Binary Instrumentation

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Limitations of SFI/NaCl Approach

- Need for compiler support
  - Does not work on arbitrary binaries --- binaries should have been compiled using a cooperative compiler
  - Otherwise, the binary will trivially fail the verification step
- Question: Can we instrument arbitrary COTS binaries to insert inline security checks?

Motivation for COTS Binary Instrumentation

- No source code needed
  - Language-neutral (C, C++ or other)
- Can be largely independent of OS
- Ideally, would provide instruction-set independent abstractions
  - This ideal is far from today’s reality
- Benefits
  - Application extension
    - Functionality
    - Security
    - Monitoring and debugging
  - Instrumenting long-running programs

Approaches

- Static analysis/transformation
  - Binaries files are analyzed/transformed
  - Benefits
    - No runtime performance impact
    - No need for runtime infrastructure
  - Weakness
    - Error-prone, problem with signed code (can work around)
- Dynamic analysis/transformation
  - Code analyzed/transformed at runtime
  - Benefit: more robust/accurate
  - Weakness
    - High runtime overhead
    - Runtime complexity (infrastructure)

Previous Works (Static)

- OM/ATOM (DEC WRL)
  - Proprietary and probably outdated
- EEL (Jim Larus et al, 1995)
  - The precursor of most modern rewriters
  - Targets RISC (SPARC)
  - Provides processor independent abstractions
  - Follow up works
    - UQBT (for RISC)
    - LEEL (for Linux/i386)

Previous Works (Dynamic)

- LibVerify (Bell Labs/RST Corp)
  - Runtime rewriting for StackGuard
- DynamoRIO (HP Labs/MIT) Disassembles basic blocks at runtime
  - Provides API to hook into this process and transform executable
- Pin (Intel/U. Colorado)
- Valgrind
- A number of virtualization implementations rely binary translation (or used to)
  - QEMU, VMWare, ...

Phases in Static Analysis of Binaries

- Disassembly
- Instruction decoding/understanding
- Insertion of new code

Static Disassembly

- Core component for static analysis of binaries
- Principal Approaches
  - Linear Sweep
  - Recursive Traversal

Linear Sweep Algorithm

- Used by GNU *objdump*
- **Problem:**
  - There can be data embedded within code
    - There may also be padding, alignment bytes or junk
  - Linear sweep will incorrectly disassemble such data

```
Addr = startAddr;
while (Addr < endAddr ) {
    ins=decode(addr);

    addr+=LengthOf(ins);

}
```

Linear Sweep Algorithm

```
804964c:   55            push   %ebp
804964d:  89 e5          mov    %esp,%ebp
804964f:    53           push   %ebx
8049650:   83 ec 04   sub   $0x4,%esp
8049653:    eb 04        jmp   0x8049658
8049655:    e6 02 04  <junk>
8049658:    be 05000000     mov   $0x5,%esi
```

```
804964c:   55            push   %ebp
804964d:   89 e5         mov    %esp,%ebp
804964f:    53           push   %ebx
8049650:   83 ec 04    sub    $0x4,%esp
8049653:   eb 04         jmp    0x8049658
8049655:   e6 02         out 0x2, al
8049657:   04 be         add al, 0xbe
8049659:   05 00000012    add eax, 0x12000000
```

- Incorrectly disassembles junk (or padding) bytes
- Confusion typically cascades past the padding, causing subsequent instructions to be missed or misinterpreted.

Self Repairing Disassembly

- Property of a disassembler where it re-synchronizes with the actual instruction stream
- Makes detecting disassembly errors difficult
  - 216 of 256 opcodes are valid
- Observation: re-synchronization happens quickly, within 2-3 instructions beyond point of error.

Self Repairing Disassembly (example)

Consider the byte stream
55 89 e5 eb 03 90 90 83 0c 03 b8 01 00 00 00 c9

- **Linear Sweep output**

```
100: push ebp
101: mov ebp, esp
103: jmp 109
105: nop
106: nop
107: or dword ptr ds:[ebx+eax*1], 0xb8
111:add dword ptr ds:[eax+eax*1], eax
113: add byte ptr ds:[eax+eax*1], al
116: leave
```

- **Correct Output**

```
100: push ebp
101: mov ebp, esp
103: jmp 109
106:  <GAP>
107:  <GAP>
108:  <GAP>
109: or al, 0x3
111: mov eax, 0x1
116: leave
```

Recursive Traversal

- Approach: Takes into account the control flow behavior of the program
- Weakness: For indirect jumps, jump target cannot be determined statically, so no recursive traversal of the target can be initiated
- Some error cases not handled, e.g., jump to the middle of an instruction

```
RecursiveTraversal (addr)  {
  while (!visited[addr]) {
     visited[addr] = true;
     ins = decode (addr);
     if (isControlTransfer(ins))
       RecursiveTraversal (target(ins))

     if (uncondJumpOrRet(ins))
       return
     else addr+=LengthOf(ins);
  }
}
```

Static Disassembly – Impediments

- Code/Data distinction
- Variable x86 instruction size
- **Indirect Branches**
  - Mainly due to function pointers
    - Cross-module calls
      - e.g., calls from executable to a library
    - GUI code (event handlers)
    - C++ code (Virtual functions)
  - Functions without explicit CALL
- **PIC** (Position-Independent Code)
- **Hand-coded Assembly**

Optimized Code Example

```c
#include <stdio.h>
void f(int c) {
  printf("%d\n", c);
}
void h(int i) {
  f(i+1);
}
int i(int j) {
  return j+1;
}
int main(int argc, char*argv[]) {
  h(i(argc));
  f(argc+2);
}
```

Compiled Code Example

```
void f(int c) {
   printf("%d\n",
  c);
}
```

```
pushl   %ebp
movl    %esp, %ebp
subl    $16, %esp

pushl   8(%ebp)
pushl   $.LC0 (“%d”)
call    printf

leave
ret
```

Function prologue

Function epilogue

Optimized Code Example

```
void h(int i) {  h:
  f(i+1);                  pushl   %ebp
}                          movl    %esp, %ebp
                           subl    $8, %esp
```

No push of arguments

```
                           incl    8(%ebp)
```

No epilogue,
not even a call!

```
                           leave
                           jmp     f
```

Optimized Code Example

```
main(int argc,
  char*argv[]) {
   h(i(argc));
   f(argc+2);
}
```

```
main:
    pushl    %ebp
    movl     %esp, %ebp
    pushl    %ebx
    subl     $16, %esp
    movl     8(%ebp), %ebx
    pushl    %ebx
    call     i
    movl     %eax, (%esp)
    call     h
    addl     $2, %ebx
    movl     %ebx, 8(%ebp)
    addl     $16, %esp
    movl     -4(%ebp), %ebx
    leave
    jmp      f
```

Return value in eax reg,

No argument push!

No push of arguments
   to f, tail call

Static Code Transformation Limitations

- Cannot move code
  - Cannot predict the destination of indirect calls, so there is no safe way to move code
  - Can copy code, if original is left in place
    - If the goal is to protect against vulnerabilities in original code, then leaving of original code defeats this purpose!
- Code insertion is tricky
  - Obvious approach: overwrite original code with unconditional jump, patch
  - Problem: There may not be enough room for jump instruction (5 bytes)
  - Possible solution: use INT 3 (one-byte) instruction
    - Higher overhead for handling (signal generation/handling)

Static Code Transformation Limitations

- Code insertion at arbitrary points is very difficult
  - Code insertion at beginning/end of function is easy
  - Other points in code are not well defined in optimized code
    - Loops may be unrolled
    - Switch statements translated to jump tables
    - Successive branches may be combined
    - Function arguments may not be explicitly pushed (nor return value popped)
    - Tail call optimization and function inlining

Code Transformation Limitations

- Relocation of static data is not feasible
  - Cannot identify and relocate static pointers, which appear as immediate constants in assembly code
  - Note: These constants may be passed through several functions before used
- Note: Most above limitations can be removed if relocation information is present in binary
- Relocation of stack/heap data possible
  - Change SP at program beginning
  - Intercept/modify malloc and/or mmap requests

Dynamic Transformation Techniques

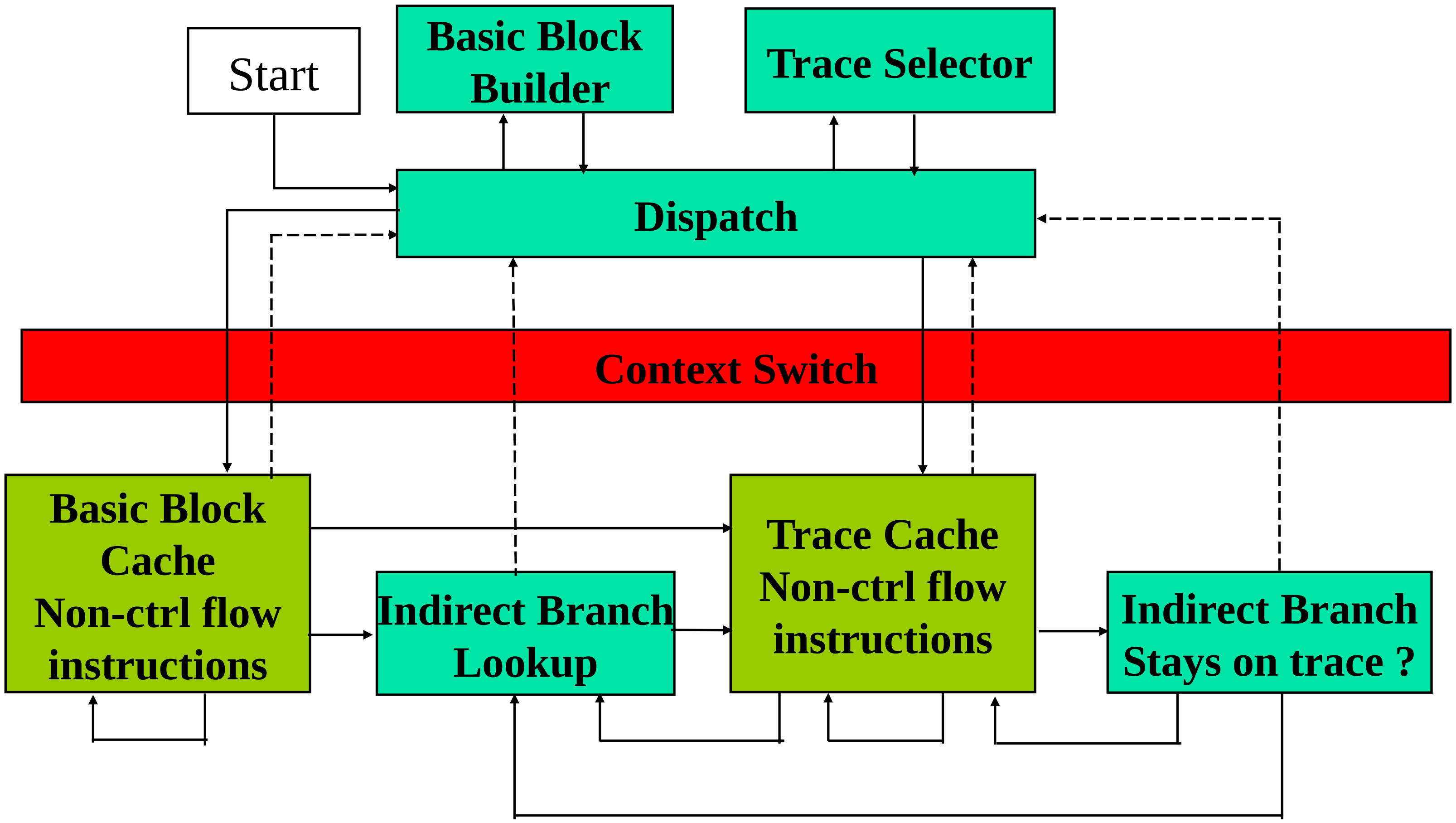
Libverify

- Inserts (StackShield) checks in binary code
  - Copy each function to heap
  - Modify first and last instruction in each function to jump to wrapper code implementing StackShield
  - Replace original copy with TRAP instructions
    - Any jump/calls to original code activates trap handler
    - Handler looks up corresponding address in copied code and transfers control there
    - If no copy exists (entry to function not discovered at load time), the function can be copied to heap and instrumented at this time
- Benefit: handles all indirect control transfers correctly
  - Note: indirect transfers will go to original code locations, unless code pointers are identified and modified to point to new locations
    - As mentioned before, this is hard to do in many cases, so this approach of using traps and runtime redirection is a good trade-off between performance and compatibility
- Drawback: performance impact if traps are repeatedly executed

DynamoRIO

- Use Libverify's runtime handling to the extreme
  - All code is discovered dynamically, analyzed dynamically, and then rewritten
  - Code is transformed one basic block at a time
    - Side-steps the thorny problem of disassembly
    - Note that it is trivial to reliably disassemble a single basic block, which is straight-line code with no control-transfers in the middle.
  - Only the first execution of a basis block requires analysis and rewriting. Subsequent executions can use the same rewritten block.
- Control transfers occur in the last instruction of a basic block. These instructions need to be checked at runtime.
- Non-control-transfer instructions are executed natively

RIO System Infrastructure


Start
Basic Block Builder
Trace Selector
Dispatch
Context Switch
Basic Block Cache Non-ctrl flow instructions
Indirect Branch Lookup
Trace Cache Non-ctrl flow instructions
Indirect Branch Stays on trace ?

DynamoRIO Operation

- Instrumented programs run in two contexts
  - DynamoRio context (above the redline, representing DynamoRIO runtime). Responsible for detecting the execution of new basic blocks (BBs)
    - These BBs are disassembled, analyzed and then transformed: just-in-time disassembly/rewriting, just before first execution
    - DynamoRIO provides an API for instrumentation: one can use this API to implement custom instrumentation, e.g., count number of BBs executed, number of memory accesses, etc.
  - Application context (below the red line, application code executes natively)
    - Non-control-transfer instructions need no special treatment
    - Control-transfers need to be checked
      - If they are direct transfers, then we check if the target has already been instrumented (and hence is in the code cache). If so, directly jump there. If not, switch into DynamoRIO context to perform instrumentation.
      - Indirect transfers need to go through a translation table

Handling Indirect CFT

- Note that indirect control transfers will use original code addresses
  - But the instrumented code is in the code cache at a different address. (We cannot use the original addresses, even if they were available: instrumentation causes code to expand, so every target except the very first function in the instrumented application will necessarily reside at a different location as compared to the original code.)
  - As discussed before, we cannot “fixup” code references either. This is because code addresses will be immediate constants in the binary, and there is no way to distinguish integer constants from code addresses
    - If we mistakenly “fixup” an integer value, that will change program behavior
    - If we mistakenly omit the fixup of a code pointer, then code will jump to an incorrect
      location, likely leading to a crash
- Clever idea put forth by DynamoRIO authors
  - Wait until a pointer is actually used
    - If it is used as a target of control transfer, then it is *obviously* a code pointer
    - Just-in-time code pointer fixup: fixup happens at the very last step.

Fixup Implementation

- Fixup is implemented using a translation table
  - A hash table `jmptab` maps the original address of a BB to its new address in the code cache (corresponding to the location of the instrumented version of code)
  - Each time DynamoRIO runtime instruments a BB, it enters the mapping between the original location and the new location in this table.
- At runtime, every indirect CFT to a location `l` is translated into `jmptab[l]`
  - Each indirect jump requires a hash table lookup, and has a performance cost
  - Fortunately, common cases (e.g., returns and repeated calls to same target) can be optimized
- If the target is not in `jmptab`, then control transferred to DynamoRIO runtime.

DynamoRIO Context Switch

- Preserve the following conditions
  - All GPRs (8 in x86-32)
  - Eflags
  - Some system state. Eg: error code
    - DynamoRIO uses one slot in TLS (thread local storage) to store error code (errno) of the application.
      - DynamoRIO will use some library routines that may modifiy the state as error code, so it is necessary to preserve application's errno.

DynamoRIO Context Switch

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

bb with conditional jump

Assumes that the BBs at 0x40106f and the immediately following BBs are not in the code cache. In this case, control has to be transferred to DynamoRIO runtime when execution reaches the end of this BB. Before context switch, all of the application state (in particular, registers) need to be saved.

```
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
```

bb in code cache

Transparency & OS Issues

- Transparency: application cannot tell that it is running inside DynamoRIO
- Why does DynamoRIO need transparency?
  - Ensures that application behaves exactly the same way as before: it can’t even tell the difference.
  - So, it can’t evade DynamoRIO, nor can it behave differently.
- Transparency Issues
  - Library transparency
  - Thread transparency
  - Stack transparency
  - Address space transparency
  - Context Translation
  - Performance transparency (not preserved)

Program Shepherding: An IRM based on DynamoRIO

- Introduces in-line checks to defend against common exploits
  - Buffer overflow attacks
  - Format string attacks
  - Injection of malicious code
  - Re-use of existing code (existing code attacks)
- Sandboxing

Program Shepherding Performance under Linux

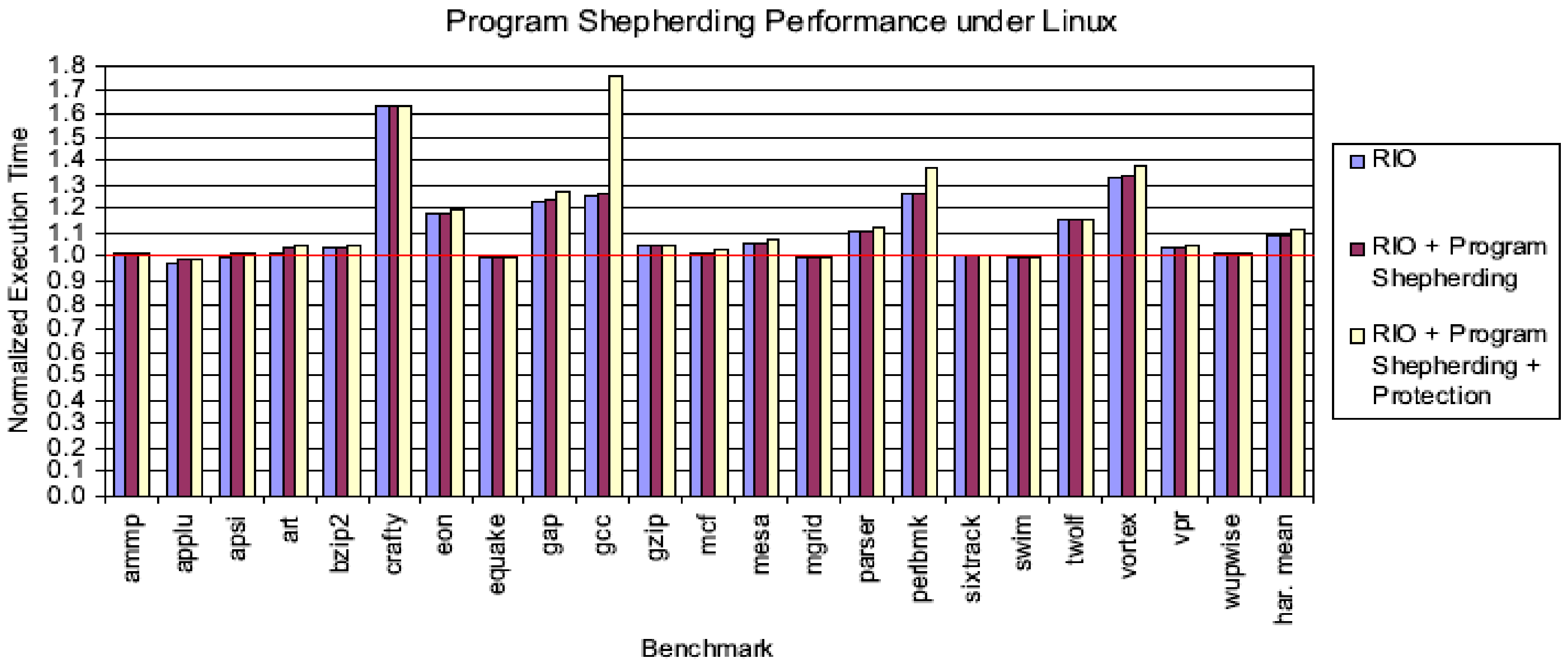


Figure 3: Normalized program execution time for our system (the ratio of our execution time to native execution time) on the SPEC2000 benchmarks [25] (excluding all FORTRAN 90 benchmarks) on Linux. They were compiled using `gcc -O3`. The final set of bars is the harmonic mean. The first bar is for RIO by itself; the middle bar shows the overhead of program shepherding (with the security policy of Table 1); and the final bar shows the overhead of the page protection calls to prevent attacks against the system itself.

- gcc is slow since it consists of many short runs with little code re-use

Program Shepherding Performance under Windows

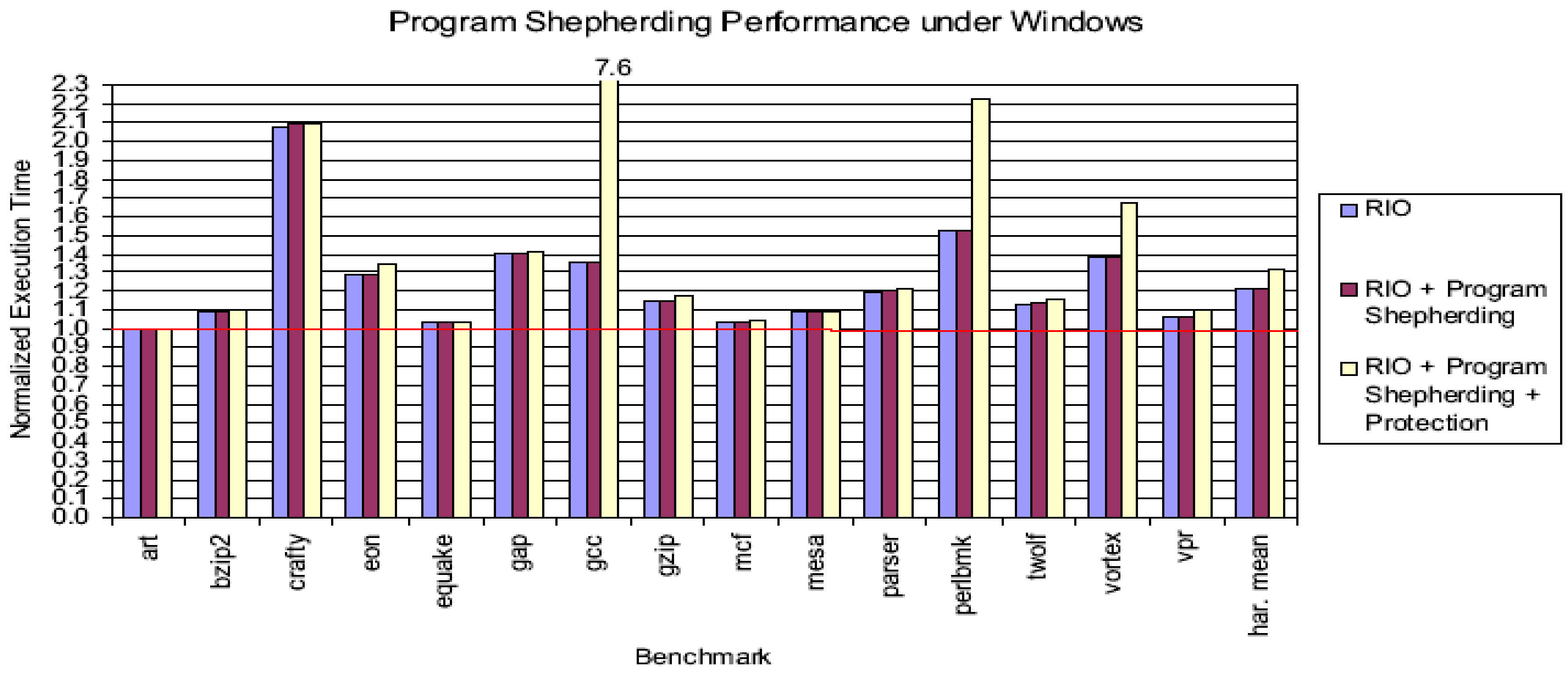


Figure 4: Normalized program execution time for our system (the ratio of our execution time to native execution time) on the SPEC2000 benchmarks [25] (excluding all FORTRAN benchmarks) on Windows 2000. They were compiled using `cl /Ox`. The final set of bars is the harmonic mean. The first bar is for RIO by itself; the middle bar shows the overhead of program shepherding (with the security policy of Table 1); and the final bar shows the overhead of the page protection calls to prevent attacks against the system itself.

- Windows is much less efficient at changing privileges on memory pages than Linux

Caveat about performance

- DBT performance measurements usually based very long-running CPU-intensive benchmarks
- These applications represent the “best case scenario” for DBT systems
  - Rewrite once, execute for a long time
- Real-world performance can be bad
  - 10x to 40x slowdown in the worst case
- Example DBT systems
  - DynamoRIO, Pin, Valgrind, …
- But its exceptional level of compatibility with arbitrary binary code can still be compelling for
  - CPU-intensive applications with tight loops
  - Coarse-granularity instrumentation (i.e., very small fraction of instructions instrumented)
  - Debugging applications

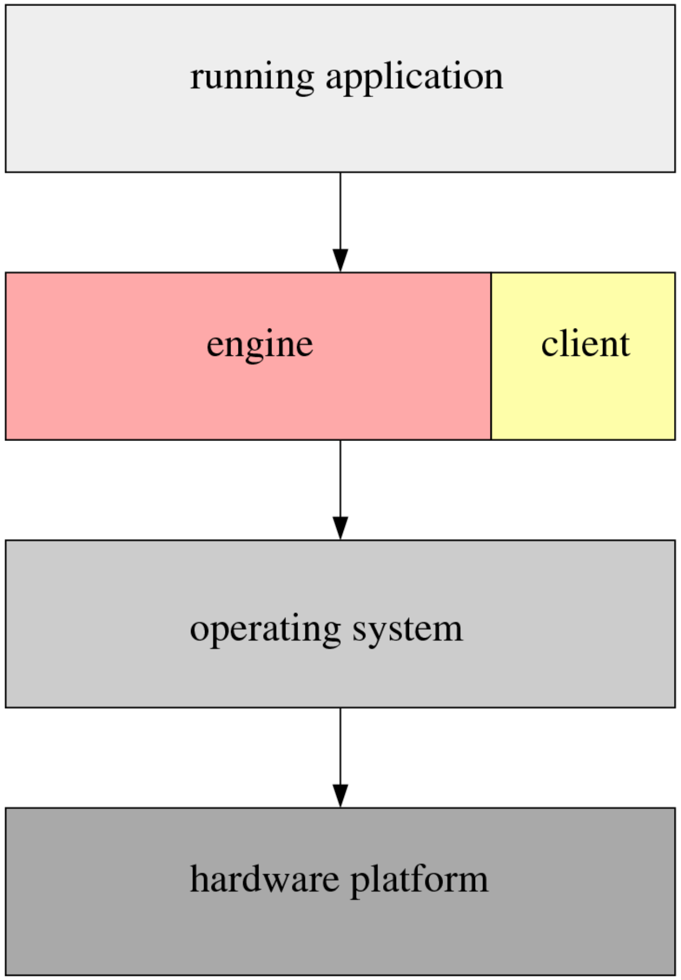
DynamoRIO API

- DynamoRIO exports an API that supports building a *DynamoRIO client*
- DynamoRIO and the client jointly operate on target input binaries
- Client registers callback functions that are invoked by DynamoRIO at specified points

DynamoRIO API

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

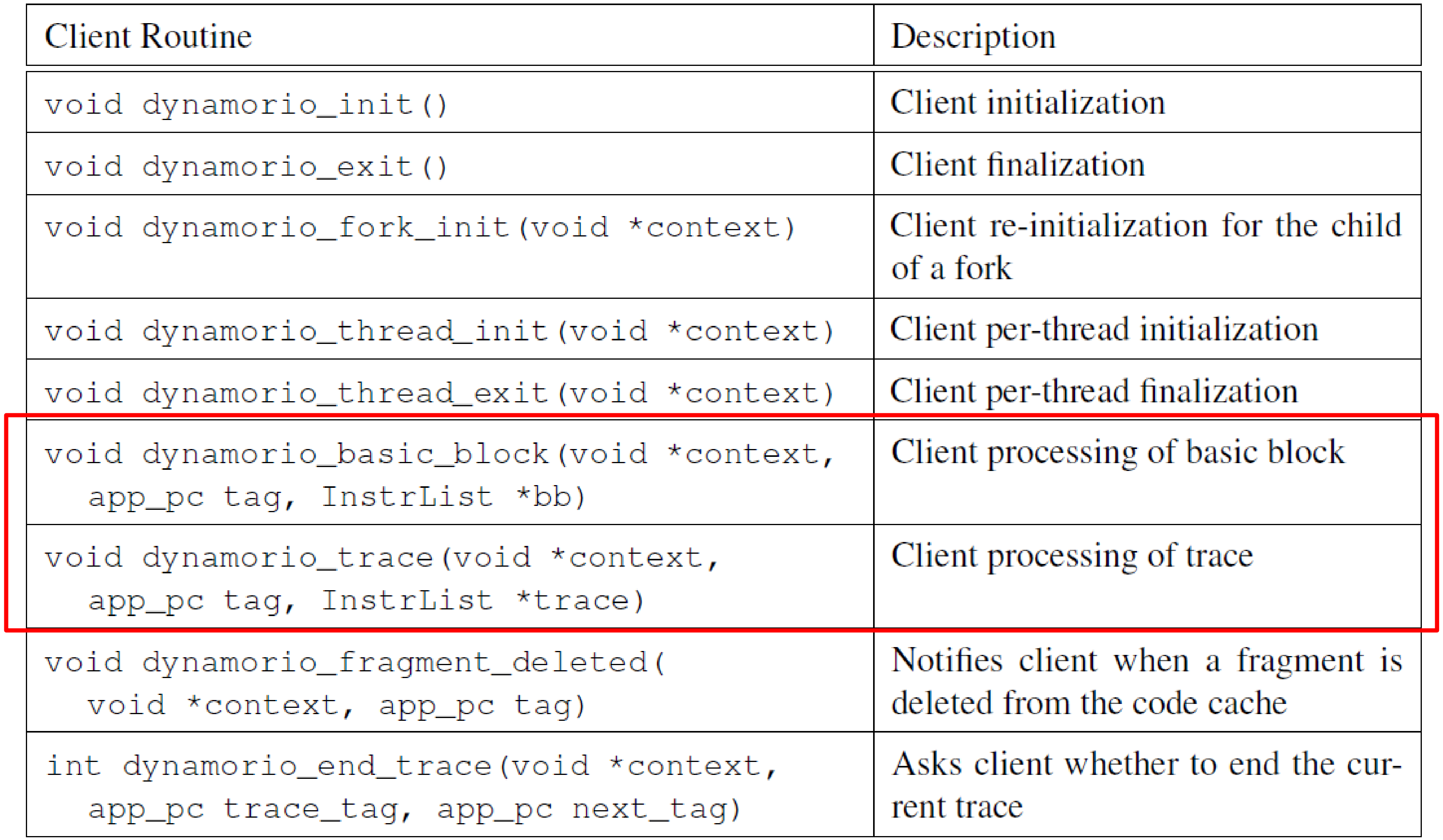
Clients are actually "plug-ins" for the DynamoRIO engine and the application



DynamoRIO API

- DynamoRIO supports 3 working modes:
  - Application Control
    - A client is built as a shared library loaded into DynamoRIO, client hooks are called before each BB executes
  - Explicit Control Interface
    - Allow application to launch DynamoRIO on its own.
    - Application decides which part to be “translated”.
  - Standalone Client
    - Client simply uses DynamoRIO as a tool library to decode/disassemble binary
- We will focus on the 1st mode, which is the easiest to work with.

Client Hooks



Client Routine	Description
`void dynamorio_init()`	Client initialization
`void dynamorio_exit()`	Client finalization
`void dynamorio_fork_init(void *context)`	Client re-initialization for the child of a fork
`void dynamorio_thread_init(void *context)`	Client per-thread initialization
`void dynamorio_thread_exit(void *context)`	Client per-thread finalization
`void dynamorio_basic_block(void *context, app_pc tag, InstrList *bb)`	Client processing of basic block
`void dynamorio_trace(void *context, app_pc tag, InstrList *trace)`	Client processing of trace
`void dynamorio_fragment_deleted( void *context, app_pc tag)`	Notifies client when a fragment is deleted from the code cache
`int dynamorio_end_trace(void *context, app_pc trace_tag, app_pc next_tag)`	Asks client whether to end the current trace

Client API

- Instruction Manipulation
  - Creating/Encoding/Decoding
    - INSTR_CREATE_push(context, opnd_create_reg(REG_EAX))
  - Inspecting/Modifying
    - Recognizing Instruction Type:
      - Instr_is_call_direct(instr)
      - Instr_is_call_indirect(instr)
      - Instr_is_syscall(instr)
  - Instrumentation:
    - dr_insert_call_instrumentation(context, bb, instr, (app_pc)at_call);
      - at_call(···) is the user function pointer
  - File Operations
    - dr_open_log_file(···)

Simple Example

Print the source & destination of ALL direct call instructions

```
static void at_call(app_pc instr_addr, app_pc target_addr){
    File f = (File) dr_get_drcontext_field(dr_get_current_drcontext());
    dr_fprintf(f, "CALL @ 0x%08x to 0x%08x\n", instr_addr, target_addr);
}

EXPORT void dynamorio_basic_block(void *context, app_pc tag, InstrList *bb) {
   Instr *instr, *next_instr;
   for (instr = instrlist_first(bb); instr != NULL; instr = next_instr) {
       next_instr = instr_get_next(instr);
       if (instr_is_call_direct(instr))
          dr_insert_call_instrumentation(context, bb, instr, (app_pc)at_call);
   }
}
```

Other Dynamic Transformation Tools

- Pin
  - better supported now than DynamoRIO
  - better engineered for Linux
- Strata
- Valgrind
  - Most popular open-source tool for finding memory errors and many other applications
- Qemu
  - Can support whole system emulation

DynamoRIO vs Pin

- Architecture dependency
  - Pin tools: written in c/c++
  - DynamoRIO: written in x86 assembly
- DynamoRIO's tools allow users to operate at a lower level
  - Have more control over efficiency, but programming can be hard, and architecture dependent.

BBCount Pin Tool

For more information, including tutorials and examples, see https://software.intel.com/en-us/articles/pin-a-dynamic-binary-instrumentation-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;
}
```

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. */
    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, flag
s))
            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_coun
t, 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);
}
```

Applicability of Static Vs Dynamic Techniques

- Some techniques require static instrumentation
  - Any technique that uses static analysis to compute a property and then enforces it at runtime
    - CFI, some aspects of bounds-checking, some types of randomizations, ...
- Others can use dynamic instrumentation
  - Stackguard, SFI (but may be limited if CFI can’t be assured)
- And yet others that cannot use static instrumentation
  - Obfuscated code, mainly malware

Obfuscation against Disassembly

- Conditional jumps where the condition is always true (or false)
    - Use an opaque predicate to hide this
- Instructions that fault
    - Execution continues in exception handler
- Embedding data in the midst of code
    - With indirect jumps that make it impossible to distinguish between code and data

Control-flow Obfuscation Against Reverse Engineering

- Split or aggregate
  - Basic blocks
  - Loops
    - e.g., one loop becomes two loops or vice-versa
  - Procedures
    - Replace one procedure by two or merge two procedures
    - Inline a procedure, or outline (i.e., create new procedure)
- Reorder
- Insert dead-code (i.e., unreachable code)
  - Obfuscate using conditions
- Replace instruction sequences w/ alternate ones
- Insert conditional jumps using “opaque” predicates
- Insert indirect jumps
- Exploit aliasing and memory errors

Data Obfuscation

- Rename variables
- Split or aggregate variables
  - Split structures into individual variables or vice-versa
- Split individual variables
  - E.g., A = B - C – instead of A, use B and C
  - Clone a variable
- Pad arrays (and possibly structures) with junk elements
- “Encrypt” data values
- Introduce extra levels of indirection
  - Instead of a simple variable, declare a pointer
- Introduce aliasing
- Introduce memory errors
- Introduce additional (or remove) function parameters