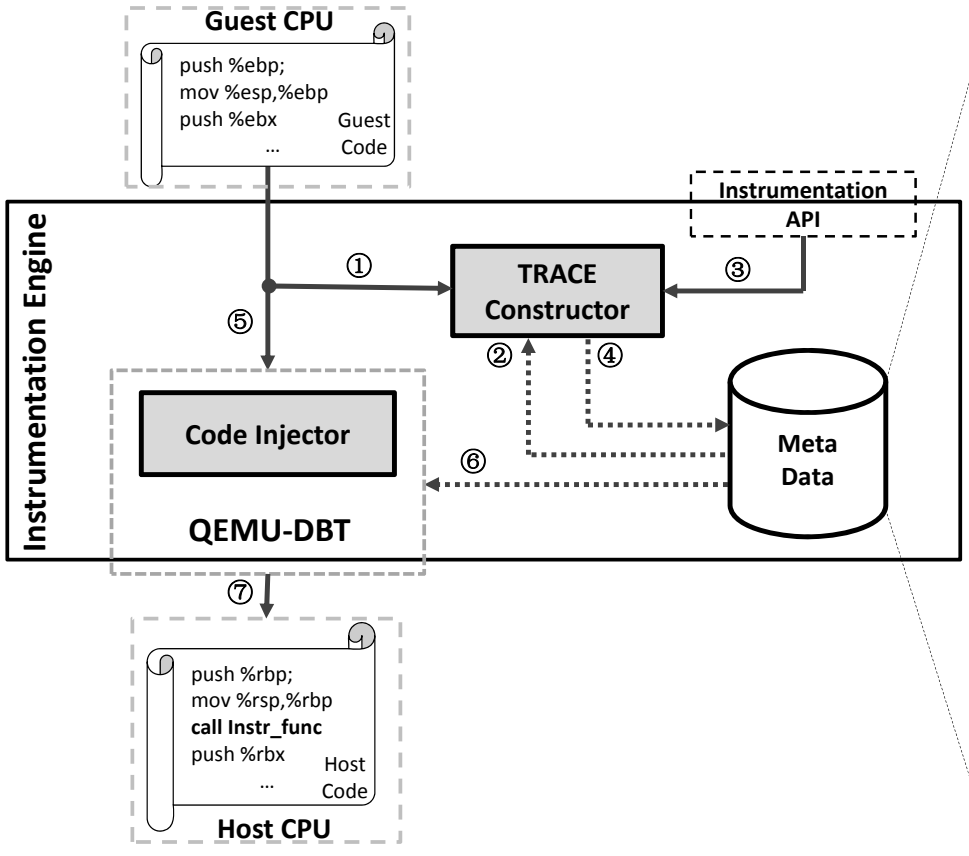
   $\Rightarrow$ Adding our own disassembler (TRACE Constructor)
2. **Ahead-of-time Instrumentation**: caches the instrumentation before the execution.
   - IMG instrumentation, e.g., `IMG_AddInstrumentFunction`
   - RTN instrumentation, eg.., `RTN_InsertCall`

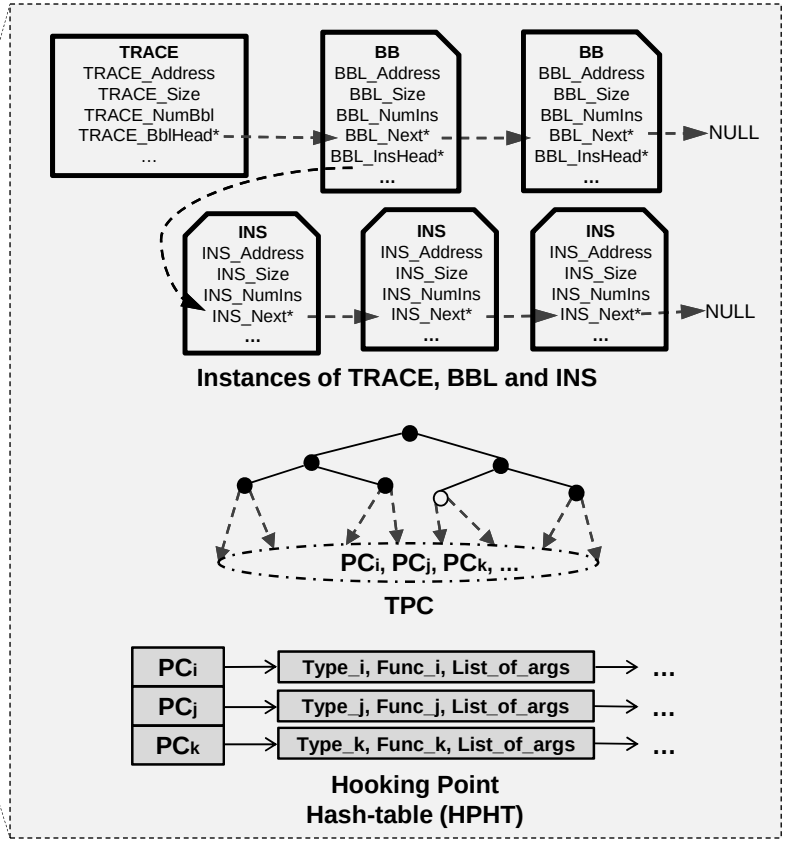
   $\Rightarrow$ Instrumenting code when image is loaded

Instrumentation Engine



Instrumentation Engine



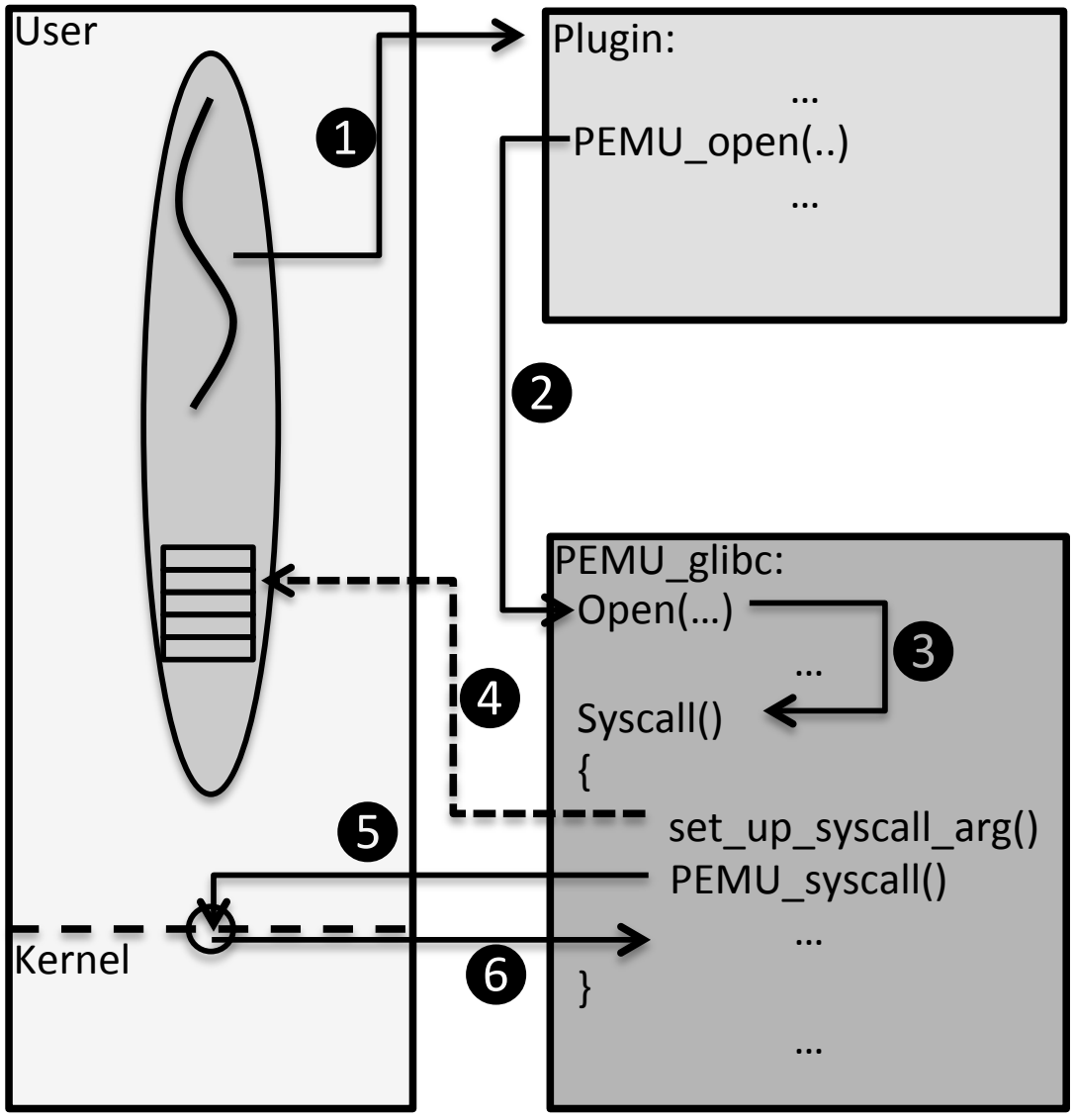


Introspection Engine

Goals and Solutions

- Identification of the monitoring process/threads
  - $\Rightarrow$ Capture the data life time of PGD (`CR3` in x86) to identify the new process
  - $\Rightarrow$ Kernel `esp` to identify new threads
- Bridging the semantic gap for the out-of-VM plugins
  - $\Rightarrow$ Using a system call redirection/forwarding approach
  - HyperShell [YFL14]

Introspection Engine: Syscall Redirection



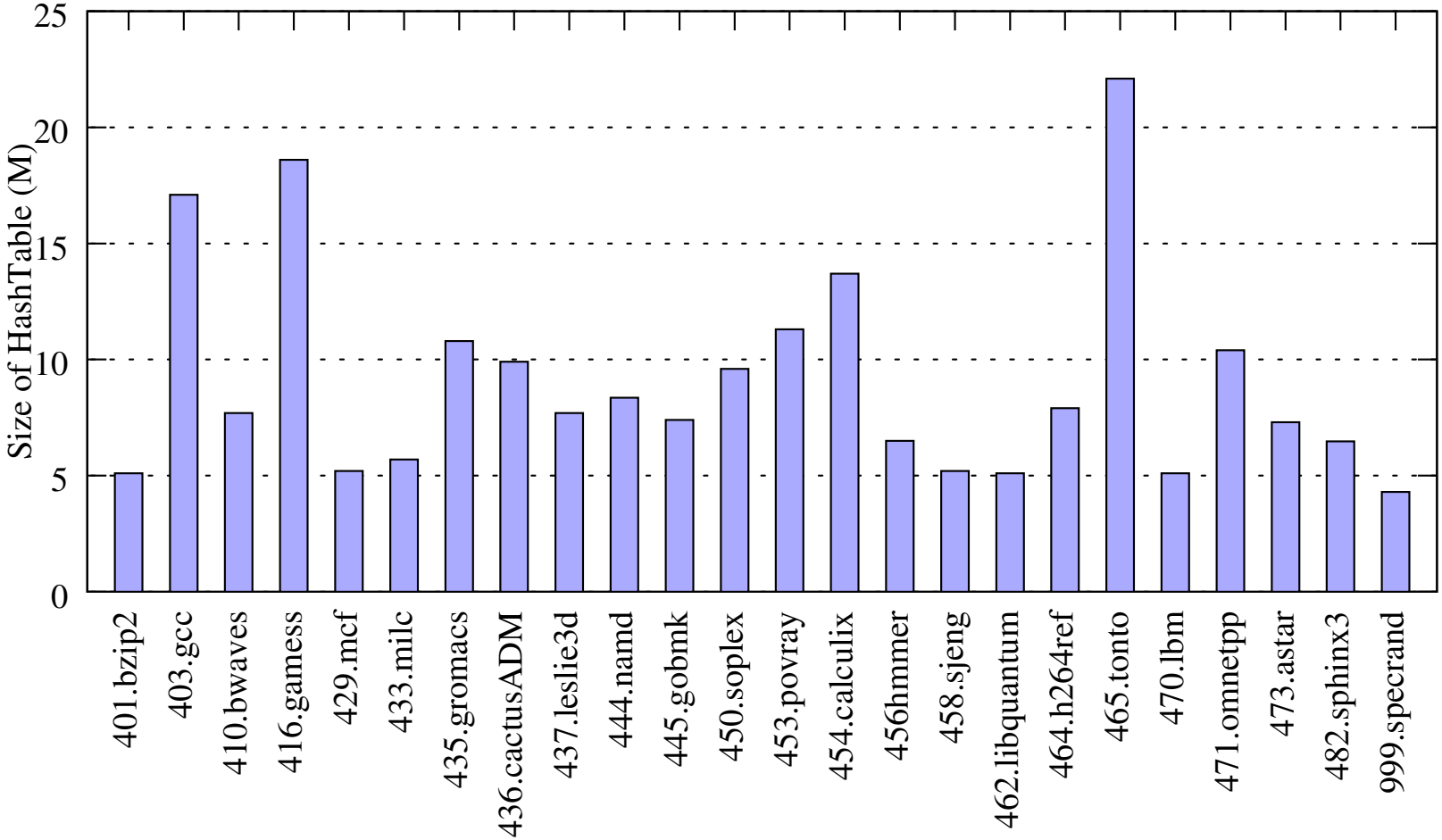
Compatibility Testing With PIN Plugins

Plugin	Description	Supported
calltrace.so	Call trace tracing	✓
extmix.so	Instruction extension mix profile	✓
inscount2_vregs.so	Counting executing instructions	✓
pinatrace.so	Memory address tracing	✓
xed-cache.so	Decode cache profile	✓
catmix.so	Instruction category mix profile	✓
fence.so	Runtime text modification guard	✓
jumpmix.so	Jmp/branch/call profiling	✓
regmix.so	Register usage mix profile	✓
xed-print.so	XED usage testing	✓
coco.so	Code coverage analyzer	✓
icount.so	Counting executing instructions	✓
ldstmix.so	Register/memory operand profiler	✓
topopcode.so	Opcode mix profiler	✓
xed-use.so	XED interface usage testing	✓
dcache.so	Data cache simulation	✗
ilenmix.so	Instruction length mix profiler	✓
malloctrace.so	Tracing calls to malloc	✓
toprtn.so	Hostest routines profiling	✓
edgcnt.so	Control flow edge profiler	✓
inscount2_mt.so	Counting executing instructions	✓
opcodemix.so	Opcode mix profiler	✗
trace.so	Compressed instruction tracer	✓

Performance Evaluation: Speed

Program	**#Inst (M)**	T_{Qemu} (s)	T_{Pemu} (s)	T_{Pemu} / T_{Qemu}	T_{Pin} (s)	T_{Qemu} / T_{Pin}	T_{Pemu} / T_{Pin}
401.bzip2	11500.27	24.55	81.15	3.31	11.17	2.20	7.26
403.gcc	4940.36	18.35	169.21	9.22	13.56	1.35	12.48
410.bwaves	29360.09	419.99	1336.57	3.18	7.44	56.45	179.65
416.gamess	2121.15	23.19	84.99	3.66	3.35	6.92	25.37
429.mcf	3562.67	23.91	70.58	2.95	3.55	6.74	19.88
433.milc	39509.49	779.07	2570.44	3.30	9.28	83.95	276.99
435.gromacs	4907.53	106.28	334.74	3.15	3.43	30.99	97.59
436.cactusADM	9730.11	304.89	1019.89	3.35	4.42	68.98	230.74
437.leslie3d	55857.54	900.01	3009.06	3.34	15.38	58.52	195.65
444.namd	74037.63	1523.78	5037.00	3.31	16.22	93.94	310.54
445.gobmk	314.88	2.43	4.17	1.72	1.71	1.42	2.44
450.soplex	63.67	1.49	2.22	1.49	1.80	0.83	1.23
453.povray	2987.41	36.16	193.17	5.34	3.52	10.27	54.88
454.calculix	187.33	2.53	6.61	2.61	2.46	1.03	2.69
456.hmmer	17862.2	46.43	260.56	5.61	6.95	6.68	37.49
458.sjeng	15514.49	48.40	432.79	8.94	14.38	3.37	30.10
462.libquantum	408.63	0.77	2.01	2.61	0.62	1.24	3.24
464.h264ref	98144.32	392.21	2751.31	7.01	34.01	11.53	80.90
465.tonto	3571.85	48.23	195.16	4.05	5.44	8.87	35.88
470.lbm	7744.81	161.22	692.51	4.30	2.92	55.21	237.16
471.omnetpp	2209.23	16.24	136.63	8.41	3.19	5.09	42.83
473.astar	26645.10	102.95	734.52	7.13	13.67	7.53	53.73
482.sphinx3	6198.21	77.95	322.26	4.13	4.94	15.78	65.23
999.specrand	6198.21	1.42	2.46	1.73	0.92	1.54	2.67
Avg.	17649.05	210.94	810.42	4.33	7.68	22.52	83.61

Performance Evaluation: Memory Cost



Applications: anti-PIN malware analysis

Background

- Anti-PIN malware: malware exits when it detects it is run inside PIN

Case Studies

- **tElock**, **Safengine Shielden**: two widely used tools to build anti-analysis software.
- **eXait**: a benchmark-like tool to test anti-instrumentation techniques

Applications: anti-PIN malware analysis

```
1  FILE *trace;
2  VOID SysBefore(ADDRINT ip, ADDRINT num) {
3     fprintf(trace,"0x%lx: %ld\n",
4             (unsigned long)ip, (long)num);
5  }
6  VOID SyscallEntry(THREADID threadIndex,
7     CONTEXT *ctxt, SYSCALL_STANDARD std, VOID *v) {
8     SysBefore(PIN_GetContextReg(ctxt, REG_INST_PTR),
9               PIN_GetSyscallNumber(ctxt, std));
10 }
11 VOID Fini(INT32 code, VOID *v) {
12    printf("program exit()\n");
13 }
14 INT32 Usage(VOID){
15    return 0;
16 }
17 int main(int argc, char * argv[]){
18    if(PIN_Init(argc, argv)) return Usage();
19    trace = fopen("strace.out", "w");
20    PIN_AddSyscallEntryFunction(SyscallEntry, 0);
21    PIN_AddFiniFunction(Fini, 0);
22    PIN_StartProgram();
23    return 0;
24 }
```

Applications: anti-PIN malware analysis

Our Result

- **tElock**, **Safengine Shielden**:
  - PIN failed to run the testing programs generated by tElock and Safengine Shielden, which detected the presence of PIN and exited at early stages.
  - The testing programs ran successfully on PEMU.
- **eXait**:
  - 17 out of 21 anti-instrumentation techniques detect the presence of PIN,
  - None of them detect the presence of PEMU.

Applications: Virtual Machine Introspection

Building VMI tools

- PEMU can be used to build many out-of-VM introspection tools.
- A number of such tools have been built atop PEMU:
  - VMST [FL12]
  - EXTERIOR [FL13]

Limitation and Future Work

- Currently Incomplete support of the PIN-APIs
- A weak semantic gap [JBZ+14]
- No optimization with the generated instrumentation and analysis routine yet

Limitation and Future Work

- Currently Incomplete support of the PIN-APIs

$\Rightarrow$ Make PEMU open source

- A weak semantic gap [JBZ+14]

$\Rightarrow$ Not trust the guest OS kernel at all

- No optimization with the generated instrumentation and analysis routine yet

Conclusion

PEMU

A new dynamic binary code instrumentation framework

1. PIN-API compatibility
2. Cross-OS (support both Windows and Linux)
3. Out-of-VM (strong isolation with the analysis routine and the target code)

Availability

The source code of PEMU is available at:
https://github.com/utds3lab/pemu

Thank you

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