Dynamic Binary Translation & Instrumentation

Pin

Building Customized Program Analysis Tools with Dynamic Instrumentation

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http://rogue.colorado.edu/Pin

Instrumentation

- Insert extra code into programs to collect information about execution
  - Program analysis:
    - Code coverage, call-graph generation, memory-leak detection
  - Architectural study:
    - Processor simulation, fault injection
- Existing binary-level instrumentation systems:
  - Static:
    - ATOM, EEL, Etch, Morph
  - Dynamic:
    - Dyninst, Vulcan, DTrace, Valgrind, Strata, DynamoRIO

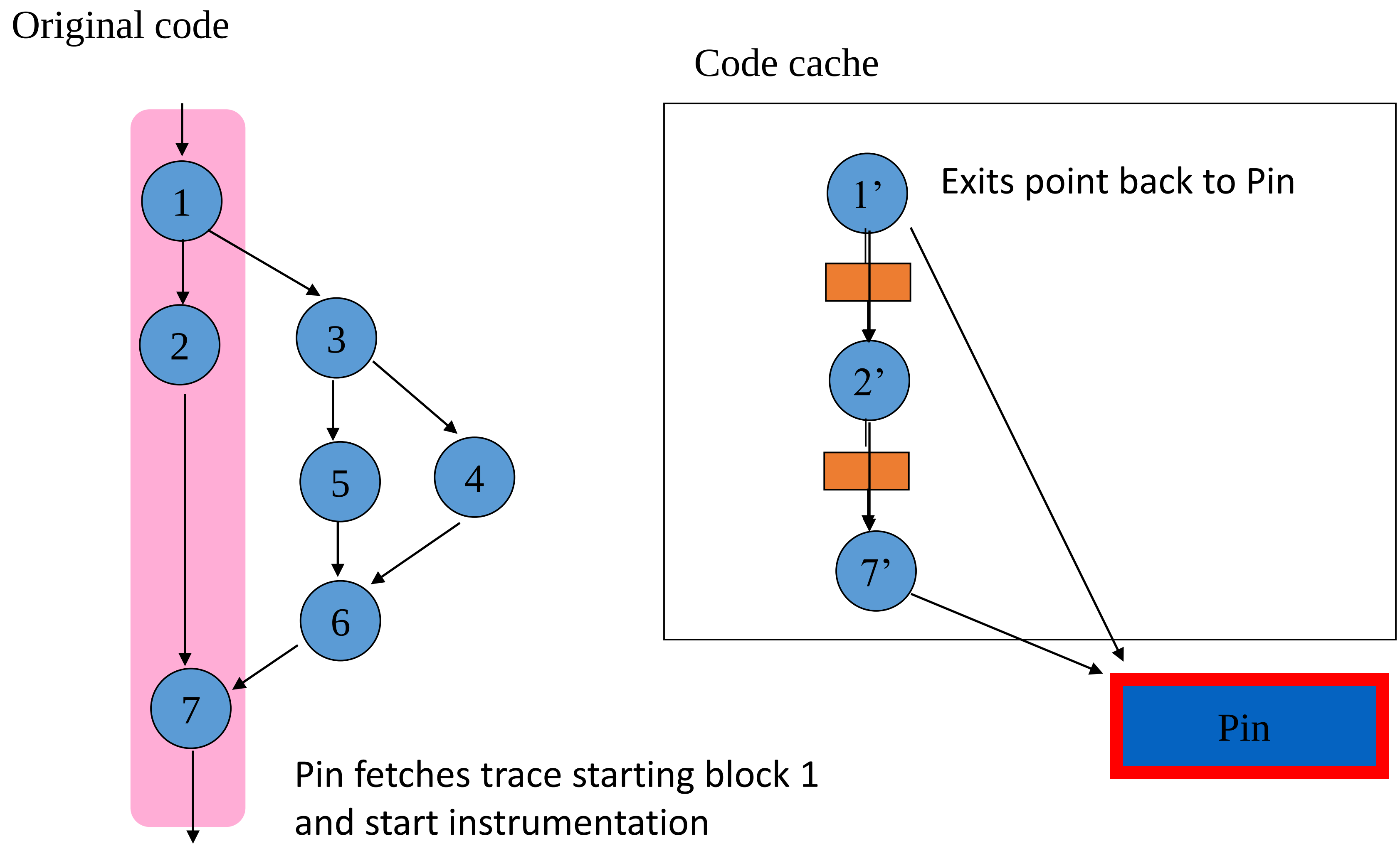
☞ ***Pin is a new dynamic binary instrumentation system***

A Pintool for Tracing Memory Writes

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

FILE*

VOID
    fp
}

VOID
    if

IARG

}

int m
    PI
    trace = fopen("atrace.out", "w");
    INS_AddInstrumentFunction(Instruction, 0);
    PIN_StartProgram();
    return 0;
}
```

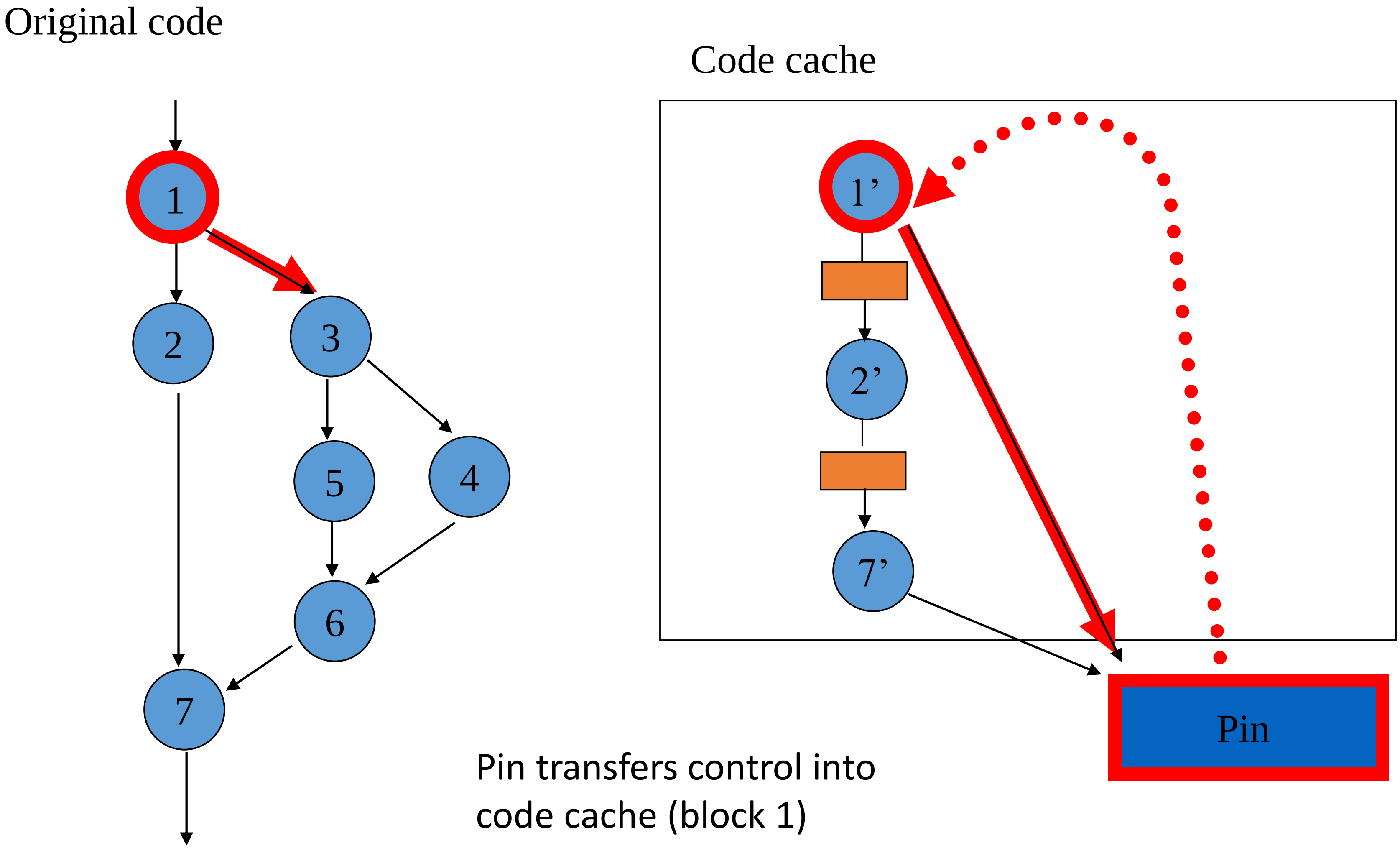
- Same source code works on the 4 architectures
  => Pin takes care of different addressing modes
- No need to manually save/restore application state
  => Pin does it for you automatically and efficiently

Dynamic Instrumentation



Pin fetches trace starting block 1
and start instrumentation

Dynamic Instrumentation

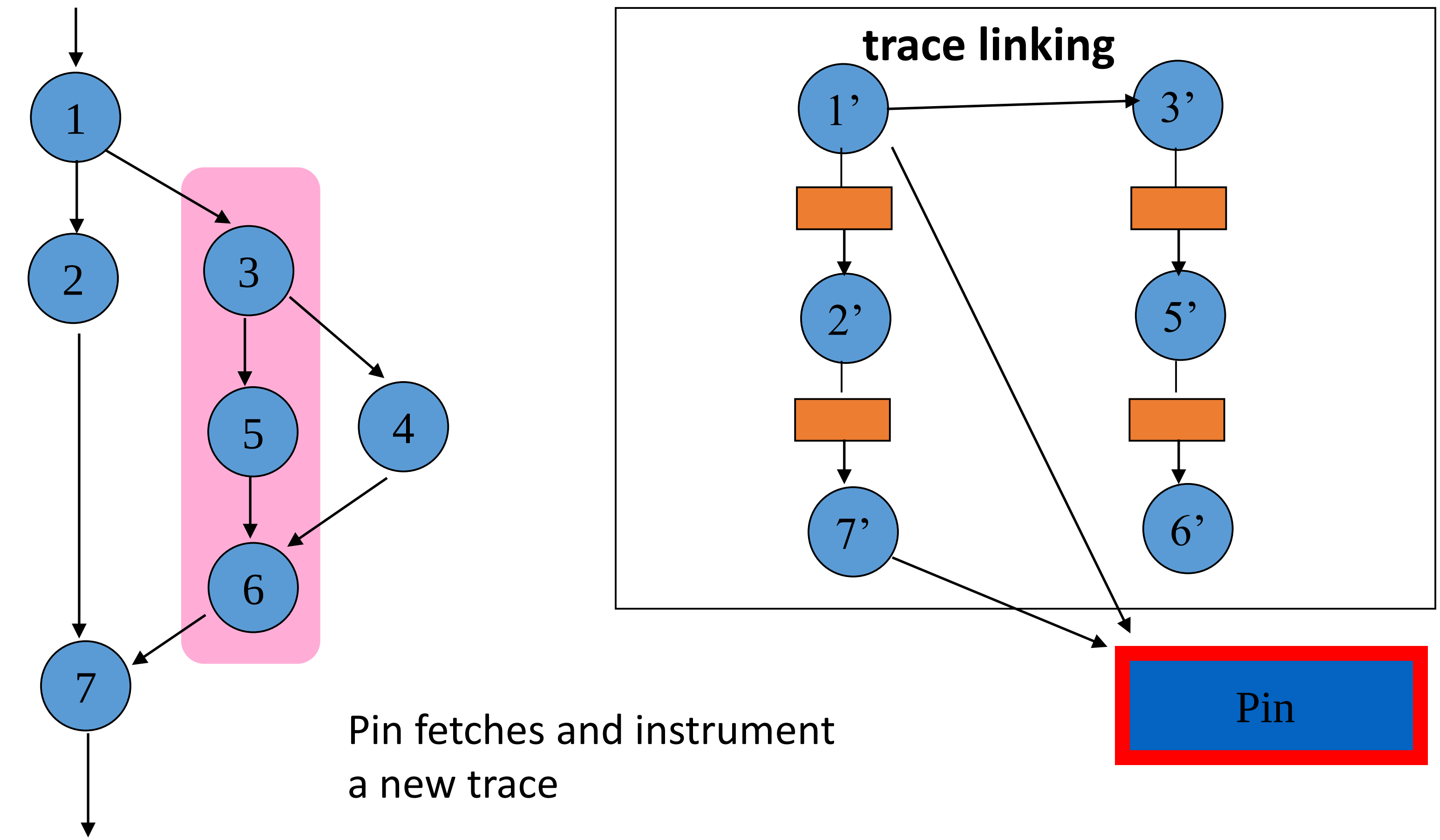


Pin transfers control into code cache (block 1)

Dynamic Instrumentation

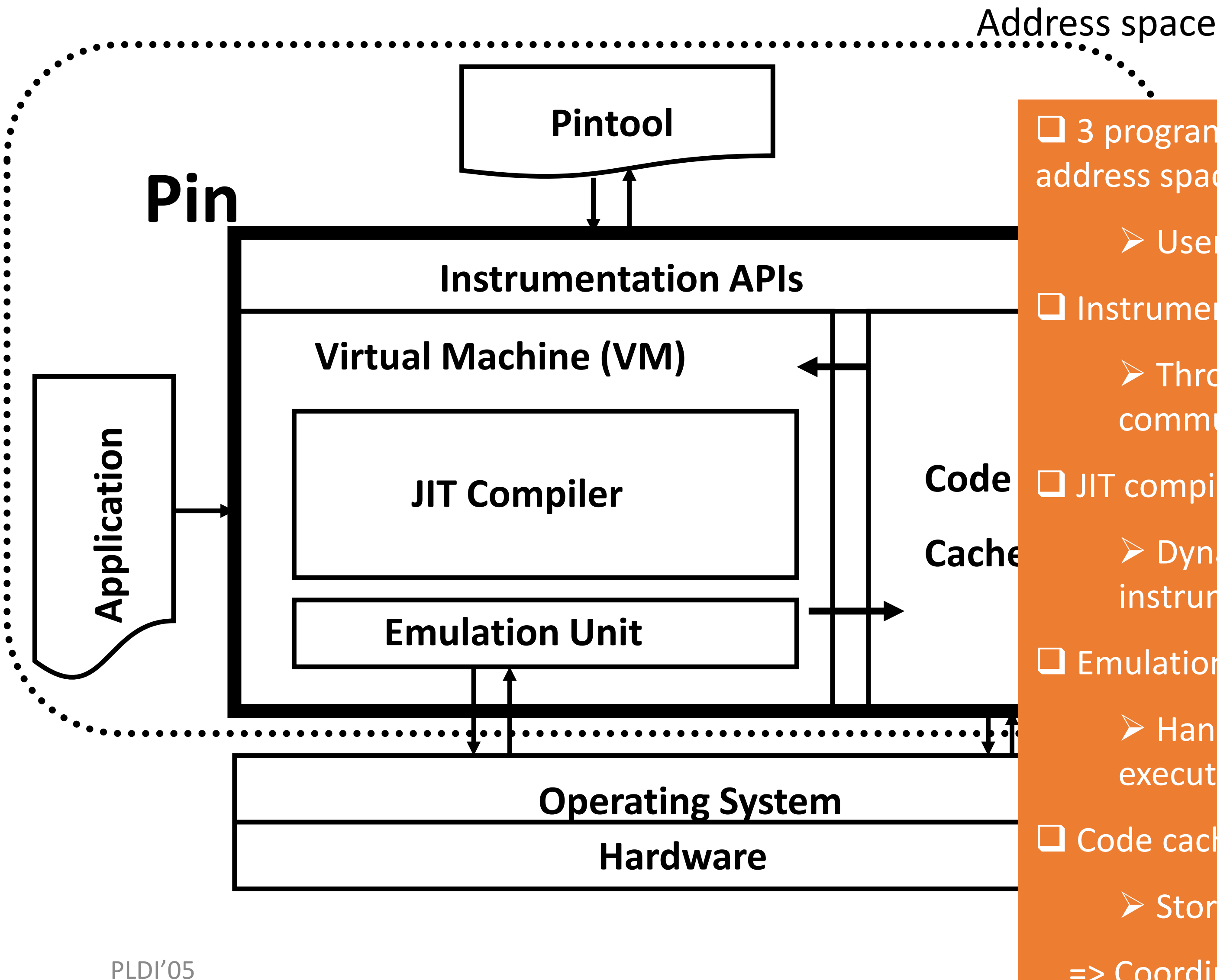
Original code

Code cache



Pin fetches and instrument a new trace

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 Internal Details

- Loading of Pin, Pintool, & Application
- An Improved Trace Linking Technique
- **Register Re-allocation**
- **Instrumentation Optimizations**
- Multithreading Support

Register Re-allocation

- Instrumented code needs extra registers. E.g.:
  - Virtual registers available to the tool
  - A virtual stack pointer pointing to the instrumentation stack
  - Many more …
- Approaches to get extra registers:
  1. Ad-hoc (e.g., DynamoRIO, Strata, DynInst)
     - Whenever you need a register, spill one and fill it afterward
  2. Re-allocate all registers during compilation
     a. Local allocation (e.g., Valgrind)
        - Allocate registers independently within each trace

     b. Global allocation (Pin)
        - **Allocate registers across traces (can be inter-procedural)**

Valgrind's Register Re-allocation

Original Code

```
    mov 1, %eax
    mov 2, %ebx
    cmp %ecx, %edx
    jz t
    . . .
t:  add 1, %eax
    sub 2, %ebx
    . . .
```

re-allocate →

Trace 1

```
mov 1, %eax
mov 2, %esi
cmp %ecx, %edx
mov %eax, SPILL_eax
mov %esi, SPILL_ebx
jz t'
```

Virtual	Physical
%eax	%eax
%ebx	**%esi**
%ecx	%ecx
%edx	%edx

Trace 2

```
t': mov SPILL_eax, %eax
    mov SPILL_ebx ,%edi
    add 1, %eax
    sub 2, %edi
    . . .
```

Virtual	Physical
%eax	%eax
%ebx	**%edi**
%ecx	%ecx
%edx	%edx

☞ ***Simple but inefficient***

- All modified registers are spilled at a trace's end
- Refill registers at a trace's beginning

Pin's Register Re-allocation

Scenario (1): Compiling a new trace at a trace exit

Original Code

```
    mov 1, %eax
    mov 2, %ebx
    cmp %ecx, %edx
    jz t
    • • •
t:  add 1, %eax
    sub 2, %ebx
    • • •
```

re-allocate

Trace 1

```
mov 1, %eax
mov 2, %esi
cmp %ecx, %edx
jz t'
```

Trace 2

```
t': add 1, %eax
    sub 2, %esi
    • • •
```

Compile Trace 2 using the binding at Trace 1's exit:

Virtual	Physical
%eax	%eax
%ebx	**%esi**
%ecx	%ecx
%edx	%edx

☞ ***No spilling/filling needed across traces***

Pin’s Register Re-allocation

Scenario (2): Targeting an already generated trace at a trace exit

Original Code

```
    mov 1, %eax
    mov 2, %ebx
    cmp %ecx, %edx
    jz t
    • • •
t:  add 1, %eax
    sub 2, %ebx
    • • •
```

re-allocate →

Trace 1 (being compiled)

```
mov 1, %eax
mov 2, %esi
cmp %ecx, %edx
mov %esi, SPILL_ebx
mov SPILL_ebx, %edi
jz t’
```

Virtual	Physical
%eax	%eax
%ebx	**%esi**
%ecx	%ecx
%edx	%edx

Trace 2 (in code cache)

```
t’: add 1, %eax
    sub 2, %edi
    • • •
```

Virtual	Physical
%eax	%eax
%ebx	**%edi**
%ecx	%ecx
%edx	%edx

☞ ***Minimal spilling/filling code***

Instrumentation Optimizations

1. Inline instrumentation code into the application

2. Avoid saving/restoring eflags with liveness analysis

3. Schedule inlined instrumentation code

Example: Instruction Counting

Original code

```
cmov %esi, %edi
cmp %edi, (%esp)
jle <target1>
```

```
add %ecx, %edx
cmp %edx, 0
je <target2>
```

```
BBL_InsertCall(bbl, IPOINT_BEFORE, docount(),
          IARG_UINT32, BBL_NumIns(bbl),
          IARG_END)
```

☞ *33 extra instructions executed altogether*

Instrument without applying any optimization

Trace

```
mov %esp,SPILL_appsp
mov SPILL_pinsp,%esp
call <bridge>
cmov %esi, %edi
mov SPILL_appsp,%esp
cmp %edi, (%esp)
jle <target1'>
```

```
mov %esp,SPILL_appsp
mov SPILL_pinsp,%esp
call <bridge>
add %ecx, %edx
cmp %edx, 0
je <target2'>
```

bridge()

```
pushf
push %edx
push %ecx
push %eax
movl 0x3, %eax
call docount
pop %eax
pop %ecx
pop %edx
popf
ret
```

docount()

```
add %eax,icount
ret
```

Example: Instruction Counting

<u>Original code</u>

```
cmov %esi, %edi
cmp %edi, (%esp)
jle <target1>
```

```
add %ecx, %edx
cmp %edx, 0
je <target2>
```

Inlining →

<u>Trace</u>

```
mov %esp,SPILL_appsp
mov SPILL_pinsp,%esp
pushf
add 0x3, icount
popf
cmov %esi, %edi
mov SPILL_appsp,%esp
cmp %edi, (%esp)
jle <target1'>
```

```
mov %esp,SPILL_appsp
mov SPILL_pinsp,%esp
pushf
add 0x3, icount
popf
add %ecx, %edx
cmp %edx, 0
je <target2'>
```

☞ ***11 extra instructions executed***

Example: Instruction Counting

Original code

```
cmov %esi, %edi
cmp %edi, (%esp)
jle <target1>
```

```
add %ecx, %edx
cmp %edx, 0
je <target2>
```

Inlining + **eflags liveness analysis**

Trace

```
mov %esp,SPILL_appsp
mov SPILL_pinsp,%esp
pushf
add 0x3, icount
popf
cmov %esi, %edi
mov SPILL_appsp,%esp
cmp %edi, (%esp)
jle <target1'>
```

```
add 0x3, icount
add %ecx, %edx
cmp %edx, 0
je <target2'>
```

☞ ***7 extra instructions executed***

Example: Instruction Counting

Original code

```
cmov %esi, %edi
cmp %edi, (%esp)
jle <target1>
```

```
add %ecx, %edx
cmp %edx, 0
je <target2>
```

Inlining + eflags liveness analysis + **scheduling**

Trace

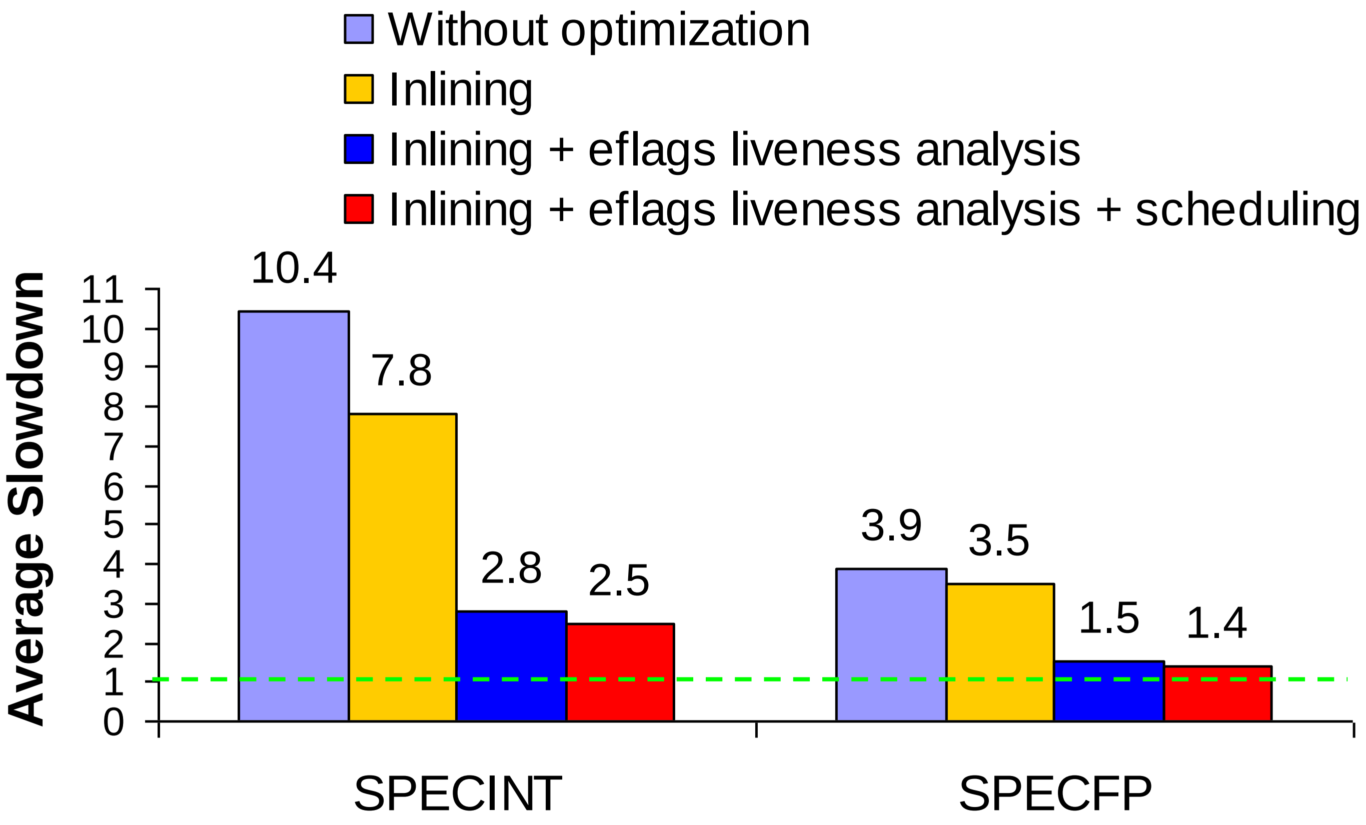
```
cmov %esi, %edi
add 0x3, icount
cmp %edi, (%esp)
jle <target1'>
```

```
add 0x3, icount
add %ecx, %edx
cmp %edx, 0
je <target2'>
```

☞ ***2 extra instructions executed***

Pin Instrumentation Performance

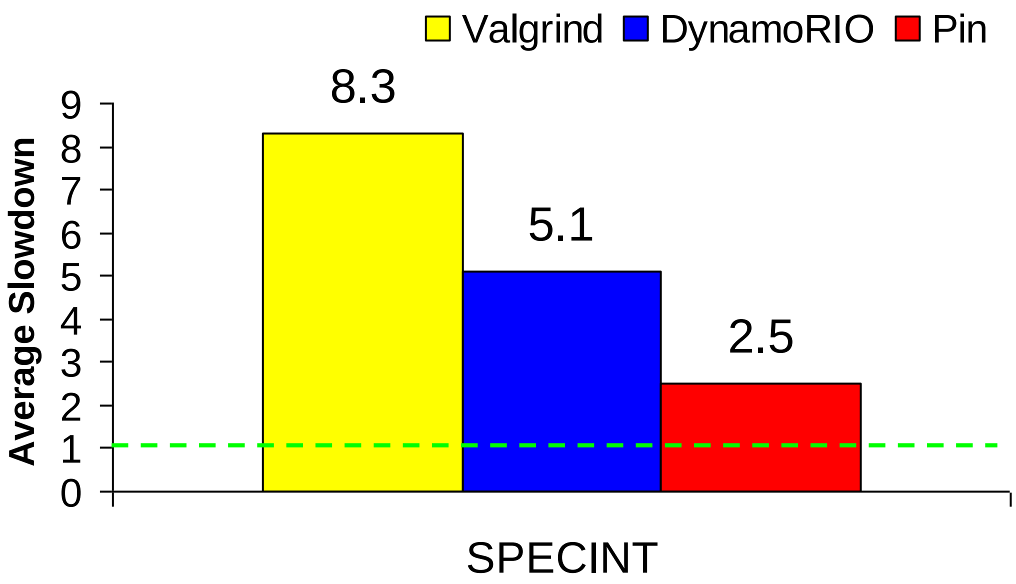
Runtime overhead of basic-block counting with Pin on IA32



(SPEC2K using reference data sets)

Comparison among Dynamic Instrumentation Tools

<u>Runtime overhead of basic-block counting with three different tools</u>



- Valgrind is a popular instrumentation tool on Linux
    - Call-based instrumentation, no inlining
- DynamoRIO is the performance leader in binary dynamic optimization
    - Manually inline, no eflags liveness analysis and scheduling

☞ ***Pin automatically provides efficient instrumentation***

Pin Applications

- Sample tools in the Pin distribution:
  - Cache simulators, branch predictors, address tracer, syscall tracer, edge profiler, stride profiler
- Some tools developed and used inside Intel:
  - *Opcodemix* (analyze code generated by compilers)
  - *PinPoints* (find representative regions in programs to simulate)
  - A tool for detecting memory bugs
- Some companies are writing their own Pintools:
  - A major database vendor, a major search engine provider
- Some universities using Pin in teaching and research:
  - U. of Colorado, MIT, Harvard, Princeton, U of Minnesota, Northeastern, Tufts, University of Rochester, …

Conclusions

- Pin
  - A dynamic instrumentation system for building your own program analysis tools
  - Easy to use, robust, transparent, efficient
  - Tool source compatible on IA32, EM64T, Itanium, ARM
  - Works on large applications
    - database, search engine, web browsers, …
  - Available on Linux; Windows version coming soon

- Downloadable from http://rogue.colorado.edu/Pin
  - User manual, many example tools, tutorials
  - 3300 downloads since 2004 July

Valgrind
A Framework for Heavyweight Dynamic Binary Instrumentation

Nicholas Nethercote — National ICT Australia
Julian Seward — OpenWorks LLP

FAQ #1

- How do you pronounce “Valgrind”?

- “**Val-grinned**”, not “Val-grined”

- Don’t feel bad: almost everyone gets it wrong at first

DBA tools

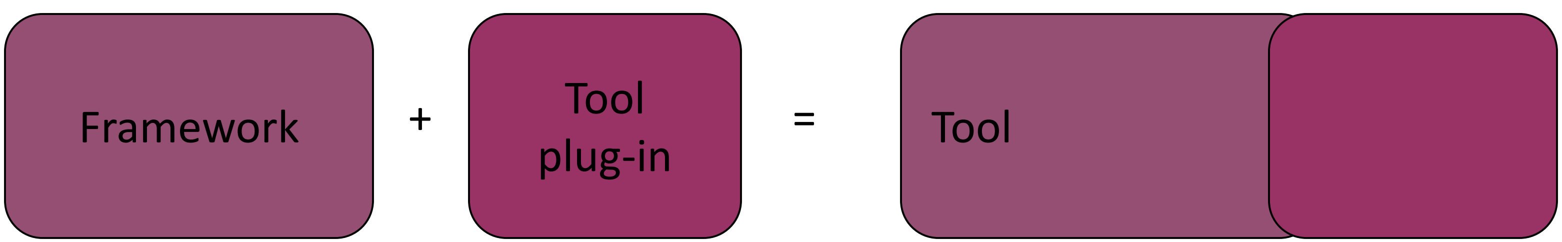
- Program analysis tools are useful
  - Bug detectors
  - Profilers
  - Visualizers

- **Dynamic binary analysis** (DBA) tools
  - Analyse a program's machine code at run-time
  - Augment original code with **analysis code**

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

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
security	Hobbes	Run-time type errors
	TaintCheck, LIFT, TaintTrace	Uses of untrusted values
propertie s	“Secret tracker”	Leaked secrets
	DynCompB	Invariants
	Redux	Dynamic dataflow

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

Valgrind basics

Valgrind

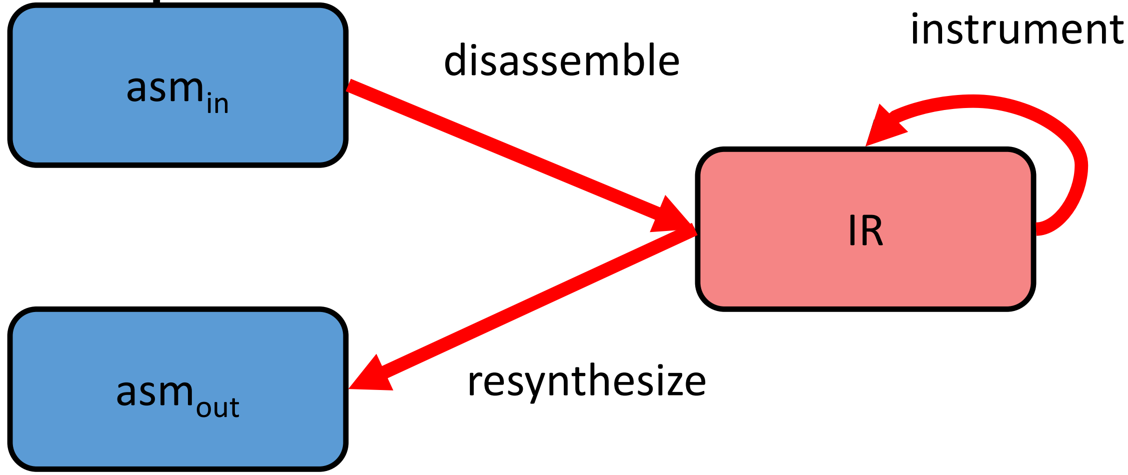
- Software
  - Free software (GPL)
  - {x86, x86-64, PPC}/Linux, PPC/AIX
- Users
  - Development: Firefox, OpenOffice, KDE, GNOME, MySQL, Perl, Python, PHP, Samba, RenderMan, Unreal Tournament, NASA, CERN
  - Research: Cambridge, MIT, Berkeley, CMU, Cornell, UNM, ANU, Melbourne, TU Muenchen, TU Graz
- Design
  - Heavyweight tools are well supported
  - Lightweight tools are slow

Two unusual features of Valgrind

#1: Code representation

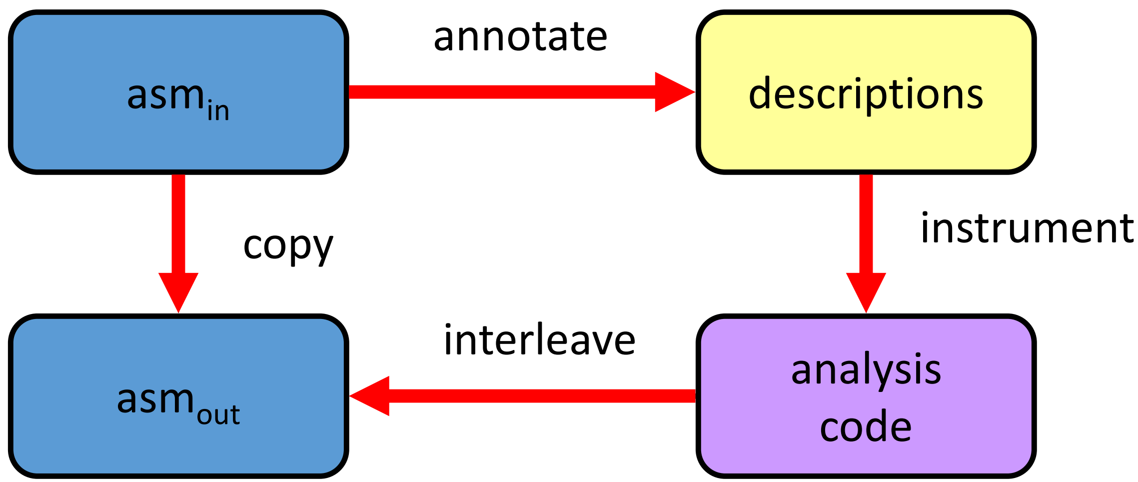
D&R

Disassemble-and-resynthesize (Valgrind)



C&A

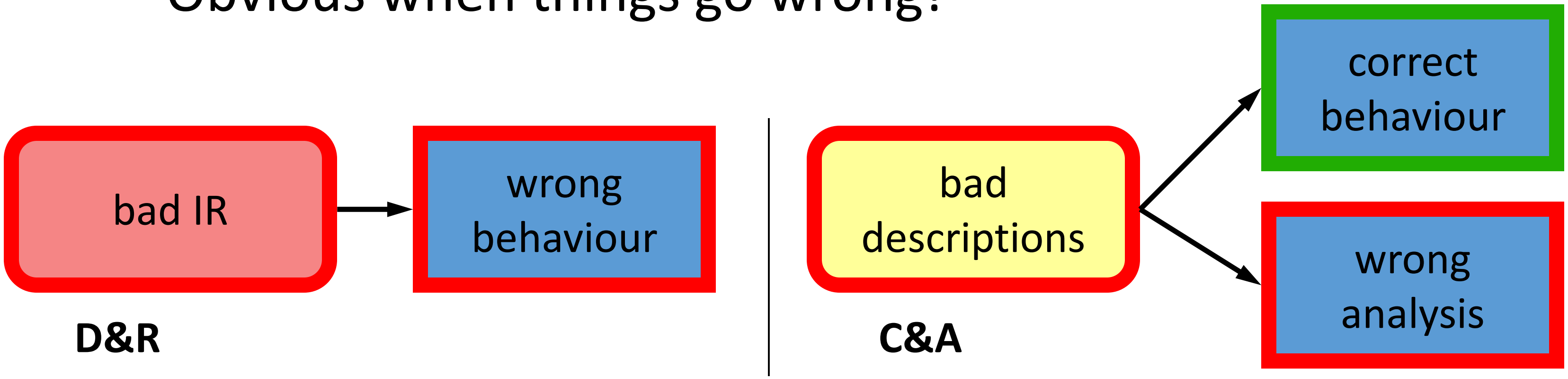
Copy-and-annotate



Pros and cons of D&R

- Cons: Lightweight tools
  - Framework design and implementation effort
  - Code translation cost, code quality

- Pros: Heavyweight tools
  - Analysis code as expressive as original code
  - Tight interleaving of original code and analysis code
  - Obvious when things go wrong!



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

#2: Thread serialisation

- Shadow memory: memory accesses no longer atomic
  - Uni-processors: thread switches may intervene
  - Multi-processors: real/shadow accesses may be reordered

- Simple solution: serialise thread execution!
  - Tools can ignore the issue
  - Great for uni-processors, slow for multi-processors...

Performance

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
LIFT	3.6x (*)

(*) LIFT limitations:

- No FP or SIMD programs
- No multi-threaded programs
- 32-bit x86 code on 64-bit x86 machines only

Post-performance

- Only Valgrind allows robust shadow value tools
  - All robust ones built with Valgrind or from scratch

- Perception: “Valgrind is slow”
  - Too simplistic
  - Beware apples-to-oranges comparisons
  - Different frameworks have different strengths

Future of DBI

The future

- Interesting tools!
    - Memcheck changed many C/C++ programmer's lives
    - Tools don't arise in a vacuum

- What do you want to know about program execution?
    - Think big!
    - Don't worry about being practical at first

If you remember nothing else...

Take-home messages

- Heavyweight tools are interesting
- Each DBI framework has its pros and cons
- Valgrind supports heavyweight tools well

www.valgrind.org