Building Dynamic Instrumentation Tools with DynamoRIO

Derek Bruening, Qin Zhao, Reid Kleckner

Google

Tutorial Outline

- 1:30-1:40 Welcome + DynamoRIO History
- 1:40-2:40 DynamoRIO Overview
- 2:40-3:00 Examples, Part 1
- *3:00-3:15 Break*
- 3:15-4:00 DynamoRIO API
- 4:00-4:45 Examples, Part 2
- 4:45-5:00 Feedback

DynamoRIO History

- Dynamo
  - HP Labs: PA-RISC late 1990’s
  - x86 Dynamo: 2000
- RIO → DynamoRIO
  - MIT: 2001-2004
- Prior releases
  - 0.9.1: Jun 2002 (PLDI tutorial)
  - 0.9.2: Oct 2002 (ASPLOS tutorial)
  - 0.9.3: Mar 2003 (CGO tutorial)
  - 0.9.4: Feb 2005
  - 0.9.5: Apr 2008 (CGO tutorial)
  - 1.0 (0.9.6): Sep 2008 (GoVirtual.org launch)

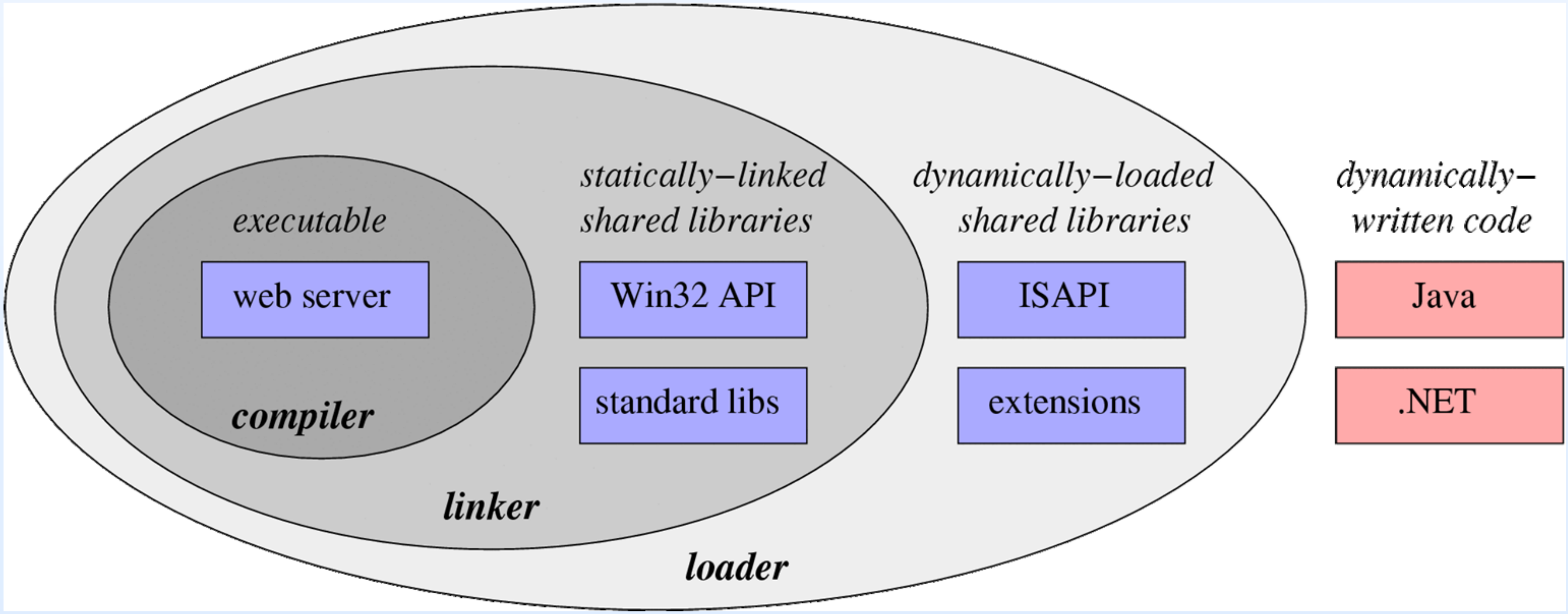
DynamoRIO History

- Determina
  - 2003-2007
  - Security company
- VMware
  - Acquired Determina (and DynamoRIO) in 2007
- Open-source BSD license
  - Feb 2009: 1.3.1 release
  - Dec 2009: 1.5.0 release
  - Apr 2010: 2.0.0 release
  - Apr 2011: 2.2.0 release
  - Jan 2012: 3.1.0 release
  - Mar 2012: 3.2.0 release

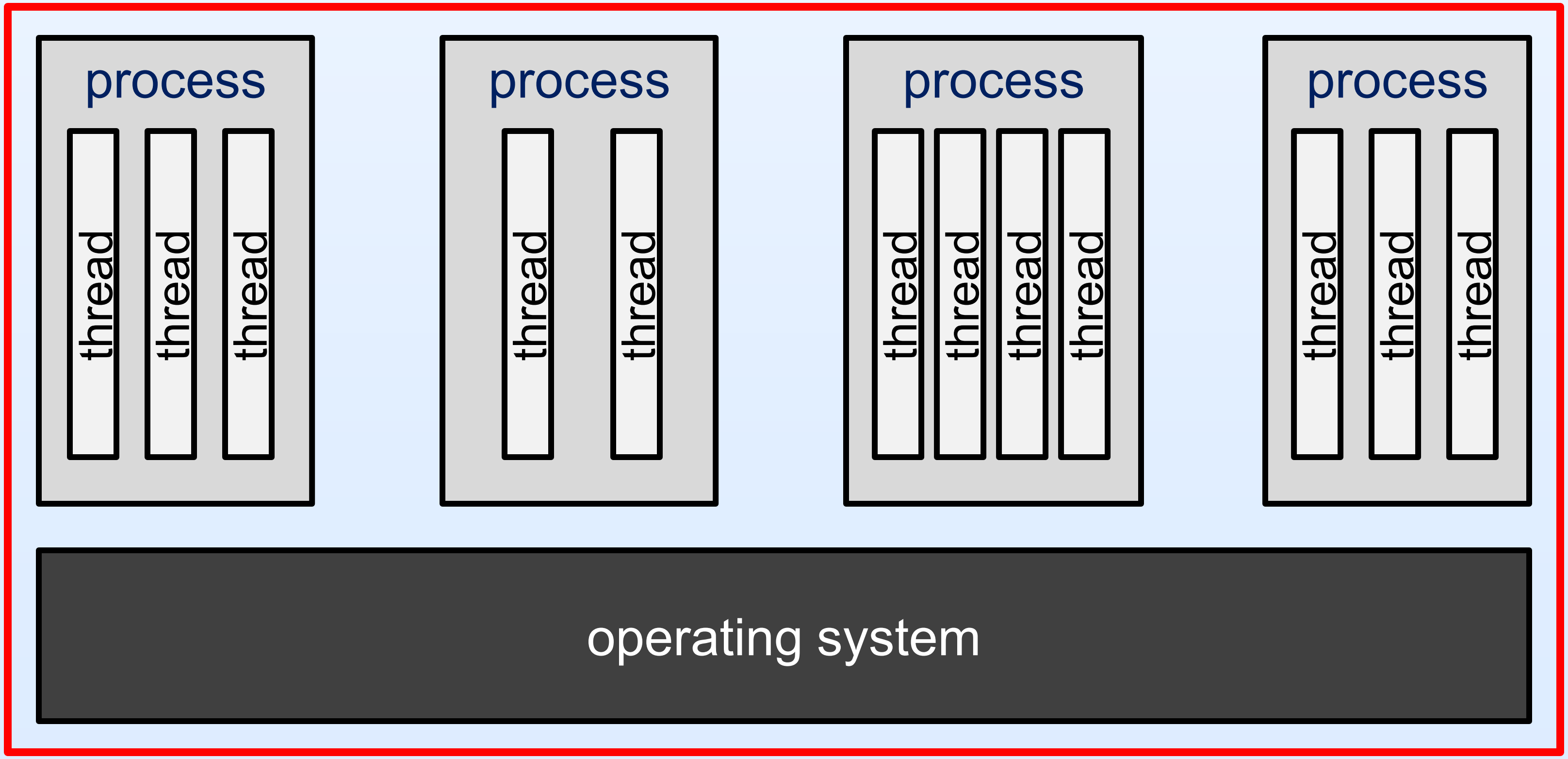
DynamoRIO Overview

1:30-1:40	Welcome + DynamoRIO History
1:40-2:40	DynamoRIO Overview
2:40-3:00	Examples, Part 1
3:00-3:15	*Break*
3:15-4:00	DynamoRIO API
4:00-4:45	Examples, Part 2
4:45-5:00	Feedback

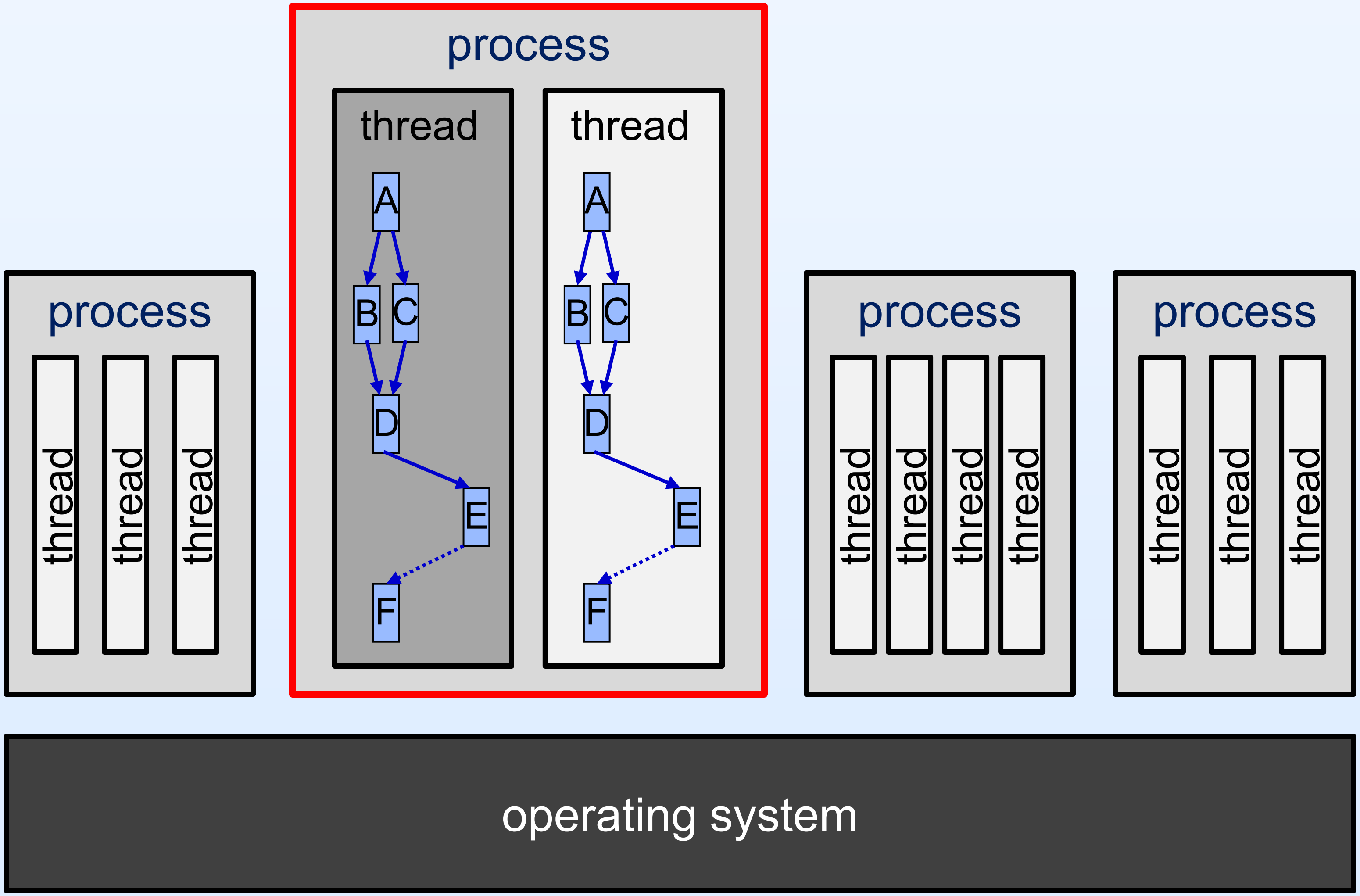
Typical Modern Application: IIS



System Virtualization



Process Virtualization



Design Goals

- Efficient
  - Near-native performance
- Transparent
  - Match native behavior
- Comprehensive
  - Control every instruction, in any application
- Customizable
  - Adapt to satisfy disparate tool needs

Challenges of Real-World Apps

- Multiple threads
  - Synchronization
- Application introspection
  - Reading of return address
- Transparency corner cases are the norm
  - Example: access beyond top of stack
- Scalability
  - Must adapt to varying code sizes, thread counts, etc.
- Dynamically generated code
  - Performance challenges

Overview Outline

- Efficient
  - Software code cache overview
  - Thread-shared code cache
- Transparent
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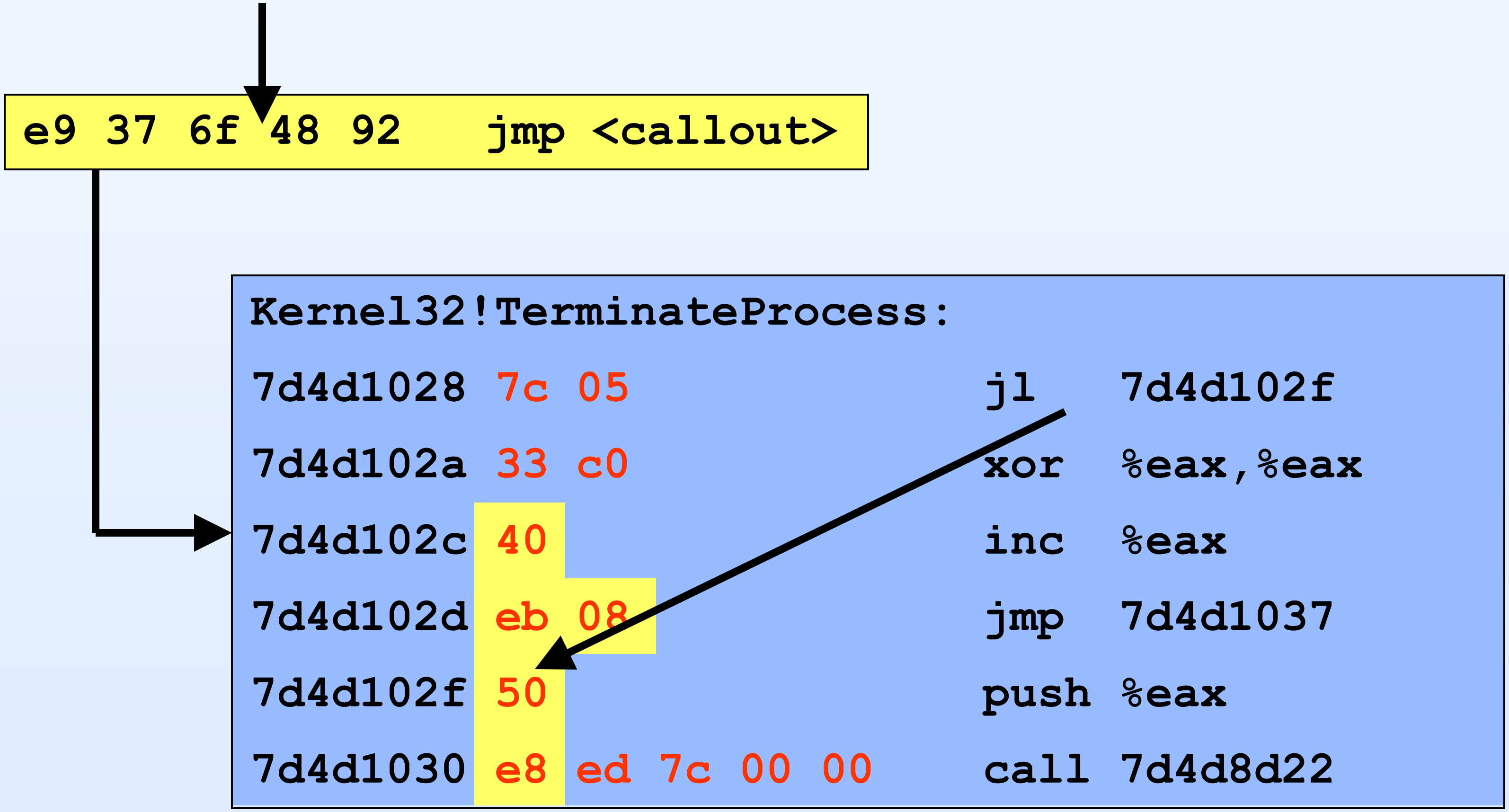
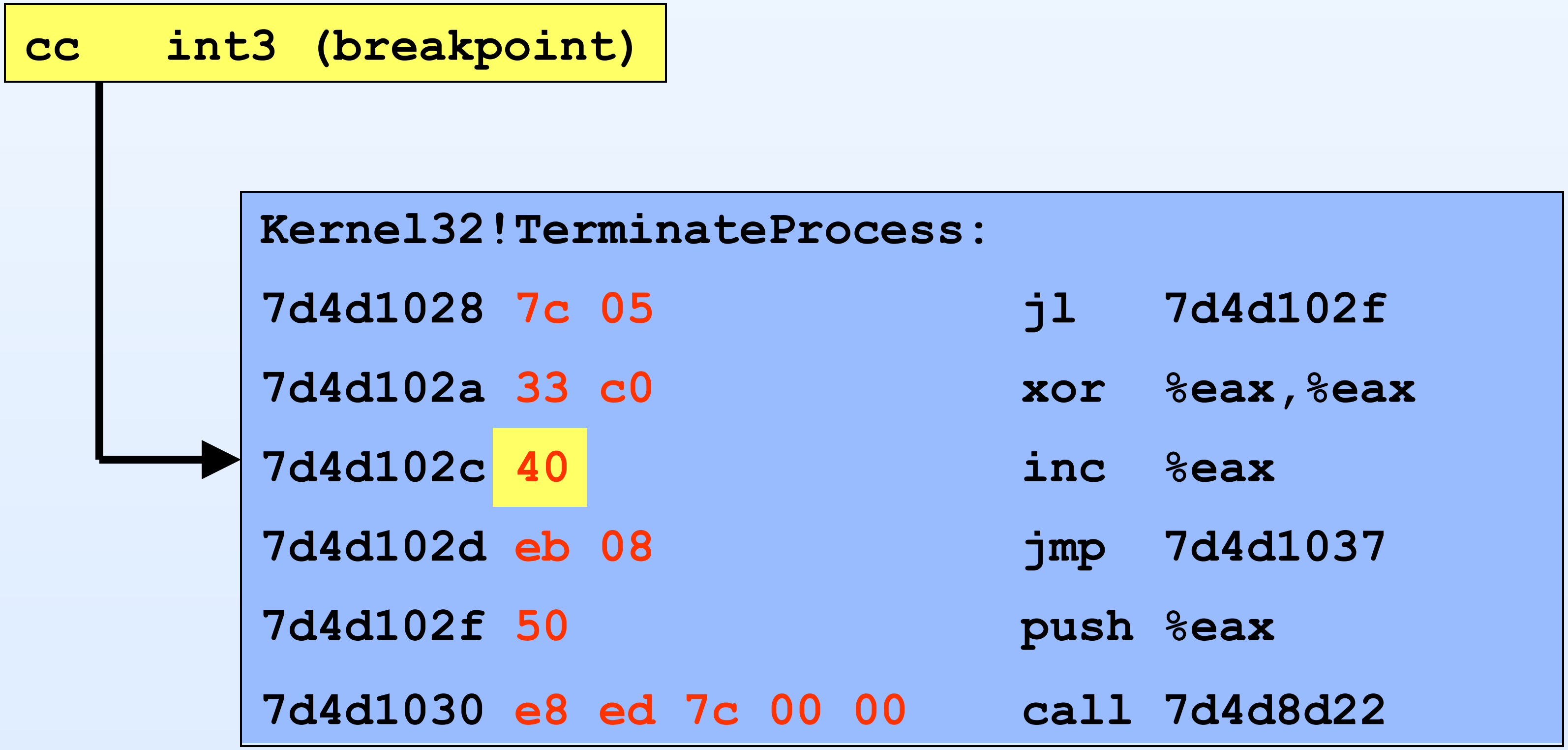
Direct Code Modification



```
e9 37 6f 48 92    jmp <callout>
```

```
Kernel32!TerminateProcess:
7d4d1028 7c 05                 jl   7d4d102f
7d4d102a 33 c0                 xor  %eax,%eax
7d4d102c 40                    inc  %eax
7d4d102d eb 08                 jmp  7d4d1037
7d4d102f 50                    push %eax
7d4d1030 e8 ed 7c 00 00        call 7d4d8d22
```

Debugger Trap Too Expensive



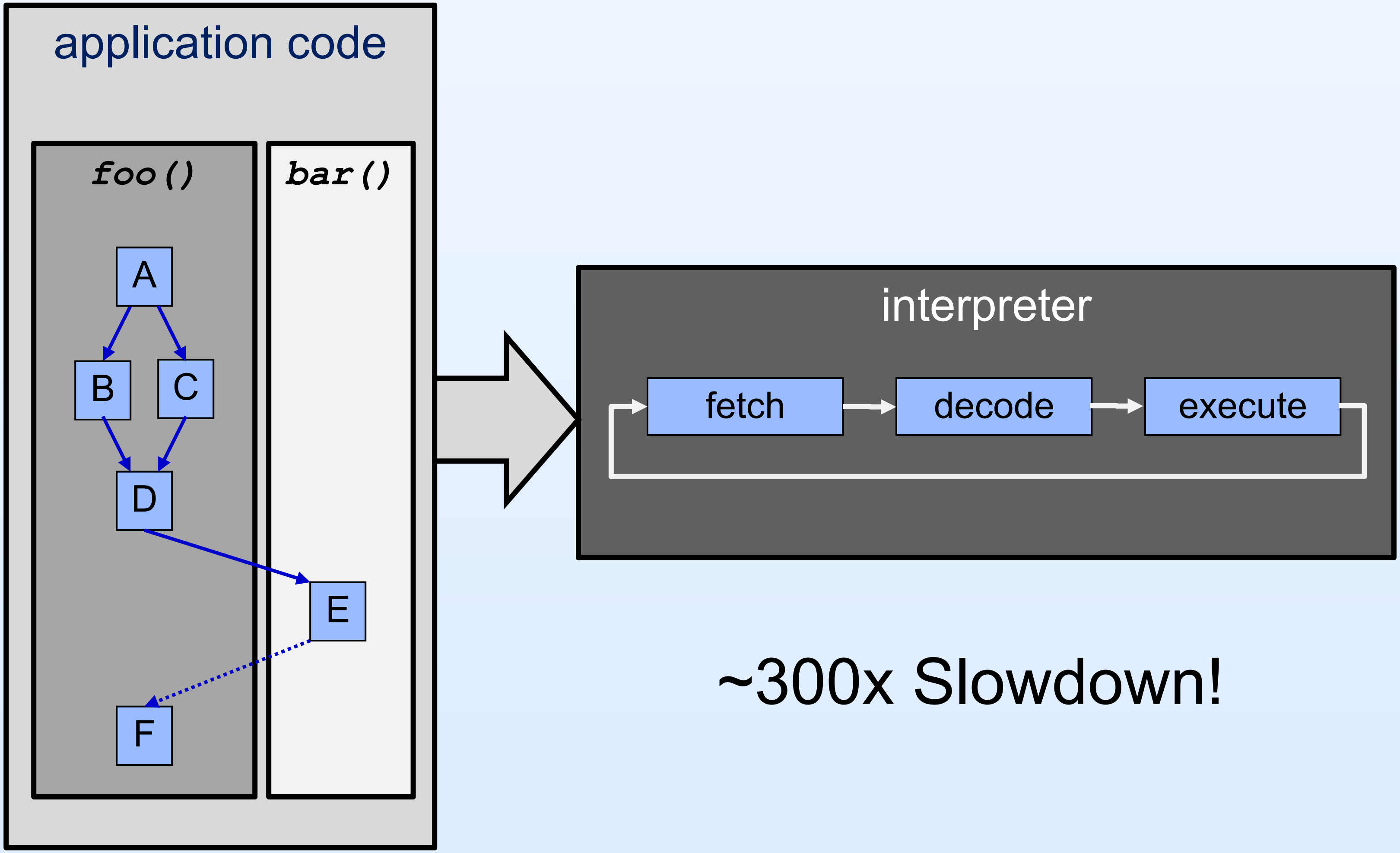
```
cc   int3 (breakpoint)
```

```
Kernel32!TerminateProcess:
7d4d1028 7c 05                jl   7d4d102f
7d4d102a 33 c0                xor  %eax,%eax
7d4d102c 40                   inc  %eax
7d4d102d eb 08                jmp  7d4d1037
7d4d102f 50                   push %eax
7d4d1030 e8 ed 7c 00 00       call 7d4d8d22
```

We Need Indirection

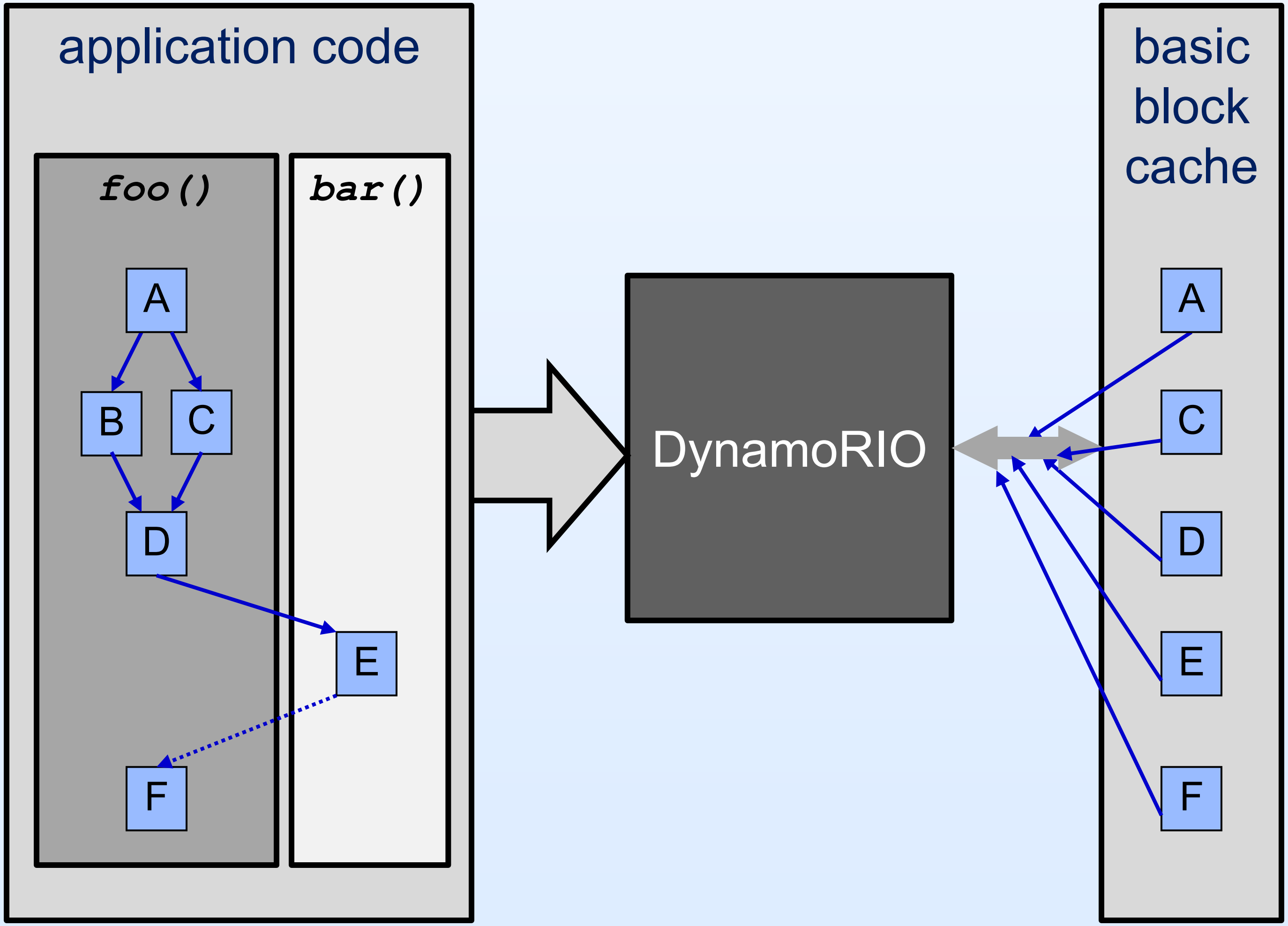
- Avoid transparency and granularity limitations of directly modifying application code
- Allow arbitrary modifications at unrestricted points in code stream
- Allow systematic, fine-grained modifications to code stream
- Guarantee that all code is observed

Basic Interpreter



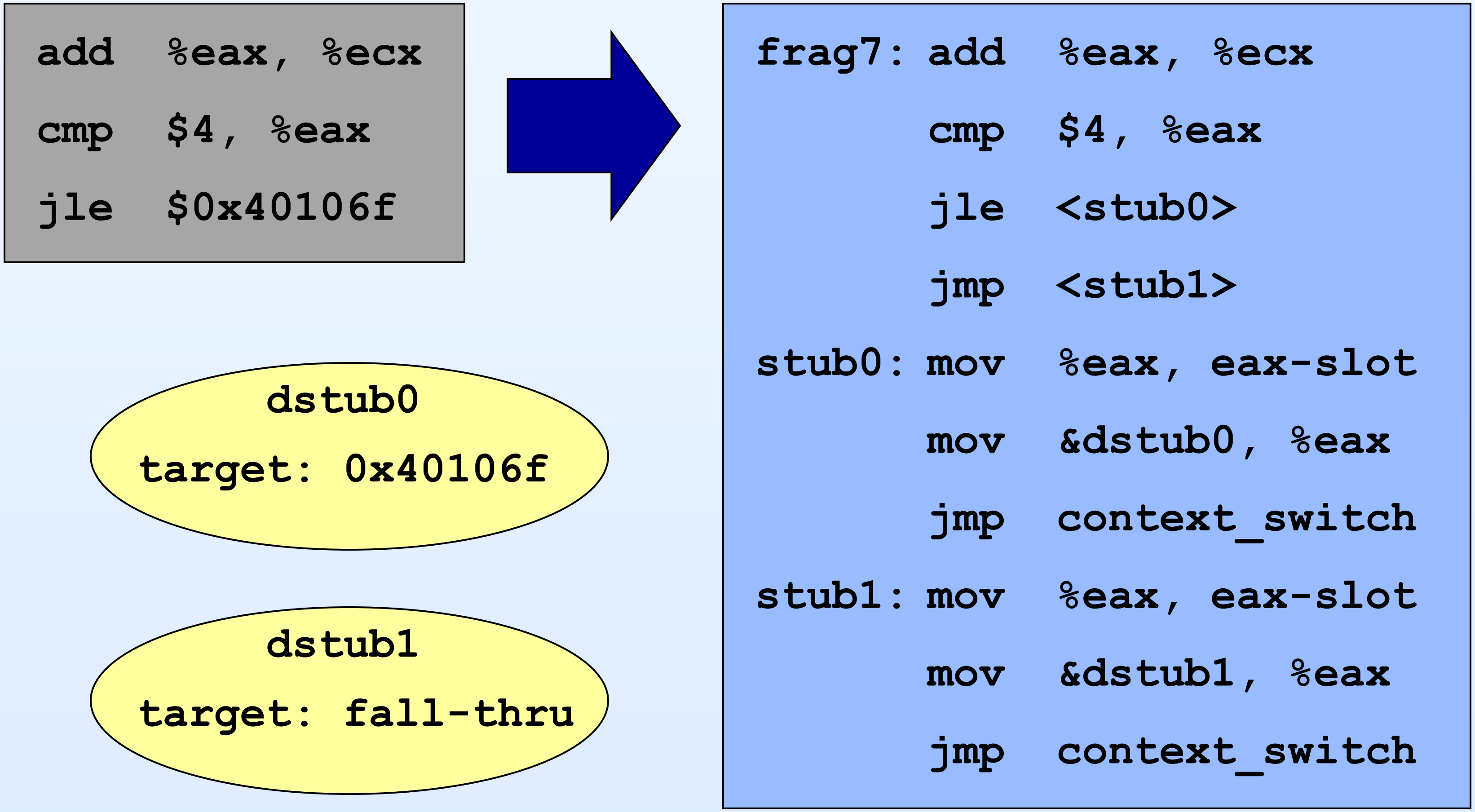
~300x Slowdown!

Improvement #1: Interpreter + Basic Block Cache



Slowdown: ~~300x~~ 25x

Example Basic Block Fragment



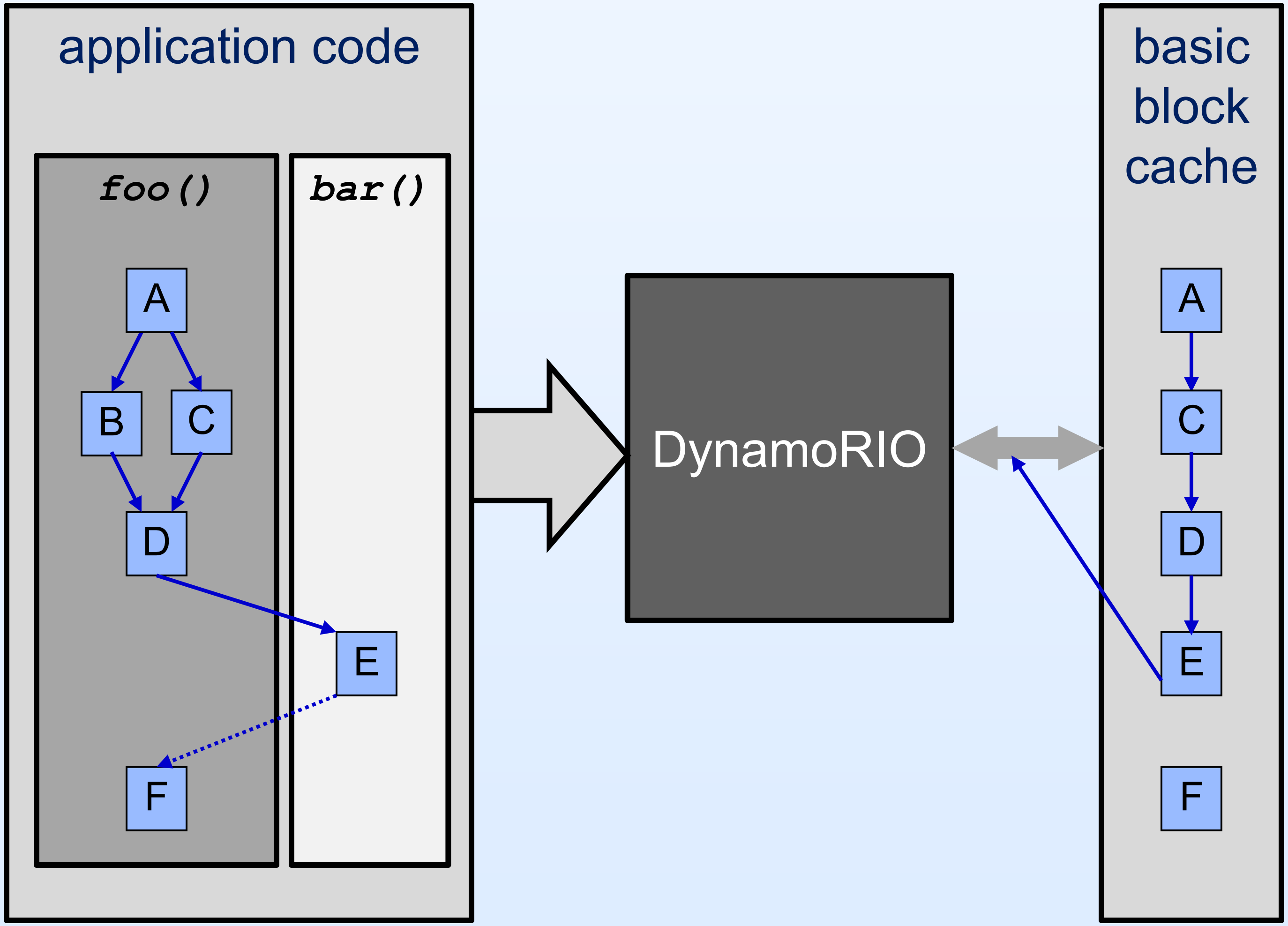
```
add   %eax, %ecx
cmp   $4, %eax
jle   $0x40106f
```

```
frag7: add   %eax, %ecx
       cmp   $4, %eax
       jle   <stub0>
       jmp   <stub1>
stub0: mov   %eax, eax-slot
       mov   &dstub0, %eax
       jmp   context_switch
stub1: mov   %eax, eax-slot
       mov   &dstub1, %eax
       jmp   context_switch
```

```
dstub0
target: 0x40106f
```

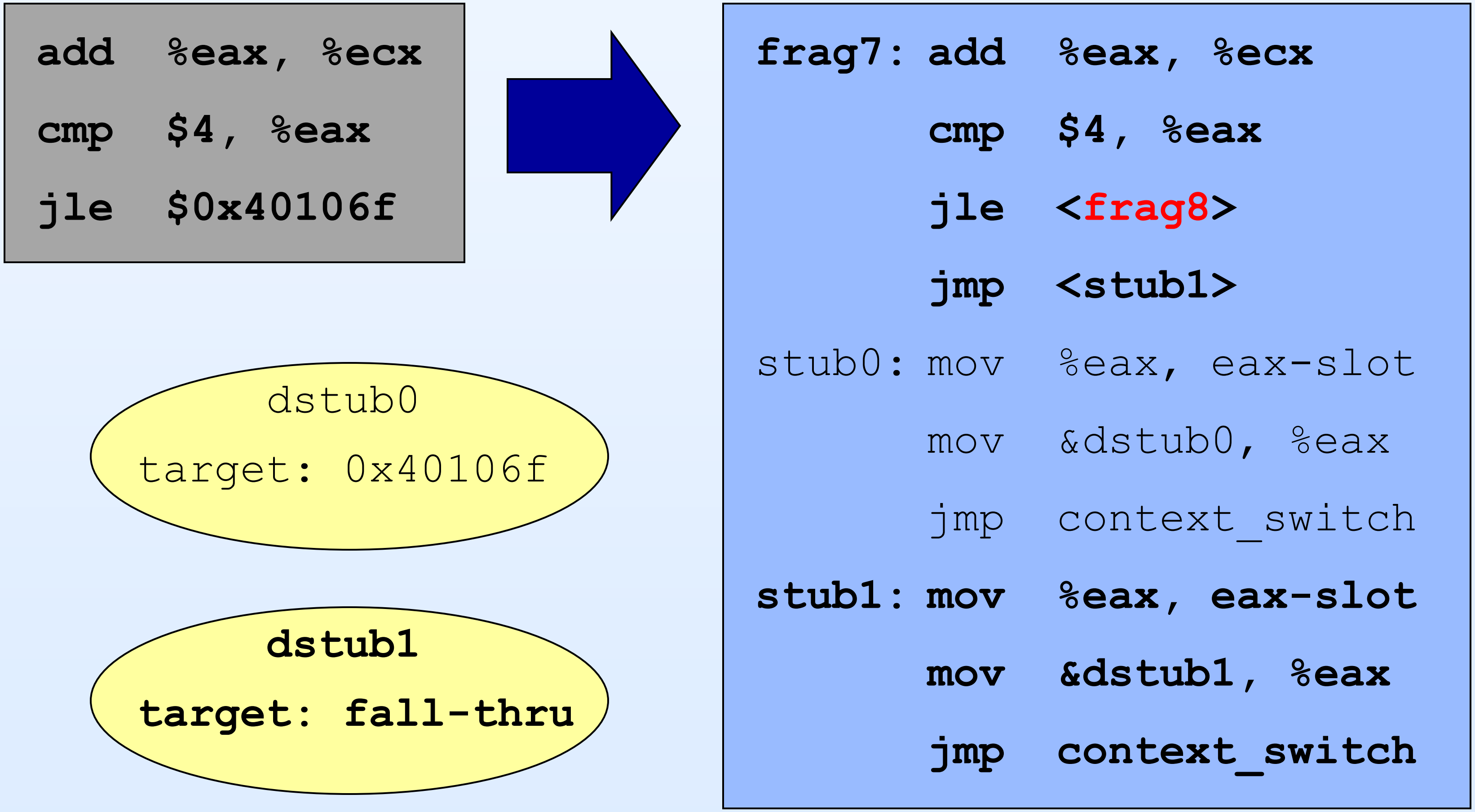
```
dstub1
target: fall-thru
```

Improvement #2: Linking Direct Branches



Slowdown: ~~300x~~ ~~25x~~ 3x

Direct Linking



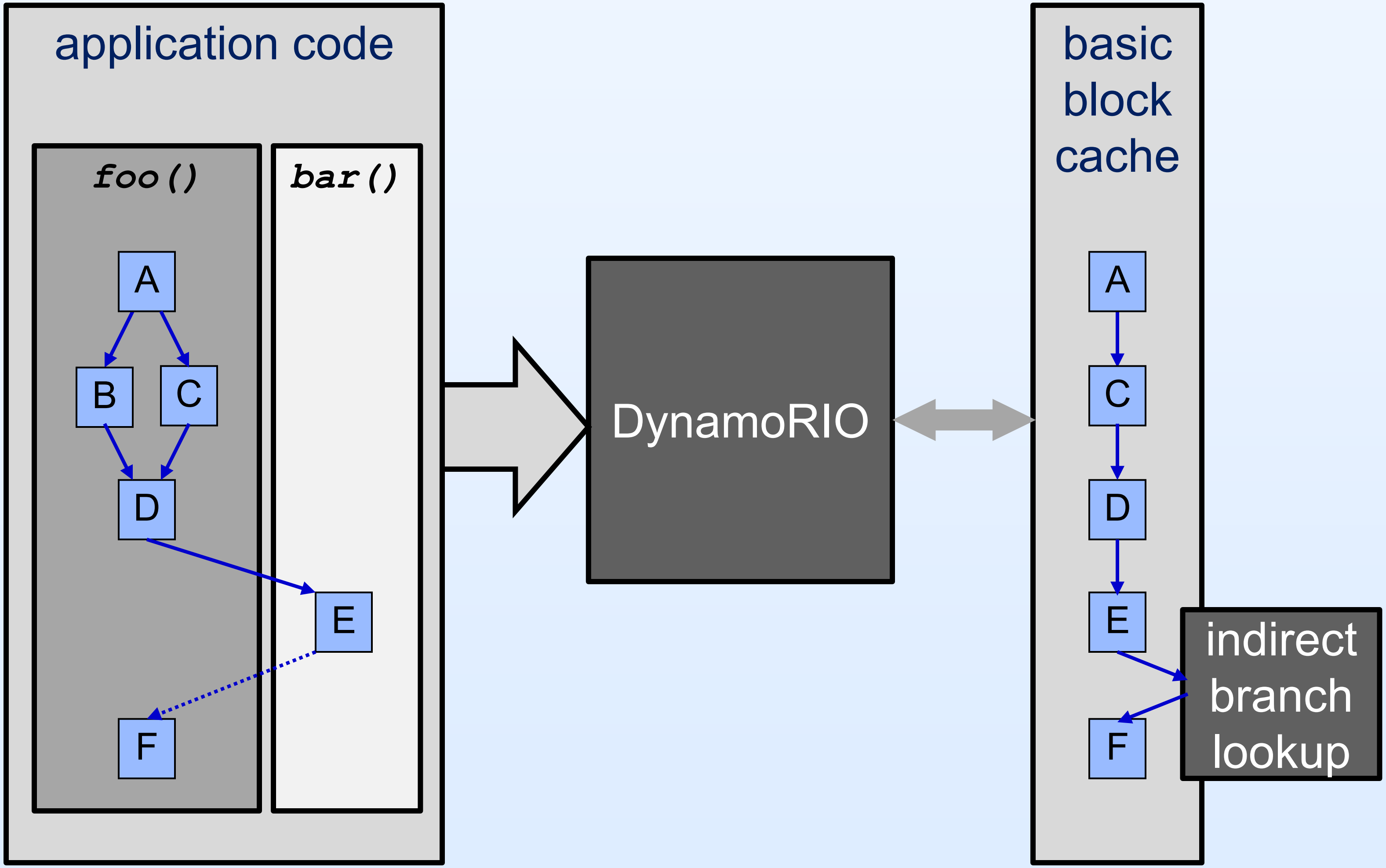
```
add   %eax, %ecx
cmp   $4, %eax
jle   $0x40106f
```

```
frag7: add   %eax, %ecx
       cmp   $4, %eax
       jle   <frag8>
       jmp   <stub1>
stub0: mov   %eax, eax-slot
       mov   &dstub0, %eax
       jmp   context_switch
stub1: mov   %eax, eax-slot
       mov   &dstub1, %eax
       jmp   context_switch
```

```
dstub0
target: 0x40106f
```

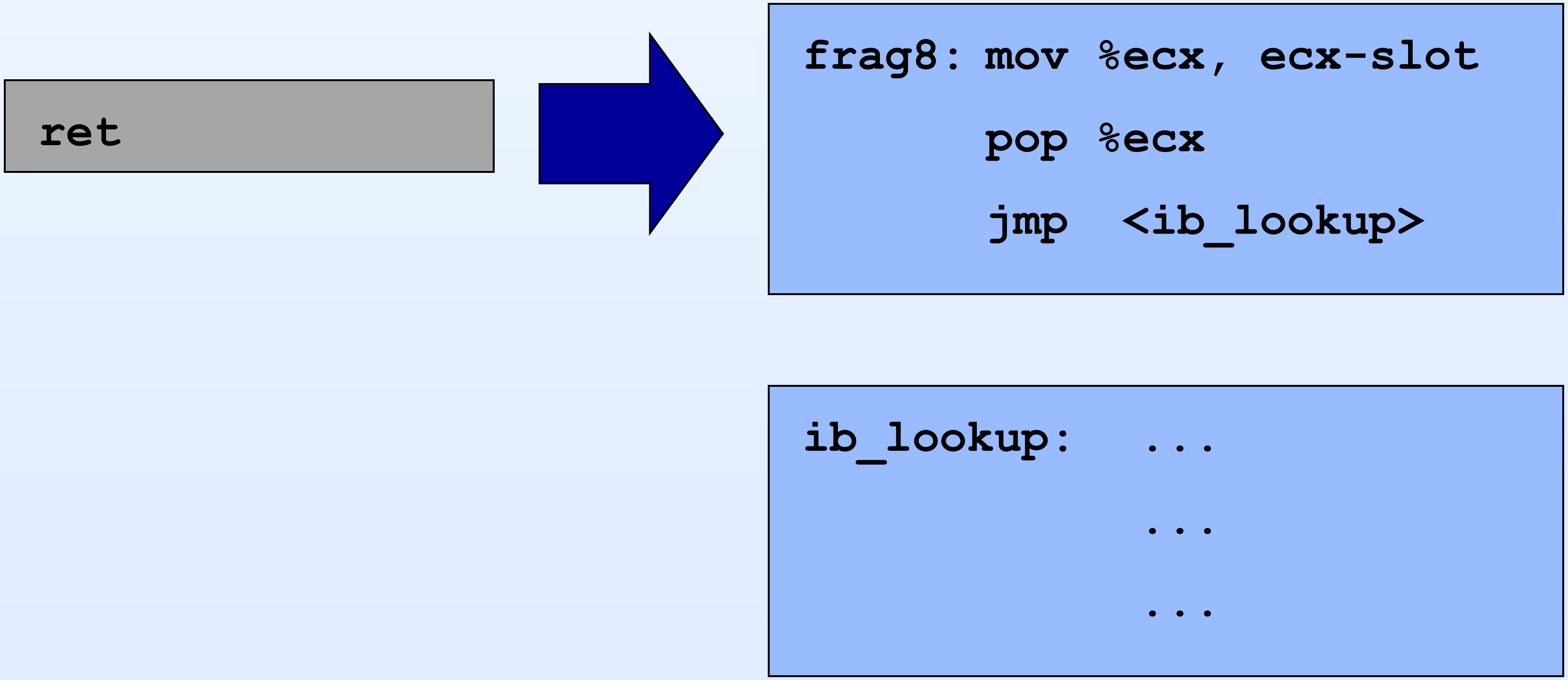
```
dstub1
target: fall-thru
```

Improvement #3: Linking Indirect Branches



Slowdown: ~~300x~~ ~~25x~~ ~~3x~~ 1.2x

Indirect Branch Transformation

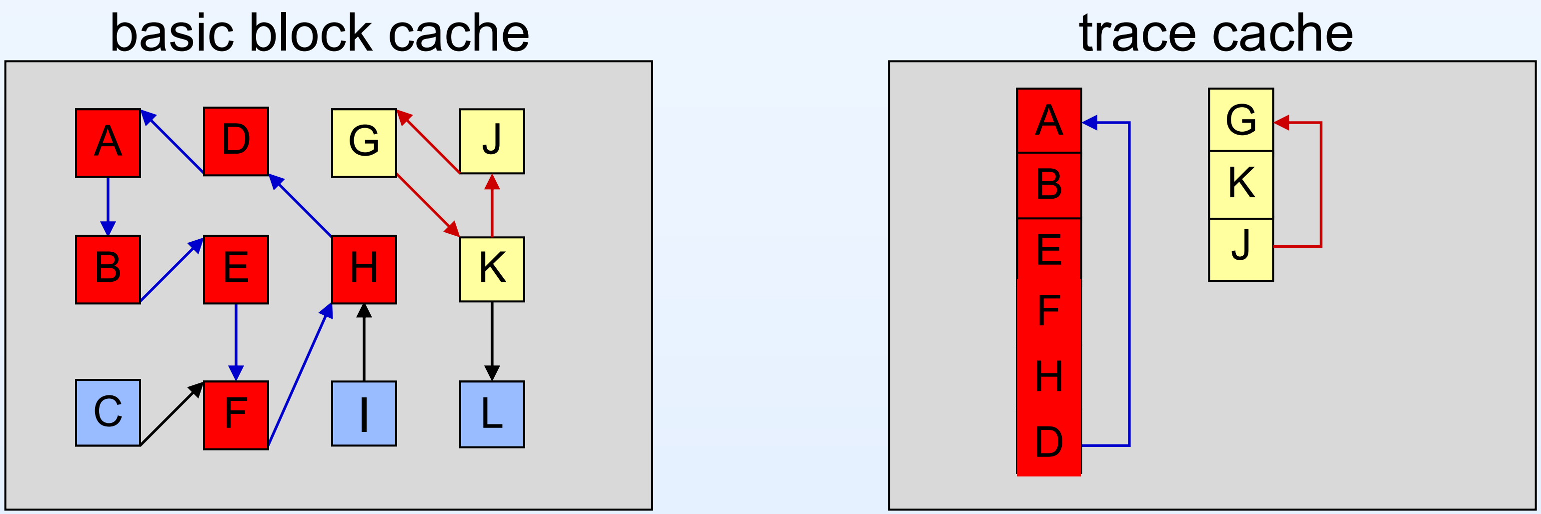


```
ret
```

```
frag8: mov %ecx, ecx-slot
       pop %ecx
       jmp  <ib_lookup>
```

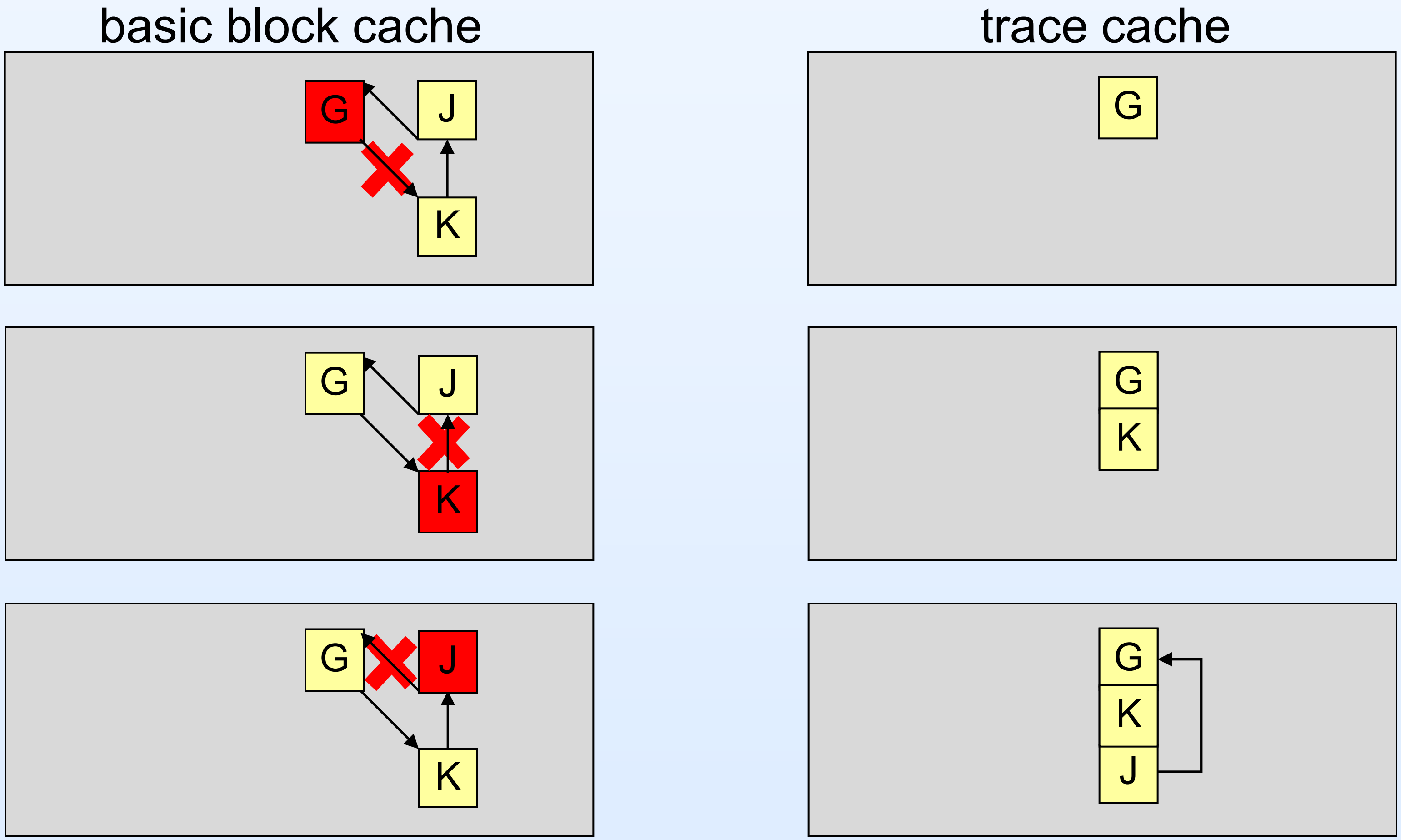
```
ib_lookup:   ...
             ...
             ...
```

Improvement #4: Trace Building



- Traces reduce branching, improve layout and locality, and facilitate optimizations across blocks
  - We avoid indirect branch lookup
- Next Executing Tail (NET) trace building scheme [Duesterwald 2000]

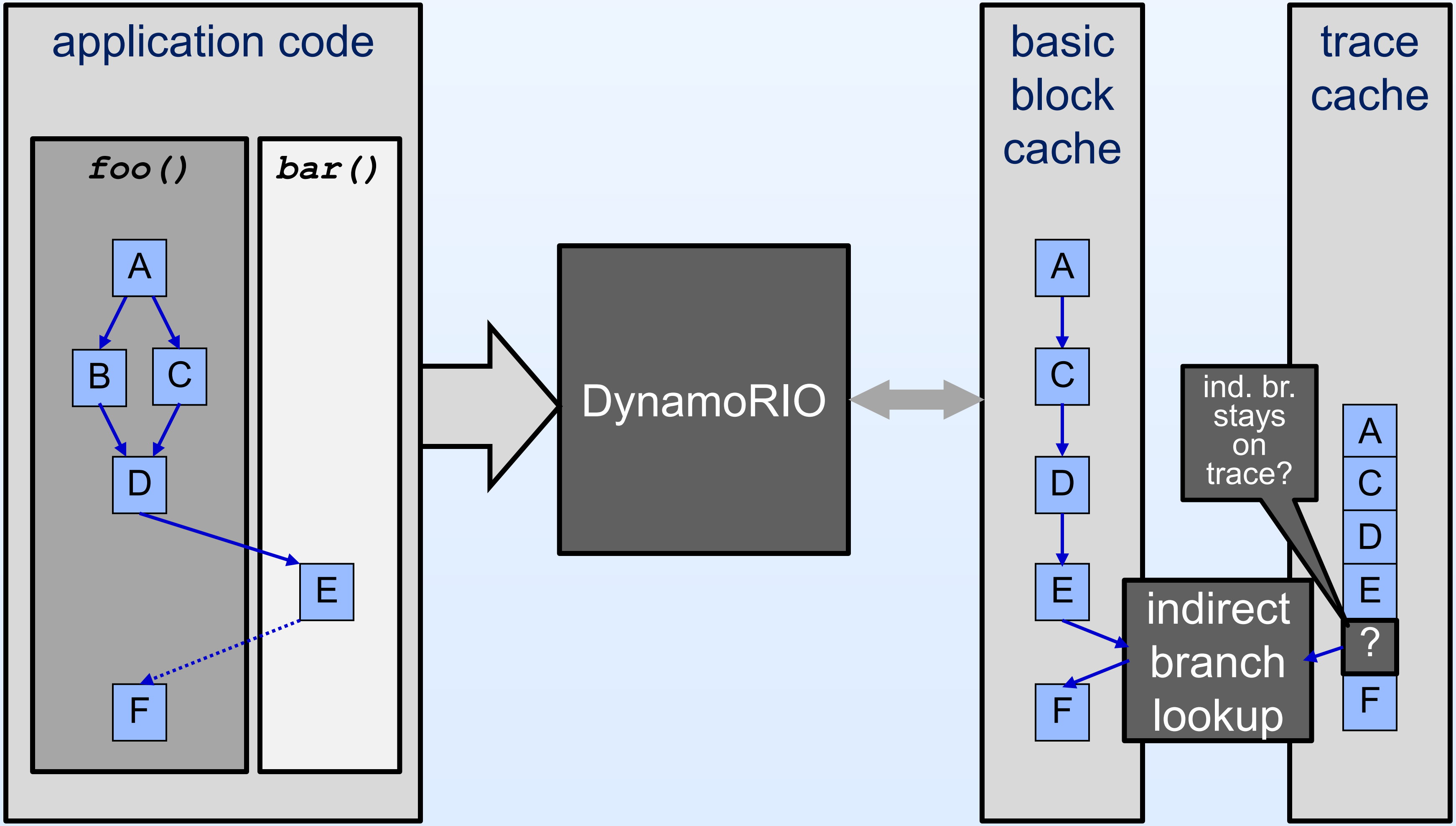
Incremental NET Trace Building



basic block cache

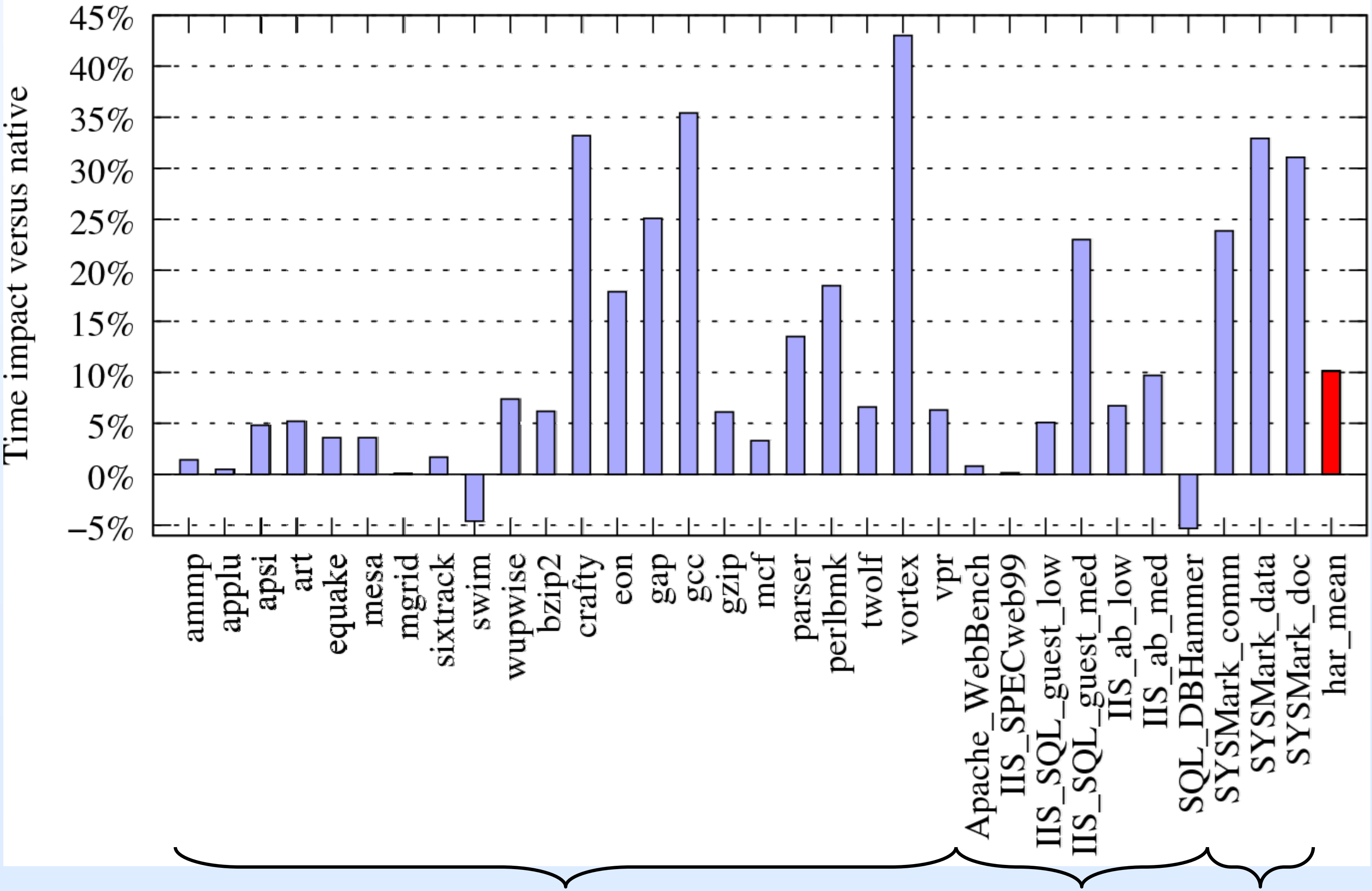
trace cache

Improvement #4: Trace Building



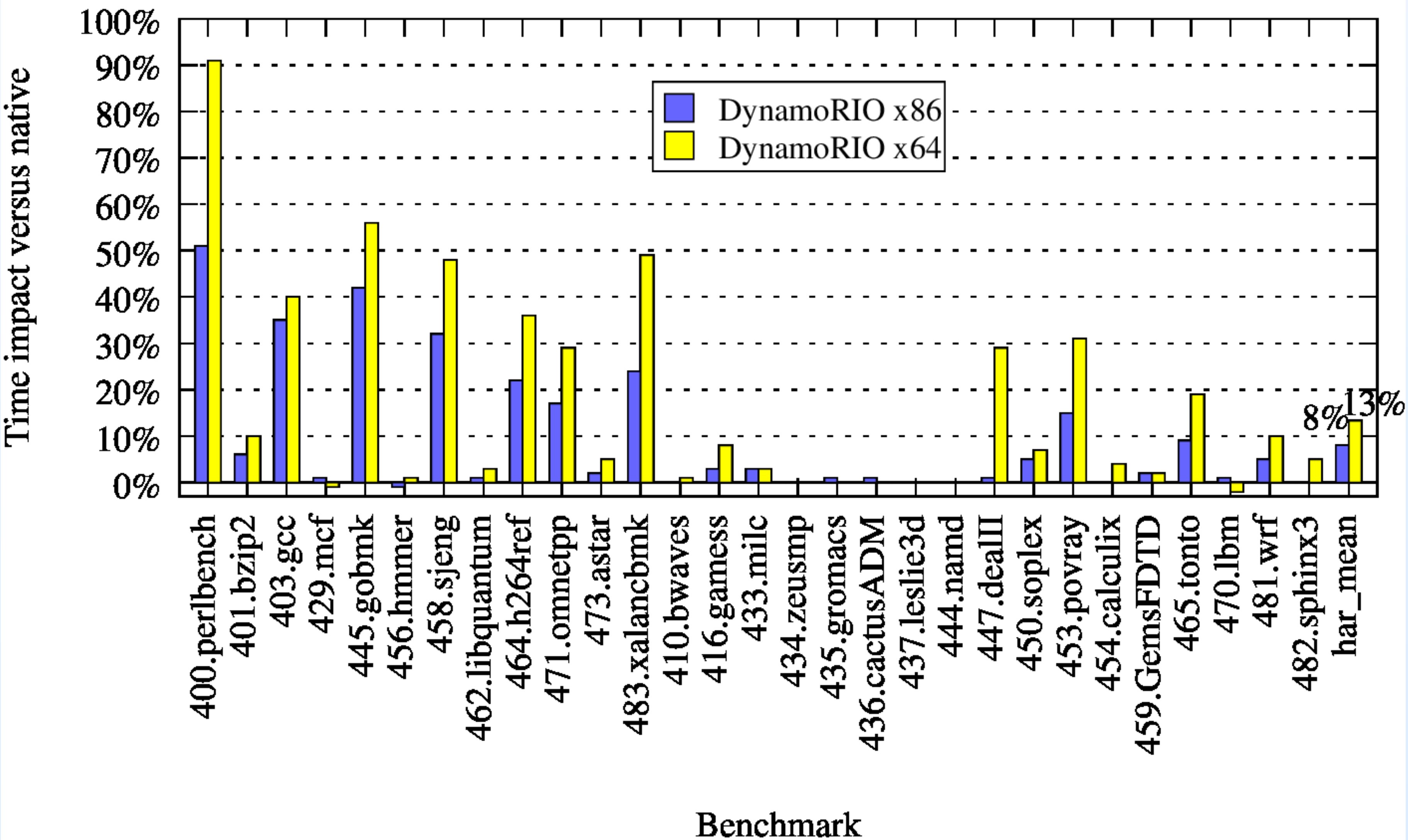
Slowdown: ~~300x~~ ~~25x~~ ~~3x~~ ~~1.2x~~ 1.1x

Base Performance



SPEC CPU2000 **Server** **Desktop**

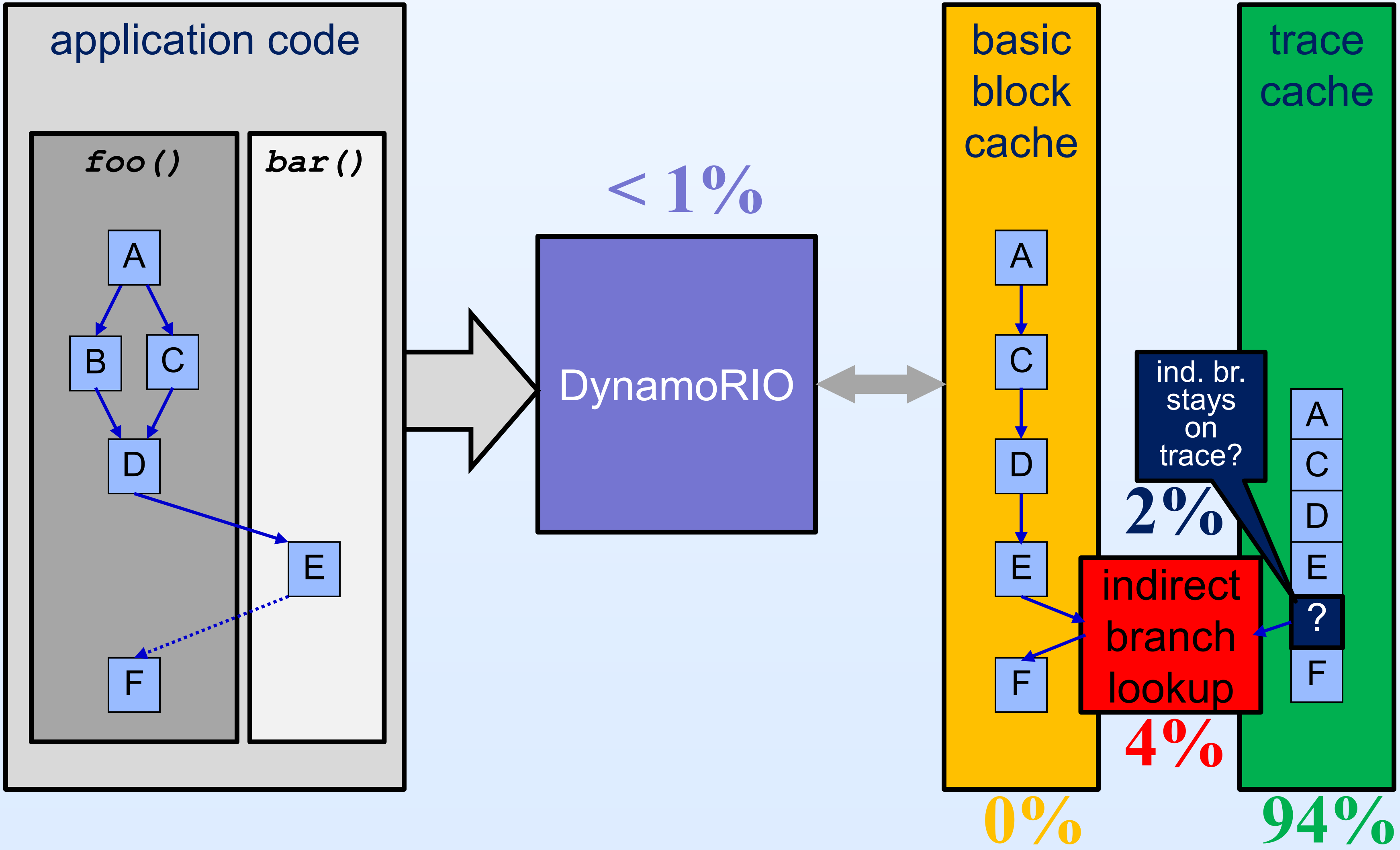
Base Performance: SPEC 2006



Sources of Overhead

- Extra instructions
  - Indirect branch target comparisons
  - Indirect branch hashtable lookups
- Extra data cache pressure
  - Indirect branch hashtable
- Branch mispredictions
  - ret becomes jmp*
- Application code modification

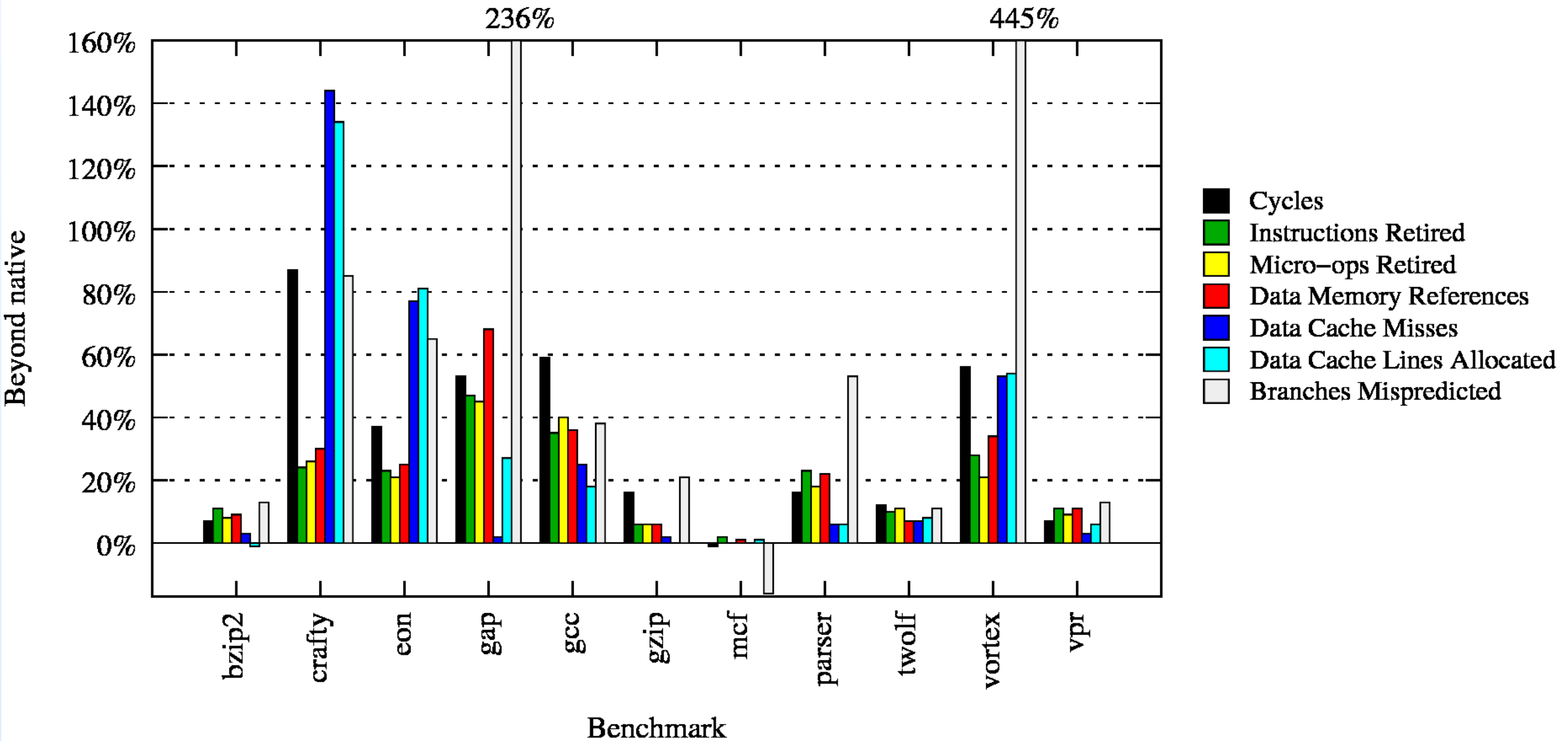
Time Breakdown for SPEC CPU INT



Not An Ordinary Application

- An application executing in DynamoRIO’s code cache looks different from what the underlying hardware has been tuned for
- The hardware expects:
  - Little or no dynamic code modification
    - Writes to code are expensive
  - call and ret instructions
    - Return Stack Buffer predictor

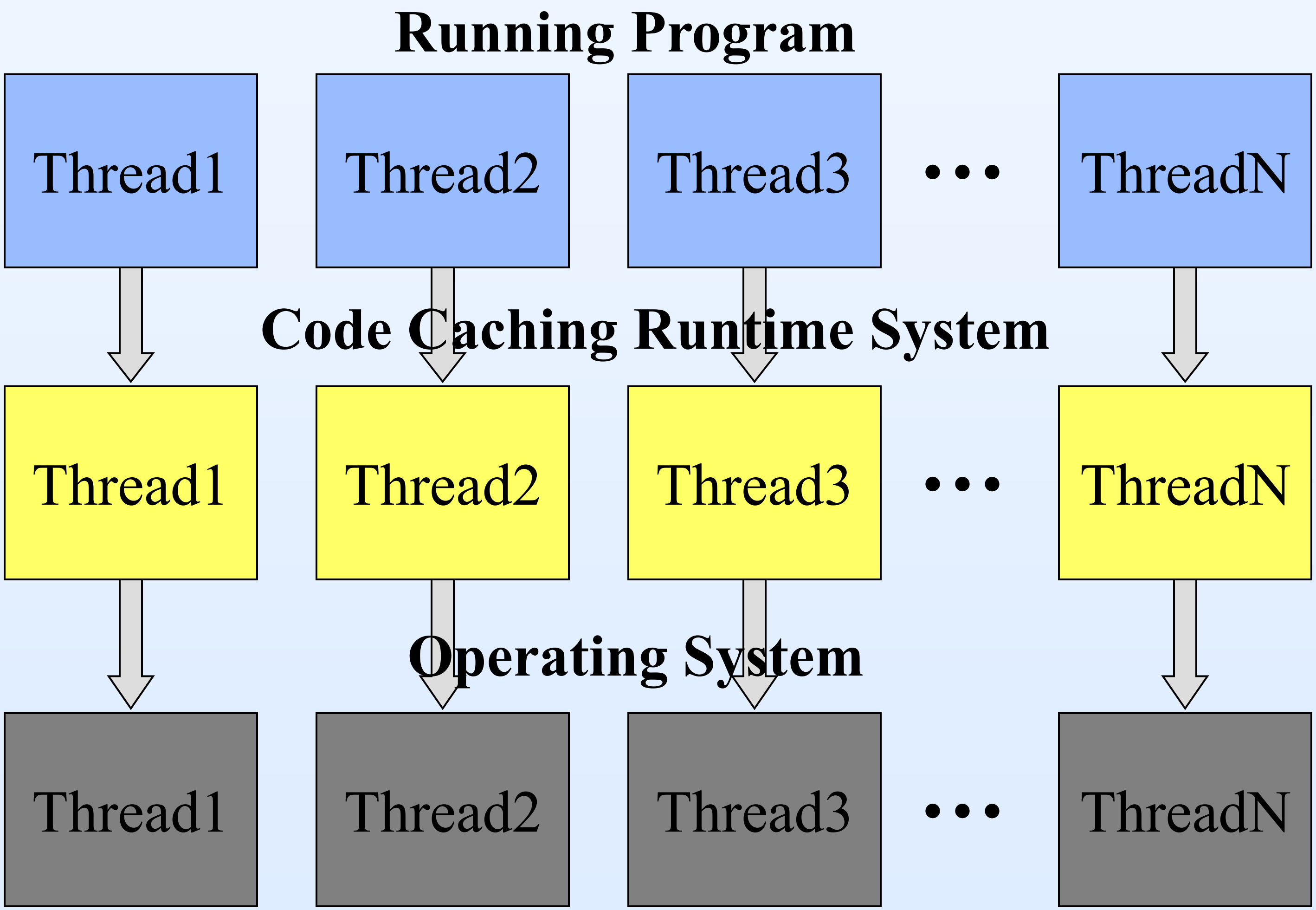
Performance Counter Data



Overview Outline

- Efficient
  - Software code cache overview
  - Thread-shared code cache
- Transparent
- Comprehensive
- Customizable

Threading Model


Running Program

Thread1 Thread2 Thread3 • • • ThreadN

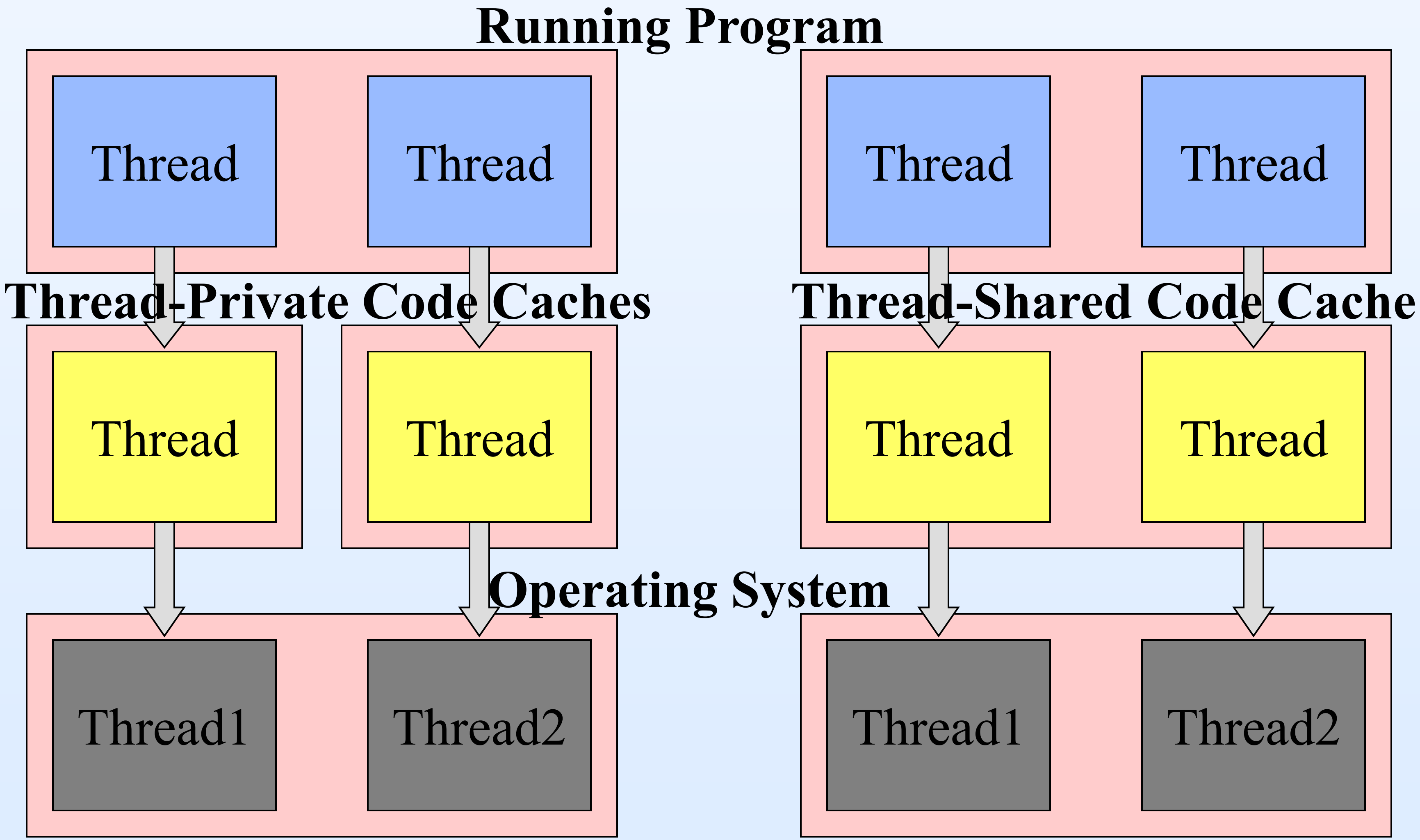
Code Caching Runtime System

Thread1 Thread2 Thread3 • • • ThreadN

Operating System

Thread1 Thread2 Thread3 • • • ThreadN

Code Space


Running Program
Thread
Thread
Thread
Thread
Thread-Private Code Caches
Thread-Shared Code Cache
Thread
Thread
Thread
Thread
Operating System
Thread1
Thread2
Thread1
Thread2

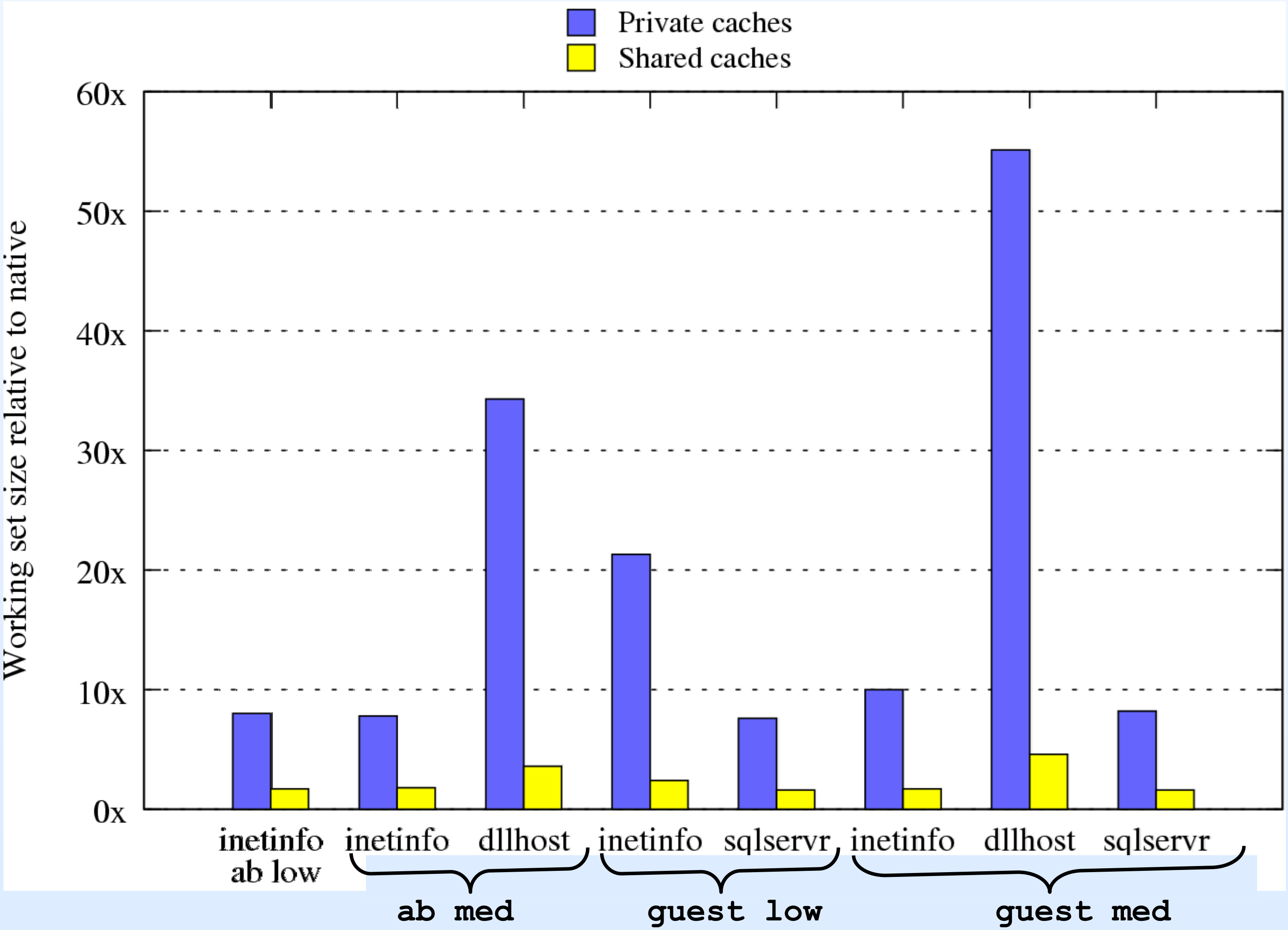
Thread-Private versus Thread-Shared

- Thread-private
  - Less synchronization needed
  - Absolute addressing for thread-local storage
  - Thread-specific optimization and instrumentation
- Thread-shared
  - Scales to many-threaded apps

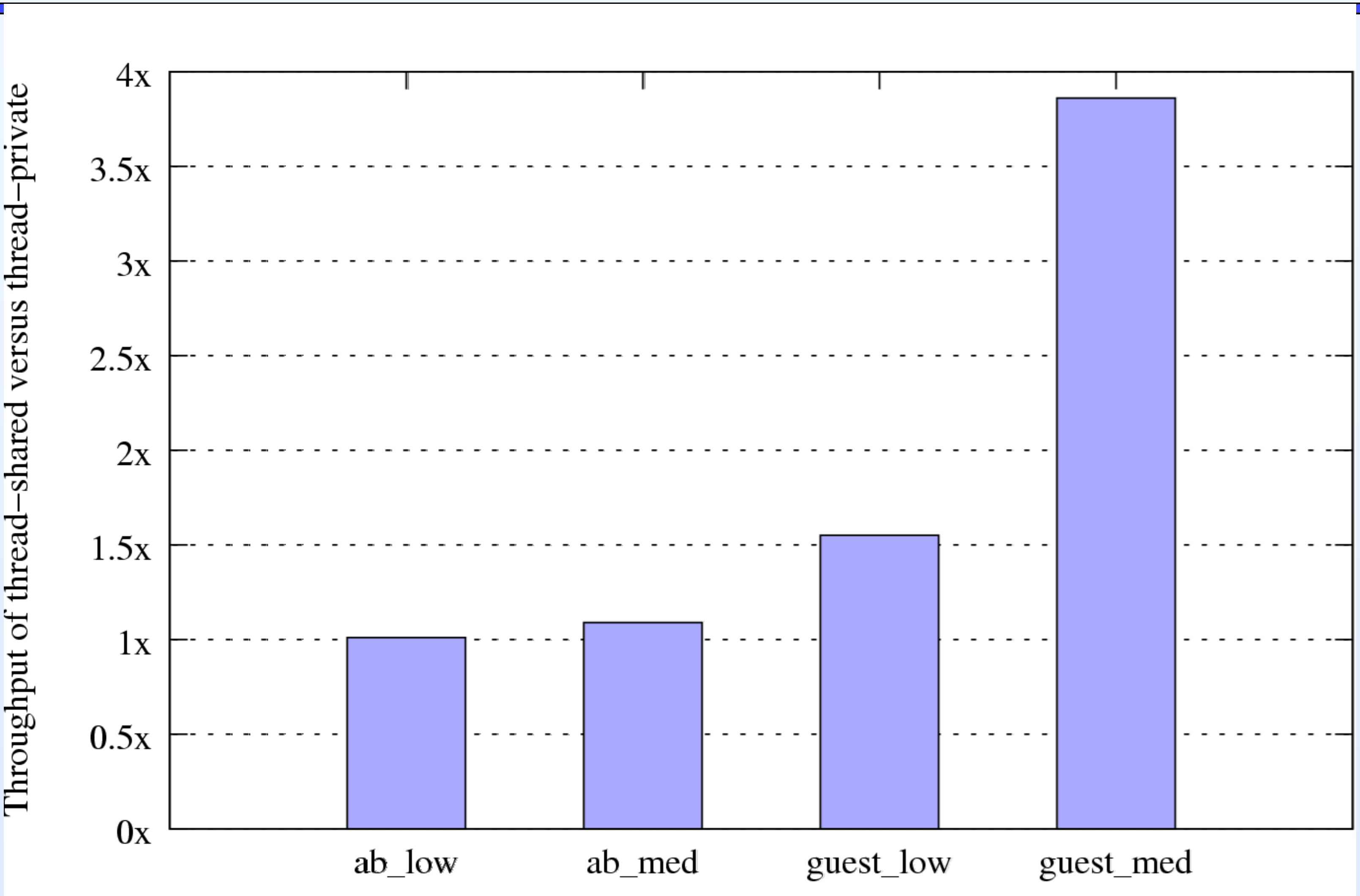
Database and Web Server Suite

Benchmark	Server	Processes
ab low	IIS low isolation	inetinfo.exe
ab med	IIS medium isolation	inetinfo.exe, dllhost.exe
guest low	IIS low isolation, SQL Server 2000	inetinfo.exe, sqlservr.exe
guest med	IIS medium isolation, SQL Server 2000	inetinfo.exe, dllhost.exe, sqlservr.exe

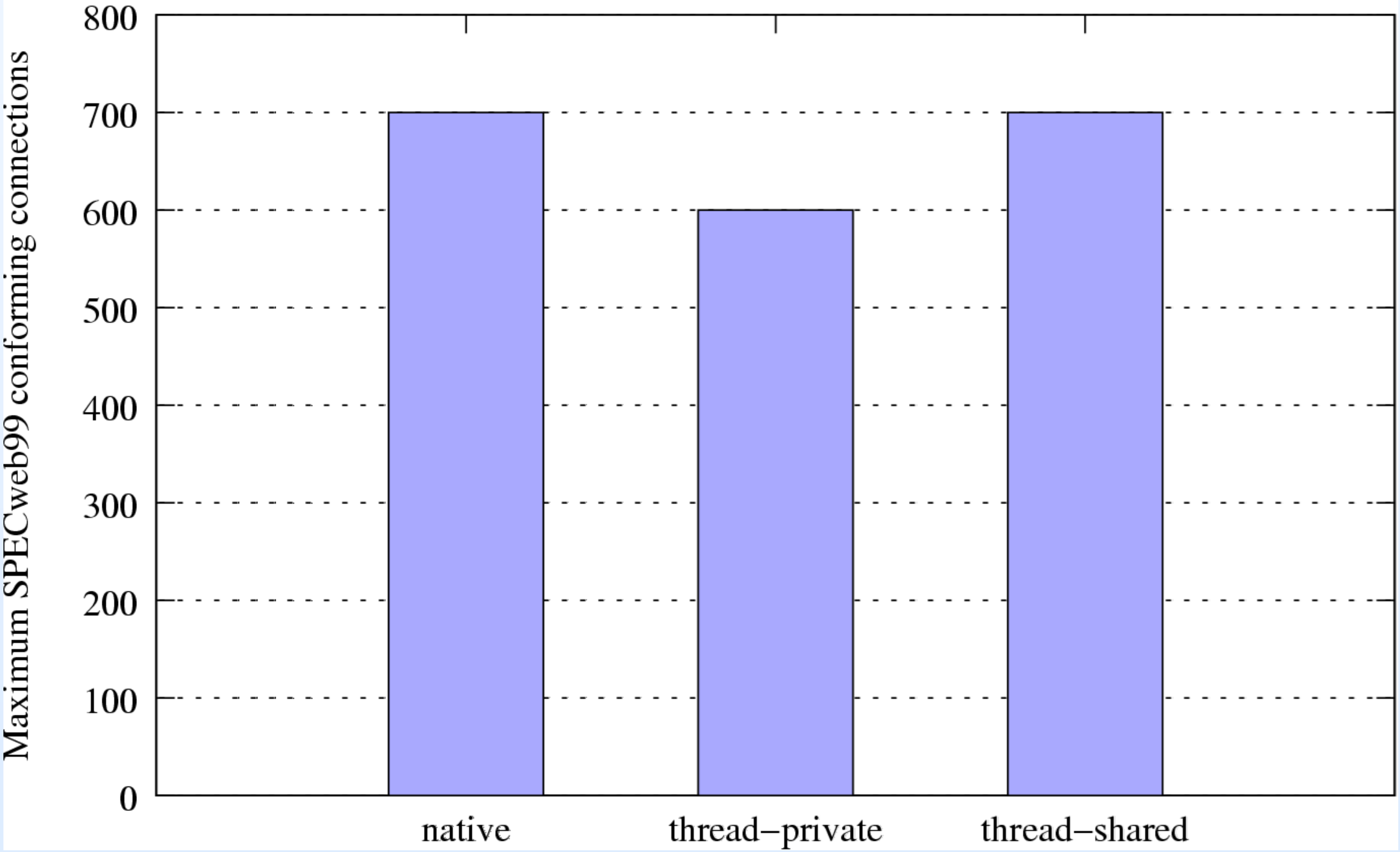
Memory Impact



Performance Impact



Scalability Limit



Overview Outline

- Efficient
- Transparent
  - Transparency principles
  - Cache consistency
  - Synchronization
- Comprehensive
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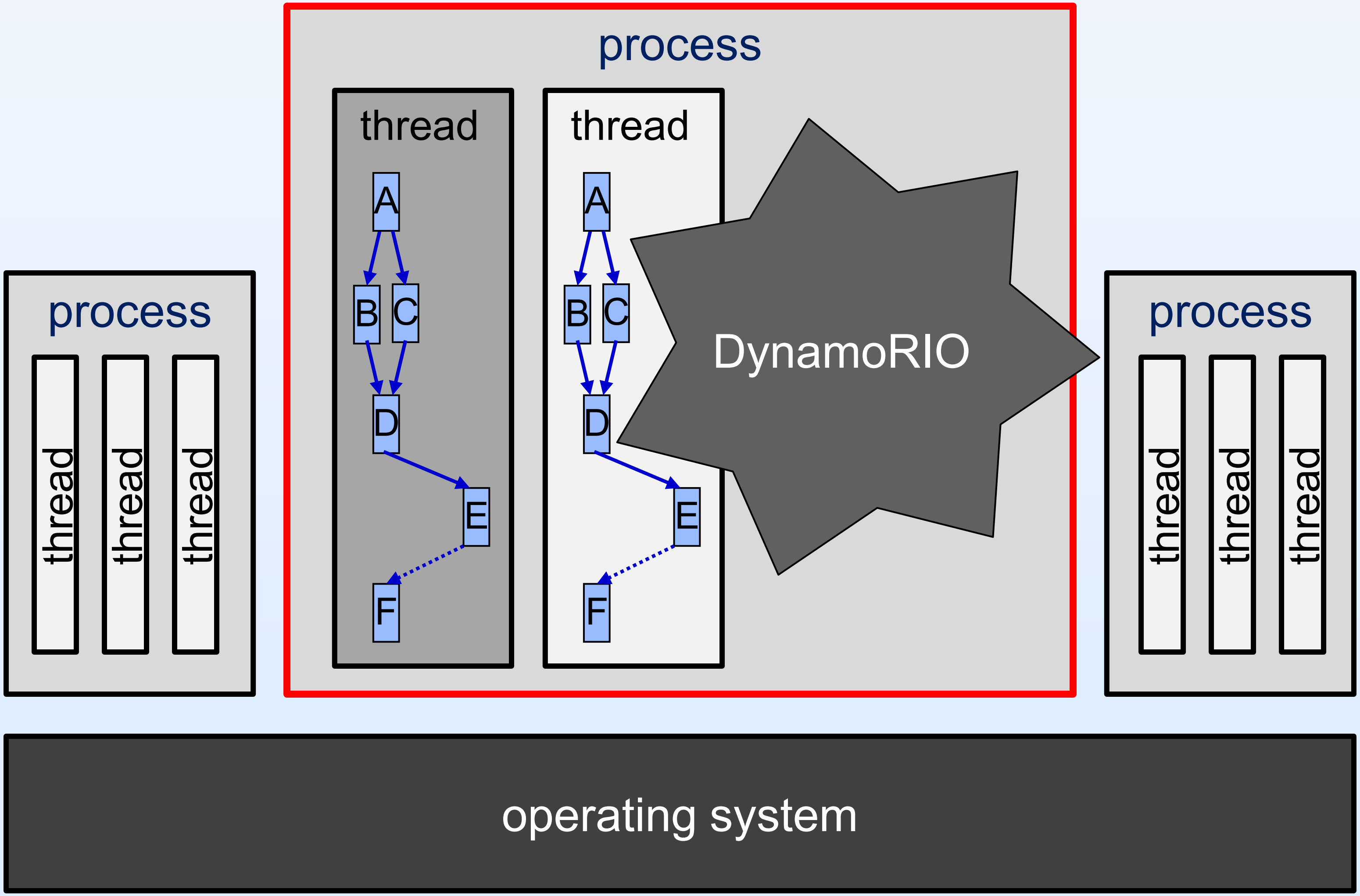
Unavoidably Intrusive



Transparency

- Do not want to interfere with the semantics of the program
- Dangerous to make any assumptions about:
  - Register usage
  - Calling conventions
  - Stack layout
  - Memory/heap usage
  - I/O and other system call use

Painful, But Necessary

- Difficult and costly to handle corner cases
- Many applications will not notice…
- …but some will!
  - Microsoft Office: Visual Basic generated code, stack convention violations
  - COM, Star Office, MMC: trampolines
  - Adobe Premiere: self-modifying code
  - VirtualDub: UPX-packed executable
  - etc.

Transparency Principles

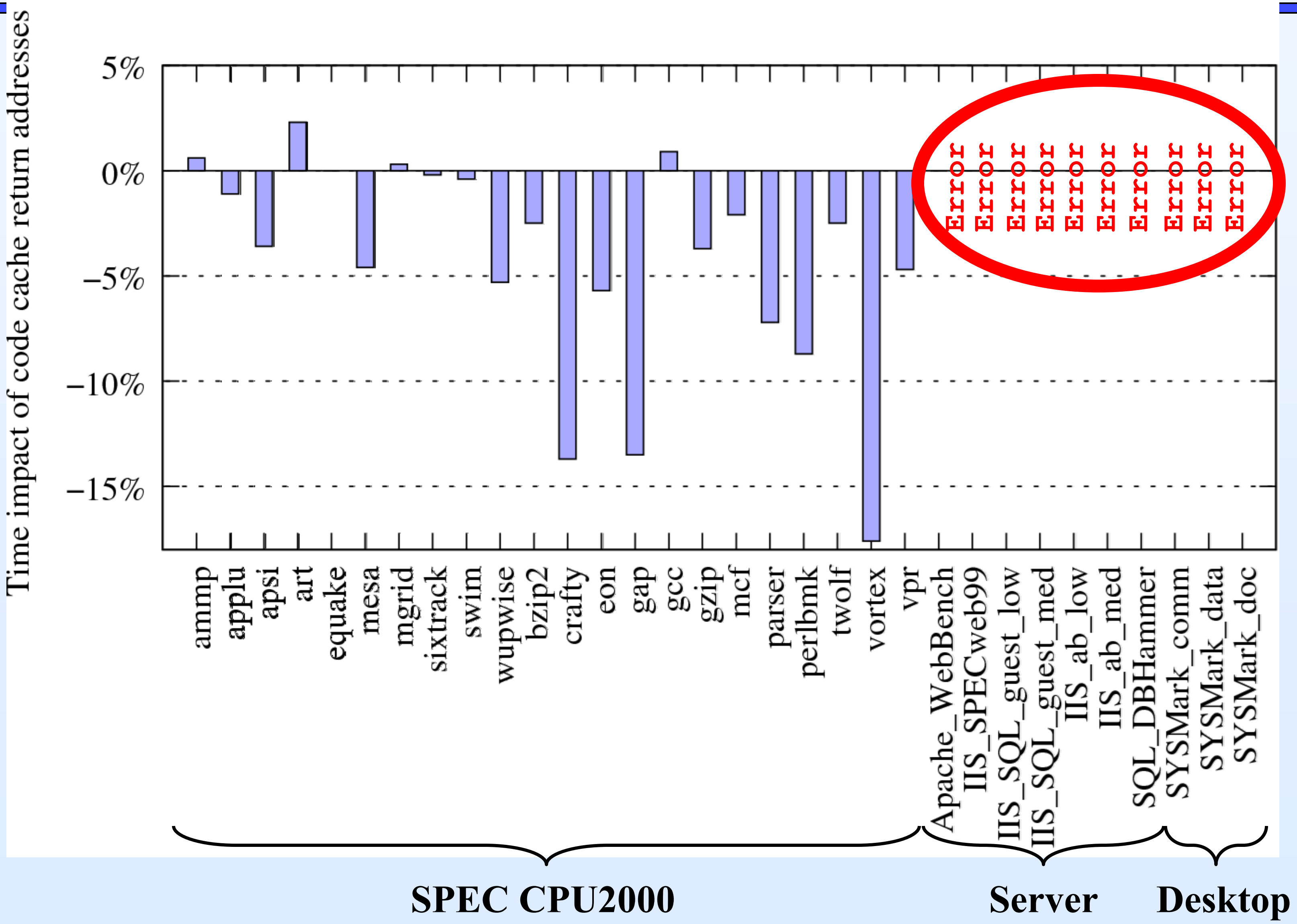
- **Principle 1: *As few changes as possible***
  - Set a high bar for value before changing the native environment
- **Principle 2: *Hide necessary changes***
  - Whatever is valuable enough to change must be hidden
  - Changes that cannot be hidden should not be made
- **Principle 3: *Separate resources***
  - Avoid intra-process resource conflicts

Bruening et al. "Transparent Dynamic Instrumentation" VEE'12

Principle 1: *As few changes as possible*

- Application code
- Executable on disk
- Stored addresses
- Threads
- Application data
  - Including the stack!

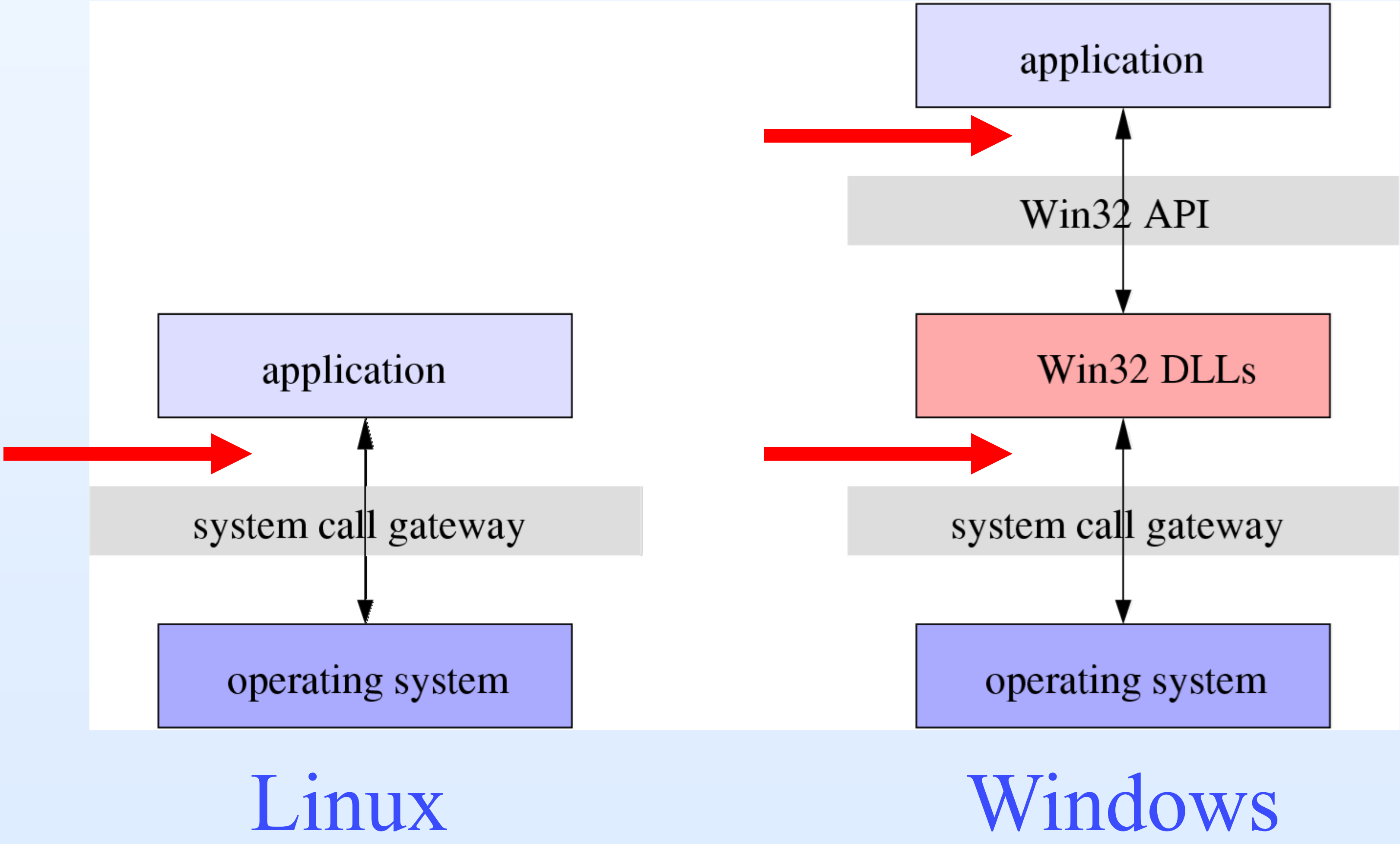
Return Address Transparency



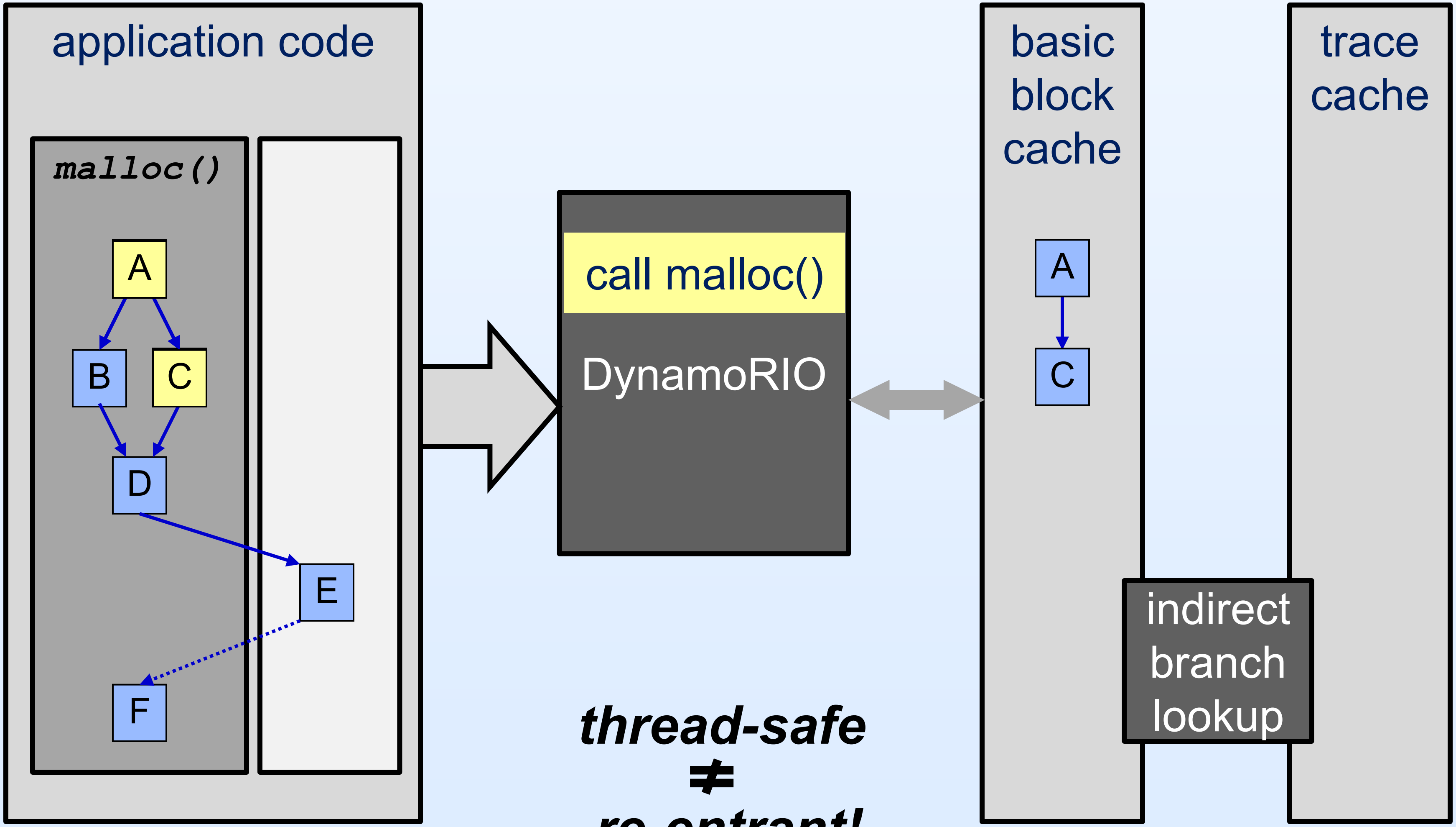
Principle 2: *Hide necessary changes*

- Application addresses
- Address space
- Error transparency
- Code cache consistency

Principle 3: *Separate resources*



Arbitrary Interleaving



thread-safe

≠

re-entrant!

Transparency Landscape

	Principle 1: ***As few changes as possible***	**Principle 2:** ***Hide necessary changes***	**Principle 3:** ***Separate resources***
Code	application code, stored addresses	machine context, cache consistency	
Data	stack, heap, registers, condition flags		separate stack, heap, context, i/o
Concurrency	threads, memory ordering		disjoint locks
Other		preserve errors	

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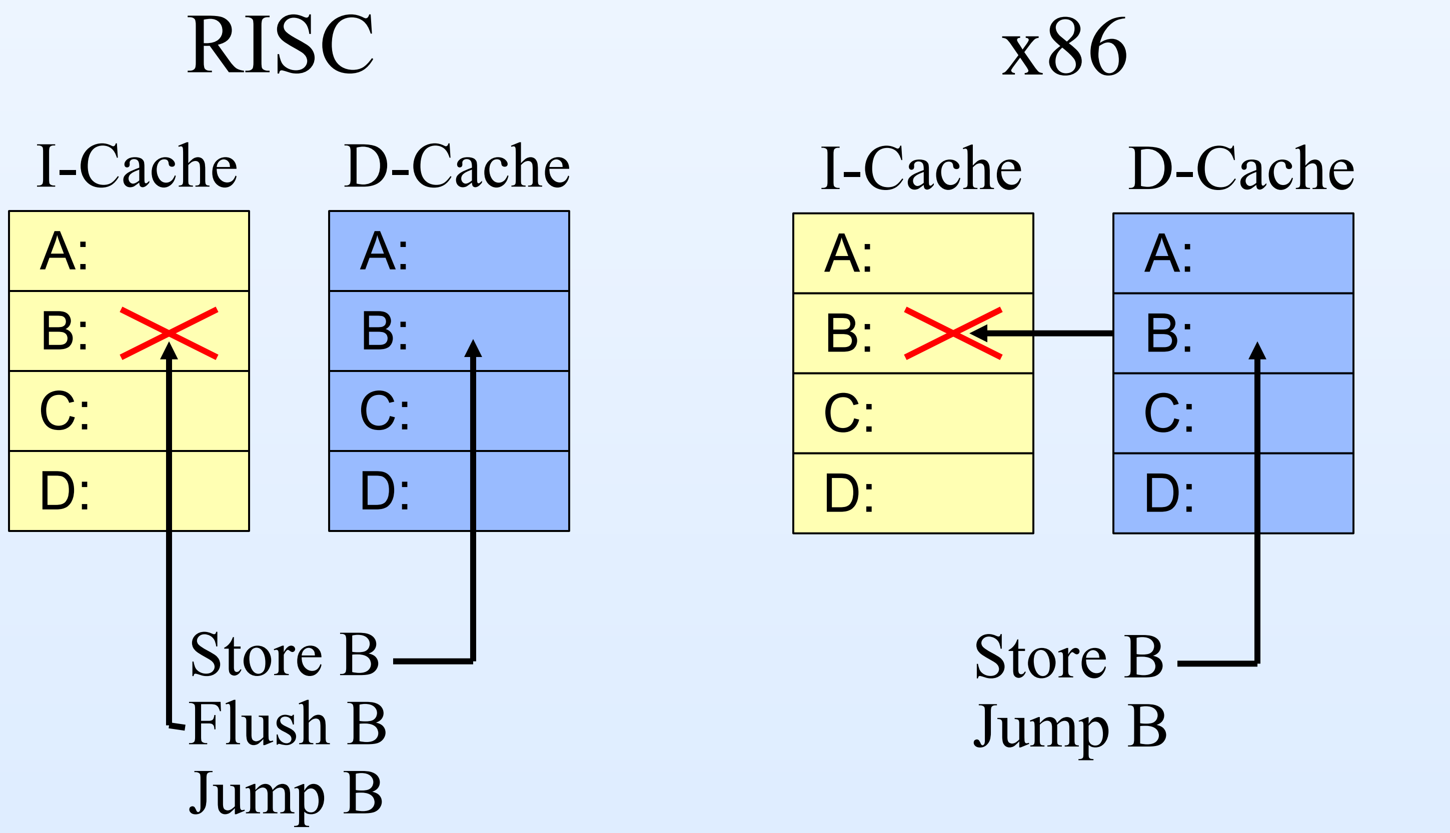
Code Change Mechanisms



How Often Does Code Change?

- Not just modification of code!
- Removal of code
  - Shared library unloading
- Replacement of code
  - JIT region re-use
  - Trampoline on stack

Code Change Events

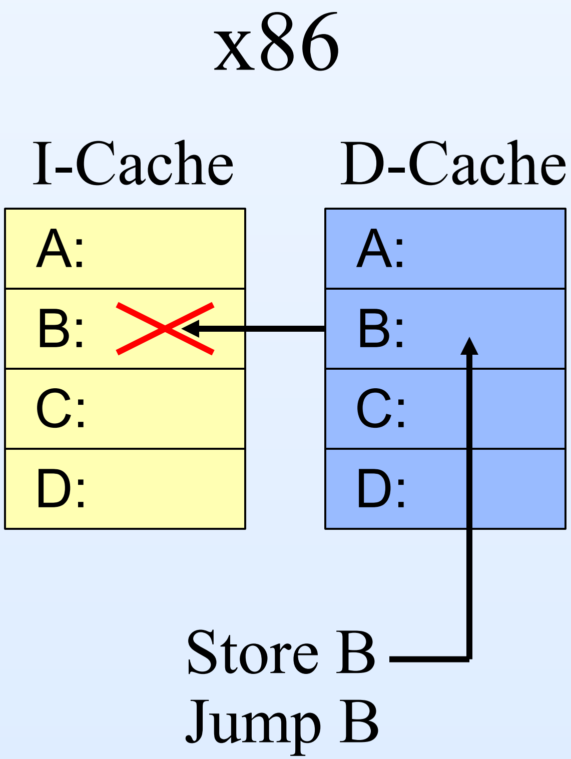
	Memory Unmappings	Generated Code Regions	Modified Code Regions
SPECFP	112	0	0
SPECINT	29	0	0
SPECJVM	7	3373	4591
Excel	144	21	20
Photoshop	1168	40	0
Powerpoint	367	28	33
Word	345	20	6

Detecting Code Removal

- Example: shared library being unloaded
- Requires explicit request by application to operating system
- Detect by monitoring system calls (munmap, NtUnmapViewOfSection)

Detecting Code Modification

- On x86, no explicit app request required, as the icache is kept consistent in hardware – so any memory write could modify code!



Page Protection Plus Instrumentation

- Invariant: application code copied to code cache must be read-only
  - If writable, hide read-only status from application
- Some code cannot or should not be made read-only
  - Self-modifying code
  - Windows stack
  - Code on a page with frequently written data
- Use per-fragment instrumentation to ensure code is not stale on entry and to catch self-modification

Adaptive Consistency Algorithm

- Use page protection by default
  - Most code regions are always read-only
- Subdivide written-to regions to reduce flushing cost of write-execute cycle
  - Large read-only regions, small written-to regions
- Switch to instrumentation if write-execute cycle repeats too often (or on same page)
  - Switch back to page protection if writes decrease

Bruening et al. "Maintaining Consistency and Bounding Capacity of Software Code Caches" CGO'05

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Synchronization Transparency

- Application thread management should not interfere with the runtime system, and vice versa
  - Cannot allow the app to suspend a thread holding a runtime system lock
  - Runtime system cannot use app locks

Disjoint Locks

- App thread suspension requires safe spots where no runtime system locks are held
- Time spent in the code cache can be unbounded
- → Our invariant: no runtime system lock can be held while executing in the code cache

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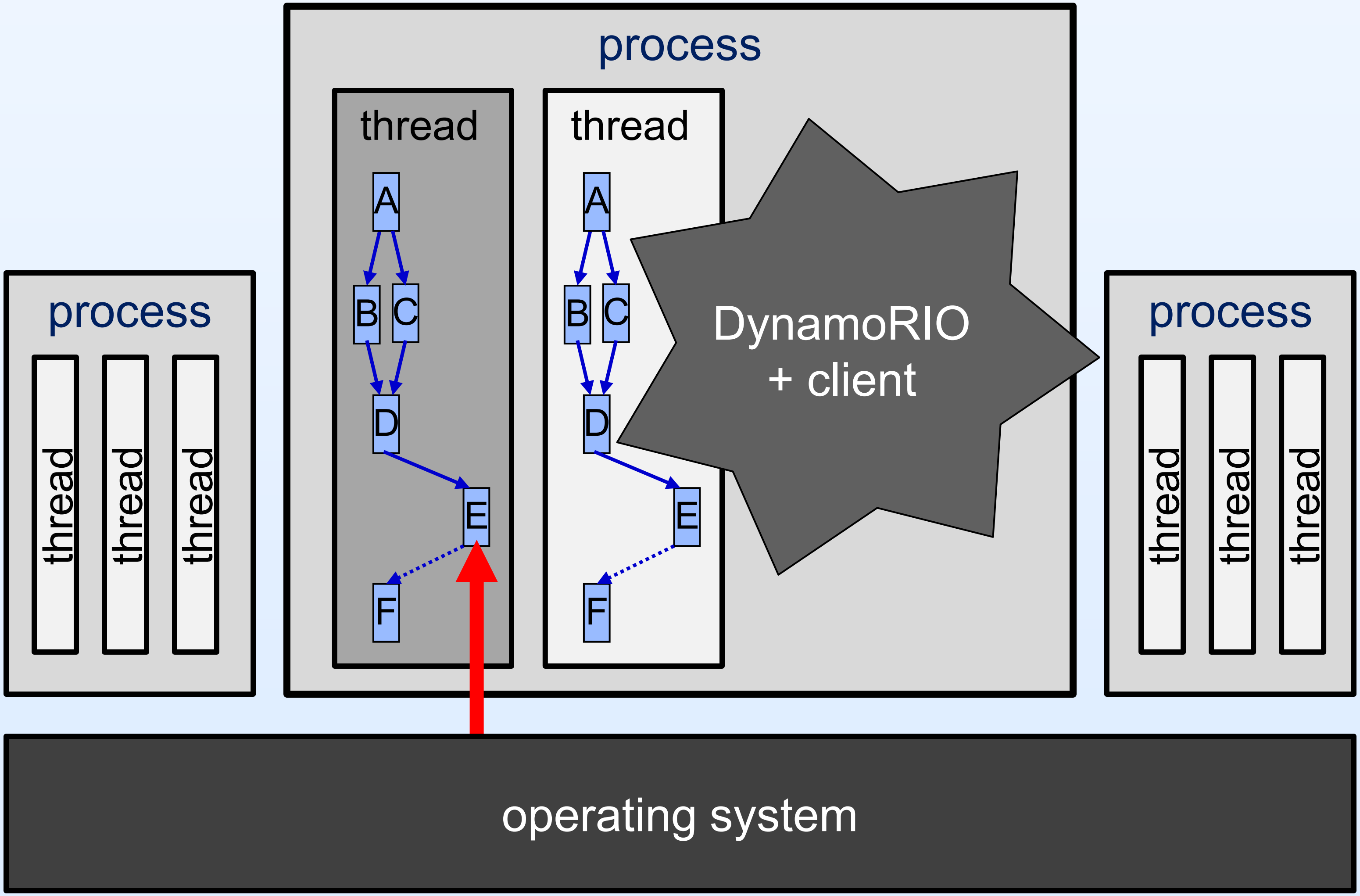
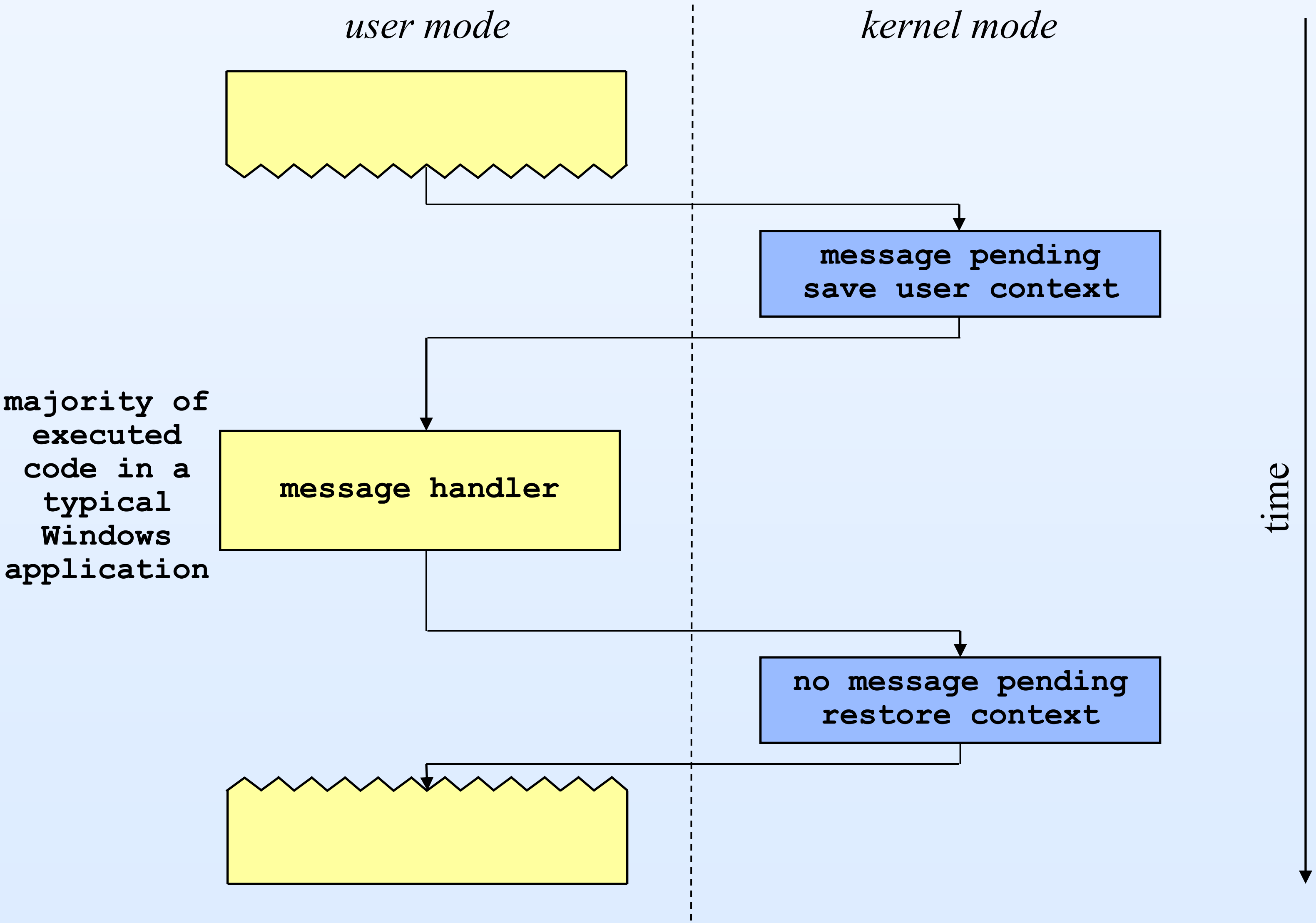
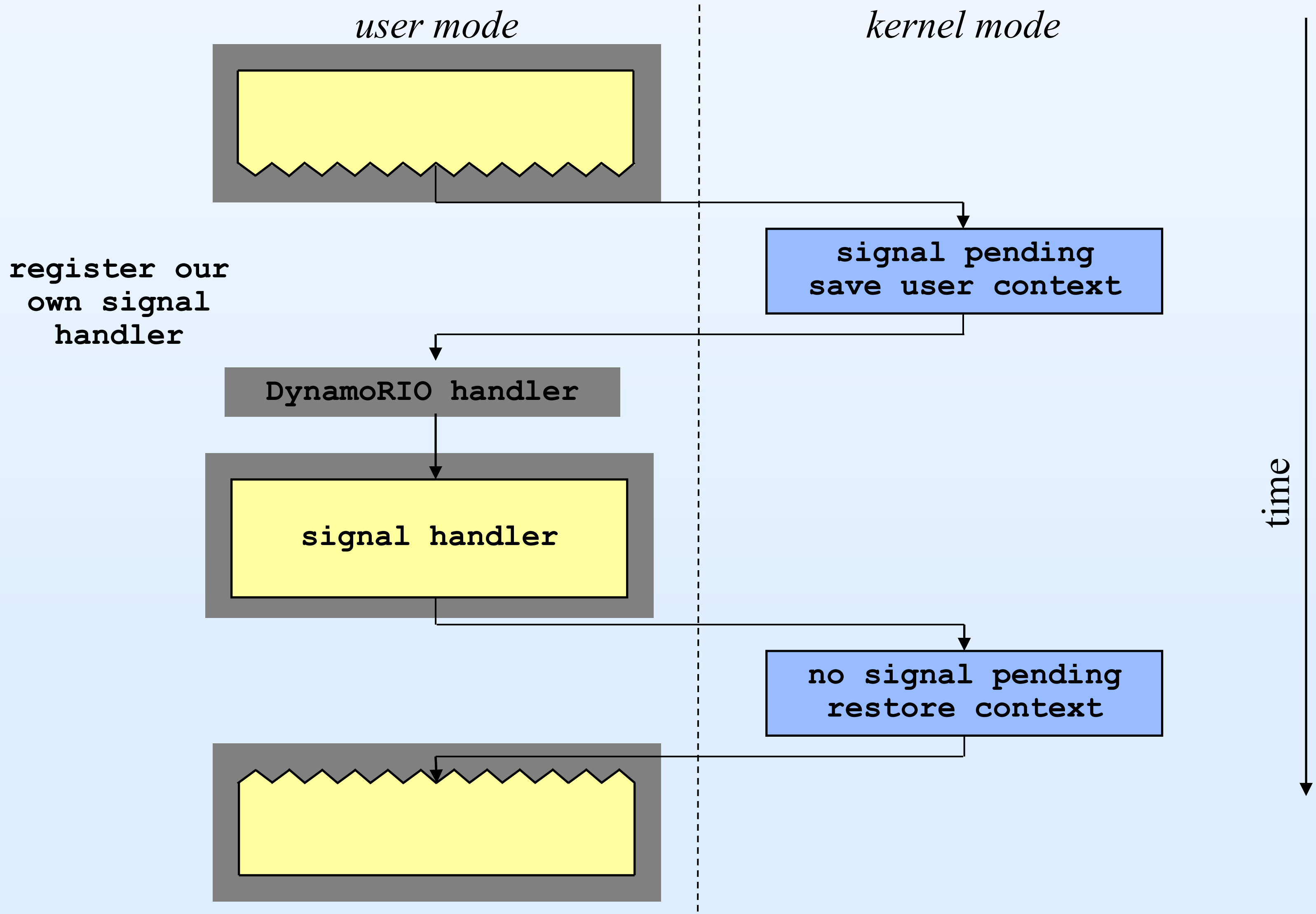
Above the Operating System



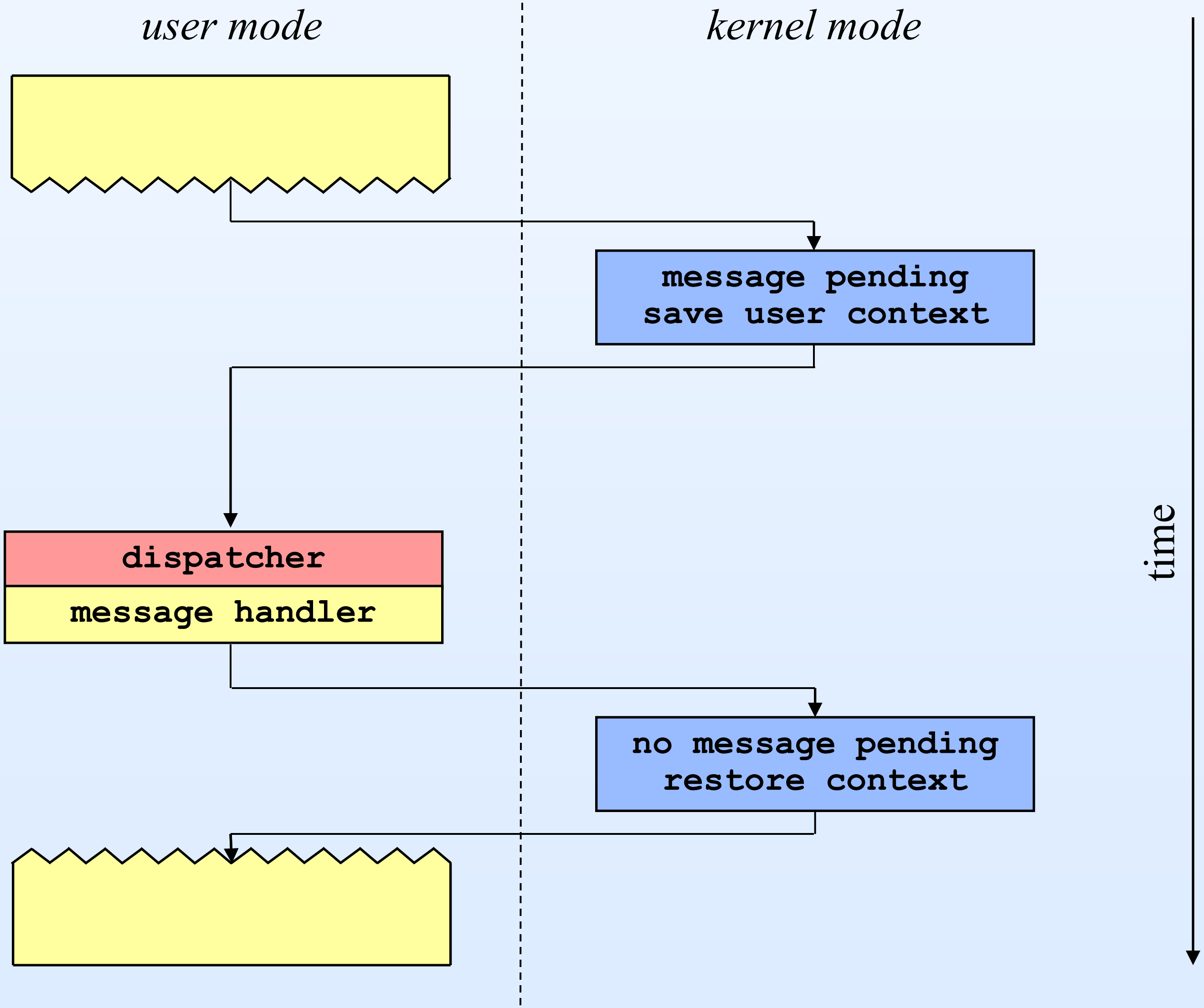
Kernel-Mediated Control Transfers



Intercepting Linux Signals



Windows Messages


user mode

kernel mode

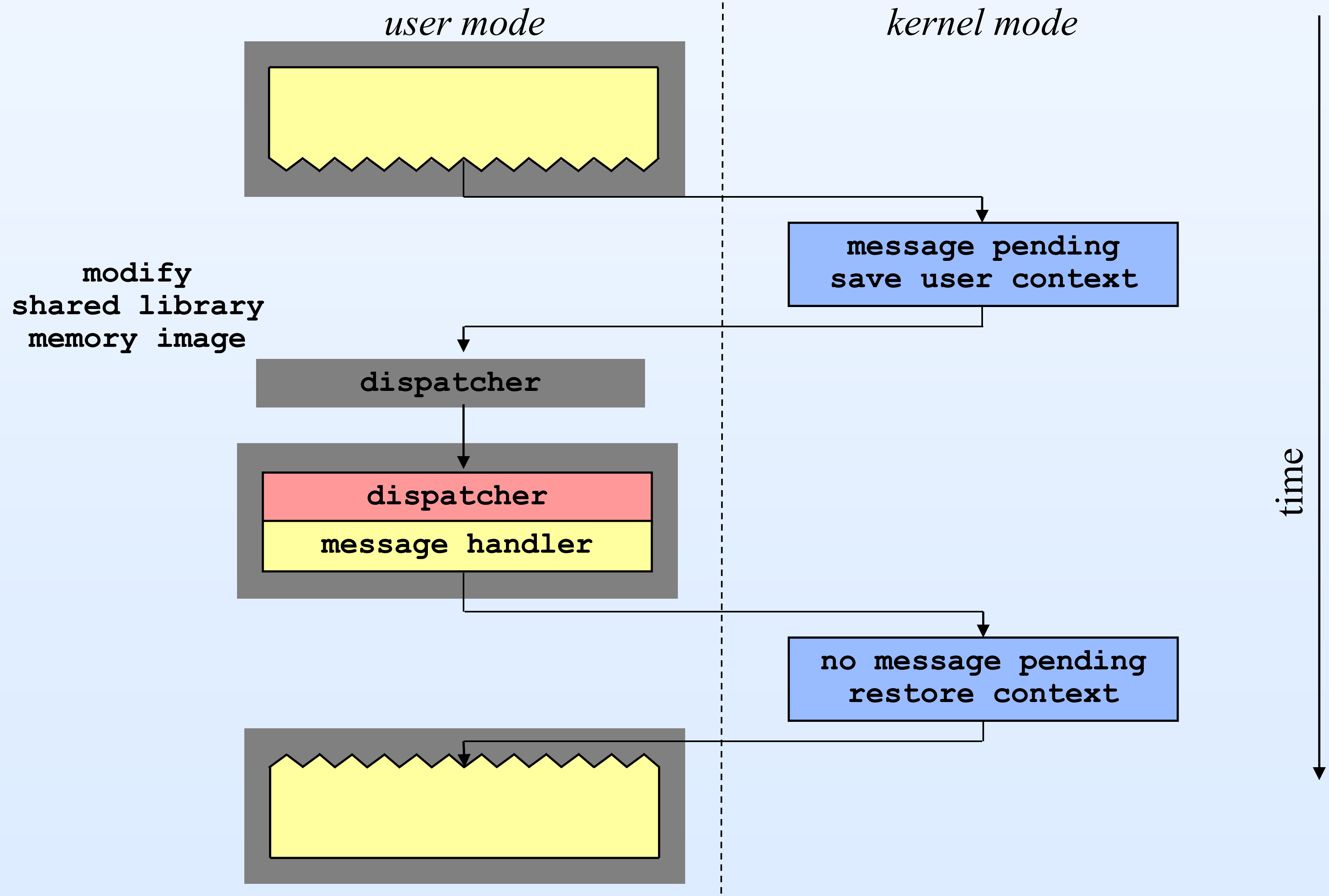
```
message pending
save user context
```

```
dispatcher
```

```
message handler
```

```
no message pending
restore context
```

Intercepting Windows Messages



user mode

kernel mode

message pending
save user context

modify
shared library
memory image

dispatcher

dispatcher

message handler

no message pending
restore context

time

Must Monitor System Calls

- To maintain control:
  - Calls that affect the flow of control: register signal handler, create thread, set thread context, etc.
- To maintain transparency:
  - Queries of modified state app should not see
- To maintain cache consistency:
  - Calls that affect the address space
- To support cache eviction:
  - Interruptible system calls must be redirected

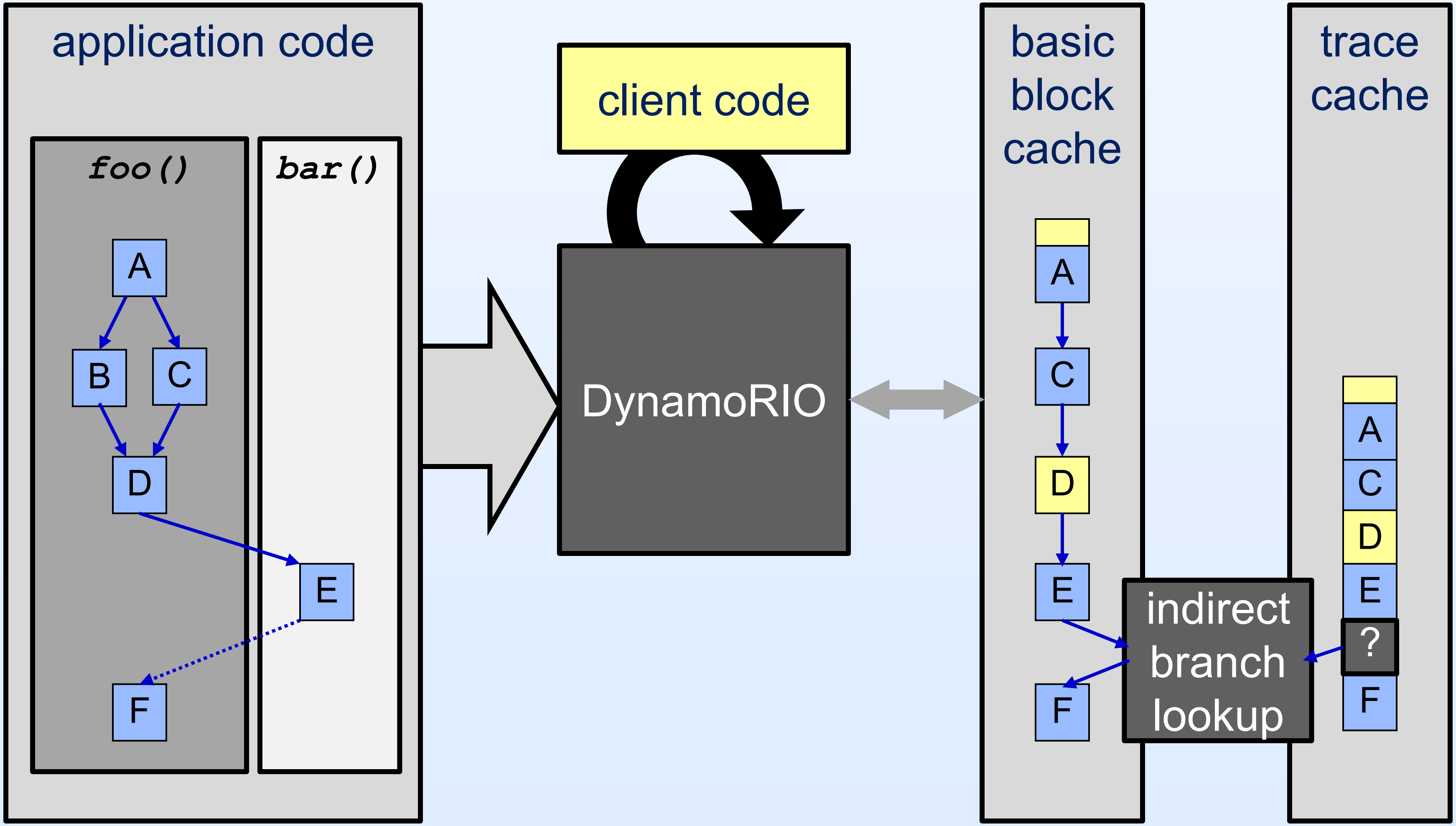
Operating System Dependencies

- System calls and their numbers
  - Monitor application’s usage, as well as for our own resource management
  - Windows changes the numbers each major rel
- Details of kernel-mediated control flow
  - Must emulate how kernel delivers events
- Initial injection
  - Once in, follow child processes

Overview Outline

- Efficient
- Transparent
- Comprehensive
- Customizable
  - Clients
  - Building and Deploying Tools

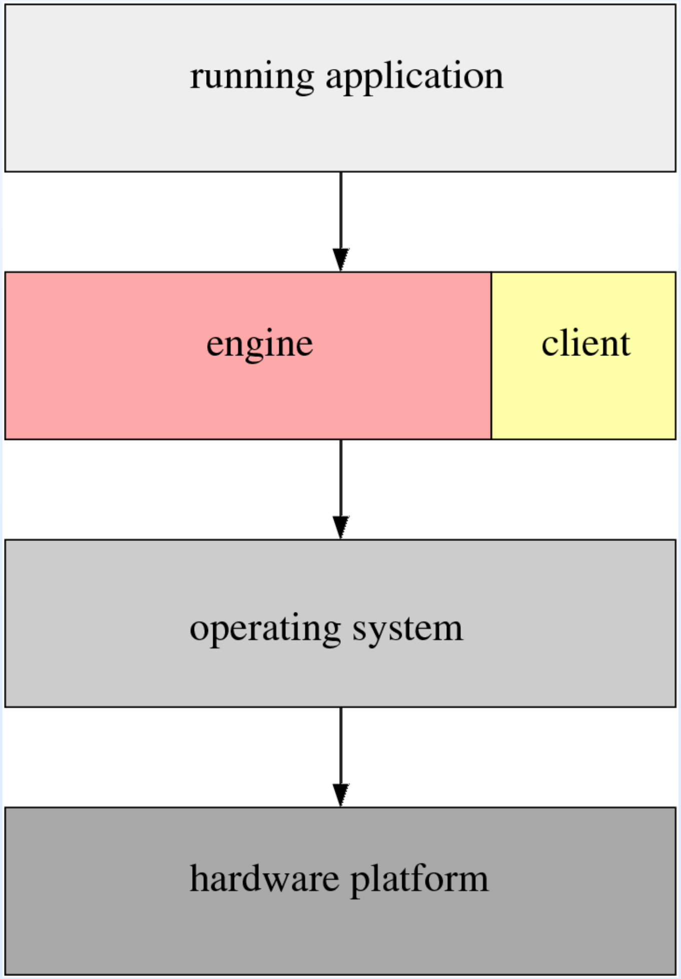
DynamoRIO + Client ⇒ Tool



Demo

Clients

- The engine exports an API for building a client
- System details abstracted away: client focuses on manipulating the code stream



Cross-Platform Clients

- DynamoRIO API presents a consistent interface that works across platforms
  - Windows versus Linux
  - 32-bit versus 64-bit
  - Thread-private versus thread-shared
- Same client source code generally works on all combinations of platforms
- Some exceptions, noted in the documentation

Building a Client

- Include DR API header file
  - `#include “dr_api.h”`
- Set platform defines
  - WINDOWS or LINUX
  - X86_32 or X86_64
- Export a dr_init function
  - `DR_EXPORT void dr_init (client_id_t client_id)`
- Build a shared library

Auto-Configure Using CMake

```
add_library(myclient SHARED myclient.c)
find_package(DynamoRIO)
if (NOT DynamoRIO_FOUND)
  message(FATAL_ERROR "DynamoRIO package
      required to build")
endif(NOT DynamoRIO_FOUND)
configure_DynamoRIO_client(myclient)
```

CMake

- Build system converted to CMake when open-sourced
  - Switch from frozen toolchain to supporting range of tools
- CMake generates build files for native compiler of choice
  - Makefiles for UNIX, nmake, etc.
  - Visual Studio project files
- http://www.cmake.org/

DynamoRIO Extensions

- DynamoRIO API is extended via libraries called Extensions
- Both static and shared supported
- Built and packaged with DynamoRIO
- Easy for a client to use
  - `use_DynamoRIO_extension(myclient extensionname)`

Operating System Dependencies

- System calls and their numbers
  - Monitor application’s usage, as well as for our own resource management
  - Windows changes the numbers each major rel
- Details of kernel-mediated control flow
  - Must emulate how kernel delivers events
- Initial injection
  - Once in, follow child processes

DynamoRIO Extensions, Cont’d

- Current Extensions:
  - *drsyms*: symbol lookup (currently Windows-only)
  - *drcontainers*: hashtable
  - *drmgr*: multi-instrumentation mediation
  - *drwrap*: function wrapping and replacing
  - *drutil*: memory tracing, string loop expansion
- Coming soon:
  - *drreg:* register stealing and allocating
  - *Umbra*: shadow memory framework
  - *Your utility library or framework contribution!*

Application Configuration

- File-based scheme
- Per-user local files
  - $HOME/.dynamorio/ on Linux
  - $USERPROFILE/dynamorio/ on Windows
- Global files
  - /etc/dynamorio/ on Linux
  - Registry-specified directory on Windows
- Files are lists of var=value

Deploying Clients

- One-step configure-and-run usage model:
  - drrun <client> <options> <app cmdline>
  - Uses an invisible temporary one-time configuration file
  - Overrides any regular config file
- Two-step usage model giving more control over children:
  - drconfig –reg <appname> <client> <options>
  - drinject <app cmdline>
- Systemwide injection:
  - drconfig –syswide_on –reg <appname> <client> <options>
  - <run app normally>

Deploying Clients On Linux

- drrun and drinject scripts: LD_PRELOAD-based
  - Take over after statically-dependent shared libs but before exe
- Suid apps ignore LD_PRELOAD
  - Place libdrpreload.so's full path in /etc/ld.so.preload
  - Copy libdynamorio.so to /usr/lib
- In the future:
  - Attach
  - Earliest injection

Deploying Clients On Windows

- drinject and drrun injection
  - Currently after all shared libs are initialized
- From-parent injection
  - Early: before any shared libs are loaded
- Systemwide injection via –syswide_on
  - Requires administrative privileges
  - Launch app normally: no need to run via drinject/drrun
  - Moderately early: during user32.dll initialization
- In the future:
  - Earliest injection for drrun/drinject and from-parent

Following Child Processes

- Runtime option –follow_children
  - Default on: follow all children
- Whitelist
  - -no_follow_children and configure files for whitelist
- Blacklist
  - -follow_children and configure files –norun for blacklist
  - *drconfig -norun* to create do-not-follow config file

Non-Standard Deployment

- drdecode
  - Static IA-32/AMD64 decoding/encoding/instruction manipulation library
- Standalone API
  - Use DynamoRIO as a library of IA-32/AMD64 manipulation routines plus cross-platform file i/o, locks, etc.
- Start/Stop API
  - Can instrument source code with where DynamoRIO should control the application

Runtime Options

- Pass options to drconfig/drrun
- A large number of options; the most relevant are:
  - -code_api
  - -client <client lib> <client ops> <client id>
  - -thread_private
  - -follow_children
  - -opt_cleancall
  - -tracedump_text and –tracedump_binary
  - -prof_pcs

Runtime Options For Debugging

- Notifications:
  - -stderr_mask 0xN
  - -msgbox_mask 0xN
- Windows:
  - -no_hide
- Debug-build-only:
  - -loglevel N
  - -ignore_assert_list '*'

Examples, Part 1

1:30-1:40	Welcome + DynamoRIO History
1:40-2:40	DynamoRIO Overview
2:40-3:00	Examples, Part 1
3:00-3:15	*Break*
3:15-4:00	DynamoRIO API
4:00-4:45	Examples, Part 2
4:45-5:00	Feedback

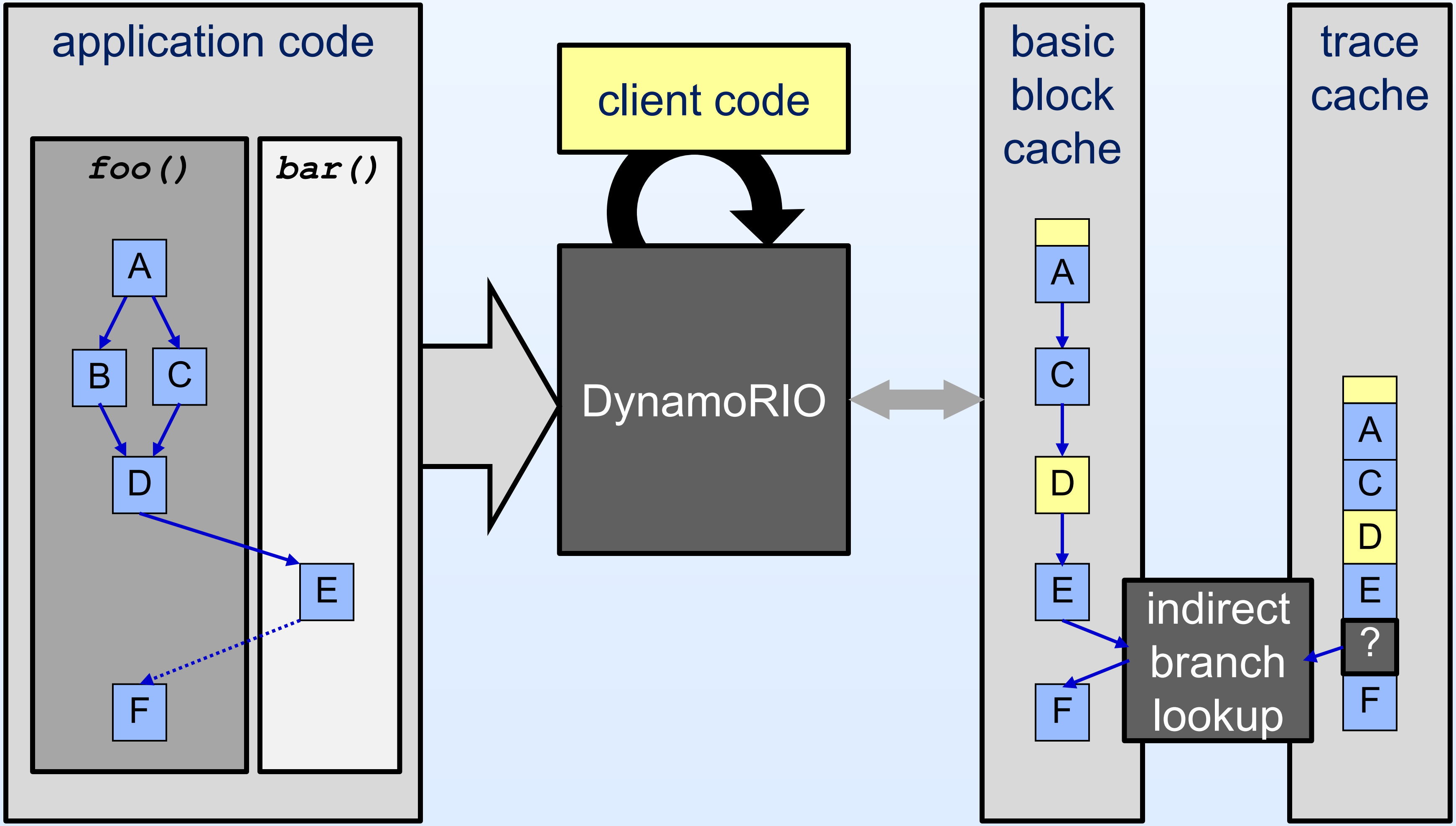
DynamoRIO API

1:30-1:40	Welcome + DynamoRIO History
1:40-2:40	DynamoRIO Overview
2:40-3:00	Examples, Part 1
3:00-3:15	*Break*
3:15-4:00	DynamoRIO API
4:00-4:45	Examples, Part 2
4:45-5:00	Feedback

DynamoRIO API Outline

- Building and Deploying
- Events
- Utilities
- Instruction Manipulation
- State Translation
- Comparison with Pin
- Troubleshooting

DynamoRIO + Client ⇨ Tool



Client Events: Code Stream

- Client has opportunity to inspect and potentially modify every single application instruction, immediately before it executes
- Entire application code stream
  - Basic block creation event: can modify the block
  - For comprehensive instrumentation tools
- Or, focus on hot code only
  - Trace creation event: can modify the trace
  - Custom trace creation: can determine trace end condition
  - For optimization and profiling tools

Simplifying Client View

- Several optimizations disabled
  - Elision of unconditional branches
  - Indirect call to direct call conversion
  - Shared cache sizing
  - Process-shared and persistent code caches
- Future release will give client control over optimizations

Basic Block Event

```
static dr_emit_flags_t
event_basic_block(void *drcontext, void *tag,
                  instrlist_t *bb, bool for_trace,
                  bool translating) {
    instr_t *inst;
    for (inst = instrlist_first(bb);
         inst != NULL;
         inst = instr_get_next(inst)) {
        /* … */
    }
    return DR_EMIT_DEFAULT;
}

DR_EXPORT void dr_init(client_id_t id) {
    dr_register_bb_event(event_basic_block);
}
```

Trace Event

```
static dr_emit_flags_t
event_trace(void *drcontext, void *tag,
            instrlist_t *trace, bool translating) {
    instr_t *inst;
    for (inst = instrlist_first(trace);
         inst != NULL;
         inst = instr_get_next(inst)) {
        /* … */
    }
    return DR_EMIT_DEFAULT;
}

DR_EXPORT void dr_init(client_id_t id) {
    dr_register_trace_event(event_trace);
}
```

Client Events: Application Actions

- Application thread creation and deletion
- Application library load and unload
- Application exception (Windows)
  - Client chooses whether to deliver or suppress
- Application signal (Linux)
  - Client chooses whether to deliver, suppress, bypass the app handler, or redirect control

Client Events: Application System Calls

- Application pre- and post- system call
  - Platform-independent system call parameter access
  - Client can modify:
    - Return value in post-, or set value and skip syscall in pre-
    - Call number
    - Params
  - Client can invoke an additional system call as the app

Client Events: Bookkeeping

- Initialization and Exit
  - Entire process
  - Each thread
  - Child of fork (Linux-only)
- Basic block and trace deletion during cache management
- Nudge received
  - Used for communication into client
- Itimer fired (Linux-only)

Multiple Clients

- It is each client's responsibility to ensure compatibility with other clients
  - Instruction stream modifications made by one client are visible to other clients
- At client registration each client is given a priority
  - dr_init() called in priority order (priority 0 called first and thus registers its callbacks first)
- Event callbacks called in reverse order of registration
  - Gives precedence to first registered callback, which is given the final opportunity to modify the instruction stream or influence DynamoRIO's operation
- drmgr Extension provides mediation among multiple components

DynamoRIO API Outline

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DynamoRIO API: General Utilities

- DynamoRIO provides safe utilities for transparency support
  - Separate stack
  - Separate memory allocation
  - Separate file I/O
- Utility options
  - Use DynamoRIO-provided utilities directly
  - Use shared libraries via DynamoRIO private loader
    - Malloc, etc. redirected to DynamoRIO-provided utilities
  - Use static libraries with dependencies redirected
- Risky for client to directly invoke system calls

DynamoRIO Heap

- Three flavors:
  - Thread-private: no synchronization; thread lifetime
  - Global: synchronized, process lifetime
  - “Non-heap”: for generated code, etc.
  - No header on allocated memory: low overhead but must pass size on free
- Leak checking
  - Debug build complains at exit if memory was not deallocated

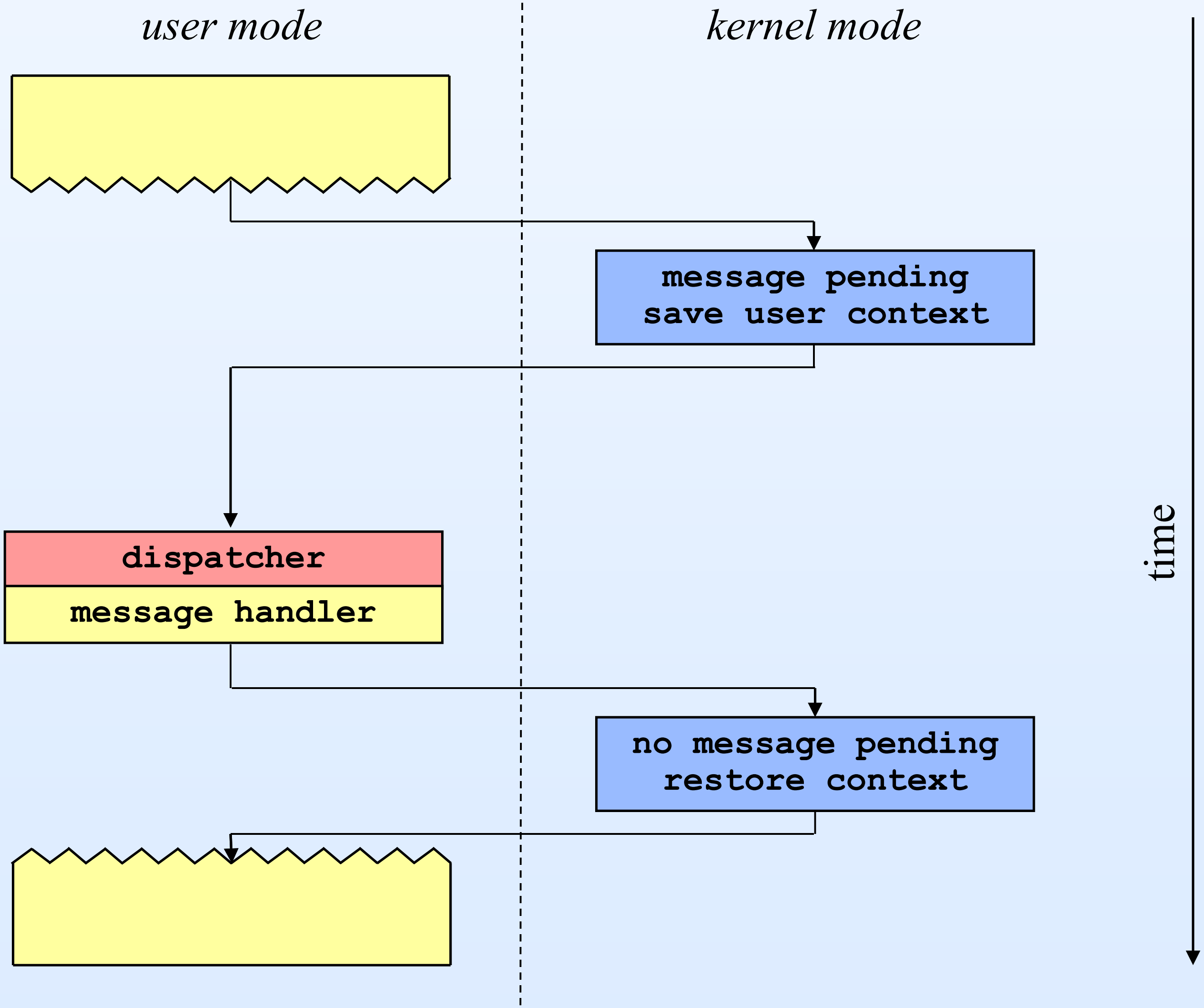
Thread Support

- Thread support
  - Thread-local storage
  - Callback-local storage
  - Simple mutexes
  - Read-write locks
  - Thread-private code caches, if requested
- Sideline support
  - Create new client-only thread
  - Thread-private itimer (Linux-only)
- Suspend and resume all other threads
  - Cannot hold locks while suspending

Thread-Local Storage (TLS)

- Absolute addressing
  - Thread-private only
- Application stack
  - Not reliable or transparent
- Stolen register
  - Performance hit
- Segment
  - Best solution for thread-shared

Callback-Local Storage (CLS)



Callback-Local Storage (CLS)

- Windows callbacks interrupt execution to process an event and later resume the suspended context
- TLS data from the suspended context will be overwritten during callback execution
- CLS data is saved at the interruption point and restored at the resumption point
- Whenever keeping persistent data specific to one context rather than overall execution, use CLS instead of TLS
  - Usually only needed when storing data specific to a system call in pre-syscall event and reading it back in post-syscall event
- Can be used for Linux signals as well
- Provided by the drmgr Extension

DynamoRIO API: General Utilities, Cont'd

- Communication
  - *Nudges:* ping from external process
  - File creation, reading, and writing
  - File descriptor isolation on Linux
- Safe read/write
  - Fault-proof read/write routines
  - Try/except facility

DynamoRIO API: General Utilities, Cont'd

- Application inspection
  - Address space querying
  - Module iterator
  - Processor feature identification
  - Symbol lookup
  - Function replacing and wrapping

Symbol Table Access

- The *drsyms* Extension provides access to symbol tables and debug information
- Currently supports the following:
  - Windows PDB
  - Linux ELF + DWARF2
  - Windows PECOFF + DWARF2
- API includes:
  - Address to symbol and line information
  - Symbol to address
  - Symbol enumeration and searching
  - Symbol demangling
  - Symbol types

Function Replacing and Wrapping

- *drwrap* Extension provides function replacing and wrapping
- Use dr_get_proc_address() to find library exports or drsyms Extension to find internal functions
- Function replacing replaces with *application code*
- Function wrapping calls pre and post callbacks that execute as client code around the target application function
- Arguments, return value, and whether the function is executed can all be examined and controlled

Third-Party Libraries

- Private loader inside DynamoRIO will load any external shared libraries a client imports from
  - Loads a duplicate copy of each library and tries to isolate from the application's copy
- On Windows, private loader does not support locating SxS libraries, so use static libc with VS2005 or VS2008
- C++ clients are built normally
- C clients by default do not link with libc
  - Set DynamoRIO_USE_LIBC variable prior to invoking configure_DynamoRIO_client() to use libc with a C client

Private Libraries

- Private loader on Windows
  - Not easy to fully isolate system data structures
    - PEB and key TEB fields are isolated
    - Some libraries like ntdll.dll are shared
  - To examine application state while in client code, use dr_switch_to_app_state()
- Private loader on Linux
  - Isolation is simpler and more complete

Optimal Transparency

- For best transparency: completely self-contained client
  - Imports only from DynamoRIO API
  - -nodefaultlibs or /nodefaultlib
- Alternatives to dynamic libc on Windows:
  - String and utility routines provided by forwards to ntdll
    - ntdll contains “mini-libc”
  - Cl.exe /MT static copy of C/C++ libraries
- Alternatives to dynamic libc on Linux:
  - For static C/C++ lib, use ld –wrap to redirect malloc to DR’s heap
  - Newer distributions don’t ship suitable static C/C++ lib

DynamoRIO API Outline

- Building and Deploying
- Events
- Utilities
- Instruction Manipulation
- State Translation
- Comparison with Pin
- Troubleshooting

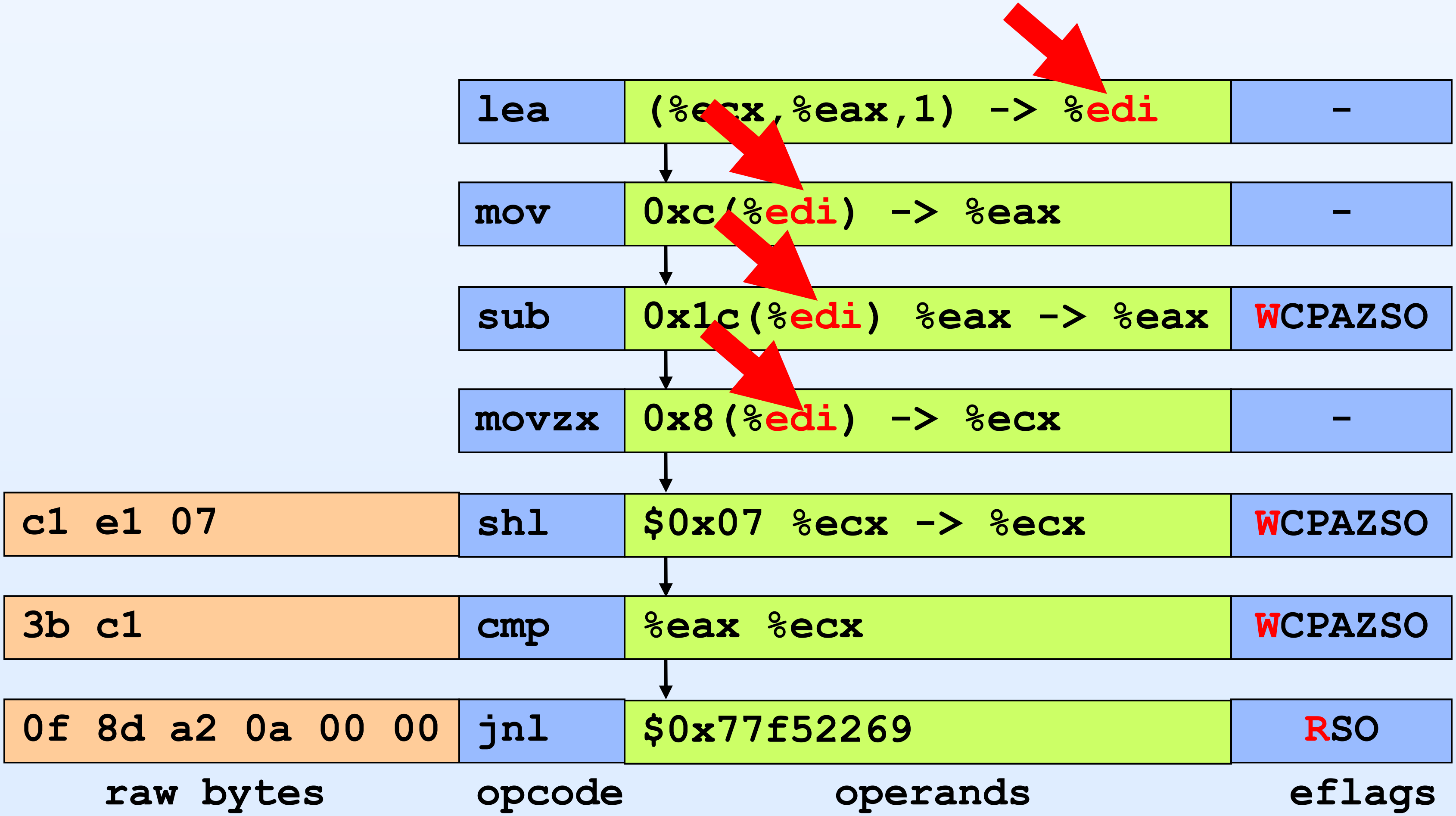
DynamoRIO API: Instruction Representation

- Full IA-32/AMD64 instruction representation
- Instruction creation with auto-implicit-operands
- Operand iteration
- Instruction lists with iteration, insertion, removal
- Decoding at various levels of detail
- Encoding

Instruction Representation

raw bytes	opcode	operands	eflags
8d 34 01	lea	(%ecx,%eax,1) -> %esi	-
8b 46 0c	mov	0xc(%esi) -> %eax	-
2b 46 1c	sub	0x1c(%esi) %eax -> %eax	WCPAZSO
0f b7 4e 08	movzx	0x8(%esi) -> %ecx	-
c1 e1 07	shl	$0x07 %ecx -> %ecx	WCPAZSO
3b c1	cmp	%eax %ecx	WCPAZSO
0f 8d a2 0a 00 00	jnl	$0x77f52269	RSO

Instruction Representation



raw bytes	opcode	operands	eflags
	lea	(%ecx,%eax,1) -> %edi	-
	mov	0xc(%edi) -> %eax	-
	sub	0x1c(%edi) %eax -> %eax	WCPAZSO
	movzx	0x8(%edi) -> %ecx	-
c1 e1 07	shl	$0x07 %ecx -> %ecx	WCPAZSO
3b c1	cmp	%eax %ecx	WCPAZSO
0f 8d a2 0a 00 00	jnl	$0x77f52269	RSO

Instruction Creation

- Method 1: use the INSTR_CREATE_opcode macros that fill in implicit operands automatically:

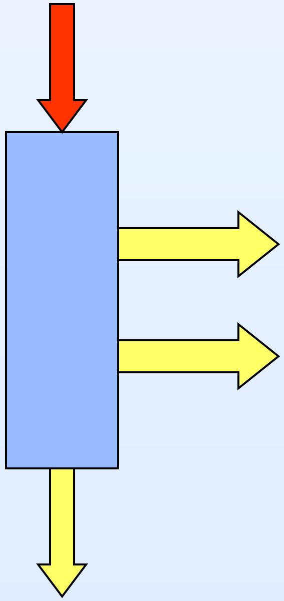
```
instr_t *instr = INSTR_CREATE_dec(dcontext,
   opnd_create_reg(DR_REG_EDX));
```

- Method 2: specify opcode + all operands (including implicit operands):

```
instr_t *instr = instr_create(dcontext);
instr_set_opcode(instr, OP_dec);
instr_set_num_opnds(dcontext, instr, 1, 1);
instr_set_dst(instr, 0, opnd_create_reg(DR_REG_EDX));
instr_set_src(instr, 0, opnd_create_reg(DR_REG_EDX));
```

Linear Control Flow

- Both basic blocks and traces are linear
- Instruction sequences are all single-entrance, multiple-exit
- Greatly simplifies analysis algorithms



64-Bit Versus 32-Bit

- 32-bit build of DynamoRIO only handles 32-bit code
- 64-bit build of DynamoRIO decodes/encodes both 32-bit and 64-bit code
  - Current release does not support executing applications that mix the two
- IR is universal: covers both 32-bit and 64-bit
  - Abstracts away underlying mode

64-Bit Thread and Instruction Modes

- When going to or from the IR, the thread mode and instruction mode determine how instrs are interpreted
- When decoding, current thread's mode is used
  - Default is 64-bit for 64-bit DynamoRIO
  - Can be changed with set_x86_mode()
- When encoding, that instruction's mode is used
  - When created, set to mode of current thread
  - Can be changed with instr_set_x86_mode()

64-Bit Clients

- Define X86_64 before including header files when building a 64-bit client
- Convenience macros for printf formats, etc. are provided
  - E.g.:

    -
      ```
      printf(“Pointer is ”PFX“\n”, p);
      ```
- Use “X” macros for cross-platform registers
  - DR_REG_XAX is DR_REG_EAX when compiled 32-bit, and DR_REG_RAX when compiled 64-bit

DynamoRIO API: Code Manipulation

- Processor information
- State preservation
  - Eflags, arith flags, floating-point state, MMX/SSE state
  - Spill slots, TLS, CLS
- Clean calls to C code
- Dynamic instrumentation
  - Replace code in the code cache
- Branch instrumentation
  - Convenience routines

Processor Information

- Processor type
  - proc_get_vendor(), proc_get_family(), proc_get_type(), proc_get_model(), proc_get_stepping(), proc_get_brand_string()
- Processor features
  - proc_has_feature(), proc_get_all_feature_bits()
- Cache information
  - proc_get_cache_line_size(), proc_is_cache_aligned(), proc_bump_to_end_of_cache_line(), proc_get_containing_page()
  - proc_get_L1_icache_size(), proc_get_L1_dcache_size(), proc_get_L2_cache_size(), proc_get_cache_size_str()

State Preservation

- Spill slots for registers
  - 3 fast slots, 6/14 slower slots
  - dr_save_reg(), dr_restore_reg(), and dr_reg_spill_slot_opnd()
  - From C code: dr_read_saved_reg(), dr_write_saved_reg()
- Dedicated TLS field for thread-local data
  - dr_insert_read_tls_field(), dr_insert_write_tls_field()
  - From C code: dr_get_tls_field(), dr_set_tls_field()
  - Parallel routines for CLS fields
- Arithmetic flag preservation
  - dr_save_arith_flags(), dr_restore_arith_flags()
- Floating-point/MMX/SSE state
  - dr_insert_save_fpstate(), dr_insert_restore_fpstate()

Clean Calls

```
if (instr_is_mbr(instr)) {
  app_pc address = instr_get_app_pc(instr);
  uint opcode = instr_get_opcode(instr);
  instr_t *nxt = instr_get_next(instr);
  dr_insert_clean_call(drcontext, ilist, nxt, (void *) at_mbr,
                       false/*don't need to save fp state*/,
                       2 /* 2 parameters */,
                       /* opcode is 1st parameter */
                       OPND_CREATE_INT32(opcode),
                       /* address is 2nd parameter */
                       OPND_CREATE_INTPTR(address));
}
```

- Saved interrupted application state can be accessed using dr_get_mcontext() and modified using dr_set_mcontext()

Clean Call Inlining

- Simple clean callees will be automatically optimized and potentially inlined
- -opt_cleancall runtime option controls aggressiveness
- Current requirements for inlining:
  - Leaf routine (may call PIC get-pc thunk)
  - Zero or one argument
  - Relatively short
- Compile the client with optimizations to improve clean call optimization
- Look in debug logfile for “CLEANCALL” to see results

Dynamic Instrumentation

- Thread-shared: flush all code corresponding to application address and then re-instrument when re-executed
  - Can flush from clean call, and use dr_redirect_execution() since cannot return to potentially flushed cache fragment
- Thread-private: can also replace particular fragment (does not affect other potential copies of the source app code)
  - dr_replace_fragment()

Flushing the Cache

- Immediately deleting or replacing individual code cache fragments is available for thread-private caches
  - Only removes from that thread's cache
- Two basic types of thread-shared flush:
  - Non-precise: remove all entry points but let target cache code be invalidated and freed lazily
  - Precise/synchronous:
    - Suspend the world
    - Relocate threads inside the target cache code
    - Invalidate and free the target code immediately

Flushing the Cache

- Thread-shared flush API routines:
  - dr_unlink_flush_region(): non-precise flush
  - dr_flush_region(): synchronous flush
  - dr_delay_flush_region():
    - No action until a thread exits code cache on its own
    - If provide a completion callback, synchronous once triggered
    - Without a callback, non-precise

Multi-Instrumentation Mediation

- The *drmgr* Extension provides mediation among multiple agents for basic block instrumentation and TLS/CLS access
- Divides instrumentation into four stages and orders the callbacks for each stage:
  - Application-to-application transformations
  - Application analysis
  - Instrumentation insertion
  - Instrumentation optimization
- Enables multi-library frameworks and modular clients

Memory Tracing

- *drutil* Extension provides utilities for memory address tracing:
  - Address acquisition
  - String loop expansion

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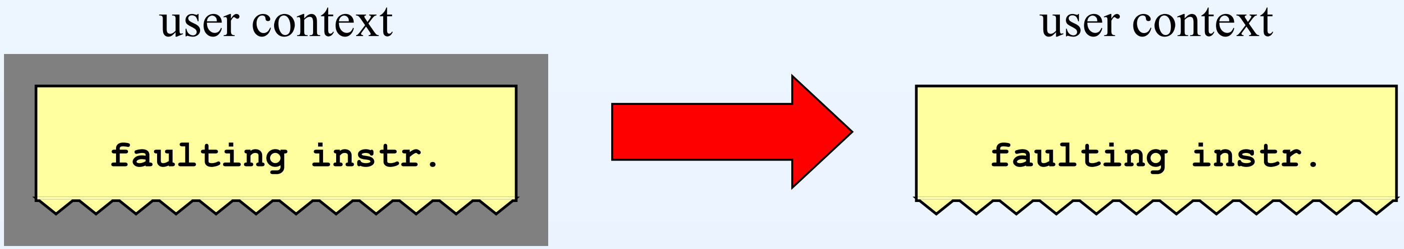
DynamoRIO API: Translation

- Translation refers to the mapping of a code cache machine state (program counter, registers, and memory) to its corresponding application state
  - The program counter always needs to be translated
  - Registers and memory may also need to be translated depending on the transformations applied when copying into the code cache

Translation Case 1: Fault



- Exception and signal handlers are passed machine context of the faulting instruction.
- For transparency, that context must be translated from the code cache to the original code location
- Translated location should be where the application would have had the fault or where execution should be resumed

Translation Case 2: Relocation

- If one application thread suspends another, or DynamoRIO suspends all threads for a synchronous cache flush:
  - Need suspended target thread in a safe spot
  - Not always practical to wait for it to arrive at a safe spot (if in a system call, e.g.)
- DynamoRIO forcibly relocates the thread
  - Must translate its state to the proper application state at which to resume execution

Translation Approaches

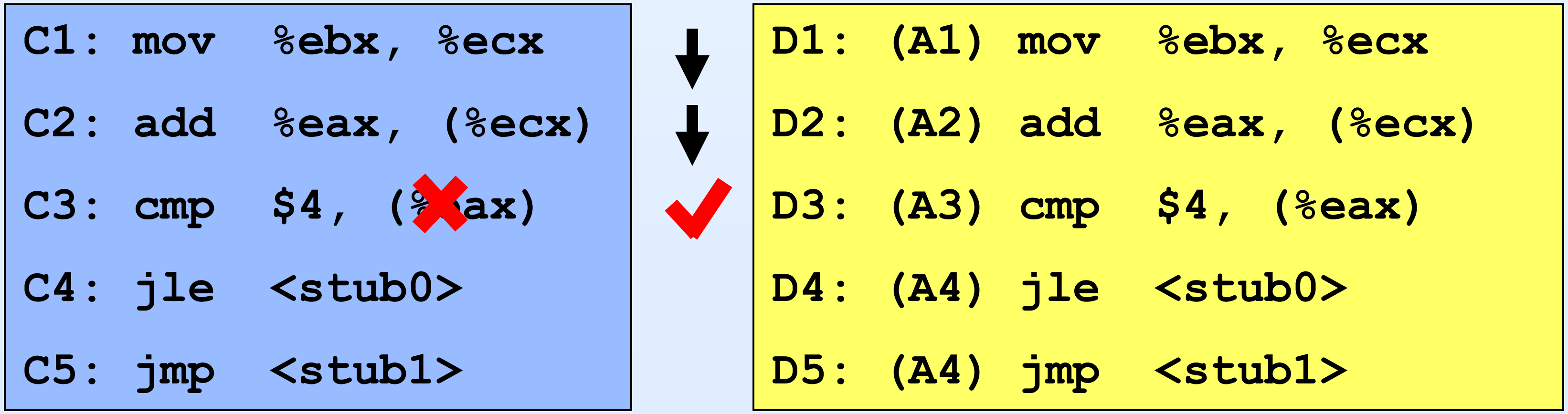
- Two approaches to program counter translation:
  - Store mappings generated during fragment building
    - High memory overhead (> 20% for some applications, because it prevents internal storage optimizations) even with highly optimized difference-based encoding. Costly for something rarely used.
  - Re-create mapping on-demand from original application code
    - Cache consistency guarantees mean the corresponding application code is unchanged
    - Requires idempotent code transformations
- DynamoRIO supports both approaches
  - The engine mostly uses the on-demand approach, but stored mappings are occasionally needed

Instruction Translation Field

- Each instruction contains a translation field
- Holds the application address that the instruction corresponds to
- Set via instr_set_translation()

Context Translation Via Re-Creation

```
A1: mov   %ebx, %ecx
A2: add   %eax, (%ecx)
A3: cmp   $4, (%eax)
A4: jle   710349fb
```



```
C1: mov   %ebx, %ecx
C2: add   %eax, (%ecx)
C3: cmp   $4, (%eax)
C4: jle   <stub0>
C5: jmp   <stub1>
```

```
D1: (A1) mov   %ebx, %ecx
D2: (A2) add   %eax, (%ecx)
D3: (A3) cmp   $4, (%eax)
D4: (A4) jle   <stub0>
D5: (A4) jmp   <stub1>
```

Meta vs. Non-Meta Instructions

- Non-meta instructions are treated as application instructions
  - They must have translations
  - Control flow changing instructions are modified to retain DynamoRIO control and result in cache populating
- Meta instructions are added instrumentation code
  - Not treated as part of the application (e.g., calls run natively)
  - Usually cannot fault, so translations not needed
- Meta instructions can reference application memory, or deliberately fault
  - A meta instruction that might fault must contain a translation
  - The client should handle any such fault
- Xref **`instr_set_ok_to_mangle()`** and **`instr_set_translation()`**

Client Translation Support

- Instruction lists passed to clients are annotated with translation information
  - Read via instr_get_translation()
  - Clients are free to delete instructions, change instructions and their translations, and add new meta and non-meta instructions (see dr_register_bb_event() for restrictions)
  - An idempotent client that restricts itself to deleting app instructions and adding non-faulting meta instructions can ignore translation concerns
  - DynamoRIO takes care of instructions added by API routines (insert_clean_call(), etc.)
- Clients can choose between storing or regenerating translations on a fragment by fragment basis.

Client Regenerated Translations

- Client returns DR_EMIT_DEFAULT from its bb or trace event callback
- Client bb & trace event callbacks are re-called when translations are needed with translating==true
- Client must exactly duplicate transformations performed when the block was generated
- Client must set translation field for all added non-meta instructions and all meta-may-fault instructions
  - This is true even if translating==false since DynamoRIO may decide it needs to store translations anyway

Client Stored Translations

- Client returns DR_EMIT_STORE_TRANSLATIONS from its bb or trace event callback
- Client must set translation field for all added non-meta instructions and all meta-may-fault instructions
- Client bb or trace hook will not be re-called with translating==true

Register State Translation

- Translation may be needed at a point where some registers are spilled to memory
  - During indirect branch or RIP-relative mangling, e.g.
- DynamoRIO walks fragment up to translation point, tracking register spills and restores
  - Special handling for stack pointer around indirect calls and returns
- DynamoRIO tracks client spills and restores *implicitly* added by API routines
  - Clean calls, etc.
  - Explicit spill/restore (e.g., dr_save_reg()) client's responsibility

Client Register State Translation

- If a client adds its own register spilling/restoring code or changes register mappings it must register for the restore state event to correct the context
- The same event can also be used to fix up the application's view of memory
- DynamoRIO does not internally store this kind of translation information ahead of time when the fragment is built
  - The client must maintain its own data structures

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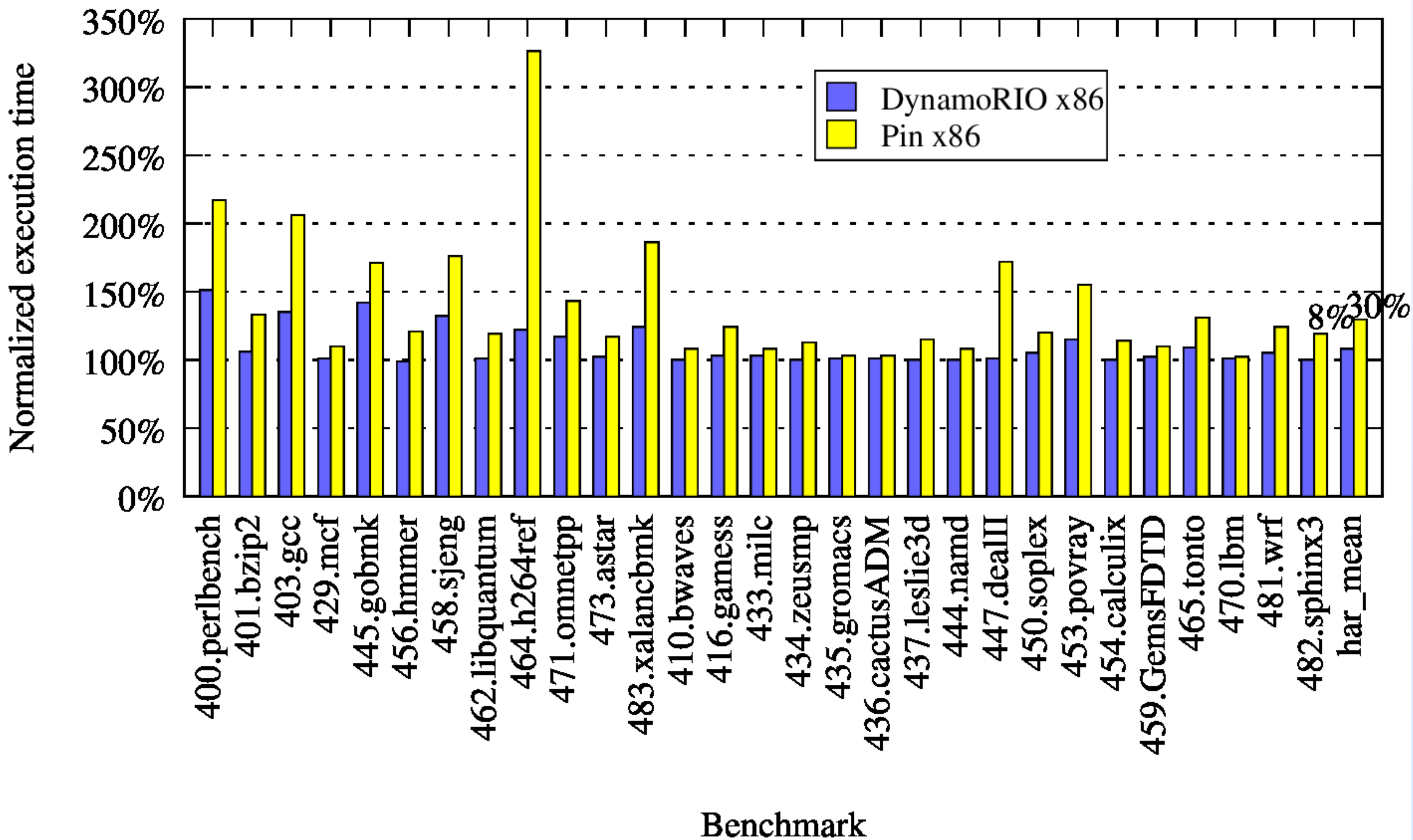
DynamoRIO versus Pin

- Basic interface is fundamentally different
- Pin = insert callout/trampoline only
  - Not so different from tools that modify the original code: Dyninst, Vulcan, Detours
  - Uses code cache only for transparency
- DynamoRIO = arbitrary code stream modifications
  - Only feasible with a code cache
  - Takes full advantage of power of code cache
  - General IA-32/AMD64 decode/encode/IR support

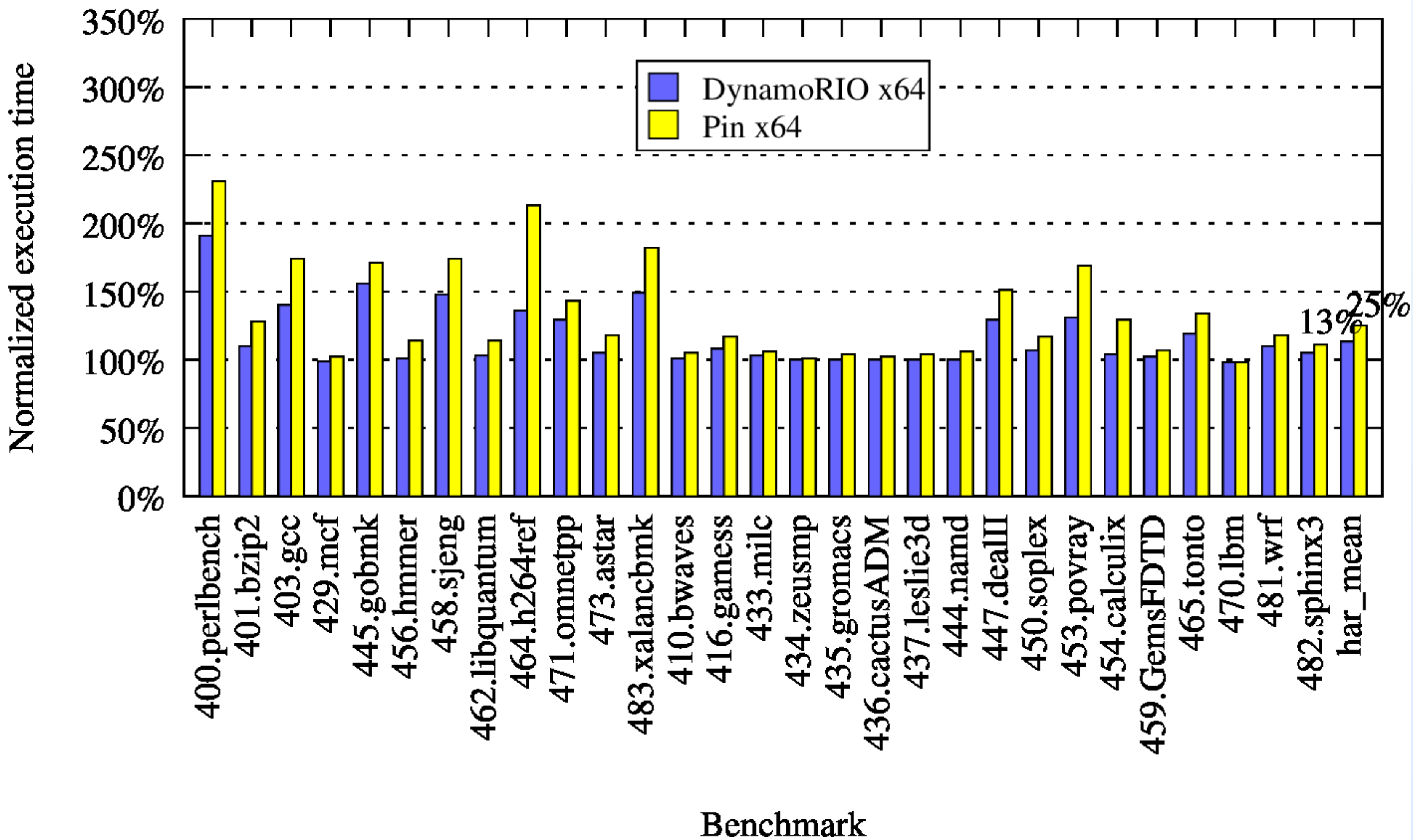
DynamoRIO versus Pin

- Pin = insert callout/trampoline only
  - Pin tries to inline and optimize
  - Client has little control or guarantee over final performance
- DynamoRIO = arbitrary code stream modifications
  - Client has full control over all inserted instrumentation
  - Result can be significant performance difference
    - PiPA Memory Profiler + Cache Simulator:
      3.27x speedup w/ DynamoRIO vs 2.6x w/ Pin
  - DynamoRIO also performs callout (“clean call”) optimization and inlining just like Pin for less performance-focused clients

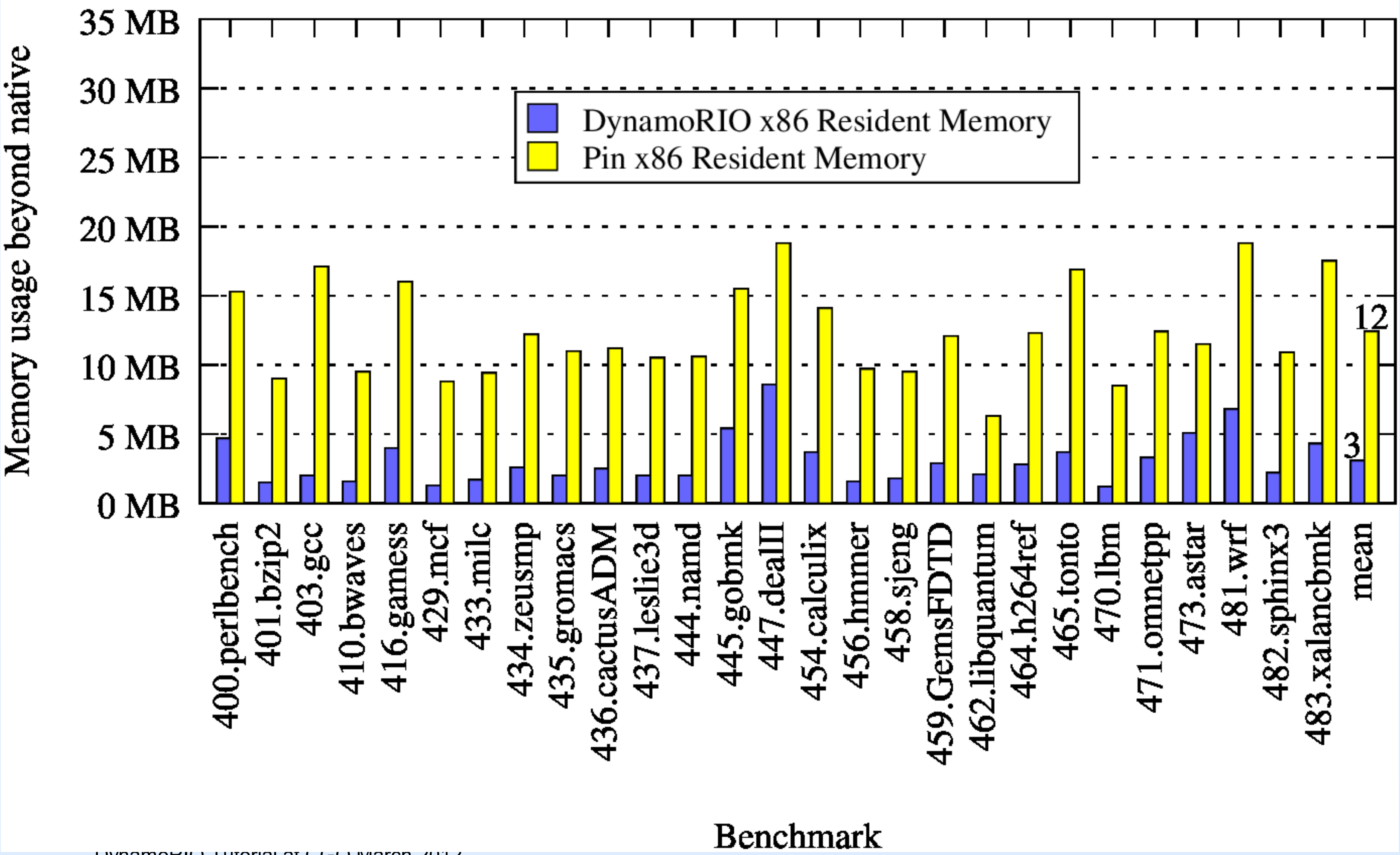
Base Performance Comparison (No Tool)



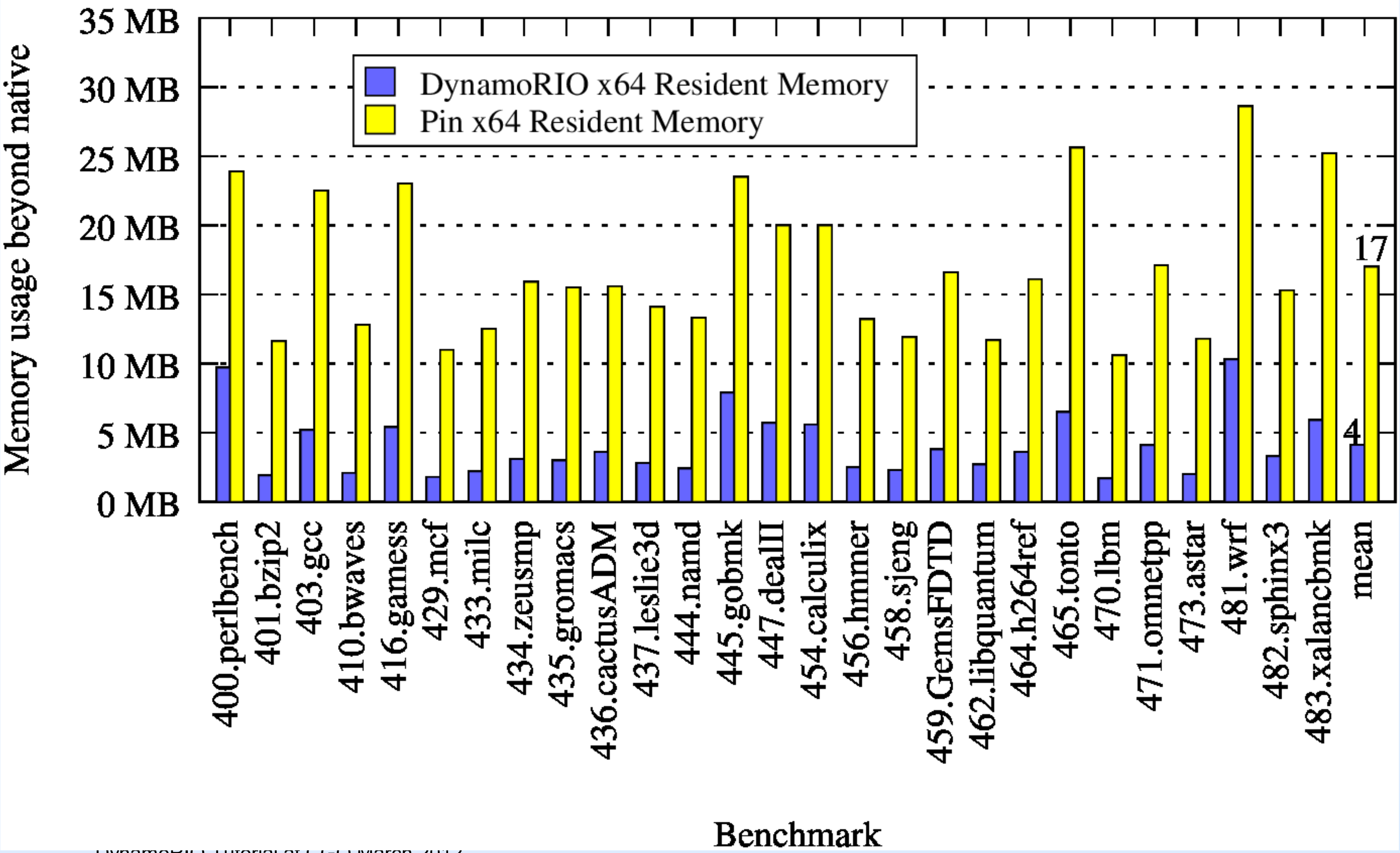
Base Performance Comparison (No Tool)



Base Memory Comparison (No Tool)



Base Memory Comparison (No Tool)



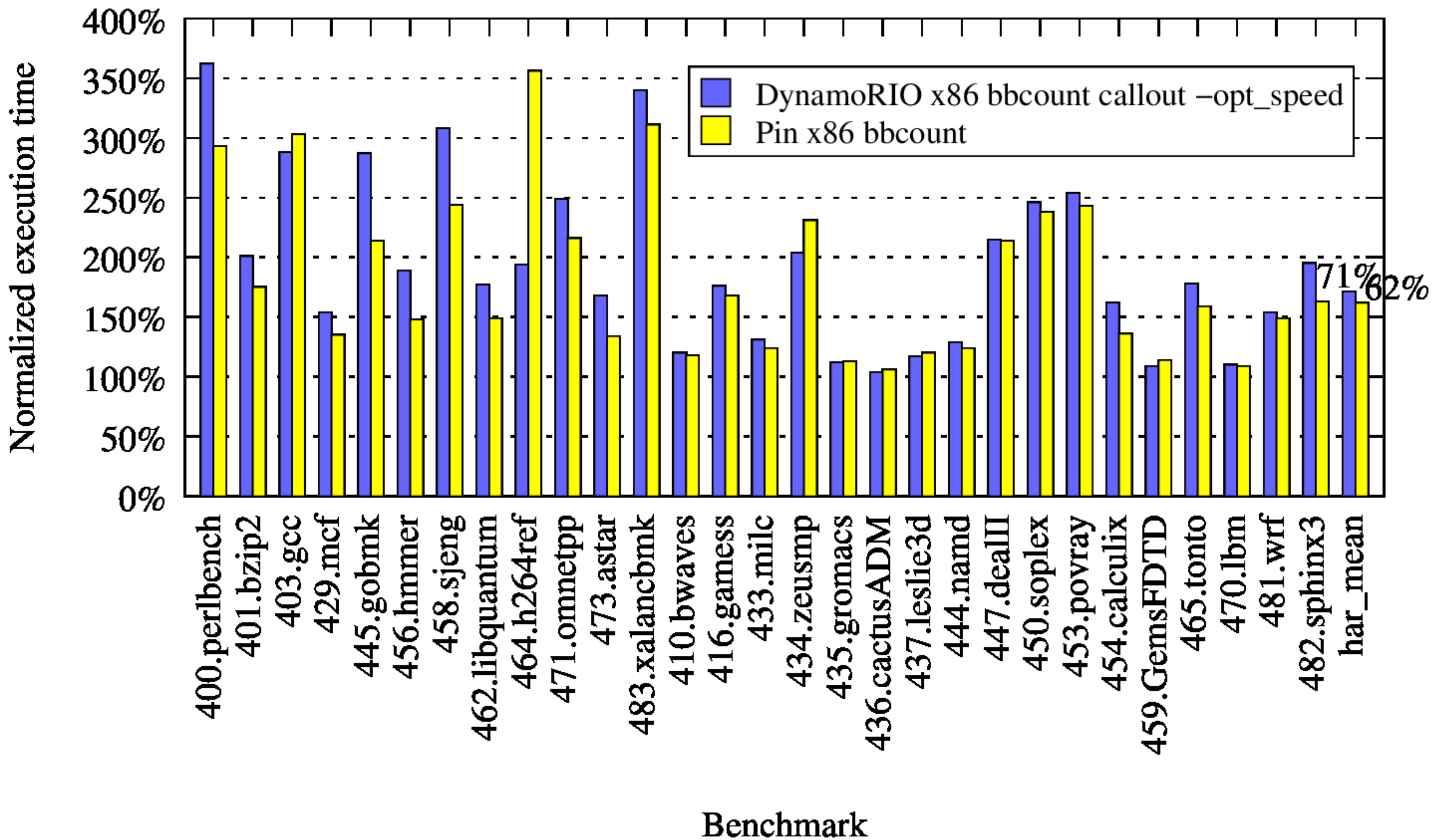
BBCount Pin Tool

```
static int bbcount;

VOID PIN_FAST_ANALYSIS_CALL docount() { bbcount++; }

VOID Trace(TRACE trace, VOID *v) {
    for (BBL bbl = TRACE_BblHead(trace); BBL_Valid(bbl); bbl = BBL_Next(bbl)) {
        BBL_InsertCall(bbl, IPOINT_ANYWHERE, AFUNPTR(docount),
                       IARG_FAST_ANALYSIS_CALL, IARG_END);
    }
}

int main(int argc, CHAR *argv[]) {
    PIN_InitSymbols();
    PIN_Init(argc, argv);
    TRACE_AddInstrumentFunction(Trace, 0);
    PIN_StartProgram();
    return 0;
}
```

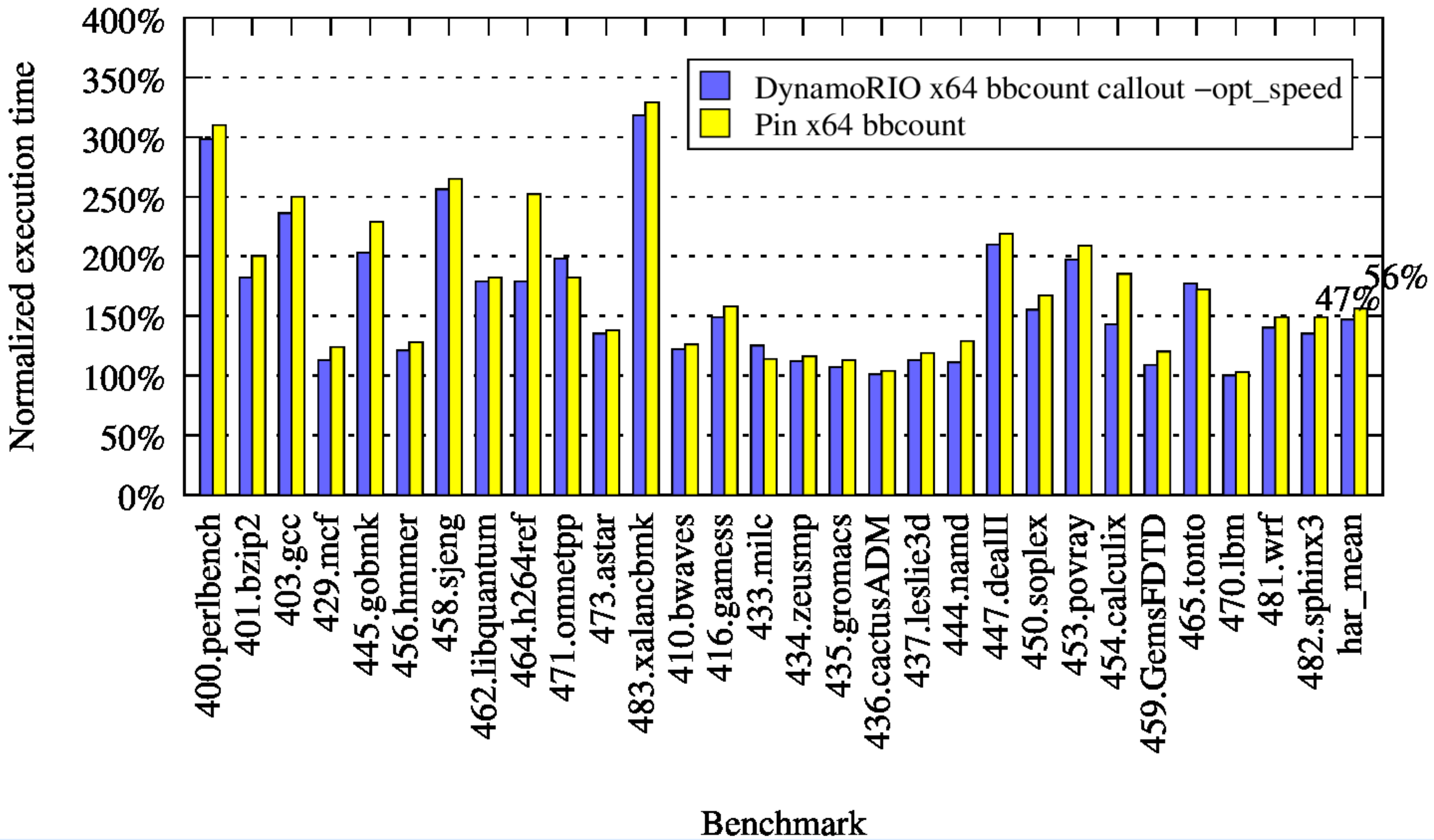
Simple BBCount DynamoRIO Tool

```
static int bbcount;

static void docount() { bbcount++; }

static dr_emit_flags_t
event_basic_block(void *drcontext, void *tag, instrlist_t *bb,
                  bool for_trace, bool translating) {
    dr_insert_clean_call(drcontext, bb, instrlist_first(bb), docount, false, 0);
    return DR_EMIT_DEFAULT;
}

DR_EXPORT void dr_init(client_id_t id) {
    dr_register_bb_event(event_basic_block);
}
```

BBCount Performance Comparison: Simple Tool



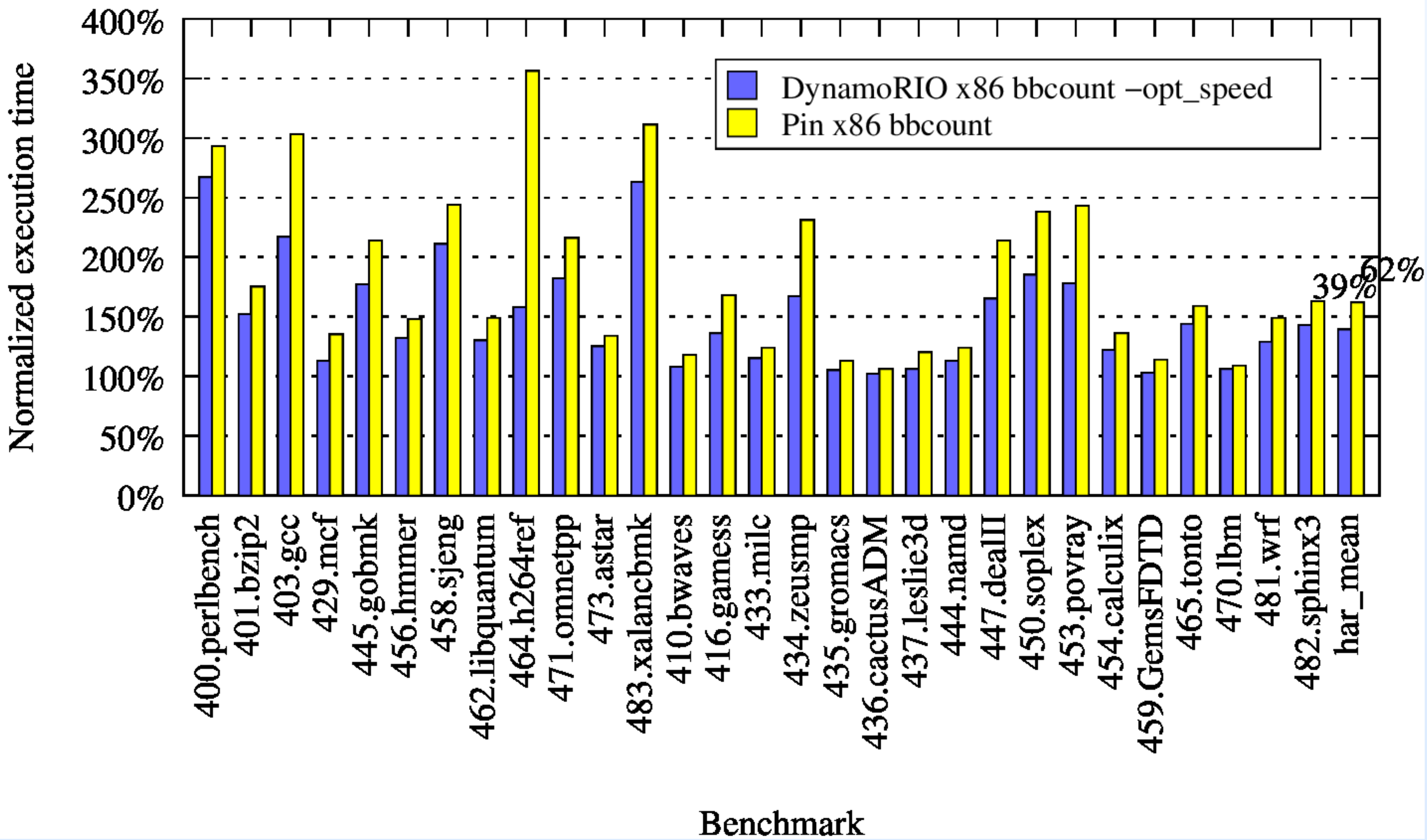
BBCount Performance Comparison: Simple Tool



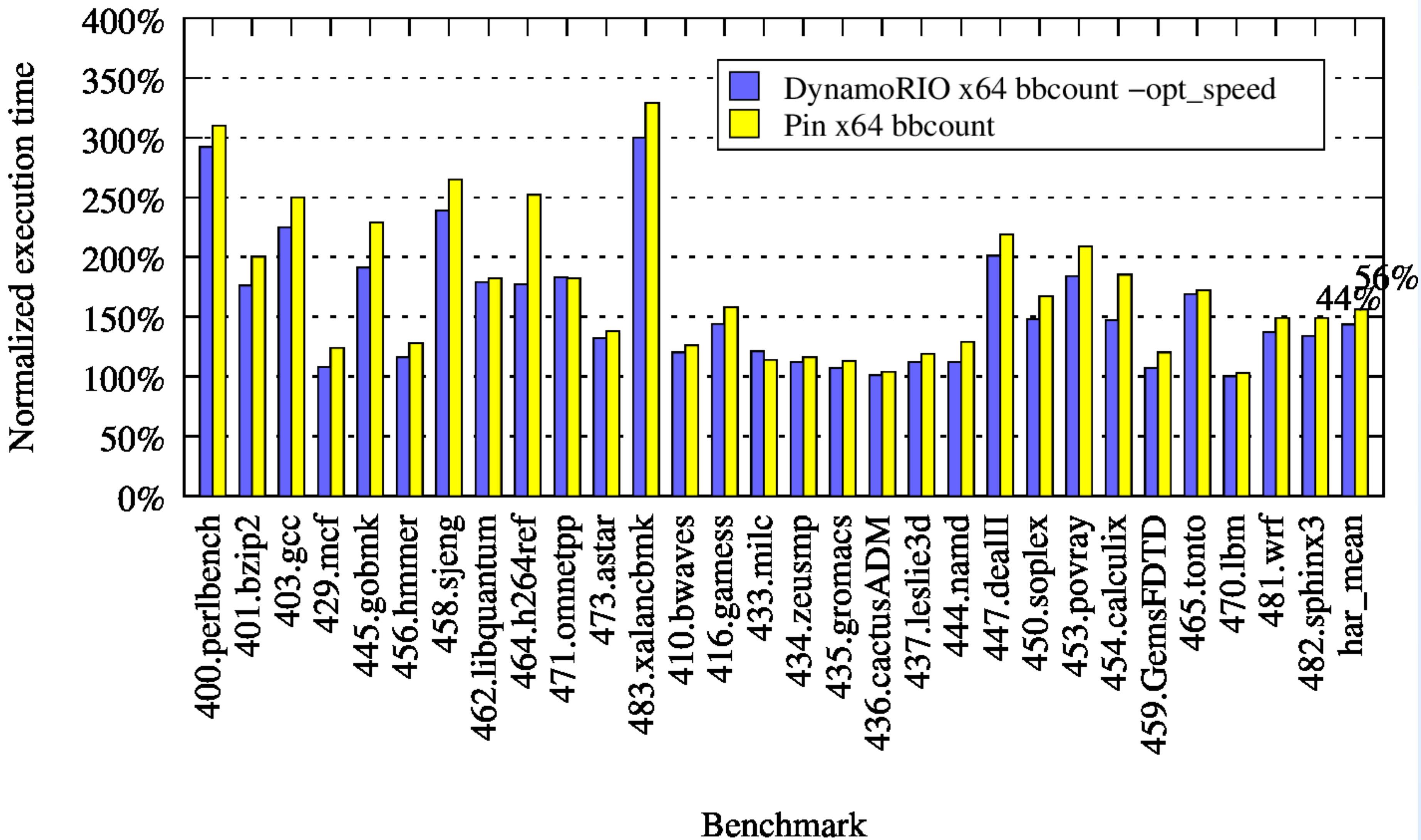
Optimized BBCount DynamoRIO Tool

```
static int global_count;

static dr_emit_flags_t
event_basic_block(void *drcontext, void *tag, instrlist_t *bb,
                  bool for_trace, bool translating) {
    instr_t *instr, *first = instrlist_first(bb);
    uint flags;
    /* Our inc can go anywhere, so find a spot where flags are dead.
     * Technically this can be unsafe if app reads flags on fault =>
     * stop at instr that can fault, or supply runtime op */
    for (instr = first; instr != NULL; instr = instr_get_next(instr)) {
        flags = instr_get_arith_flags(instr);
        /* OP_inc doesn't write CF but not worth distinguishing */
        if (TESTALL(EFLAGS_WRITE_6, flags) && !TESTANY(EFLAGS_READ_6, flags))
            break;
    }
    if (instr == NULL)
        dr_save_arith_flags(drcontext, bb, first, SPILL_SLOT_1);
    instrlist_meta_preinsert(bb, (instr == NULL) ? first : instr,
        INSTR_CREATE_inc(drcontext, OPND_CREATE_ABSMEM((byte *)&global_count, OPSZ_4)));
    if (instr == NULL)
        dr_restore_arith_flags(drcontext, bb, first, SPILL_SLOT_1);
    return DR_EMIT_DEFAULT;
}

DR_EXPORT void dr_init(client_id_t id) {
    dr_register_bb_event(event_basic_block);
}
```

BBCount Performance Comparison: Opt Tool



BBCount Performance Comparison: Opt Tool



DynamoRIO API Outline

- Building and Deploying
- Events
- Utilities
- Instruction Manipulation
- State Translation
- Comparison with Pin
- Troubleshooting

Obtaining Help

- Read the documentation
  - http://dynamorio.org/docs/
- Look at the sample clients
  - In the documentation
  - In the release package: samples/
- Ask on the DynamoRIO Users discussion forum/mailing list
  - http://groups.google.com/group/dynamorio-users

Debugging Clients

- Use the DynamoRIO debug build for asserts
  - Often point out the problem
- Use logging
  - -loglevel N
  - stored in logs/ subdir of DR install dir
- Attach a debugger
  - gdb or windbg
  - -msgbox_mask 0xN
  - -no_hide
  - windbg: .reload myclient.dll=0xN
- More tips:
  - http://code.google.com/p/dynamorio/wiki/Debugging

Reporting Bugs

- Search the Issue Tracker off http://dynamorio.org first
  - http://code.google.com/p/dynamorio/issues/list
- File a new Issue if not found
- Follow conventions on wiki
  - http://code.google.com/p/dynamorio/wiki/BugReporting
  - CRASH, APP CRASH, HANG, ASSERT
- Example titles:
  - CRASH (1.3.1 calc.exe) vm_area_add_fragment:vmareas.c(4466)
  - ASSERT (1.3.0 suite/tests/common/segfault) study_hashtable:fragment.c:1745 ASSERT_NOT_REACHED

Changes From Prior Releases

- 3.0+ is mostly backward compatible with 2.0 and above
- Source and binary compatibility changes:
  - dr_mcontext_t struct layout (for AVX)
  - dr_mcontext flags and size field must be set prior to usage
  - drsyms API changes: flags parameters added to routines
  - drwrap_unwrap signature change
- Also mostly backward compatible with 1.0 and above
  - Except configuration and deployment scheme and tools: switched to file-based scheme to support unprivileged and parallel execution on Windows
- Not backward compatible with 0.9.1-0.9.5

New Features

- 3.2 highlights:
  - PECOFF + DWARF2 support in drsyms
  - drwrap high-performance options
- 3.1 highlights:
  - Linux private loader
  - Linux ELF + DWARF2 support in drsyms
  - drutil Extension
  - drdecode static decoding library

Examples, Part 2

1:30-1:40	Welcome + DynamoRIO History
1:40-2:40	DynamoRIO Overview
2:40-3:00	Examples, Part 1
3:00-3:15	*Break*
3:15-4:00	DynamoRIO API
4:00-4:45	Examples, Part 2
4:45-5:00	Feedback

Feedback

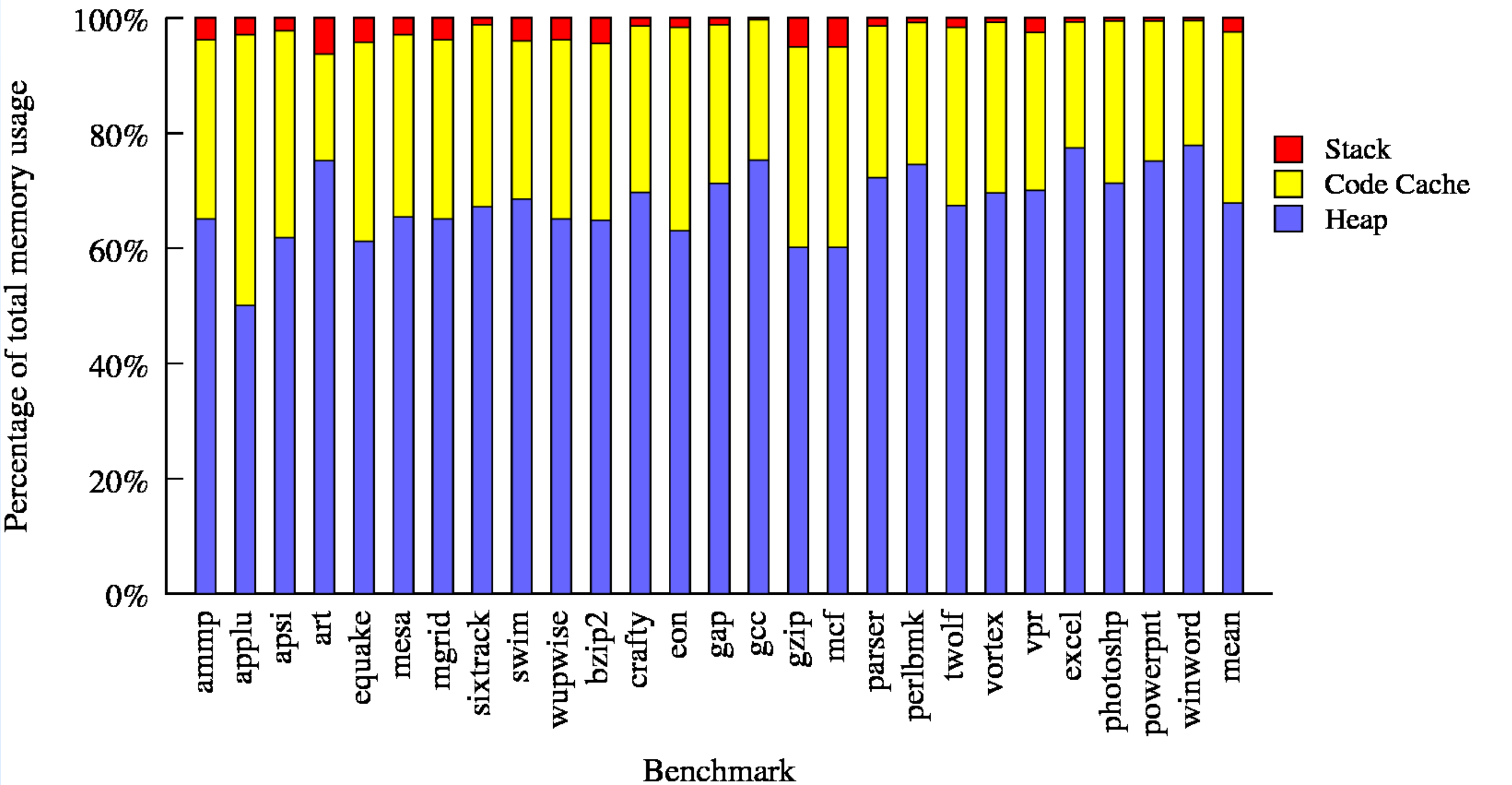
1:30-1:40	Welcome + DynamoRIO History
1:40-2:40	DynamoRIO Overview
2:40-3:00	Examples, Part 1
3:00-3:15	*Break*
3:15-4:00	DynamoRIO API
4:00-4:45	Examples, Part 2
4:45-5:00	Feedback

Optional Slides: Advanced Code Cache Topics

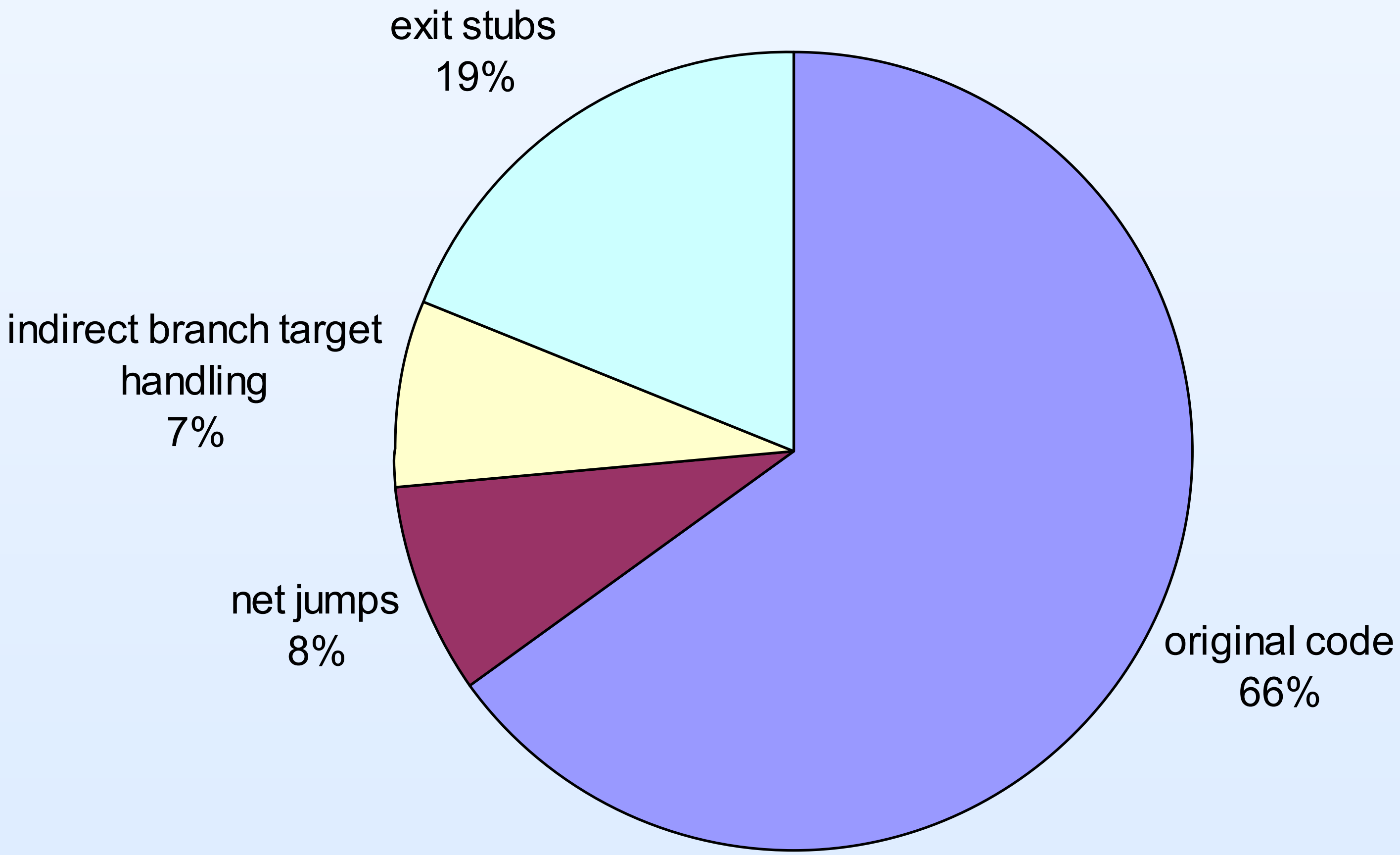
Overview Outline

- Efficient
  - Software code cache overview
  - Thread-shared code cache
  - Cache capacity limits
  - Data structures
- Transparent
- Comprehensive
- Customizable

Added Memory Breakdown



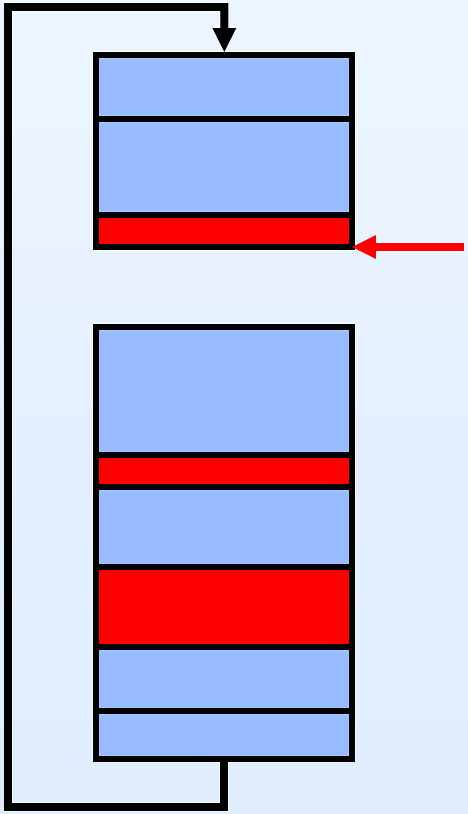
Code Expansion



Cache Capacity Challenges

- How to set an upper limit on the cache size
  - Different applications have different working sets and different total code sizes
- Which fragments to evict when that limit is reached
  - Without expensive profiling or extensive fragmentation

Adaptive Sizing Algorithm



- Enlarge cache if warranted by percentage of new fragments that are *regenerated*
- Target *working set* of application: don't enlarge for once-only code
- Low-overhead, incremental, and reactive

Cache Capacity Settings

- Thread-private:
  - Working set size matching is on by default
  - Client may see blocks or traces being deleted in the absence of any cache consistency event
  - Can disable capacity management via
    - -no_finite_bb_cache
    - -no_finite_trace_cache
- Thread-shared:
  - Set to infinite size by default
  - Can enable capacity management via
    - -finite_shared_bb_cache
    - -finite_shared_trace_cache
- *Reset* triggered when hit up-front reservation

Overview Outline

- Efficient
  - Software code cache overview
  - Thread-shared code cache
  - Cache capacity limits
  - Data structures
- Transparent
- Comprehensive
- Customizable

Two Modes of Code Cache Operation

- Fine-grained scheme
  - Supports individual code fragment unlink and removal
  - Separate data structure per code fragment and each of its exits, memory regions spanned, and incoming links
- Coarse-grained scheme
  - No individual code fragment control
  - Permanent intra-cache links
  - No per-fragment data structures at all
  - Treat entire cache as a unit for consistency

Data Structures

- Fine-grained scheme
  - Data structures are highly tuned and compact
- Coarse-grained scheme
  - There are no data structures
  - Savings on applications with large amounts of code are typically 15%-25% of committed memory and 5%-15% of working set

Status in Current Release

- Fine-grained scheme
  - Current default
- Coarse-grained scheme
  - Select with –opt_memory runtime option
  - Possible performance hit on certain benchmarks
  - In the future will be the default option
  - Required for persisted and process-shared caches

Adaptive Level of Granularity

- Start with coarse-grain caches
  - Plus freezing and sharing/persisting
- Switch to fine-grain for individual modules or sub-regions of modules after significant consistency events, to avoid expensive entire-module flushes
  - Support simultaneous fine-grain fragments within coarse-grain regions for corner cases
- Match amount of bookkeeping to amount of code change
  - Majority of application code does not need fine-grain

Many Varieties of Code Caches

- Coarse-grained versus fine-grained
- Thread-shared versus thread-private
- Basic blocks versus traces

Optional Slides:
Dr. Memory

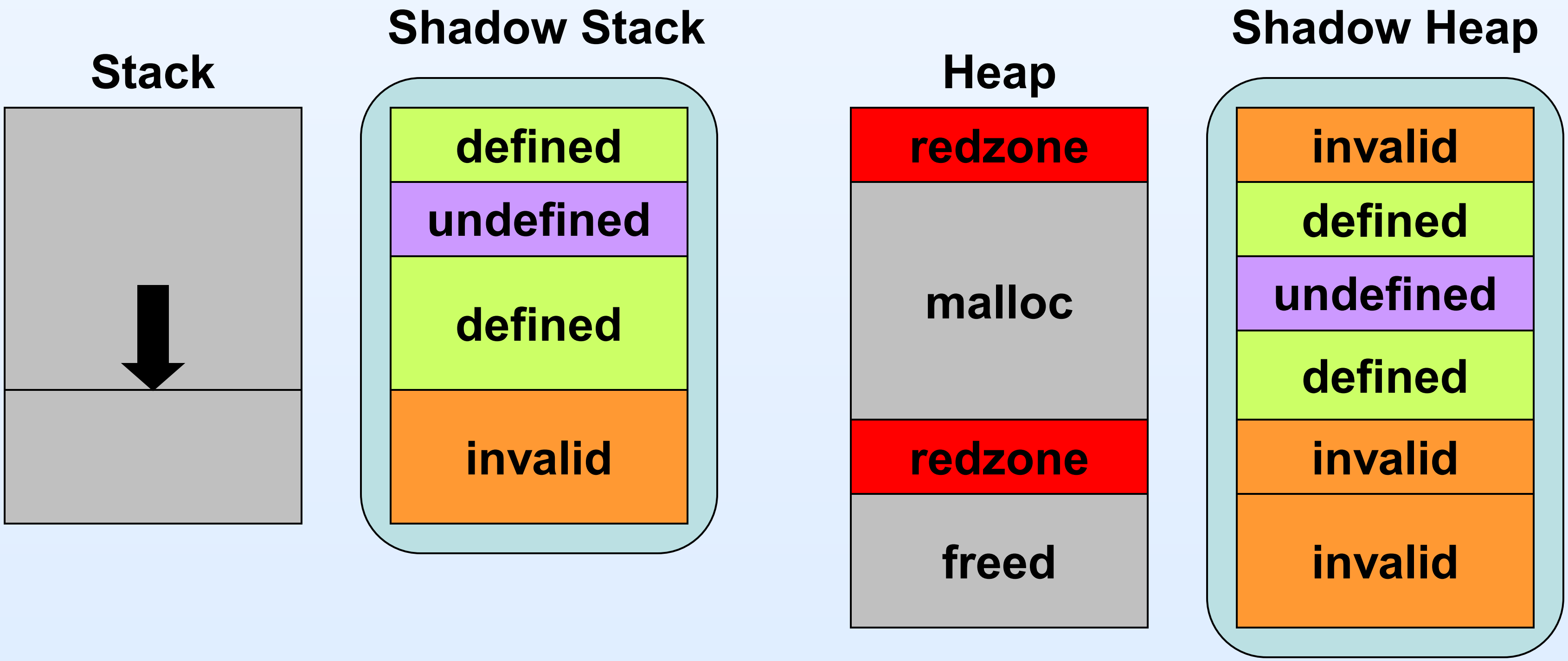
Dr. Memory

- Detects reads of uninitialized memory
- Detects heap errors
  - Out-of-bounds accesses (underflow, overflow)
  - Access to freed memory
  - Invalid frees
  - Memory leaks
- Detects other accesses to invalid memory
  - Stack tracking
  - Thread-local storage slot tracking
- Operates at runtime on unmodified Windows & Linux binaries

Dr. Memory Instrumentation

- Monitor all memory accesses, stack adjustments, and heap allocations
- Shadow each byte of app memory
- Each byte's shadow stores one of 4 values:
  - Unaddressable
  - Uninitialized
  - Defined at byte level
  - Defined at bit level → escape to extra per-bit shadow values

Dr. Memory


Stack
Shadow Stack
defined
undefined
defined
invalid
Heap
redzone
malloc
redzone
freed
Shadow Heap
invalid
defined
undefined
defined
invalid
invalid

Partial-Word Defines But Whole-Word Transfers

- Sub-dword variables are moved around as whole dwords
- Cannot raise error when a move reads uninitialized bits
- Must propagate on moves and thus must shadow registers
  - Propagate shadow values by mirroring app data flow
- Check system call reads and propagate system call writes
  - Else, false negatives (reads) or positives (writes)
- Raise errors instead of propagating at certain points
  - Report errors only on “significant” reads

Shadowing Registers

- Use multiple TLS slots
  - dr_raw_tls_calloc()
  - Alternative: steal register
- Can read and write w/o spilling
- Bring into spilled register to combine w/ other args
  - Defined=0, uninitialized=1
  - Combine via bitwise or

Monitoring Stack Changes

- As stack is extended and contracts again, must update stack shadow as unaddressable vs uninitialized
- Push, pop, or any write to stack pointer
- Try to distinguish large alloc/dealloc from stack swap

Kernel-Mediated Stack Changes

- Kernel places data on the stack and removes it again
  - Windows: APC, callback, and exception
  - Linux: signals
- Linux signals as an example:
  - intercept sigaltstack changes
  - intercept handler registration to instrument handler code
  - use DR's signal event to record app xsp at interruption point
  - when see event followed by handler, check which stack and mark from either interrupted xsp or altstack base to cur xsp as defined (ignoring padding)
  - record cur xsp in handler, and use to undo on sigreturn

Types Of Instrumentation

- Clean call
  - Simplest, but expensive in both time and space: full context switch from application state to tool state with separate stack to execute C code
- Shared clean call
  - Saves space
- Lean procedure
  - Shared routine with smaller context switch than full clean call
  - Jump-and-link rather than swapping stack
  - Array of routines, one per pair of dead registers
- Inlined
  - Smallest context switch, but should limit to small sequences of instrumentation

Non-Code-Cache Code

- Use dr_nonheap_alloc() to allocate space to store code
- Generate code using DR’s IR and emit to target space
- Mark read-only once emitted via dr_memory_protect()

Jump-and-Link

- Rather than using call+return, avoid stack swap cost by using jump-and-link
  - Store return address in a register or TLS slot
  - Direct jump to target
  - Indirect jump back to source

```
PRE(bb, inst, INSTR_CREATE_mov_st(drcontext,
    spill_slot_opnd(drcontext, SPILL_SLOT_2),
    opnd_create_instr(appinst)));
PRE(bb, inst, INSTR_CREATE_jmp(drcontext,
    opnd_create_pc(shared_slowpath_region)));
...
PRE(ilist, NULL, INSTR_CREATE_jmp_ind(drcontext,
    spill_slot_opnd(SPILL_SLOT_2)));
```

Inter-Instruction Storage

- Spill slots provided by DR are only guaranteed to be live during a single app instr
  - In practice, live until next selfmod instr
- Allocate own TLS for spill slots
  - dr_raw_tls_calloc()
- Steal registers across whole bb
  - Restore before each app read
  - Update spill slot after each app write
  - Restore on fault

Using Faults For Faster Common Case Code

- Instead of explicitly checking for rare cases, use faults to handle them and keep common case code path fast
- Signal and exception event and restore state extended event all provide pre- and post-translation contexts and containing fragment information
- Client can return failure for extended restore state event
  - When can support re-execution of faulting cache instr, but not re-start translation for relocation

Address Space Iteration

- Repeated calls to dr_query_memory_ex()
- Check dr_memory_is_in_client() and dr_memory_is_dr_internal()
- Heap walk
  - API on Windows
- Initial structures on Windows
  - TEB, TLS, etc.
  - PEB, ProcessParameters, etc.

Intercepting Library Routines

- Common task
- Dr. Memory monitors malloc, calloc, realloc, free, malloc_usable_size, etc.
  - Alternative is to replace w/ own copies
- Locating entry point
  - Module API
- Pre-hooks are easy
- Post-hooks are hard
  - Three techniques, each with its own limitations
  - See paper in CGO 2011
  - drwrap Extension now provides function wrapping

Replacing Library Routines

- Dr. Memory replaces libc routines containing optimized code that raises false positives
  - memcpy, strlen, strchr, etc.
- Simplification: arrange for routines to always be entered in a new bb
  - Do not request elision or indcall2direct from DR
- Want to interpret replaced routines
  - DR treats native execution differently: aborts on fault, etc.
- Replace entire bb with jump to replacement routine
- drwrap Extension now provides function replacement

Delayed Fragment Deletion

- Due to non-precise flushing we can have a flushed bb made inaccessible but not actually freed for some time
- When keeping state per bb, if a duplicate bb is seen, replace the state and increment a counter ignore_next_delete
- On a deletion event, decrement and ignore unless below 0
- Can't tell apart from duplication due to thread-private copies: but this mechanism handles that if saved info is deterministic and identical for each copy

Callstack Walking

- Use case: error reporting
- Technique:
  - Start with xbp as frame pointr (fp)
  - Look for <fp,retaddr> pairs where retaddr = inside a module
- Interesting issues:
  - When scanning for frame pointer (in frameless func, or at bottom of stack), querying whether in a module dominates performance
  - msvcr80!malloc pushes ebx and then ebp, requiring special handling
  - When displaying, use retaddr-1 for symbol lookup
  - More sophisticated techniques needed in presence of FPO

Suspending The World

- Use case: Dr. Memory leak check
  - GC-like memory scan
- Use dr_suspend_all_other_threads() and dr_resume_all_other_threads()
- Cannot hold locks while suspending

Using Nudges

- Daemon apps do not exit
- Request results mid-run
- Cross-platform
  - Signal on Linux
  - Remote thread on Windows

Tool Packaging

- DynamoRIO is redistributable, so can include a copy with your tool
- Front end to configure and launch app
  - On Linux use a script that execs drrun
  - On Windows use drinjectlib.dll