Advanced Topics in Malware Analysis

Execution Tracing

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Tracing: Source Level Instrumentation

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Lesson Objectives

- Employ the execution tracing for dynamic analysis
- Apply static and dynamic binary instrumentation
- Create a Pintool to utilize PIN
- Discuss Valgrind and QEMU techniques for instrumentation

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The Dynamic Analysis Swiss Army Knife

- Tracing is a process that faithfully records detailed information of program execution
  - **Benefits**: Lossless, simple to implement, low overhead
  - **Problems**: Requires heavy after-the-fact analysis on the execution trace
- Control flow tracing
  - Logs the sequence of **executed** statements
- Dependence tracing
  - Logs the sequence of **exercised** dependencies
- Value tracing
  - Logs the sequence of **values** that are produced by each instruction
- Memory access tracing
  - Logs the sequence of **memory** references during an execution

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You Have Already Performed Tracing!

Tracing by **printf**

```
int max = 0;
for (p = head; p; p = p->next)
{
    printf("In the loop!\n");
    if (p->value >= max)
    {
        printf("True branch.\n");
        max = p->value;
    }
}
```

This is the essence of dynamic tracing!

May seem silly, but…

Consider this output:

```
In the loop!
In the loop!
True branch.
In the loop!
True branch.
In the loop!
True branch.
```

- How many elements in the list?
- How many negative values?

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Tracing by Source Level Instrumentation

- Typically performed via a compiler plugin
  - LLVM, GCC plugin, etc.

1. Read a source file and parse it into **abstract syntax trees** (**ASTs**)
2. Annotate the ASTs with instrumentation
3. Translate the instrumented ASTs into a new source file
4. Compile the new source
5. Execute the instrumented program and a trace is produced

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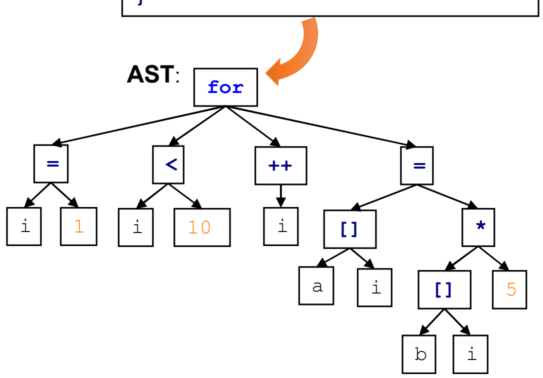
Tracing by Source Level Instrumentation

```
for(i = 1;   < 10; i++) {
        a[i] = b[i] * 5;
}
```



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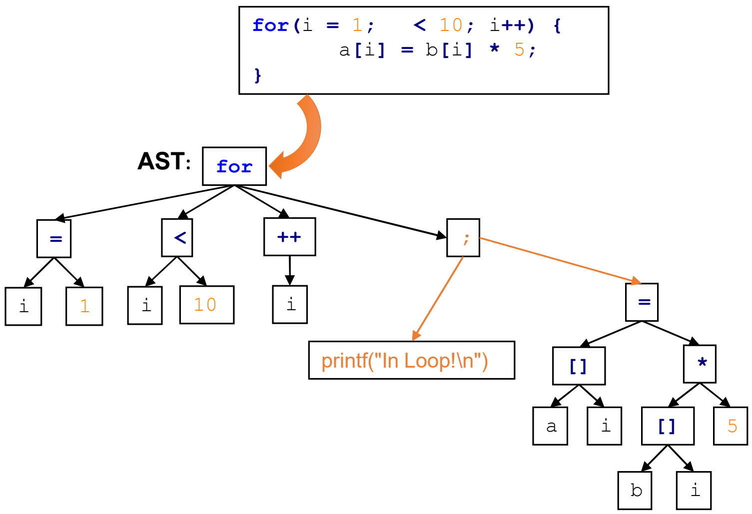
Tracing by Source Level Instrumentation



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Limitations of Source Level Instrumentation

- **Requires source code**
  - Worms and viruses are rarely provided with source code
  - Closed source software
  - That is why we are in this class ☺
- **Hard to handle libraries**
  - Proprietary libraries: communication (MPI, PVM), linear algebra (NGA), database query (SQL libraries)
- **Hard to handle multi-lingual programs**
  - Source code level instrumentation is language dependent
  - Have to rewrite everything for Java, C++, Python, …

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Tracing: Binary Instrumentation

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Tracing by Binary Instrumentation

- The **most important** binary-analysis capability to date: **Binary Instrumentation**
- **Two flavors**:
    1. Static Binary Instrumentation
    2. Dynamic Instrumentation
- **Features:**
    - No source code required
    - Directly handles library binaries (either statically instrumenting or during their execution)
    - Does not care what language(s) the program is written in --- any binary can be instrumented
        - **Worst case example**: Instrument the JVM & monitor the Java program during execution

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Static Binary Instrumentation

- Insert instrumentation into the binary executable
- Instrumentation will run next time the binary is executed
- A.K.A. Binary "Rewriting"

1. Given a binary executable, **parse** it into **intermediate** representation
   - Could be as simple as instruction models (like we did in Lab 3 & Lab 4)
   - More advanced representations such as control flow graphs may also be generated
2. Design tracing instrumentation for the intermediate representation
   - E.g., Control flow tracing → for each (instruction in binary): printf("%i", instruction.address);
3. A lightweight "compiler" inserts the instrumentation logic into a new executable

Static Binary Instrumentation Example

Original Source:

```c
#include <stdio.h>

int main(int argc, char* argv[]) {
  if (argc == 2)
    printf("Hello %s\n", argv[1]);
  return 0;
}
```

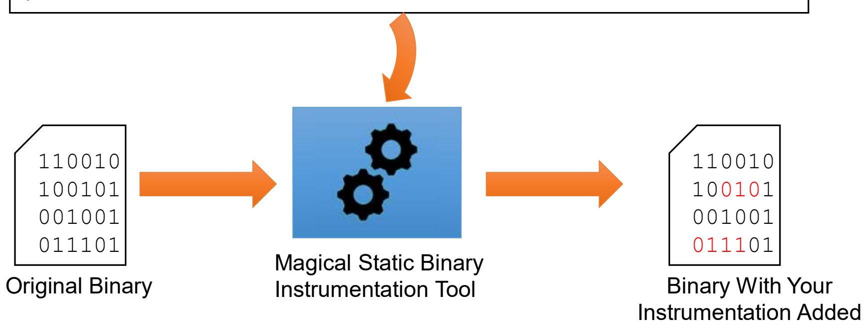
Original Binary
(64-bit Linux with -O3)

```
        cmp     edi, 2
        jz      print
        xor     eax, eax
        retn
print:  push    rax
        mov     rsi, [rsi+8]
        mov     edi, offset format ; "Hello %s\n"
        xor     eax, eax
        call    _printf
        xor     eax, eax
        pop     rdx
        retn
```

Static Binary Instrumentation Example

Your Instrumentation Logic:

```
void trace_ctrl_flow(inst *current_inst) {
    printf("%u\n", current_inst->address);
}
...
for(inst *in = get_instructions(); in; in = in->next) {
    add_instrumentation(in, trace_ctrl_flow);
}
```



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Static Binary Instrumentation Example

```
inst:      push   rsi    ; save all dirty regs
           push   rax
           push   rflags
           mov    rsi, rdi  ; embedded instrumentation
           mov    edi, offset u ; "%u\n"
           call   _printf
           pop    rflags ; restore dirty regs
           pop    rax
           pop    rsi
           ret
...
1.         cmp       edi, 2
           push   rdi    ; call instrumentation
           mov    rdi, 1
           call   inst
           pop    rdi
           push   rdi     ; call instrumentation
           mov    rdi, 2
           call   inst
           pop    rdi
2.         jz        print   ; be careful on ctrl flow!
```

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Static Binary Instrumentation Example

```
3.          xor     eax, eax
            push    rdi    ; call instrumentation
            mov     rdi, 3
            call    inst
            pop     rdi
            push    rdi    ; call instrumentation
            mov     rdi, 4
            call    inst
            pop     rdi
4.          retn
5. print:   push    rax
            push    rdi    ; call instrumentation
            mov     rdi, 5
            call    inst
            pop     rdi
6.          mov     rsi, [rsi+8]
            push    rdi    ; call instrumentation
            mov     rdi, 6
            call    inst
            pop     rdi
```

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The Good & Bad of Static Binary Instrumentation

- Almost impossible to do accurately!
  - Pointers must be carefully preserved or adjusted
  - Memory data must not be corrupted
  - Original disassembly must be 100% correct
    - You cannot instrument data that was misinterpreted as code!
  - Suggested readings:
    - Deng, Z., Zhang, X., & Xu, D. (2013). BISTRO: Binary Component Extraction and Embedding for Software Security Applications. *Proceedings of the 18th European Symposium on Research in Computer Security- – ESORICS 2013*.
    - Wartell, R., Mohan, V., Hamlen, K. W., & Lin, Z. (2012). Securing untrusted code via compiler-agnostic binary rewriting. *Proceedings of the 28th Annual Computer Security Applications Conference- ACSAC 12.*
- Significantly increases executable file size
- Good: FAST! All the instrumentation logic is “baked in” to the executable

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Binary Instrumentation: Static vs Dynamic

- **Static Binary Instrumentation:** Given an original binary executable and generate an instrumented executable that can be executed with our analysis embedded within!
  - Instrument statically = before runtime
- **Dynamic Binary Instrumentation:** Given an original binary executable and an input, start executing the binary with the input, and during execution add instrumentation to the binary on the fly
  - Instrument dynamically = during runtime
- **Advantages for Dynamic Instrumentation**:
  - No need to recompile or relink
  - Discover code at runtime
  - Handle dynamically-generated code
  - Attach to running processes

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Dynamic Binary Instrumentation Example

- Original Source:

```c
#include <stdio.h>

int main(int argc, char* argv[]) {
  if (argc == 2)
    printf("Hello %s\n", argv[1]);
  return 0;
}
```

Original Binary
(64-bit Linux with -O3)

```
           cmp     edi, 2
           jz      print
           xor     eax, eax
           retn
print:     push    rax
           mov     rsi, [rsi+8]
           mov     edi, offset format ; "Hello %s\n"
           xor     eax, eax
           call    _printf
           xor     eax, eax
           pop     rdx
           retn
```

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Dynamic Binary Instrumentation Example

Your Instrumentation Logic:

```
void trace_ctrl_flow(inst *current_inst) {
    printf("%u\n", current_inst->address);
}
...
for(inst *in = get_instructions(); in; in = in->next) {
    add_instrumentation(in, INST_AFTER, trace_ctrl_flow);
}
```

Notice: Could also be INST_BEFORE or others…

```
cmp     edi, 2
jz      print
push    rax
mov     rsi, [rsi+8]
```

Instructions that should be executed (starting from entry point)

Magical Dynamic Instrumentation Tool

```
cmp     edi, 2
push    rdi; call inst
mov     rdi, 1
call    inst
pop     rdi
```

Instruction with added implementation that will be executed

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Dynamic Binary Instrumentation

- A few flavors.
- We will look at:
  - **Platform-specific** --- instrumentation targets the exact instructions that are executing on the CPU
  - **Emulation-based** --- instrumentation targets some intermediate language
  - Others (some are hybrids of these categories)

Pin

QEMU

Valgrind

DynamoRIO The DR. is in.

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PIN

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The King of x86 Dynamic Instrumentation: PIN

- **Pin** is a platform for dynamic instrumentation of binary programs
- **Pin** is maintained by **Intel**
- Supports Intel architectures: **x86, x86-64**, **Itanium**, **Xscale**
- Can instrument executables on a variety of OS's: Windows, Linux, OSX, Android
- You write a "**Pintool**" which instructs Pin on how you want to instrument the execution
- Pintools are very powerful (that is why Pin is king) because they can **insert arbitrary code** (written in C or C++) at **arbitrary locations** in an executable
- Instrumentation code is added dynamically while the executable is running
  - It can also be changed on-the-fly!
  - Handles threads & asynchronous signals!
  - This makes it possible to attach Pin to an already running process

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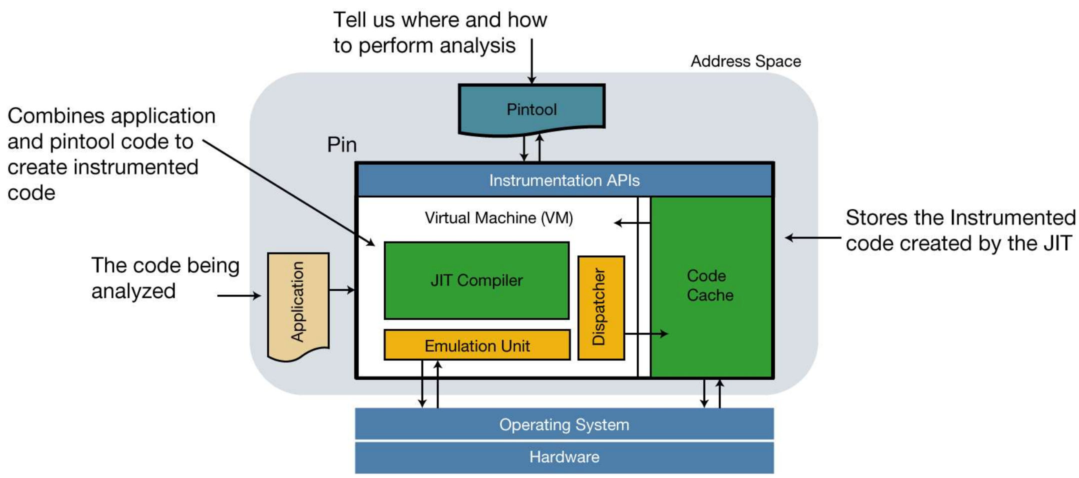
The King of x86 Dynamic Instrumentation: PIN



Read More: Pin: building customized program analysis tools with dynamic instrumentation. In ACM SIGPLAN Notices (Vol. 40, No. 6, pp. 190-200).

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PinTools

- https://software.intel.com/en-us/articles/pin-a-dynamic-binary-instrumentation-tool
- Launch and instrument an application:

$ pin -t pintool.so --application

Instrumentation engine
(provided in the kit)

Instrumentation tool(write your own, or
use one provided in the kit)

- Attach to and instrument an application: $ pin -t pintool.so -pid 1234
- Like IDA, Pintools are specific to 32-bit and 64-bit!
  - May share code (watch out for incompatibilities!), but must be compiled separately

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Pintools API

- Basic APIs are architecture independent
- Provide common functionalities like determining:
  - Control-flow changes
  - Memory accesses
- Architecture-specific APIs
  - E.g., info about opcodes and operands
- State change APIs
  - E.g., process create/end, interrupt received
- Call-based APIs:
  - Instrumentation routines
  - Analysis routines

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Pintools Structure

Two types of core routines:

1. **Instrumentation routines** define where instrumentation is inserted
   - E.g., before instruction
   - Occurs first time an instruction is executed
   - Other APIs can remove instrumentation after it has been inserted

2. **Analysis routines** define what to do when instrumentation is activated
   - E.g., print instruction address, increment counter
   - Occurs every time an instruction is executed

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Pintool Example:

ManualExamples/itrace.cpp

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```
#include <stdio.h>
#include "pin.h"
FILE * trace;

void printip(void *ip) {
    fprintf(trace, "%p\n", ip);
}

void Instruction(INS ins, void *v) {
    INS_InsertCall(ins, IPOINT_BEFORE,
        (AFUNPTR)printip, IARG_INST_PTR,
IARG_END);
}

void Fini(INT32 code, void *v) {
    fclose(trace);
}

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

Instruction ptr arg!

Pintool Example: ManualExamples/itrace.cpp

Analysis Routine

Instrumentation Routine

State change Analysis Routine

Main calls the Pin APIs to register the instrumentation routines

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Why PIN is King

- Versatility! Pin can do sooooo many things
- Sample tools in the Pin distribution:
  - See **C:\pin\source\tools** directory!!
  - 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
- Companies are writing their own Pintools
- Universities use Pin in teaching and research
  - My PhD was one big journey in Pin --- https://github.com/bdsaltaformaggio/DSCRETE
  - Many others…

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Dynamic Binary Instrumentation - Valgrind

- Developed by Julian Seward at Cambridge University
  - Google - O'Reilly Open Source Award for "Best Toolmaker" 2006
  - A merit (bronze) Open Source Award 2004
  - Open source (Pin is not!)
  - Works on many platforms: x86, PowerPC, ARM, …
- Overhead is a big problem
- 5-10 ***times*** slowdown **without** any instrumentation
  - Pin has very little slowdown for no instrumentation
- Suggested reading:
  - Nethercote, N., & Seward, J. (2007). Valgrind: A Framework for Heavyweight Dynamic Binary Instrumentation. *Proceedings of the 2007 ACM SIGPLAN Conference on Programming Language Design and Implementation - PLDI 07*.

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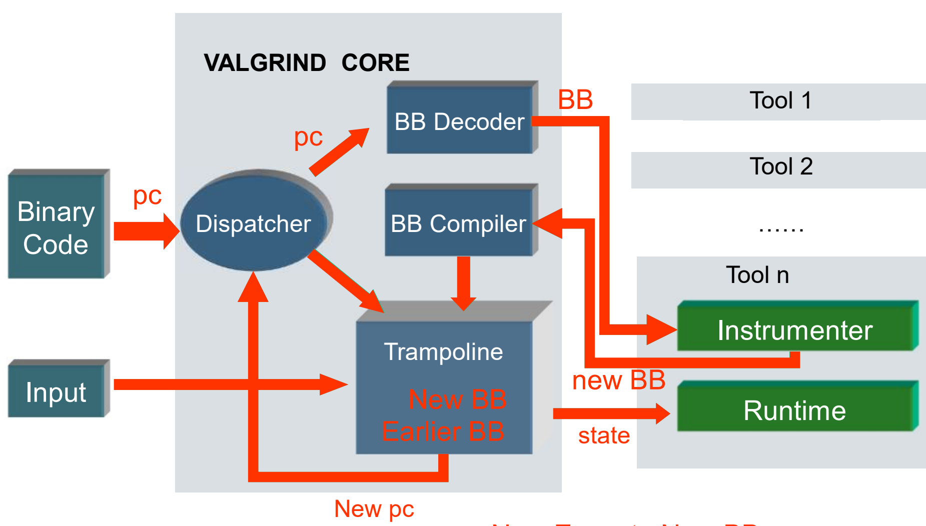
Valgrind Infrastructure



Now Execute New BB

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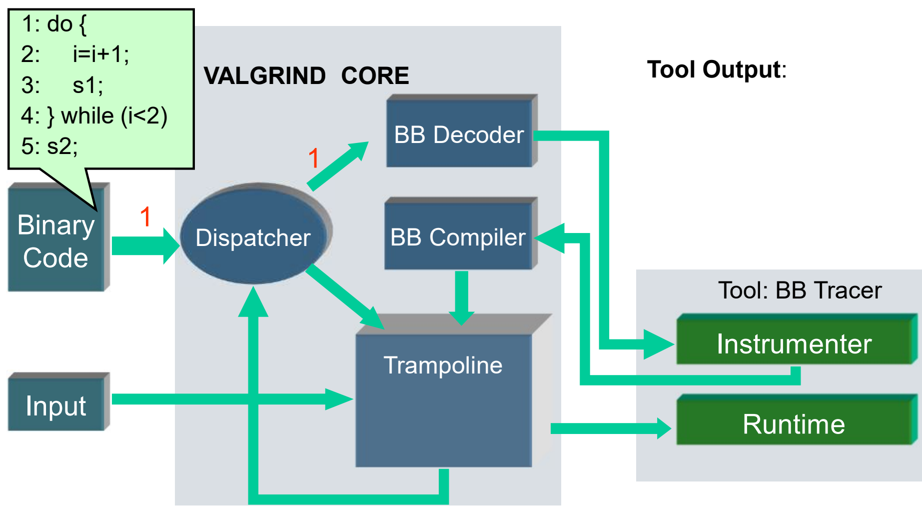
Valgrind Example



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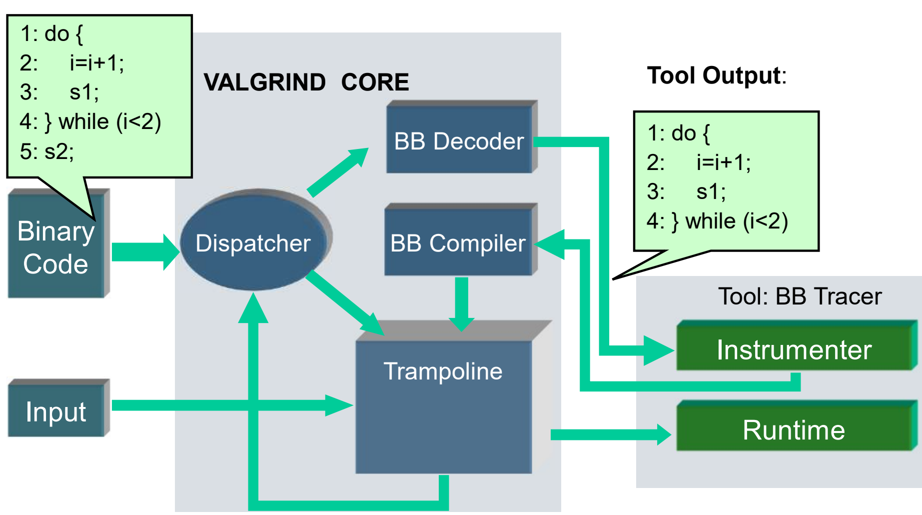
Valgrind Example



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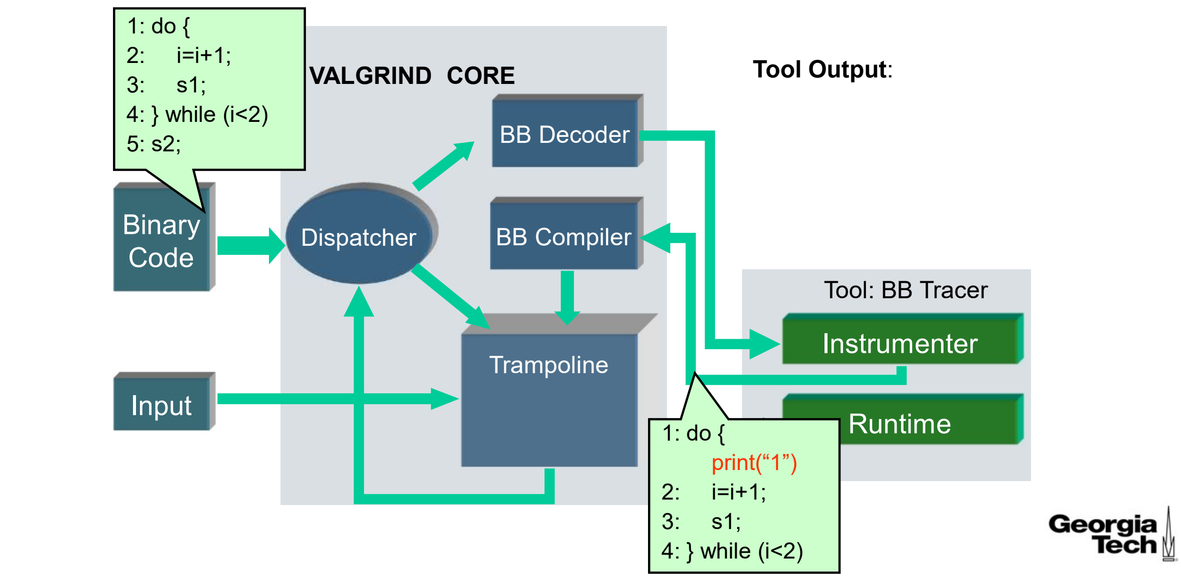
Valgrind Example



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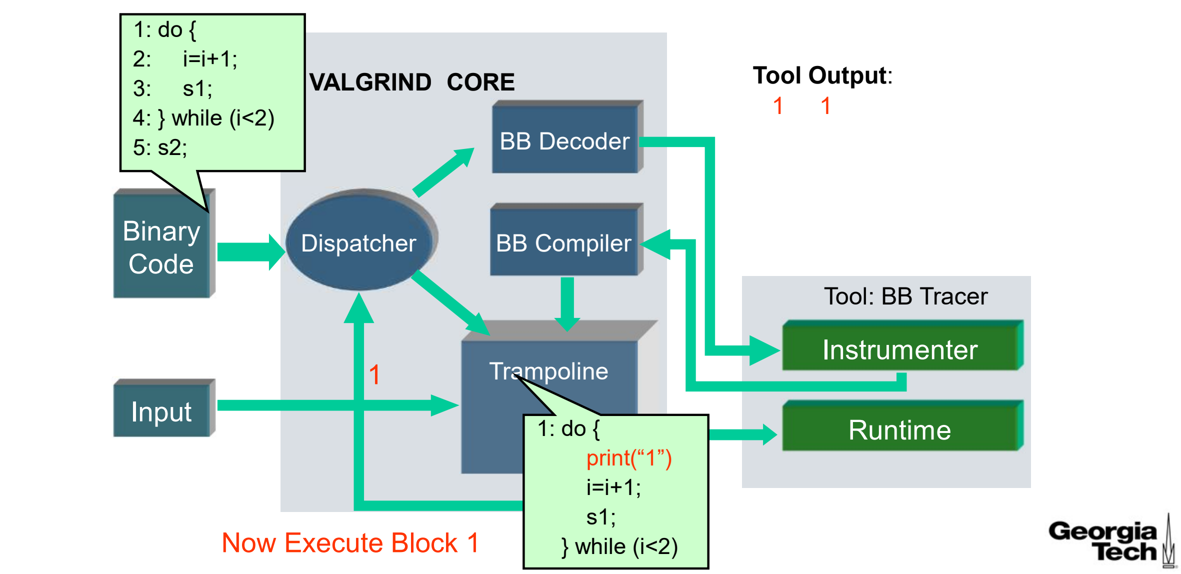
Valgrind Example



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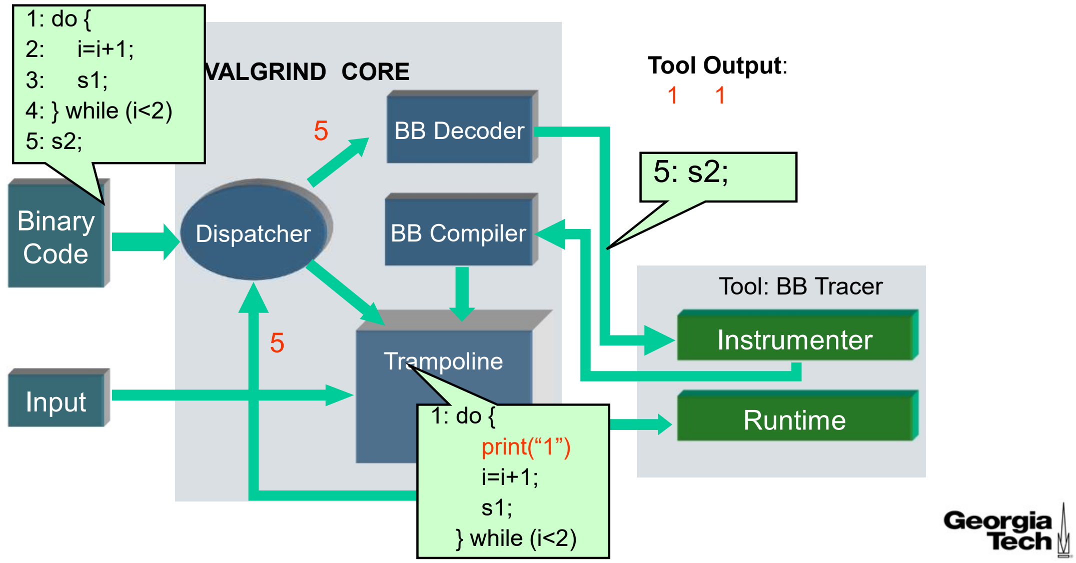
Valgrind Example



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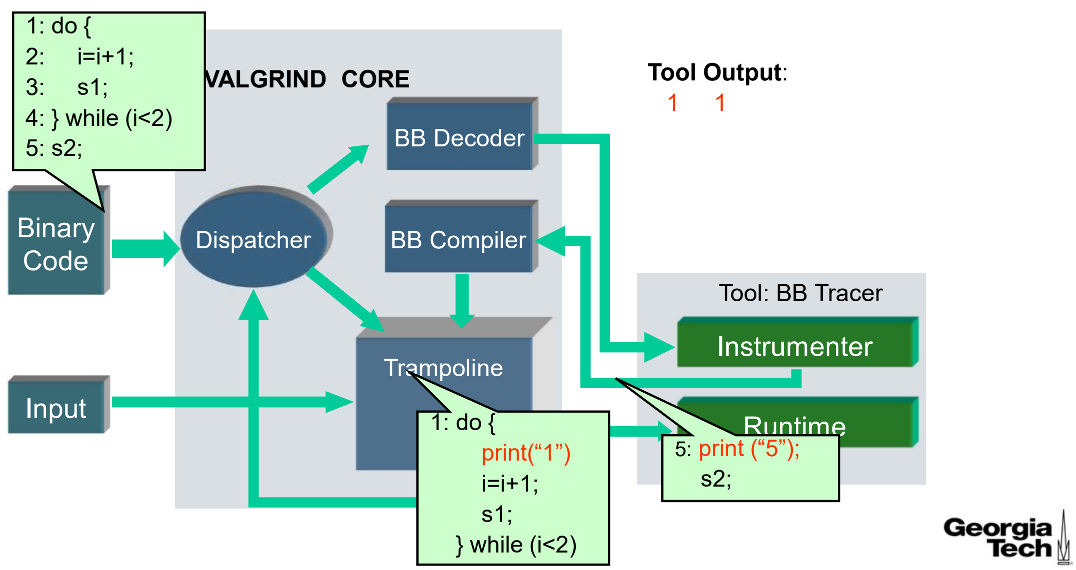
Valgrind Example



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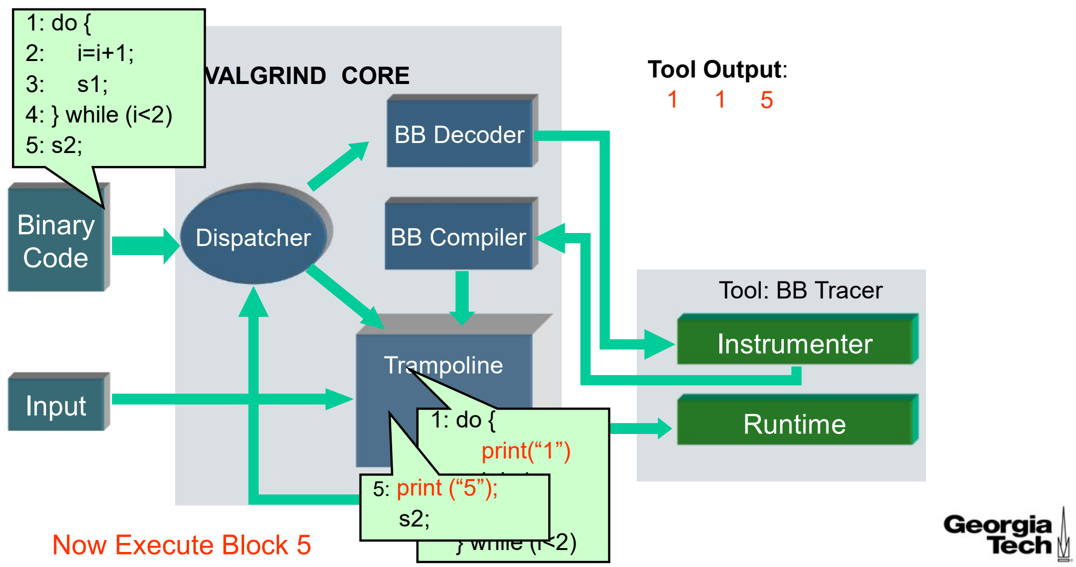
Valgrind Example



Now Execute Block 5

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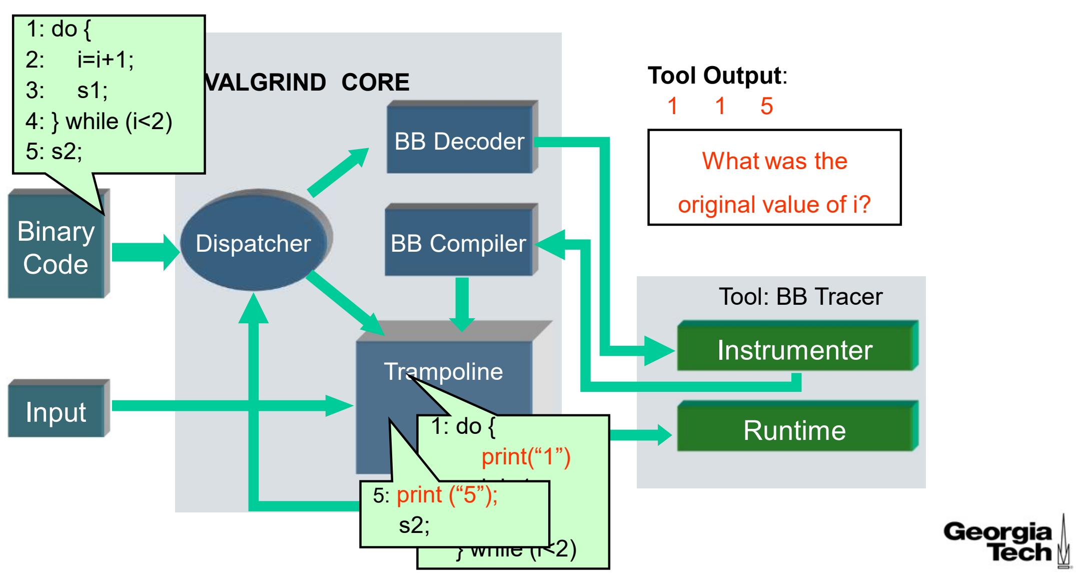
Valgrind Example



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QEMU

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QEMU Emulation-based Instrumentation

- QEMU is a generic and open source machine **emulator** and hypervisor (VM manager)
- As a **machine emulator**, QEMU can run OSes and programs made for one machine (e.g. an ARM board) on a different machine (e.g. your own PC)
  - By using dynamic translation, it achieves very good performance
- As a **hypervisor**, QEMU achieves near native performance by executing the guest code directly on the host CPU
  - QEMU supports virtualization when executing under the Xen hypervisor or using the KVM kernel module in Linux
  - When using KVM, QEMU can virtualize x86, server and embedded PowerPC, and S390 guests
- In either case, you can add your analysis routines to QEMU's code base to instrument the entire guest OS as it is executing!

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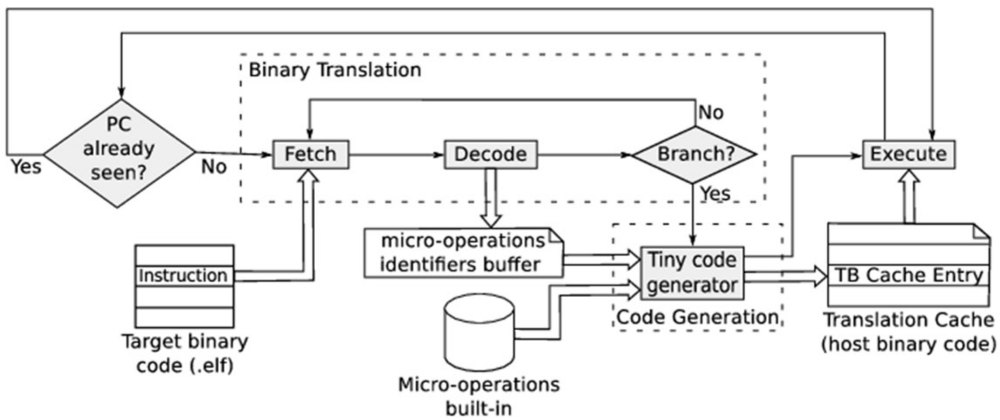
QEMU Infrastructure

- How does QEMU execute ARM code on x86?



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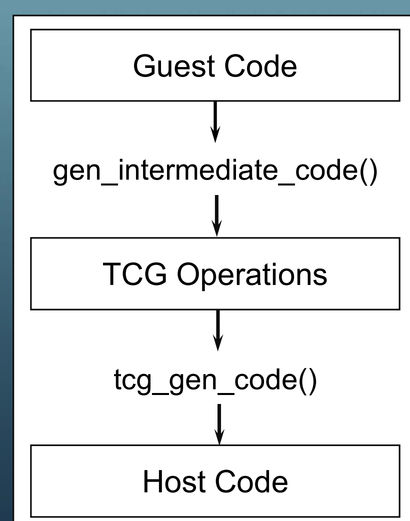
QEMU Code Translation

- QEMU uses an intermediate representation (IR)
- Frontends are in the “target” directory
  - These are guest architectures
  - “What QEMU executes”
  - Includes alpha, arm, cris, i386, m68k, mips, ppc, sparc, …
- Backends are in tcg/
  - “Tiny Code Generator”
  - These are host CPU operations
  - “Where QEMU executes”
  - Includes arm/, i386/, ia64/, mips/, ppc/, ppc64/, s390/, sparc/, …



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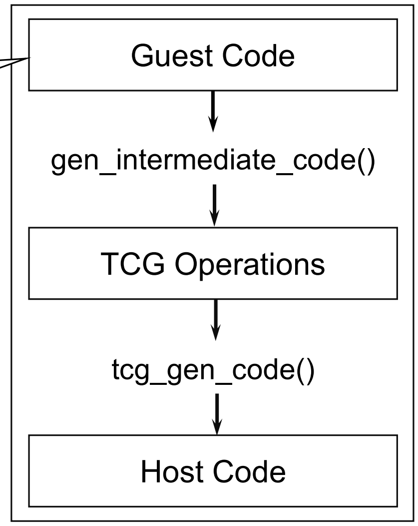
QEMU Code Translation Example
x86 Guest -> x86 Host

```
push   ebp
mov    ebp, esp
not    eax
add    edx, eax
mov    eax, edx
xor    eax, 0x55555555
pop    ebp
ret
```



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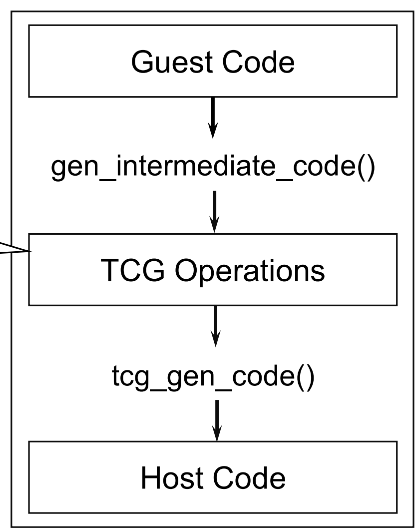
QEMU Code Translation Example
x86 Guest -> x86 Host

```
ld_i32        tmp2,env,$0x10
qemu_ld32u    tmp0,tmp2,$0xffffffff
ld_i32        tmp4,env,$0x10
movi_i32      tmp14,$0x4
add_i32       tmp4,tmp4,tmp14
st_i32        tmp4,env,$0x10
st_i32        tmp0,env,$0x20
movi_i32      cc_op,$0x18
exit_tb       $0x0
```



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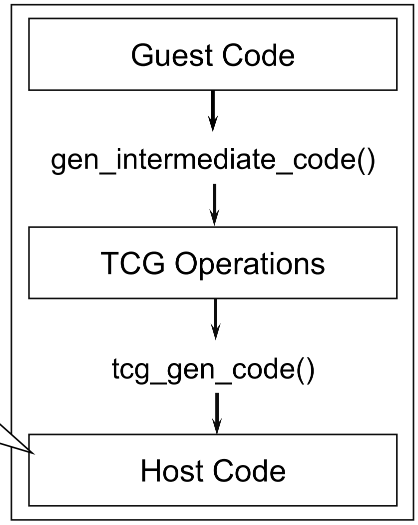
QEMU Code Translation Example
x86 Guest → x86 Host

```
mov 0x10(%ebp),%eax
mov 0x10(%ebp),%edx
mov (%ecx),%eax
mov %eax,%ecx
add $0x4,%edx
mov %edx,0x10(%ebp)
mov %eax,0x20(%ebp)
mov $0x18,%eax
mov %eax,0x30(%ebp)
xor %eax,%eax
jmp 0xba0db428
. . .
/* This represents just
the ret instruction! */
```



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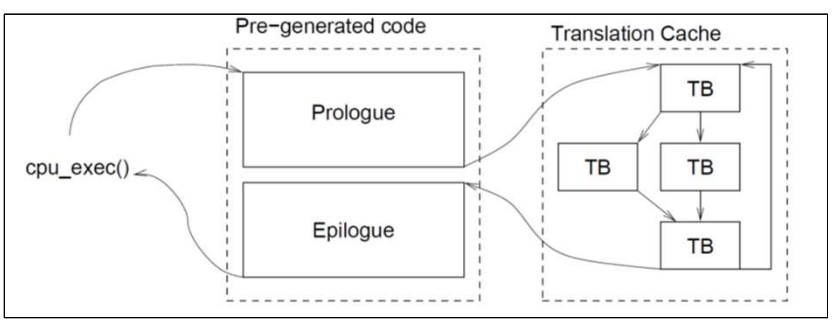
Qemu Block Chaining

- Like we saw in Valgrind, returning to the dispatcher from the code cache is very slow!
- Solution: jump directly between basic blocks!
  - Make space for a jump, followed by a return to the epilogue
  - Every time a block returns, try to chain it



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Offline Trace Reconstruction

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Key Word: Lossless

- Dynamic tracing is assumed to be lossless
  - NO processing of output during runtime!
  - All analysis & processing takes place offline
- A trace must allow offline analysis tool to faithfully recreate the analysis target
  - **Control flow tracing** --- sequence of executed statements
  - **Dependence tracing** --- sequence of exercised dependencies
  - **Value tracing** --- sequence of values that are produced by each instruction
  - **Memory access tracing** --- sequence of memory references during an execution
- Therefore, tracing is the most fine-grained of all possible dynamic analyses

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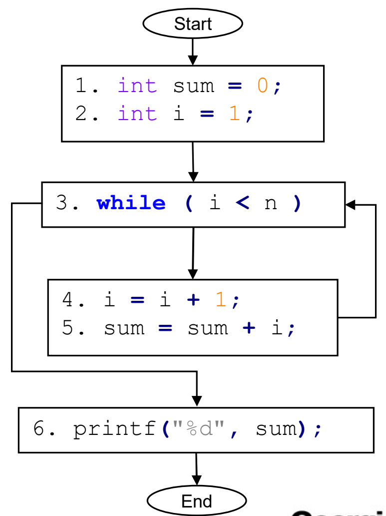
Fine-Grained Tracing is Expensive

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d",
sum);
}
```



Trace(n=6) = ?

Trace(n=6): 1 2 3 4 5 3 4 5 3 4 5 3 4 5 3 4 5 3 6

Space Complexity: 4 bytes * Execution length!

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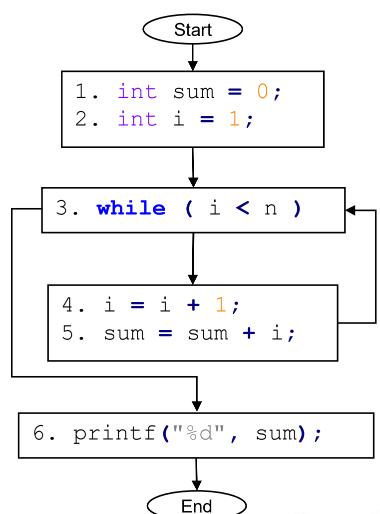
Basic Block Level Tracing

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d",
sum);
}
```



Trace (n=6) : 1 2 3 4 5 3 4 5 3 4 5 3 4 5 3 4 5 3 6

BB Trace: 1 34 34 34 34 34 36

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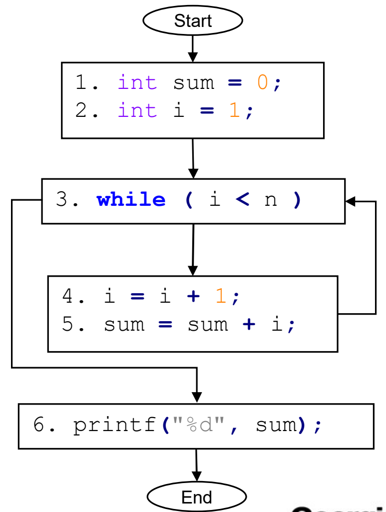
More Ideas

- Would function level tracing work?
  - Each trace entry is a function call & its parameters
  - No…
  - Function's behavior can be affected by global variables ☹
  - Cannot distinguish between nested functions or those called in sequence! ☹
- Predicate tracing

Fine-grained Trace	Predicate Trace
1 2 3 6	F
1 2 3 4 5 3 6	T F

- The trace is no longer randomly accessible
- Must start from the beginning to understand



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Lesson Summary

- Discussed how to employ the tracing process for dynamic analysis
- Discussed how to Apply Static and Dynamic BinaryInstrumentation
- Discussed how to Create a Pintool to utilize PIN
- Discussed Valgrind and QEMU techniques of instrumentation

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