Measurement: Instrumentation

Vojtěch Horký  Peter Libič  Petr Tůma

2010 – 2023

This work is licensed under a “CC BY-NC-SA 3.0” license. Created to support the Charles University Performance Evaluation lecture. See [http://d3s.mff.cuni.cz/teaching/performance-evaluation](http://d3s.mff.cuni.cz/teaching/performance-evaluation) for details.

Contents

1 Overview  1
2 Source Code Instrumentation  2
3 Bytecode Instrumentation  3
4 Machine Code Instrumentation  7
5 Instrumentation Overwriting Code  9
6 Instrumentation Translating Code  15

1 Overview

Purpose

Instrumentation inserts measurement code (probes) into well defined program locations to facilitate data collection.

Examples of instrumentation:
- Static instrumentation in source files
- Dynamic instrumentation in object model
- Static or dynamic instrumentation in bytecode
- Static or dynamic instrumentation in machine code
- Static preparation in source files that allows dynamic instrumentation in machine code

Collected Information

Information that is interesting but cannot be measured directly:
- Precise program traces
- Program state snapshots
- Function parameter values
- Anything else the program can observe ...

Applications

Useful for many dynamic analyses:
- Test coverage
- Race detection
- Taint tracking
- Origin tracking
- Memory usage checks

## 2 Source Code Instrumentation

### Source Code Instrumentation

#### Benefits
- Relatively easy to insert
  - Source code is made to be modified
  - Automated tools sometimes struggle
- Program state naturally available
- Locations relevant to code structure

#### Challenges
- Instrumentation is subject to compiler optimization:
  - Optimized together with surrounding code
  - Can impact surrounding optimizations
  - Can be subject to code motion
- Conditional instrumentation possibly tricky
- Requires source code and compilation

### Source Code Instrumentation

#### Manual
Programmer inserts measurement code into locations of interest.
- Fine grained placement control
- Tedious and possibly error prone

#### Assisted
Tool inserts measurement code into specified locations.
- Tool guarantees systematic coverage
- Specification of locations limited

For tool examples think about logging frameworks or macro processors.

### Source Code Instrumentation Problems

#### Configurability
We want to have simple way to turn instrumentation on and off.
- Preprocessing
- Conditional calls

Think what a modern runtime will do with the following:

```java
log.debug ("App_results_are_" + results.toString () + ":");
log.debug ("App_results_are_{"}, results);
if (log.isDebugEnabled ()) {
    log.debug ("App_results_are_" + results.toString () + ":");
}
```
Reliability
We need reliable association between instrumentation and application code.

Think what a modern compiler will do with the following:

```c
int sqrt_counter = 0;
inline double counted_sqrt (double x) {
    sqrt_counter ++;
    return (sqrt (x));
}
```

This is the square root function disassembly:

```
sqrt:  pxor    xmm1,xmm1   // Set xmm1 to zero
       ucomisd xmm1,xmm0   // Compare argument to zero
       ja fail            // Negative argument check
       sqrtsd xmm0,xmm0   // Compute square root
       ret                // Register passing
```

3 Bytecode Instrumentation

**Bytecode Instrumentation**

**Benefits**
- Still relatively easy to insert
- Bytecode contains much metadata
- Compilation produces predictable bytecode
- Program state still naturally available
- Can be done at runtime without sources

**Challenges**
- Requires tools
- Not all languages and environments have bytecode
- Locations in bytecode possibly different from code structure

For tool examples consider ASM or DiSL.
Also aspect oriented frameworks such as AspectJ.

**ASM**

Library for bytecode manipulation.

Main features of ASM are:
- Core API based on visitor design pattern
  - `ClassReader` to generate events from class file
  - `ClassWriter` to generate class file from events
  - Transformations implemented as event pipes
  - Adapters for predefined transformations
- Tree API for in memory class file representation
  - Can build representation from Core API events
  - Can generate Core API events from representation

[http://asm.ow2.io](http://asm.ow2.io)

**Aspect Oriented Programming**

**Idea**

What if we could express independent concerns by separate code fragments?
concern  Program feature that stands apart from other features.
join point  Program location where concern code resides.
pointcut  Specification of a set of join points.
advice  Code inserted at pointcut.
weave  Insert advice.

Obviously AOP can be used to insert measurement instrumentation. Some pointcut specifications can introduce significant perturbation.

**AspectJ**

Aspect oriented programming framework for Java.

Main features of AspectJ are:
- Byte code instrumentation at compile time and load time
- Declarative language for defining instrumentation points
- Instrumenting code written in Java

http://www.eclipse.org/aspectj

**Instrumentation with AspectJ**

```java
aspect Measurement {

  // Select all executions of methods of class Main.
  pointcut allMainMethods (): execute (* Main.*(..));

  // Attach an around advice that measures time.
  Object around (): allMainMethods () {
    long timeBefore = System.nanoTime ();
    Object result = proceed ();
    long timeAfter = System.nanoTime ();
    System.out.println (timeAfter - timeBefore);
    return (result);
  }
}
```

**AspectJ Join Points**

Join points are:
- call and execution of a method or a constructor,
- execution of an exception handler,
- execution of a static initializer,
- read or write access to a field,
- execution of an advice.

```java
execution (int SomeClass.someMethod (int))
execution (String * .getName (..))
call (* AnotherClass.* (String))
call (*.new (long))
handler (RemoteException+)
get (int *.counter)
```

Join points can be further constrained by:
- presence of an annotation,
- location within a class or a method,
- actual type of the current object, called object, arguments,
- control flow selected by particular pointcut,
- boolean expression.

this (SomeClass)
target (AnotherClass)
args (int, int, int, int)
cflow (SomePointcut)
within (SomeClass)

AspectJ Pointcuts

Pointcuts combine specifications of join points using standard operators &&, ||, !.

pointcut callToSomeClassFromMain ():
   within (Main) && target (SomeClass+);

pointcut nonRecursiveCallToSomeClass ():
   call (*) SomeClass.* (..)) && !within (SomeClass)

Pointcuts can make accessible variables in their context:
- current object,
- target object,
- arguments.

pointcut callToSomeClass (SomeClass o):
   call (*) SomeClass.* (..)) && target (o);

pointcut namingSomething (String name):
   call (void *.setName (String)) && args (name);

AspectJ Advice

Advice can be associated with join point:
- before the join point,
- after the join point
  - when it returns normally,
  - when it throws an exception,
- around the join point.

before SomePointcut ():
   Object [] arguments = thisJoinPoint.getArgs ();
   for (Object argument : arguments) {
      System.out.println (argument);
   }

Object around AnotherPointcut ():
   return (proceed ());

More AspectJ Features

Aspects can include declarations across types:
- declare new fields,
- declare new methods,
- declare new constructors,
- introduce new parents,
- introduce new interfaces.
private interface HasCounter {} 
declare parents: 
 (SomeClass || AnotherClass) implements HasCounter; 
private long HasCounter.executionCount = 0; 
before (HasCounter o): 
  execution (* ..) && this (o) { 
    o.executionCount ++; 
  }

**Bytecode Instrumentation Problems**

Consider
Inserted instrumentation executes in the same virtual machine as program.

Can this cause any problems?
- Deadlock between analysis and application
- State corruption inside application code
- Arbitrary assumptions in virtual machine
- Bytecode verification failures
- Shared reference handlers
- Coverage approximation
- ...

**Program State Corruption**

Coverage
Analyses may require total code coverage:
- Memory allocation tracking (leaves important)
- Taint tracking (and any other data flow)
- Reliable race detection
- ...

What happens if we try to instrument every class of the application?
This includes Object, String, System classes.
These will likely be used by instrumentation and analysis code too.
It is (too) easy to run into infinite recursion or state corruption problems.

**Dynamic Bypass Pseudocode**

```java
static boolean instrumentationOnline = false;

// Instrumentation snippet
if (!instrumentationOnline) {
  instrumentationOnline = true;
  // Actual instrumentation here

  instrumentationOnline = false;
}
```

Simple with single-threaded programs, can be tricky with multiple threads.

**DiSL**

[1] Based on Kell et al.: The JVM is Not Observable ... doi:10.1145/2414740.2414747
A bytecode instrumentation framework with emphasis on coverage.

- Language and framework for Java bytecode instrumentation
- Similar to aspects, but read only and with more control
- Allows to write instrumentation snippets directly in Java
- Instrumentation points are selected using annotations
- Dynamic bypass is provided automatically

http://disl.ow2.org

Example Instrumentation Snippet

```java
@Before (  
    marker = BodyMarker.class,  
    scope = "TargetClass.print_(boolean)",  
    order = 8)
public static void precondition () {  
    System.out.println ("Precondition!");
}
```

snippet  Code inserted as instrumentation.

marker  Specification of location to instrument.

scope  Specification of classes to instrument.

guard  Instrumentation condition.

DiSL Architecture

Instrumentation Server

Standalone server responsible for creating instrumented classes.

- Standalone to minimize perturbation
- Instrumentation using ASM
- Optimizations

Application Client

Java virtual machine executing the instrumented application.

- JVMTI agent to intercept class loading process
- Remote communication with instrumentation server
- Also executes whatever instrumentation code is inserted

More DiSL Examples

Look at the examples from the DiSL distribution. Use the ant run command to execute individual examples.

smoke  A minimum example demonstrating the before and after advice on a method.

local  An example demonstrating the use of a synthetic local variable.

scope  Limiting instrumentation scope.

marker  Implementing custom marker.

guard  Using guards to restrict instrumentation.

static  Using and implementing static context.

dynamic  Using dynamic context.

4 Machine Code Instrumentation

Machine Code Instrumentation

Benefits

- Machine code (almost) always available
- Looking at code in very fine resolution
Challenges
– Machine code difficult to analyze
– Mixing code and data
– Variable length instructions
– Very far from source code structure
– Inserting extra code difficult
– No space for extra instructions
– Register state must be preserved
– Some patterns complicate things
– Auto generated or self modifying code
– Computed branch targets

Recognizing Machine Code

DUMP

.. 04 0A 11 1F 11 11..

AS CODE
...
04 0A add $0xa,%al
11 1F adc %ebx,(%rdi)
11 11 adc %edx,(%rcx)
...

AS BITS
0 0 0 0
0 0 0
0 0 0
0 0 0
0 0 0
0 0 0
0 0 0

Shifting Machine Code

BEFORE PATCH

8A 02 mov (%rdx),%al
84 C0 test %al,%al
74 05 je loop_exit
48 FF C2 inc %rdx
EB F5 jmp loop_head
...

AFTER PATCH

8A 02 mov (%rdx),%al
EB 01 02 03 04 callq probe
84 C0 test %al,%al
74 05 je loop_exit
48 FF C2 inc %rdx
EB F5 jmp loop_head
...

Machine Code Instrumentation

Available tools use combinations of many techniques:
– Overwrite instrumentation locations
– Instrument only prepared locations
– Use dynamic translation
Example tools: DTrace, KProbes, PIN, Valgrind, DynamoRIO.

5 Instrumentation Overwriting Code

**Overwriting Instructions**

Instrumentation can be inserted by overwriting the instruction(s) at the target location.

**Challenges**
- Must overwrite only single location
  - As little as single byte on variable opcode length architectures
  - Single instruction on constant opcode length architectures
- Overwrite must be an atomic operation
- Original instruction must be replayed
- Specialized instructions
  - Intel INT 3 opcode is single byte 0xCC
  - Translates into SIGTRAP on Linux
  - But also writes on stack
- Hardware support
  - Explicit control transfers or barriers sometimes needed
- Trampolines

**Instrument Prepared Locations**

Instrumentation can be inserted at locations that were previously prepared for such use.

**Challenges**
- Identifying suitable locations
- Low overhead when not instrumented
- Prologues
  - Compilers can generate suitable function prologue
- Exported symbols
  - Reasonable location to expect instrumentation at
  - Often called through relatively standard code (PLT)
- Specialized instructions
  - Intel NOP has opcode variants for up to nine bytes
  - Atomic updates for long variants require some care

**Linux Kernel Function Tracer**

System for tracing calls to kernel functions:
- Instrumentation locations prepared by compiler /sys/kernel/debug/tracing/available_filter_functions
- Probes dynamically disabled and enabled

**Kernel Function Tracer Details**

The kernel function tracer requires compiler support. When the kernel configuration includes the FTRACE infrastructure, the -pg -mfentry command line options are included among the compiler arguments. This option, originally intended for profiling, tells GCC to insert a call to a profiling probe at the start of each function. The kernel uses this call to produce function execution traces.

To minimize overhead, the kernel replaces all calls to the profiling probe with NOP instructions at boot time.

---

1See Chamith et al.: Living On The Edge ... doi:10.1145/2908080.2908084
2See Linux kernel Documentation/trace/ftrace.rst
When tracing is enabled, probes are inserted in place of the *nop* instructions. To play with the function tracer and other tracing modules, try:

```plaintext
cd /sys/kernel/debug/tracing
# See what tracers are available.
cat available_tracers
# Enable the function tracer and see the output.
echo function > current_tracer
cat trace
# Constrain the function trace to only trace particular function.
echo do_mmap > set_ftrace_filter
cat trace
# Attach a trace filter command to particular function.
echo do_mmap:stacktrace > set_ftrace_filter
cat trace
# Enable the function graph tracer and see the output.
echo do_mmap > set_graph_function
echo function_graph > current_tracer
cat trace
# Pause and resume the current tracer.
echo 0 > tracing_on

# Disable the current tracer.
echo nop > current_tracer
```

Note that tracing is disabled while the trace file is being read. This makes sense but means the `tail` command does not show continuous tracing output.

The kernel function tracer can also be controlled through the `perf` tool.

To see how the function entry point is modified for tracing, install the kernel symbol information and disassemble the live kernel using the `crash` tool. This is the output of `dis do_sys_open` with tracing disabled:

```
crash> dis do_sys_open
0xffffffff99315e00 <do_sys_open>: nopl 0x0(%rax,%rax,1) [FTRACE NOP]
0xffffffff99315e05 <do_sys_open+5>: push %r15
0xffffffff99315e07 <do_sys_open+7>: and $0xffff,%cx
0xffffffff99315e0c <do_sys_open+12>: push %r14
0xffffffff99315e0e <do_sys_open+14>: or $0x8000,%cx
0xffffffff99315e13 <do_sys_open+19>: push %r13
0xffffffff99315e15 <do_sys_open+21>: push %r12
...```

The same with tracing enabled:

```
crash> dis do_sys_open
0xffffffff99315e00 <do_sys_open>: callq 0xffffffffc0ee1000
0xffffffff99315e05 <do_sys_open+5>: push %r15
0xffffffff99315e07 <do_sys_open+7>: and $0xffff,%cx
0xffffffff99315e0c <do_sys_open+12>: push %r14
0xffffffff99315e0e <do_sys_open+14>: or $0x8000,%cx
0xffffffff99315e13 <do_sys_open+19>: push %r13
0xffffffff99315e15 <do_sys_open+21>: push %r12
...```

Remember to exit the tool between changes to see the updates.
Linux Static Kernel Trace Points

System for tracing predefined kernel events of interest:
- Inserted by kernel developers into appropriate locations /sys/kernel/debug/tracing/available_events /sys/kernel/debug/tracing/events
- Probes dynamically disabled and enabled
- Accessed through debug file system /sys/kernel/debug/tracing/set_event /sys/kernel/debug/tracing/trace

Static Kernel Trace Points Details

Implementing a static kernel trace point entails defining the structure holding the trace record and implementing associated copy and print functions. See https://elixir.bootlin.com/linux/latest/source/samples/trace_events.

To play with the static kernel trace points, try:

cd /sys/kernel/debug/tracing

# See what trace points are available.
cat available_events

# Enable a trace point and see the output.
echo sched:sched_switch > set_event
cat trace

# See the structure of the trace record for a trace point.
cat events/sched/sched_switch/format

# Restricting a trace point with filter expressions.
echo 'prev_comm=="bash"' > events/sched/sched_switch/filter

# Associating a trigger (action) with a trace point.
echo 'stacktrace:88' > events/sched/sched_switch/trigger

Each trace point is associated with an instance of the tracepoint structure, the trace point code is simply a function that tests the key field of the structure to see whether the associated trace point is enabled.

Linux Kernel Probes

Interfaces that allow to instrument:
- Any single instruction in kernel (Kprobes)
- Any function entry and exit in kernel (Return Probes)

Kprobes

Replace target instruction with breakpoint instruction
- Breakpoint instruction is single byte
- Control transfer similar to interrupt
- Jumps can also be used (faster)

Execute probe code
- Registers saved as in other interrupts
- Handler for both pre code and post code

Single step the replaced instruction
- Must be done inside interrupt handler

See Linux kernel Documentation/trace/tracepoints.rst
See Linux kernel Documentation/trace/kprobes.rst
- Requires understanding all instructions

### Return Probes

Replace function entry with Kprobe

- Kprobe saves original return address
  - Limit on concurrently executing functions with return probes
  - Invocations exceeding limit are counted but not intercepted
- Kprobe modifies function return address to point to trampoline
- Trampoline is instrumented with another Kprobe at system boot time

Execute function code

- Function executes normally
- On return control is passed to trampoline Kprobe

### Kernel Probe Details


### Linux Static User Mode Probe Points

System for marking predefined user mode locations of interest:

- Inserted by application developers into appropriate locations

```c
#include <sys/sdt.h>
STAP_PROBE (app, location)
STAP_PROBE1 (app, location, arg1)
STAP_PROBE2 (app, location, arg1, arg2)
...
```

- Probes compile into
  - A NOP instruction in the probe location
  - A probe record in the ELF stapsdt note section

The `perf` tool recognizes user mode probe points after scanning the binary with `perf buildid-cache`.

### Static User Mode Probe Points Details

Use the `readelf --notes` command to display the content of the `.note.stapsdt` section of an instrumented binary.

### Linux User Mode Probes

System for tracing dynamically instrumented user mode code locations:

- Instrumentation code inserted by kernel on code load
- Controlled through debug filesystem `/sys/kernel/debug/tracing/uprobe_events` echo `"<type> <file>:<offset> [arglist]`.

Support included in the `perf` tool:

```
> perf probe -x <file> --funcs
> perf probe -x <file> --line <func>
> perf probe -x <file> --vars <func>:<line>
> perf probe -x <file> <func>:<line> [<var> ...]
```

---

*See man stapprobes

*See Linux kernel Documentation/trace/uprobetracer.rst*
Linux User Mode Probe Details


# List what functions are available for probing.
```bash
perf probe -x basic -F
```

# List what lines are available for probing within a function.
```bash
perf probe -x basic -L main
```

# List what variables are available for probing on a line within a function.
```bash
perf probe -x basic -V main:13
```

# Set a user mode probe on a line and include variable content in event record.
```bash
perf probe -x basic main:13 i primes
```

Once the probe is set, it can be used as any other trace point, for example with other **perf** commands. It can also be examined directly in the kernel tracing infrastructure.

# See how the probe was defined in the debug file system.
```bash
cat /sys/kernel/debug/tracing/uprobe_events
```

# Enable the probe tracing event and observe the trace and the profile.
```bash
echo 1 > /sys/kernel/debug/tracing/events/probe_basic/main_L13/enable
timeout 1 ./basic
cat /sys/kernel/debug/tracing/trace
cat /sys/kernel/debug/tracing/uprobe_profile
```

To see how the probe point is modified, keep the probe enabled and compare file disassembly with live code disassembly:

# File disassembly. Does not show the probe.
```bash
objdump --disassemble=main --source basic
```

```plaintext
... // Any number that is still marked
// as potentially prime is prime.
  if (can_be_prime [i]) {
    4010cd: 80 ba 80 41 40 00 00 cmpb $0x0,0x404180(%rdx)
    4010d4: 74 ea je 4010c0 <main+0x20>
    ...
```

# Live code disassembly. Shows the probe.
```bash
./basic & gdb -ex "disassemble /rs main" basic $!
```

```plaintext
... 21 // Any number that is still marked
22 // as potentially prime is prime.
23 if (can_be_prime [i]) {
  0x00000000404180 cmpb $0x0,0x404180(%rdx)
  0x000000004010cd <+45>: cc int3
  0x00000000404180ce <+46>: ba 40 41 40 00 mov $0x404180,%edx
  0x000000004010d3 <+51>: 74 ea 8d add %dh,-0x73(%rdx,%rbp,8)
  ...
```

Note how the disassembly is confused by the fact that the seven byte **cmp** instruction is replaced with the one byte **int** instruction. The disassembler considers the leftover part of the **cmp** instruction opcode to be the opcode of the next instruction after **int**. This is what the processor would also do if the execution resumed immediately after the **int** instruction. The probe handler must therefore adjust the return address after executing the original **cmp** instruction. Essentially, this is done by single stepping the original instruction copied to a different location, details are available in kernel sources in [arch/x86/kernel/uprobes.c](https://elixir.bootlin.com/linux/latest/source/arch/x86/kernel/uprobes.c) (online).
**Linux Extended Berkeley Packet Filters**

Framework for securely injecting code into kernel.

**Code**

Injected code written in limited bytecode:
- RISC style instructions
- Limit on instruction count (1M)
- Limit on branching (no loops)
- Static memory access checks

Bytecode supported by LLVM backend.

**Maps**

Data export through maps:
- In kernel key value stores
- Both global and per processor

---

**More bpf Examples**

Examine the bpftrace examples from [https://github.com/iovisor/bpftrace](https://github.com/iovisor/bpftrace).

It is also possible to examine the bpf programs produced by bpftrace. Consider the following example, taken from the bpftrace oneliners, which counts the number of system calls per process:

```
bpftool prog list
...
96: tracepoint name sys_enter tag 0123456789abcdef gpl
    loaded at 2000-01-01T12:34:56+0000 uid 0
    xlated 216B jited 125B memlock 4096B map_ids 33
...
```

While the command is executing, we can locate and dump the bpf program:

```
bpftool prog dump xlated id 96
```

0: (b7) r1 = 0 ;zero used to initialize local variables
1: (7b) *(u64 *)(r10 -24) = r1 ;current process name buffer
2: (7b) *(u64 *)(r10 -16) = r1 ;of size 16 at frame-24
3: (bf) r6 = r10
4: (07) r6 += -24
5: (bf) r1 = r6 ;first argument is buffer address
6: (b7) r2 = 16 ;second argument is buffer size
7: (85) call bpf_get_current_comm
8: (18) r1 = map[id:33] ;first argument is map
10: (bf) r2 = r6 ;second argument is *key
11: (85) call htab_percpu_map_lookup_elem
12: (b7) r1 = 1 ;initial count when no value
13: (15) if r0 == 0x0 goto pc+2
14: (79) r1 = *(u64 *)(r0 +0)
15: (07) r1 += 1
16: (7b) *(u64 *)(r10 -8) = r1 ;new count in local variable at frame-8
17: (18) r1 = map[id:33] ;first argument is map
19: (bf) r2 = r10 ;second argument is *key
20: (07) r2 += -24
21: (bf) r3 = r10 ;third argument is *value

*See man *bpf*
The r10 register serves as a frame pointer to a 512 byte stack frame reserved for the function. Function arguments are passed in registers starting with r1, the return value is in r0.

The native version of the program is displayed with bpf_tool prog dump jited id 96.

### 6 Instrumentation Translating Code

#### Dynamic Instrumentation

Instrumentation can be inserted by translating code during execution.

**Challenges**
- Identifying code to translate
- Keeping execution overhead reasonably low
- Making translation invisible to application
- Code recognized during execution
  - Anything executed must be code
  - Translate in units of basic blocks
  - Chain basic blocks from hot paths into traces
  - Cache and reuse translations during execution
- Instrument inside basic block discovery notification
- Interface to internal code representation
  - Close to binary form in "Copy and Annotate" (PIN, DynamoRIO)
  - Close to compiler IR in "Disassemble and Resynthesize" (Valgrind)

#### PIN


- C and C++ API
- Provides multiple instrumentation points such as Routine (RTN), Image (IMG), Instruction (INS)
- Instrumentation snippet is normal C/C++ code
- Operates in JIT mode or probe mode
- Supports x86

#### PIN Tool Example

```c
int main (int argc, char * argv []) {
    if (PIN_Init (argc, argv)) exit (1);
    INS_AddInstrumentFunction (CountInstruction, 0);
    PIN_StartProgram ();
}

VOID CountInstruction (INS ins, VOID * v) {
    INS_InsertCall (ins, IPOINT_BEFORE, (AFUNPTR) DoCount, IARG_END);
}

VOID DoCount () { ... }
```

*Based on code from Intel PIN examples*
Valgrind

Open source dynamic binary instrumentation tool. http://valgrind.org

- C API
- Compiler style intermediate representation (VEX)
- Instrumentation implemented as VEX manipulation
- Targets heavyweight instrumentation
- Supports x86, ARM, PPC, MIPS ...

Valgrind VEX Example

Original Instruction

add eax,ebx

------ IMark(0x123456, 2, 0) ------

# Connects VEX to original code address and length

```
t3 = GET:I32(8) # Guest state offset 8 is EAX
t2 = GET:I32(20) # Guest state offset 20 is EBX
t1 = Add32(t3,t2)
PUT(8) = t1
```

# Does not show flags and program counter updates

Valgrind VEX Example

Original Instruction

add [eax+4],edx

------ IMark(0x123456, 4, 0) ------

# Connects VEX to original code address and length

```
t3 = Add32(GET:I32(8),0x4:I32) # Non flattened
t2 = LDle:I32(t3) # Little endian load
t1 = GET:I32(16) # Guest state offset 16 is EDX
t0 = Add32(t2,t1)
STle(t3) = t0 # Little endian store
```

# Does not show flags and program counter updates

Debugging With valgrind

Valgrind debugging support can be used to examine the internal program representation on the fly. The example uses the prime sieve example from [https://github.com/d-iii-s/teaching-performance-evaluation/tree/master/src/experiment-prime-sieve](https://github.com/d-iii-s/teaching-performance-evaluation/tree/master/src/experiment-prime-sieve)

# Launch valgrind with debug server after 0 errors detected
valgrind --tool=lackey --vgdb-error=0 ./basic

```
==8086== Lackey, an example Valgrind tool
```

10 Based on code from Valgrind headers
11 Based on code from Valgrind headers
# Launch gdb and connect to debug server in separate terminal
gdb ./basic

target remote | /usr/libexec/valgrind/../../bin/vgdb

# This should be after after primes counter increment
break basic.cc:26
cont

Breakpoint 1, main () at basic.cc:26
26 for (int j = 2 * i ; j < N ; j += i) {

disassemble/s main

... 18 19 // Check numbers from smallest to largest.
19 for (int i = 2 ; i < N ; i++) {
        0x00000000004010c0 <+32>: add $0x1,%rdx                 
        0x00000000004010c4 <+36>: cmp $0x8000000,%rdx     
        0x00000000004010cb <+43>: je 0x40110e <main()+110>

... monitor v.translate 0x4010c0

==== SB 1234 (evchecks 0) [tid 0] 0x4010c0 main+32 basic+0x4010c0

------------------------ After instrumentation ------------------------

IRSB {
    t0:164 t1:164 t2:164 t3:164 t4:164 t5:164 t6:11 t7:164
    t8:164 t9:164 t10:164 t11:164 t12:164 t13:164 t14:11 t15:11

    DIRTY 1:11 :: add_one_SB_entered(0x58001090)()
    DIRTY 1:11 :: add_one_IRStmt(0x580010b0)()
    DIRTY 1:11 :: add_one_guest_instr(0x580010c0)()
    ------- IMark(0x4010c0, 4, 0) -------
    DIRTY 1:11 :: add_one_IRStmt(0x580010b0)()
    t2 = GET:164(32)
    DIRTY 1:11 :: add_one_IRStmt(0x580010b0)()
    t0 = Add64(t2,0x1:164)
    DIRTY 1:11 :: add_one_IRStmt(0x580010b0)()
    PUT(32) = t0
    DIRTY 1:11 :: add_one_IRStmt(0x580010b0)()
    DIRTY 1:11 :: add_one_guest_instr(0x580010c0)()
    ------- IMark(0x4010c4, 7, 0) -------

... Note that the dump is shown in the valgrind terminal, not in the debugger terminal.