Dynamic Binary Translation & Instrumentation

Pin

Building Customized Program Analysis Tools with Dynamic Instrumentation

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http://rogue.colorado.edu/Pin

Instrumentation

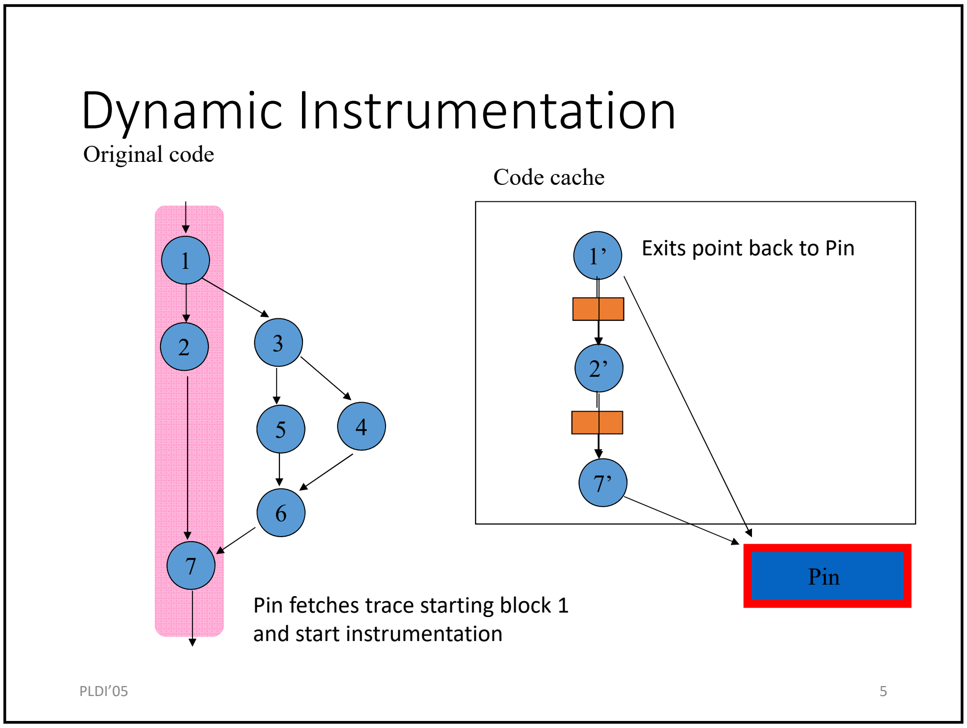
- Insert extra code into programs to collect information about execution
  - Program analysis:
    - Code coverage, call-graph generation, memory-leak detection
  - Architectural study:
    - Processor simulation, fault injection
- Existing binary-level instrumentation systems:
  - Static:
    - ATOM, 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
Original code
Code cache
1
2
3
4
5
6
7
1’
2’
7’
Exits point back to Pin
Pin
Pin fetches trace starting block 1
and start instrumentation
PLDI’05
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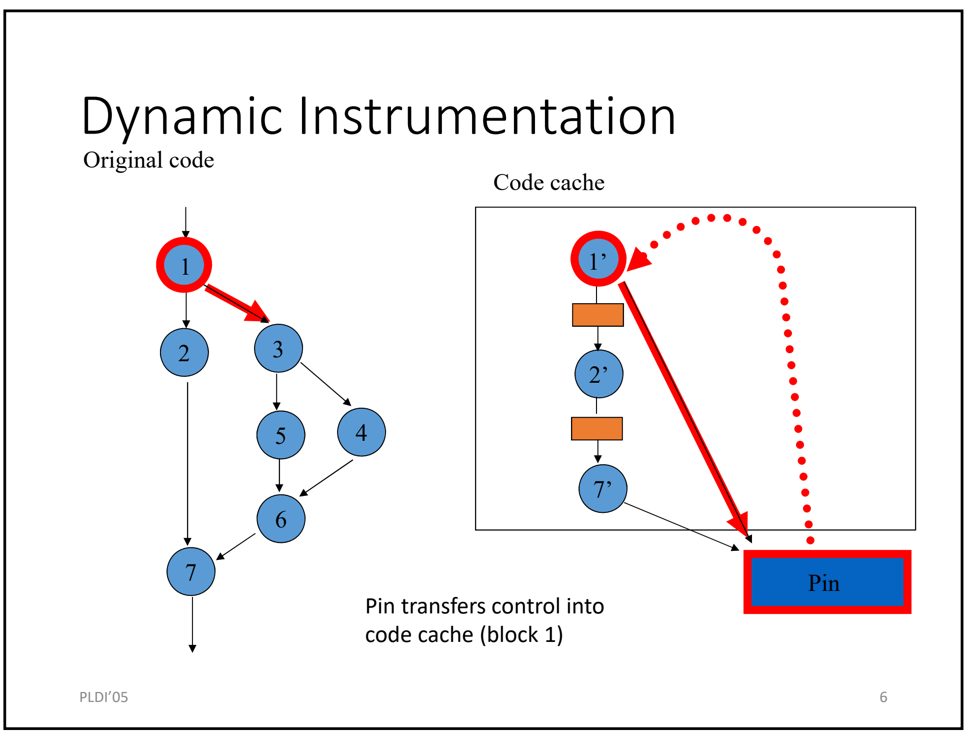
Dynamic Instrumentation
Original code
Code cache
1
2
3
4
5
6
7
1’
2’
7’
Pin
Pin transfers control into
code cache (block 1)
PLDI’05
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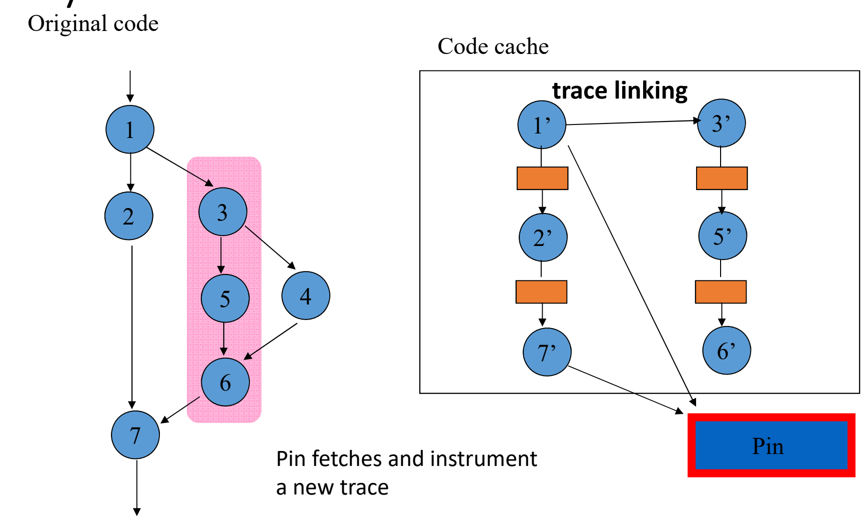
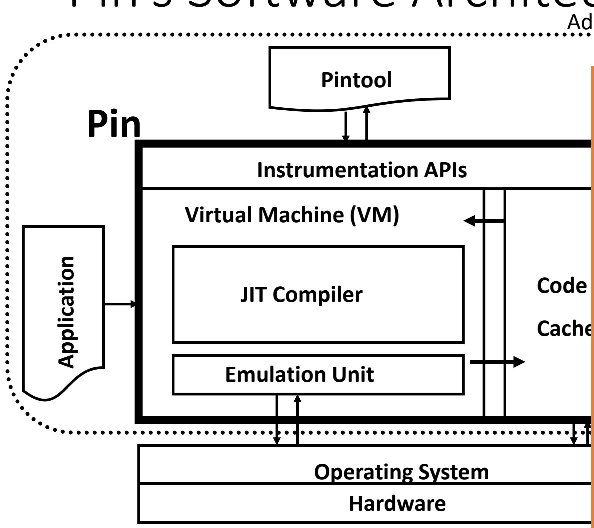
Dynamic Instrumentation



Pin's Software Architecture



- 3 programs (Pin, Pintool, App) in sam 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 directl 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

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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'
```

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

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

Trace 2

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

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

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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
```

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Example: Instruction Counting

Original code

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

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

Inlining

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'>
```

```
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*

PLDI'05

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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*

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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*

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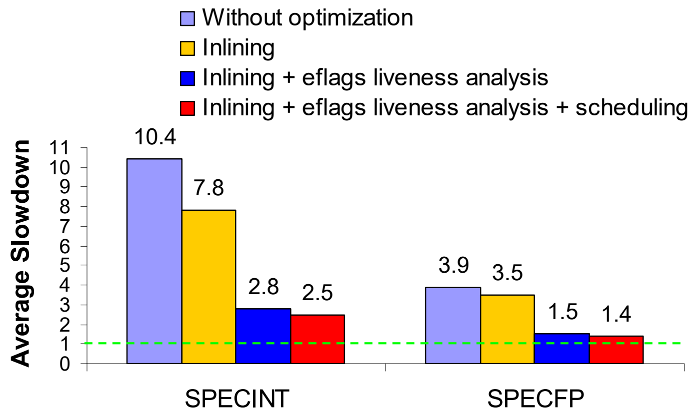
Pin Instrumentation Performance

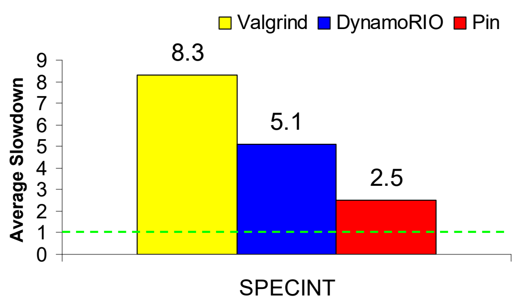
Runtime overhead of basic-block counting with Pin on IA32



(SPEC2K using reference data sets)

Comparison among Dynamic Instrumentation Tools

Runtime overhead of basic-block counting with three different tools



- 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

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FAQ #1

- How do you pronounce "Valgrind"?
- "**Val-grinned**", not "Val-grined"
- Don't feel bad: almost everyone gets it wrong at first

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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**

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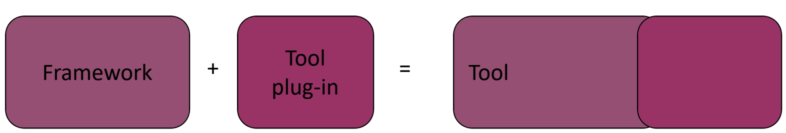
Building DBA tools

- **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.



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Prior work

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

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

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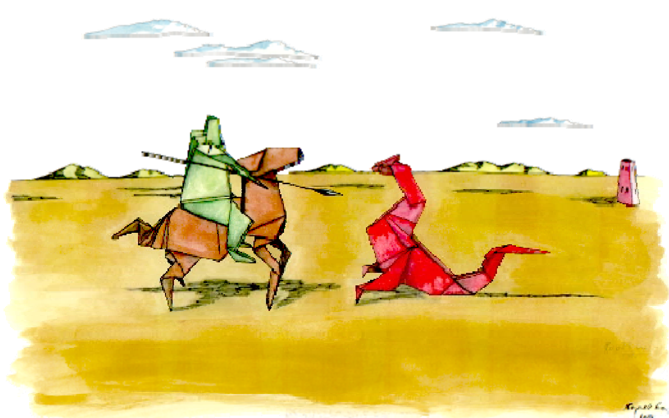
Shadow value tools



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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**
security	Annelid	Array bounds violations
	Hobbes	Run-time type errors
properties	TaintCheck, LIFT, TaintTrace	Uses of untrusted values
	“Secret tracker”	Leaked secrets
	DynCompB	Invariants

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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

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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

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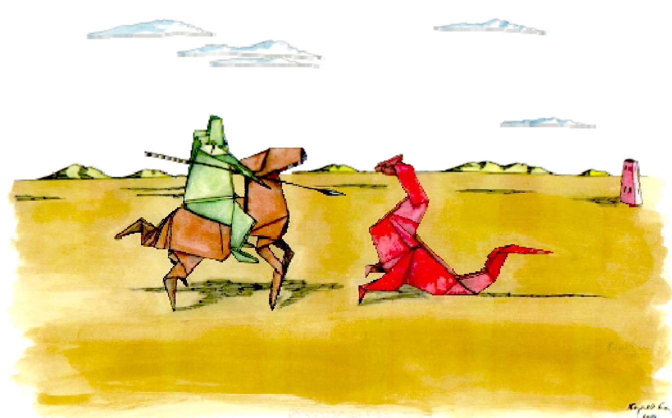
Valgrind basics



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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

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Two unusual features of Valgrind

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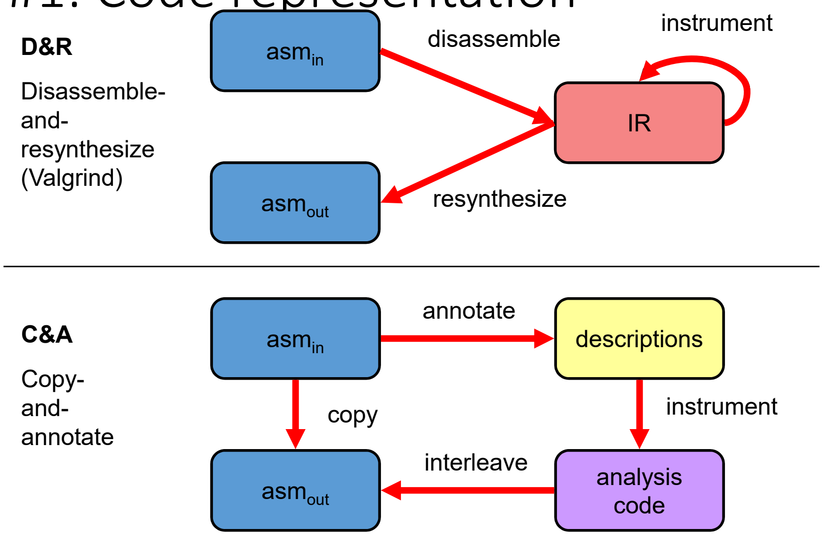
#1: Code representation



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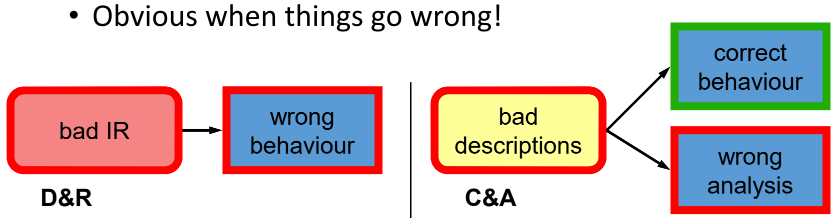
Pros and cons of D&R

- 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!



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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

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#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...

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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 (*)

(*) L

- 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

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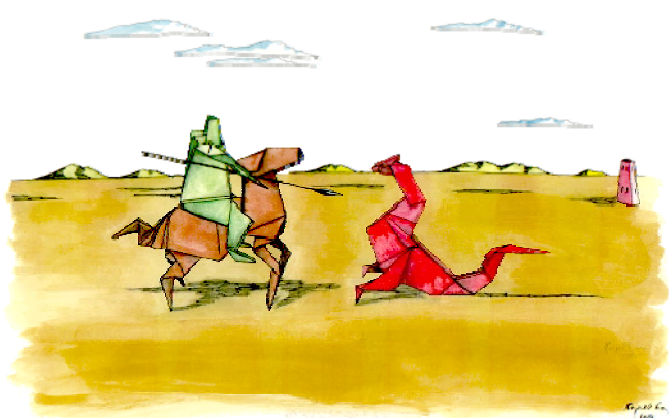
Future of DBI



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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

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If you remember nothing else...

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Take-home messages

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

www.valgrind.org

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