UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

CS 250: Software Security

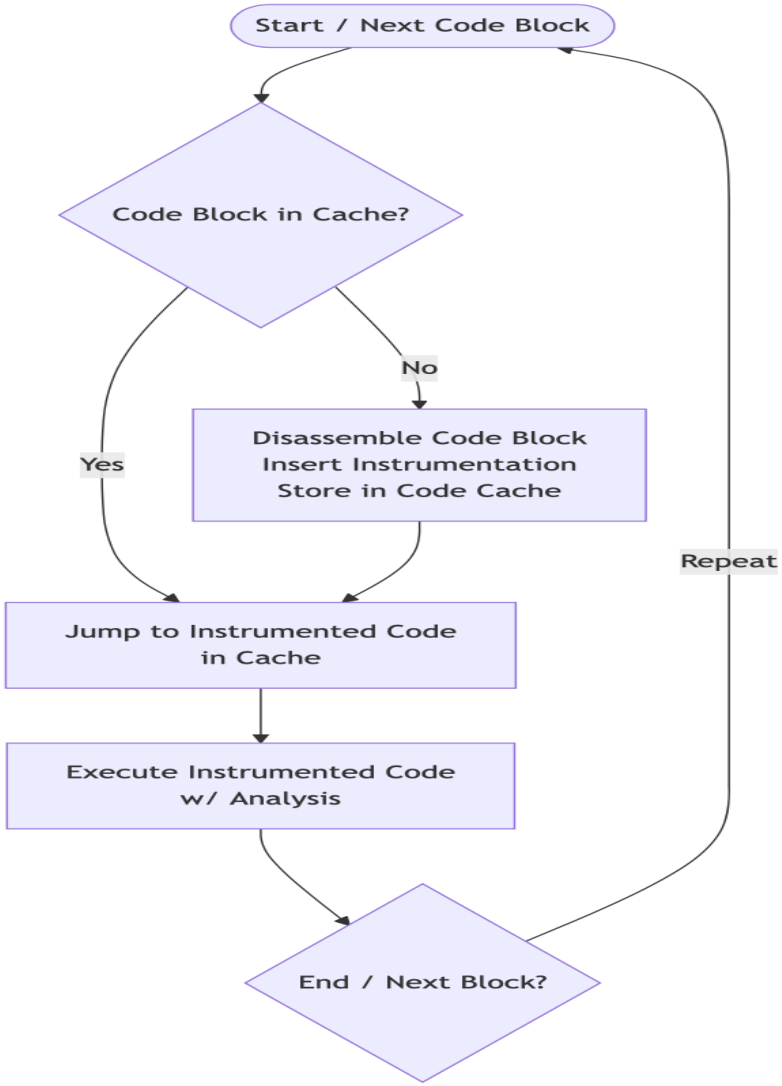
Dynamic Binary Instrumentation

What is Binary Instrumentation

UCR

- Insert analysis and monitoring code into a binary program
- Different from source code instrumentation
  - Add code during compilation process
- Applications
  - Collect runtime information for perf. optimization, greybox fuzzing, concolic execution, etc.
  - Protect the binary
- Two approaches
  - Static Instrumentation
    - Statically rewrite the binary
    - Hard, because correct disassembly is difficult
  - Dynamic Instrumentation
    - Insert code at runtime
    - No need to statically disassemble the code
    - More overhead

Dynamic Binary Instrumentation



DBI Tools

- Pin: A user-mode DBI tool from Intel
  - JIT-based rewriting of x86/x64 instructions
  - Provides an API to insert callbacks around instructions, basic blocks, functions, and system calls
  - Closed-source
- Valgrind: A framework best known for Memcheck
  - Translates binary code into an intermediate representation (VEX IR)
  - Insert analysis code (in form of IR)
  - Built for heavyweight analysis
  - Open-source
- QEMU: An emulator/virtualizer
  - Full-system mode and user mode
  - Can emulate different architectures
  - Translates binary code into an IR (TCG)
  - Open-source: not analysis tool, but many tools are built on top of it

A Pintool for Tracing Memory Writes

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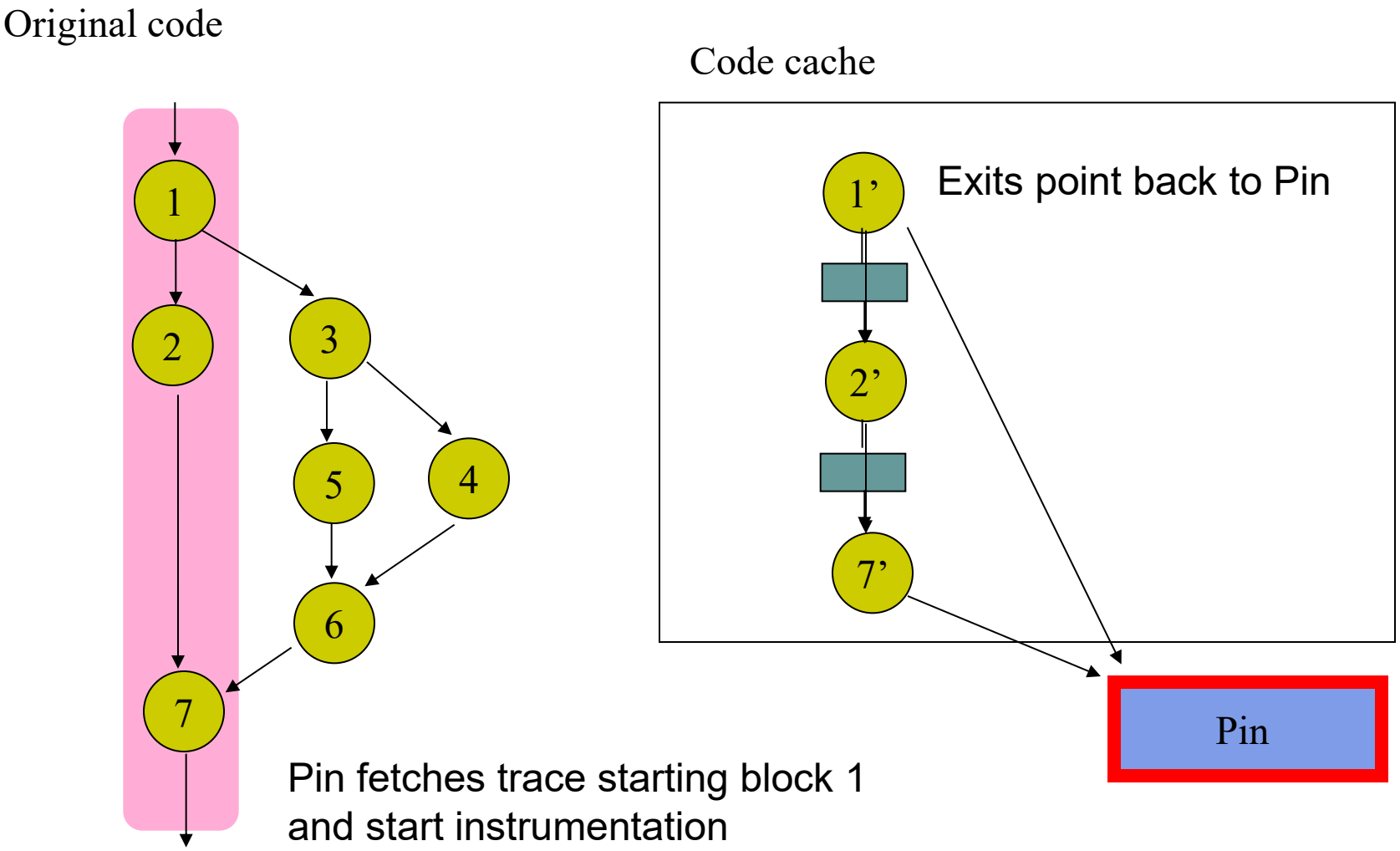
```
#include <iostream>
#include "pin.H"

FILE* trace;

VOID RecordMemWrite(VOID* ip, VOID* addr, UINT32 size) {
    fprintf(trace, "%p: W %p %d\n", ip, addr, size);
}

VOID Instruction(INS ins, VOID *v)  {
    if (INS_IsMemoryWrite(ins))
        INS_InsertCall(ins, IPOINT_BEFORE, AFUNPTR(RecordMemWrite),
            IARG_INST_PTR, IARG_MEMORYWRITE_EA, IARG_MEMORYWRITE_SIZE,
            IARG_END);
}

int main(int argc, char * argv[]) {
    PIN_Init(argc, argv);
    trace = fopen("atrace.out", "w");
    INS_AddInstrumentFunction(Instruction, 0);
    PIN_StartProgram();
    return 0;
}
```

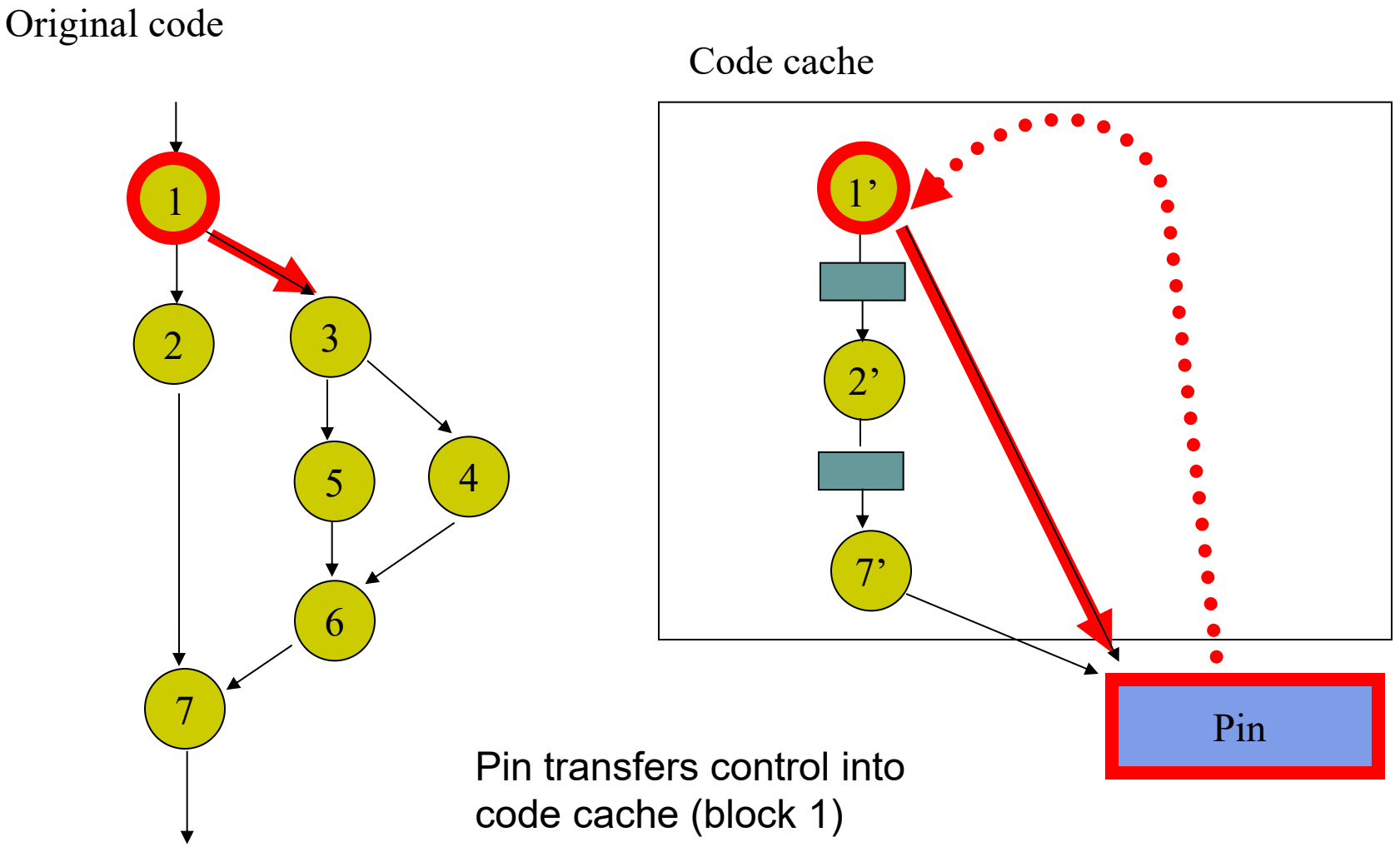
executed immediately before a write is executed

executed when an instruction is dynamically compiled

Dynamic Instrumentation

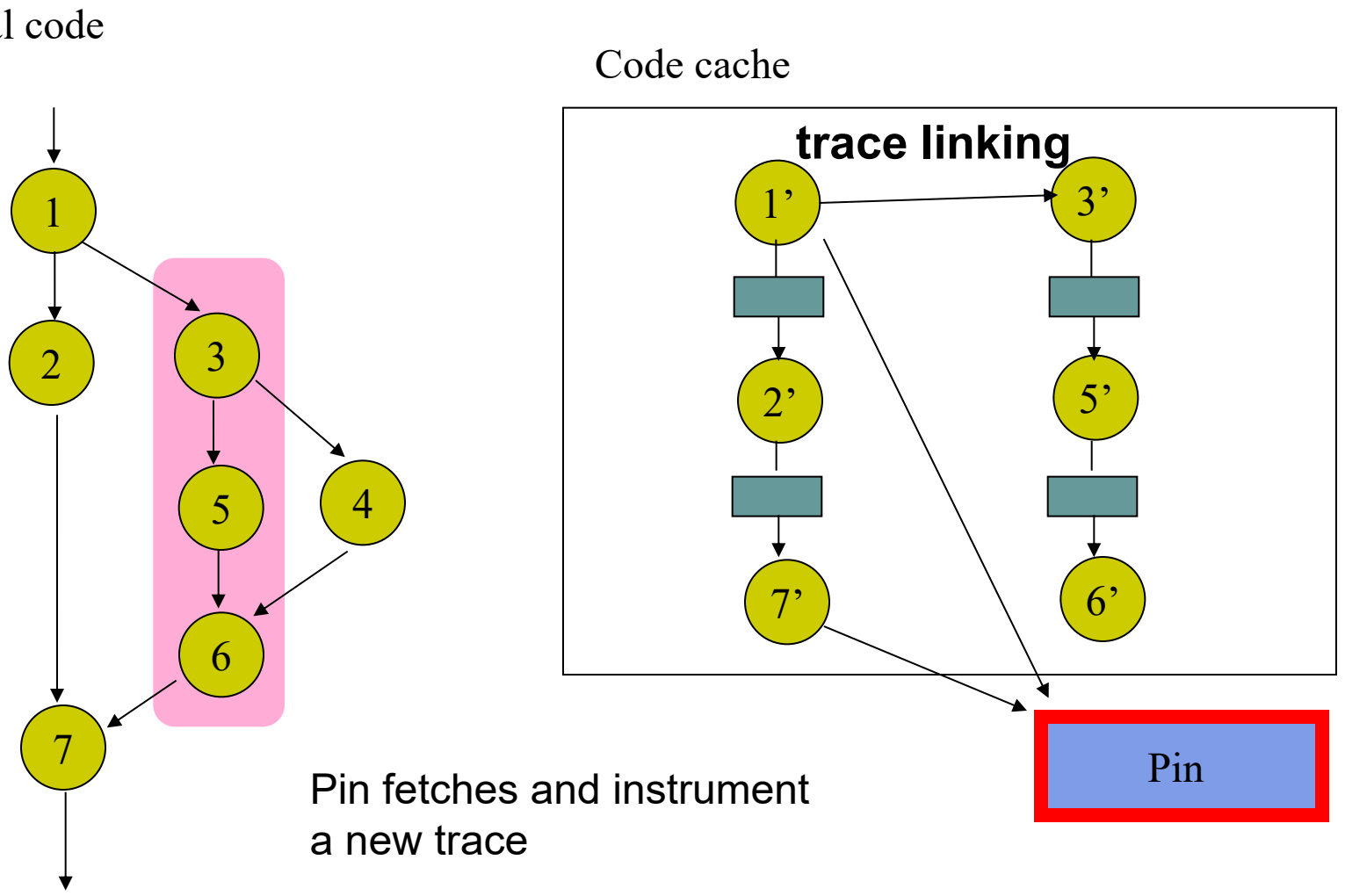


Dynamic Instrumentation

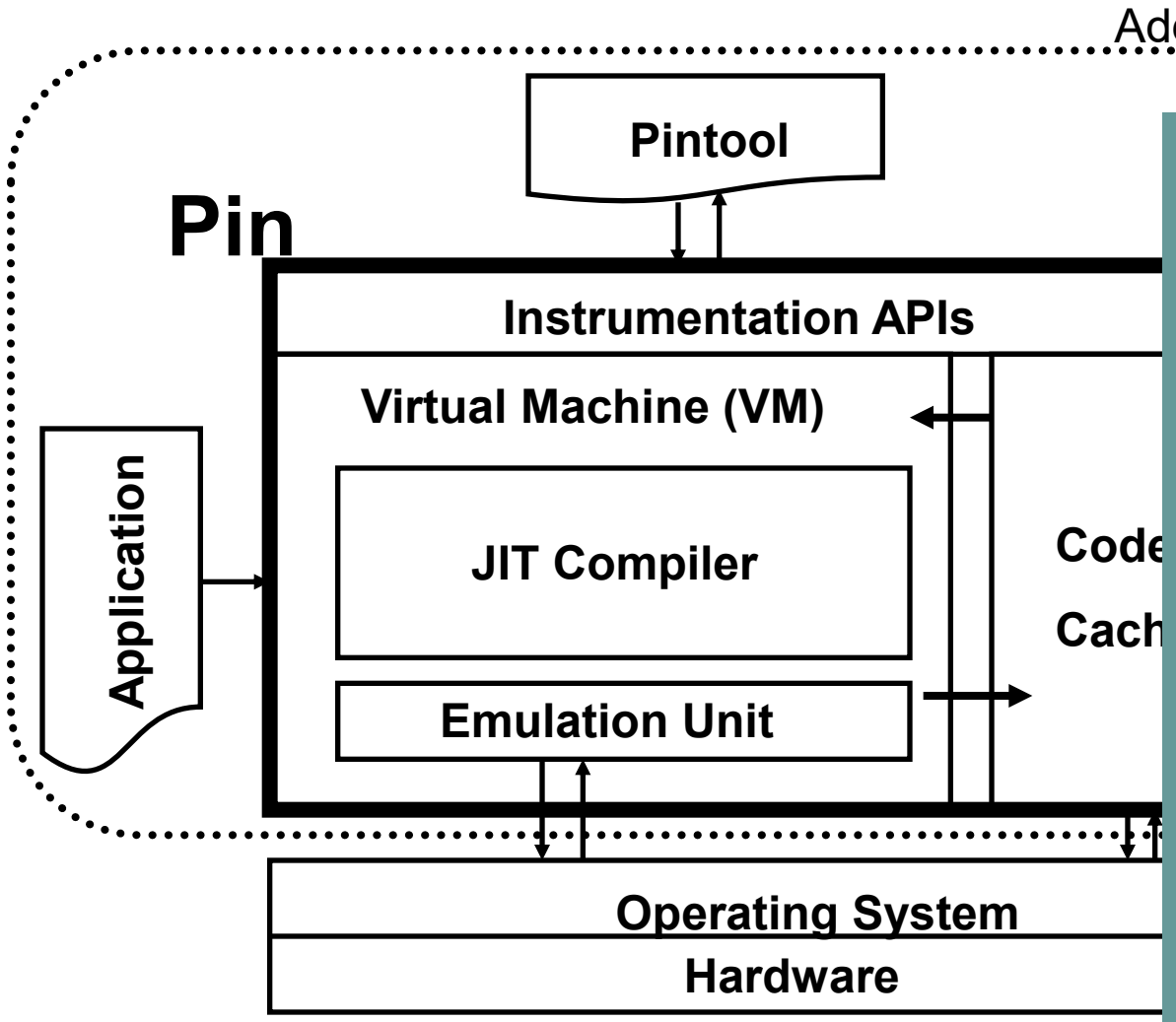


Pin transfers control into code cache (block 1)

Dynamic Instrumentation



Pin's Software Architecture

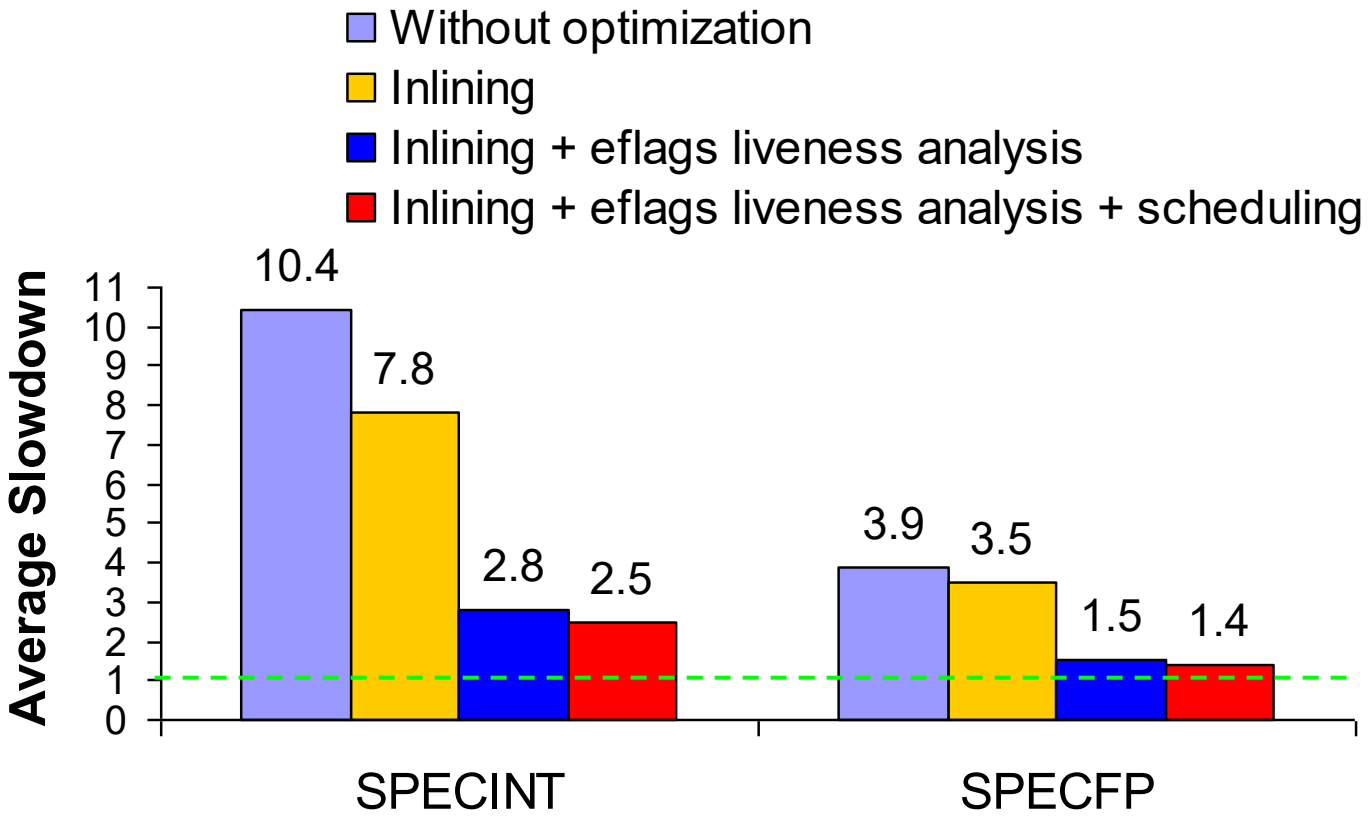


- 3 programs (Pin, Pintool, App) in same address space:
  - User-level only
- Instrumentation APIs:
  - Through which Pintool communicates with Pin
- JIT compiler:
  - Dynamically compile and instrument
- Emulation unit:
  - Handle insts that can't be directly executed (e.g., syscalls)
- Code cache:
  - Store compiled code

=> Coordinated by VM

Pin Instrumentation Performance

Runtime overhead of basic-block counting with Pin on IA32



(SPEC2K using reference data sets)

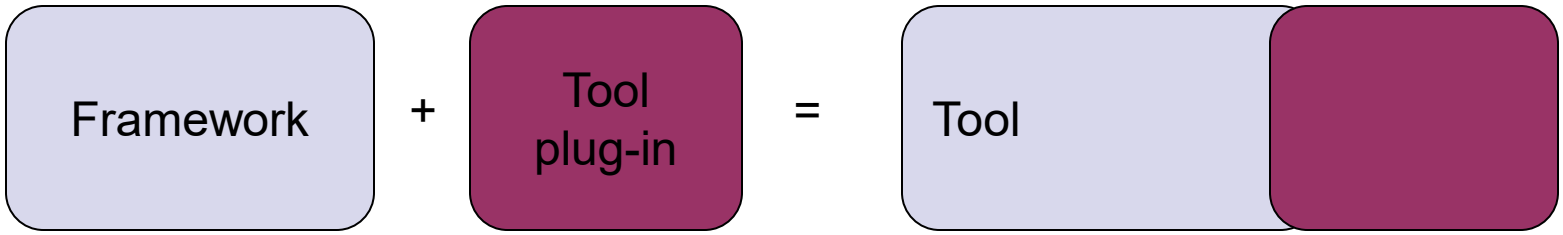
Valgrind
A Framework for Heavyweight Dynamic Binary Instrumentation

Nicholas Nethercote — National ICT Australia

Julian Seward — OpenWorks LLP

Building DBA tools

- **Dynamic binary instrumentation** (DBI)
  - Add analysis code to the original machine code at run-time
  - No preparation, 100% coverage
- DBI frameworks
  - Pin, DynamoRIO, Valgrind, etc.



Prior work

Well-studied	Not well-studied
Framework performance	Instrumentation capabilities
Simple tools	Complex tools

- **Potential of DBI has not been fully exploited**
  - Tools get less attention than frameworks
  - Complex tools are more interesting than simple tools

Shadow value tools (I)

- Shadow every value with another value that describes it
  - Tool stores and propagates shadow values in parallel

	Tool(s)	Shadow values help find...
bugs	**Memcheck**	**Uses of undefined values**
	Annelid	Array bounds violations
	Hobbes	Run-time type errors
security	TaintCheck, LIFT, TaintTrace	Uses of untrusted values
	“Secret tracker”	Leaked secrets
properties	DynCompB	Invariants
	Redux	Dynamic dataflow graphs

Memcheck

- Shadow values: defined or undefined

Original operation	Shadow operation
int* p = malloc(4)	sh(p) = undefined
R1 = 0x12345678	sh(R1) = defined
R1 = R2	sh(R1) = sh(R2)
R1 = R2 + R3	sh(R1) = add_{sh}(R2, R3)
if R1==0 then goto L	complain if sh(R1) is
	undefined

- 30 undefined value bugs found in OpenOffice

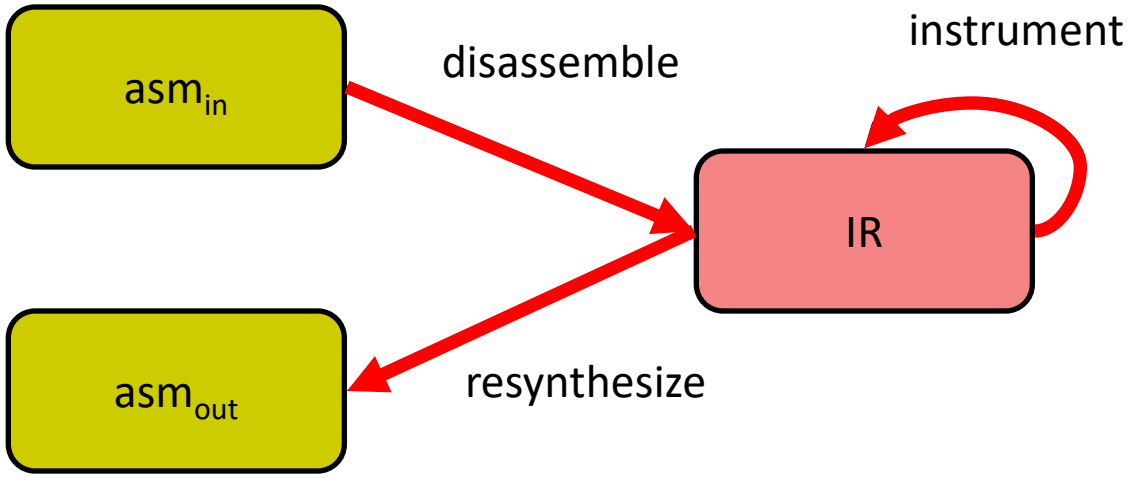
Shadow value tools (II)

- All shadow value tools work in the same basic way
- Shadow value tools are **heavyweight** tools
  - Tool's data + ops are as complex as the original programs's
- Shadow value tools are hard to implement
  - Multiplex real and shadow registers onto register file
  - Squeeze real and shadow memory into address space
  - Instrument most instructions and system calls

#1: Code Representation

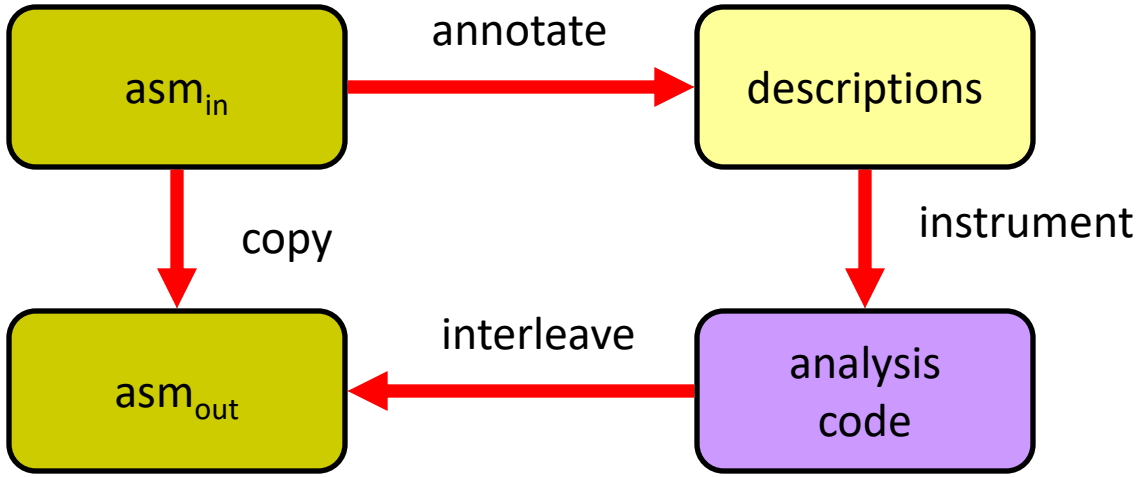
D&R

Disassemble-and-resynthesize (Valgrind)



C&A

Copy-and-annotate



Other IR features

Feature	Benefit
First-class shadow registers	As expressive as normal registers
Typed, SSA	Catches instrumentation errors
RISC-like	Fewer cases to handle
Infinitely many temporaries	Never have to find a spare register

- Writing complex inline analysis code is easy

SPEC2000 Performance

Valgrind, no-instrumentation	4.3x
Pin/DynRIO, no-instrumentation	~1.5x

Memcheck	22.1x (7--58x)
Most other shadow value tools	10--180x

QEMU

UCR

- Not a DBI tool by itself
- Open-source CPU emulator
- Two modes:
  - User mode: emulate a Linux process
  - System mode: emulate a virtual machine

- Flow
  - Guest code bock -> TCG IRs -> Host code block (stored in code cache)
  - Allows custom instrumentation

Questions

- Compare Pin, Valgrind, and QEMU
- What are the similarities?
- What are the differences?