Reverse Engineering and Control Flow Analysis with Intel Processor Trace

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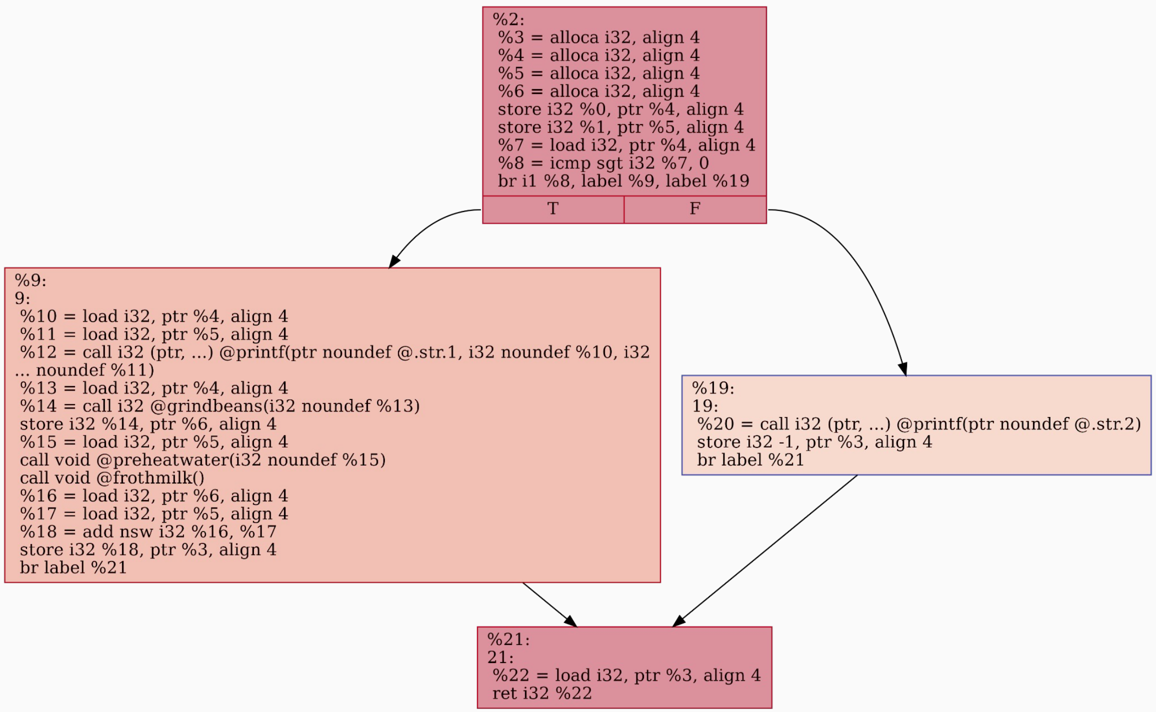
Introduction and Overview

Objective: Intel PT is a surprisingly powerful tool for understanding how software runs, but it's still unfamiliar to many - and not widely documented for reverse engineering use cases. *This talk aims to make Intel PT more accessible and show you how it can transform the way how to analyze program flow* - focusing on RE use cases.



CFG for 'brewcoffee' function

```
$ clang -Xclang -disable-O0-optnone -emit-llvm -S -o f1.ll f1.c
$ opt f1.ll -passes=dot-cfg -cfg-dot-filename-prefix=f1 -disable-output
```

Agenda

1. Control Flow Analysis: Concepts and Techniques
2. Introduction to Intel Processor Trace
3. Using Perf with Intel PT for Control Flow Analysis
4. Practical Tips and Extensions
5. Q&A and Closing Remarks

Basic Elements and Concepts

Control Flow Analysis: Concepts and Techniques

Static Analysis:

- Examines code without execution
- Analyzes structure (control/data flow) for design intent

Dynamic Analysis:

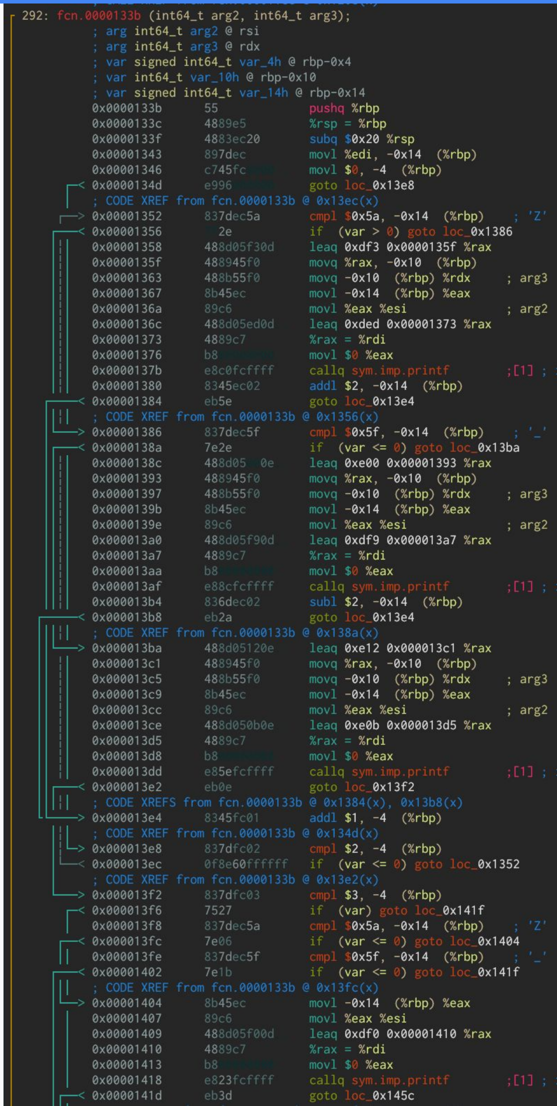
- Observes code behavior during execution
- Traces memory, function calls, and control flow

Basic Block:

- A straight-line sequence of instructions with a single entry point and a single exit point, where the flow of control enters at the beginning and leaves at the end without any possibility of branching except at the end

Control Flow Graphs (CFG): logical flow between basic blocks within a function

Call Graphs: relationships between functions, showing which functions call others



Static Control Flow Analysis

Control Flow Analysis: Concepts and Techniques

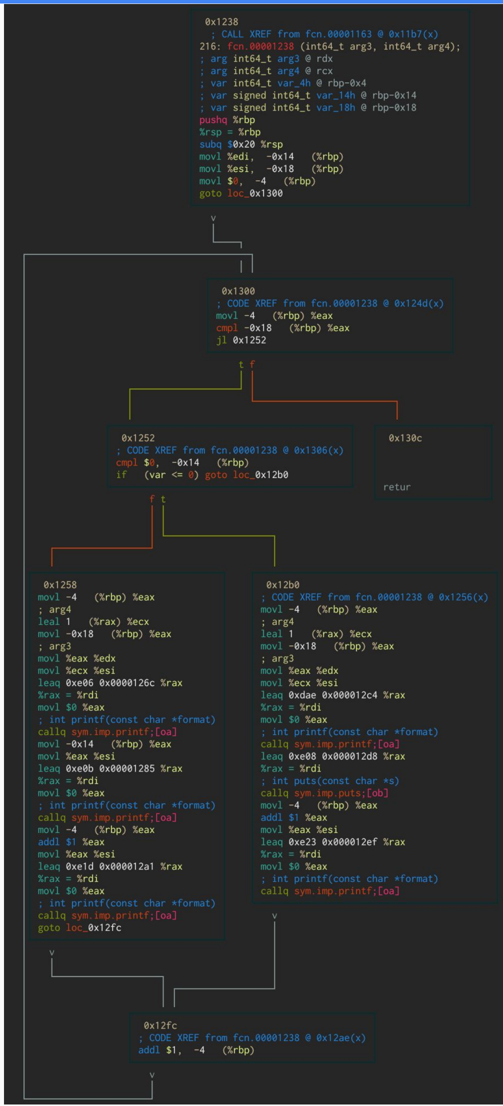
Static Control Flow Analysis

- The flow control graph is an important building block in (static) program analysis
- Control Flow Graph: a map that details execution paths through basic blocks and control paths
- Basic blocks as nodes and jumps/calls/rets/etc as edges
- Control flow can be constructed on local and global basis (function).
- Tools: Radare2, Binary Ninja, Ghidra, BinNavi, Hopper, Angr, IDA, ...

Disassembly → **Building the CFG** → **Analyzing** {Basic Blocks, Control Structures, Function Analysis, Cross-Referencing}

Goals: understand the flow of a program

- Understanding Program Logic
- Identifying Key Functions
- Detecting Obfuscation



Dynamic Flow Control Analysis

Control Flow Analysis: Concepts and Techniques

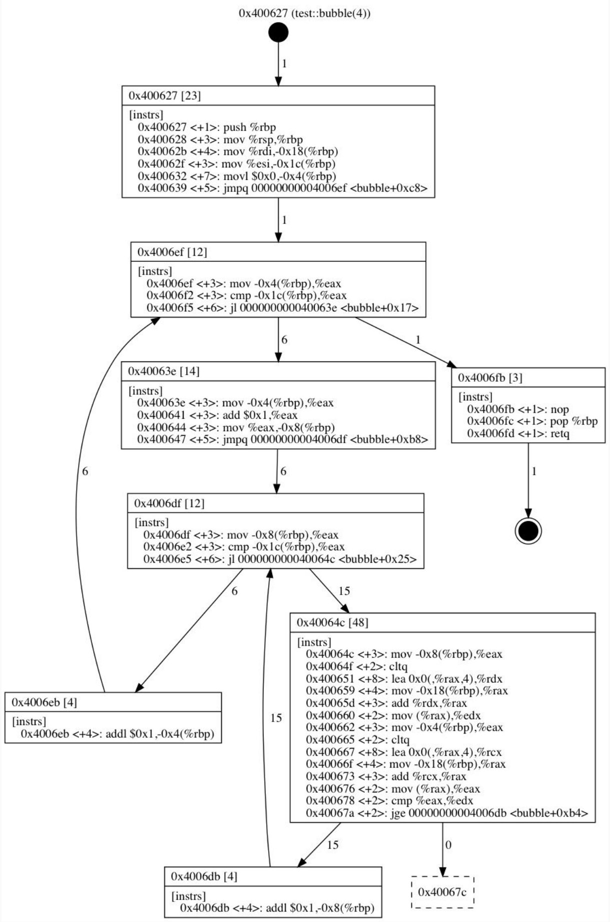
Static control flow has limits

- Certain control-flow transitions are inherently difficult or impossible to resolve:
- Indirect Jumps and Calls (jmp eax; call [ebx]), Dynamic Code Generation, Self-Modifying Code, Data-Driven Control Flow (wget example.com/.text)

Dynamic Flow Analysis: running it and observing the behavior in real-time

Why dynamic flow control is crucial

- Static control flow represents all possible branches and potential paths, but this doesn't reflect actual execution
- For example, a distribution kernel may have 10MiB of .text section, but only a small fraction of it is executed in reality
- Dynamic flow control captures the real execution paths, providing accurate insights into the code's behavior



https://github.com/rimsa/CFGgrind

Dynamic Control Flow Analysis

Control Flow Analysis: Concepts and Techniques

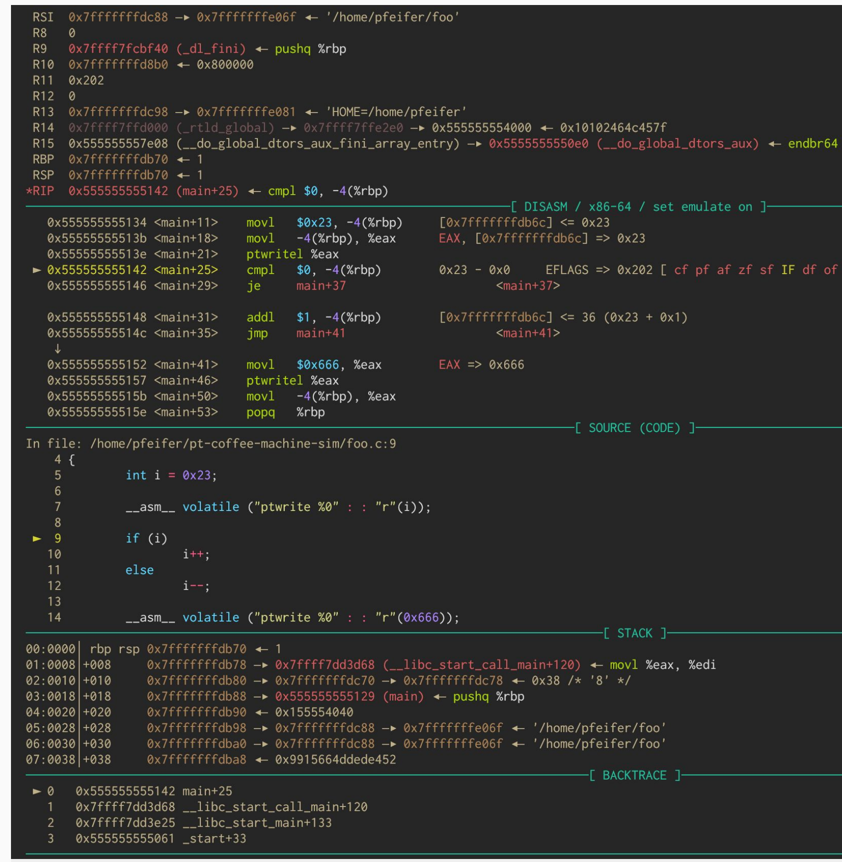
GDB - best in its class, comprehensive feature set, wide language, os and arch support, though it lacks built-in graphical views

R2 - reverse engineering framework and debugger (gdb too), flexible control flow visualization and scripting. Optional: use clutter for graphical frontend

DCFG (Intel Pin) - plugin for Intel Pin that dynamically generates call flow graphs, showing function relationships in real time, great for visualizing complex binary structure

CFGgrind (Valgrind) - Linux-based profiling tool with exhaustive tracing for detailed control flow graphs, offering depth over speed, ideal for precise analysis

Unicorn Emulation (QEMU) - emulates specific code segments efficiently, useful for isolated control flow analysis without full-system



pwndbg (gef, …)

Complexity Layers in Reverse Engineering

Control Flow Analysis: Concepts and Techniques

Code Obfuscation: alters code structure to make it unreadable with techniques like control flow changes, modifies control flow to create complex, non-linear paths

Anti-Debugging: detects and disrupts debuggers using breakpoint and timing checks

Anti-Tampering: uses checksums or signatures to prevent unauthorized code changes

Packers/Cryptors: compress or encrypt code, only decrypting at runtime

Virtualization Protection: runs code in a custom virtual machine, complicating analysis

Self-Modifying Code: dynamically changes its own instructions during execution

Environmental Checks: alters behavior based on system configuration to evade analysis

Anti-Virtualization: detects VMs and behaves differently or refuses execution

Resource Obfuscation: encrypts data and resources to hide information

Note: Intel PT won’t solve all challenges, but it can assist in certain areas and expand the personal toolkit.

What is Intel Processor Trace

Intel Processor Trace

Overview: Intel PT is a hardware-based tracing tool that provides highly detailed insights into program execution. No sampling

Tracing Scope: Intel PT traces branches, calls, returns, and special events like timestamps or exceptions in a highly compressed format. Note that unconditional jumps are not traced

Data Decoding: compressed format is decoded to reconstruct the full instruction stream. Since all control-flow-influencing instructions and their targets are traced, the complete control flow can be accurately reconstructed.

Performance Efficiency: Data is captured with minimal impact on performance and detectability, making it valuable for reverse engineering, with an overhead typically between 2% and 15%

Data Volume: Despite the compression, the amount of captured data can still be large (e.g., assuming a branch every 5 instructions)

Processor Support: Intel PT has been supported since Broadwell CPUs (2014) as a successor to Branch Trace Store (BTS)

Processor Trace Packets

Intel Processor Trace

<table>
<tr><td>TNT
Taken Not Taken</td><td>TIP
Target IP</td><td>FUP
Flow Update Packet</td><td>PIP
Paging Information Packet</td><td>MODE
Mode</td><td>CBR
Core Bus Ratio</td><td>PSB
Packet Stream Boundary</td><td>OVF
Overflow</td><td>TSC
Time-Stamp Counter</td><td>MTC
Mini Time Counter</td><td>CYC
Cycle-Accurate Mode</td><td>PAD
Padding</td></tr>
<tr><td colspan="2">Inside</td><td>Outside</td><td colspan="3">Execution</td><td colspan="2">Trace</td><td colspan="3">Time</td><td>Alignment</td></tr>
<tr><td colspan="3">Redirecton</td><td colspan="5">Environment</td><td colspan="4">Misc</td></tr>
</table>

Packet Variety: more than 10 packet types are available, each encoding specific types of data

Extended Packet Types: since Skylake, several additional packet types have been introduced, primarily for time-related data

Configurable Options: configuration options allow some control over some of the generated packet types

Examples:

- **TNT (Taken/Not Taken):** Encodes taken and not taken branches in two variants with 6 or 47 decision bits and also encodes returns
- **TIP (Target IP):** Encodes target addresses for indirect jumps, exceptions, and interrupts
- **CBR (Core-Bus Ratio):** Indicates changes in the ratio between core and bus clock speeds
- **CYC (Cycle Count):** Provides elapsed time in core clock cycles, relative to the last CYC packet

Raw Recording Information

Intel Processor Trace

```
objdump --disassemble=main
--visualize-jumps=color foo
```

```
int main(int ac, char **av)
{
        int i = 0x23;

        __asm__ volatile ("ptwrite %0" : : "r"(i));

        if (i)
                i++;
        else
                i--;

        __asm__ volatile ("ptwrite %0" : : "r"(0x666));

        return i;
}
```

```
r2 -Aq -c "s main; agf" foo
```

```
0000000000001129 <main>:
    1129:       55                      push   %rbp
    112a:       48 89 e5                mov    %rsp,%rbp
    112d:       89 7d ec                mov    %edi,-0x14(%rbp)
    1130:       48 89 75 e0             mov    %rsi,-0x20(%rbp)
    1134:       c7 45 fc 23 00 00 00    movl   $0x23,-0x4(%rbp)
    113b:       8b 45 fc                mov    -0x4(%rbp),%eax
    113e:       f3 0f ae e0             ptwrite %eax
    1142:       83 7d fc 00             cmpl   $0x0,-0x4(%rbp)
    1146:    ,----- 74 06               je     114e <main+0x25>
    1148:    |      83 45 fc 01         addl   $0x1,-0x4(%rbp)
    114c:    |   ,-- eb 04              jmp    1152 <main+0x29>
    114e:    '--|-> 83 6d fc 01         subl   $0x1,-0x4(%rbp)
    1152:       '-> b8 66 06 00 00      mov    $0x666,%eax
    1157:       f3 0f ae e0             ptwrite %eax
    115b:       8b 45 fc                mov    -0x4(%rbp),%eax
    115e:       5d                      pop    %rbp
    115f:       c3                      ret
```

```
 0x1129
39: int main (int argc, char **argv, char **envp);
; var uint32_t var_4h @ rbp-0x4
; var int64_t var_20h @ rbp-0x20
addb %al,   (%rax)
addb %al,   (%rax)
addb %al,   (%rax)
addb %al,   (%rax)
movl %esi,  -0x20   (%rbp)
movl $0x23,  -4    (%rbp)
cmpl $0,    -4    (%rbp)
if   (!var) goto loc_0x1147

        f t

 0x1141                          0x1147
addl $1,   -4    (%rbp)         ; CODE XREF from main @ 0x113f(x)
goto loc_0x114b                 subl $1,   -4    (%rbp)

        v                               v

 0x114b
; CODE XREF from main @ 0x1145(x)
movl -4   (%rbp) %eax
popq %rbp
retur
```

PT Recording Start

```
 .  00001f0c:  59 d7                  MTC 0xd7
 .  00001f0e:  8c                     TNT NNNTTN (6)
 .  00001f0f:  04                     TNT N (1)
 .  00001f10:  4d 1b ee 7a 5f         TIP 0x5f7aee1b
 .  00001f15:  14                     TNT NTN (3)
 .  00001f16:  6d 00 70 e4 ce 9f 55   TIP 0x559fcee47000
 .  00001f1d:  38                     TNT TTNN (4)
 .  00001f1e:  2d 20 71               TIP 0x7120
 .  00001f21:  59 d8                  MTC 0xd8
 .  00001f23:  1c                     TNT TTN (3)
 .  00001f24:  6d 00 d9 9a 5f 7b 7f   TIP 0x7f7b5f9ad900
 .  00001f2b:  14                     TNT NTN (3)
 .  00001f2c:  59 d9                  MTC 0xd9
 .  00001f2e:  14                     TNT NTN (3)
 .  00001f2f:  6d 29 71 e4 ce 9f 55   TIP 0x559fcee47129
 .  00001f36:  02 12 23 00 00 00      PTWRITE 0x23 IP:0
8893 .  00001f3c:  04                 TNT N (1)
 .  00001f3d:  02 12 66 06 00 00      PTWRITE 0x666 IP:0
 .  00001f43:  0e                     TNT TT (2)
 .  00001f44:  59 da                  MTC 0xda
 .  00001f46:  e0                     TNT TTNNNN (6)
 .  00001f47:  0c                     TNT TN (2)
 .  00001f48:  6d 20 ae 99 5f 7b 7f   TIP 0x7f7b5f99ae20
 .  00001f4f:  04                     TNT N (1)
 .  00001f50:  4d 70 48 81 5f         TIP 0x5f814870
 .  00001f55:  04                     TNT N (1)
 .  00001f56:  59 db                  MTC 0xdb
```

PT Recording End

Introduction to Perf

Using perf with Intel PT for Control Flow Analysis

Linux Perf: in-kernel performance monitoring framework and userspace tool for profiling system and application performance, supporting hardware counters, tracepoints and custom event tracking

Events: hw, sw, tracepoint, pmu, sdt and metric's

Recording:

Generic Syntax

```
$ perf record --event pmu/config=M,config1=N,config3=K/ -- <workload>
```

Intel PT Specific

```
$ perf record -e intel_pt/ptw,cyc,cyc_thresh=5/u -o perf.data -- foo
```

Setting up Perf with Intel PT – Decoding

Using perf with Intel PT for Control Flow Analysis

Decoding is Key: recording is essential, but the true potential unfolds through decoding. Drill deep and examine data from different angles to analyze vast amounts of information and gain valuable insights

Advice: start with high-level analysis, then drill down to the instruction level as needed

- **Call Trace:** `perf script --call-trace --ns -F -cpu,-tid,-time`
- **Assembly Stream:** `perf script --insn-trace=disasm -F -cpu,-tid,-time`

Miscellaneous Decoding: various helpful decoding methods

- **Raw Trace:** `perf script --dump-raw-trace`
- **Mmap Events:** `perf script --no-itrace --show-mmap-events`
- **Branch Focus:** `perf script --itrace=iybxwpe -F+flags`
- **Power Events:** `perf script --itrace=p`
- **Decoder Debug:** `perf script --itrace=d`

Setting up Perf with Intel PT – Decoding

Using perf with Intel PT for Control Flow Analysis

Call Trace

```
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )     _dl_init
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )         call_init
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )         call_init
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )             _init_first
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )             __init_misc
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                 strrchr@plt
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )             check_stdfiles_vtables
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )             _IO_stdfiles_init
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )         call_init
foo (/home/pfeifer/foo                                 ) _start
foo (/home/pfeifer/foo                                 )     __libc_start_main@@GLIBC_2.34
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )         __cxa_atexit
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )         __cxa_atexit
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )             __new_exitfn
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )         _init
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )         frame_dummy
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )         _dl_audit_preinit@plt
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )         __libc_start_call_main
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )             _setjmp
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )             main
foo  IP: 0 payload: 0x23 #
foo  IP: 0 payload: 0x666
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )             exit
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                 __run_exit_handlers
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                     __call_tls_dtors
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                     _dl_fini
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         pthread_mutex_lock@@GLIBC_2.2.5
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_audit_activity_nsid
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_sort_maps
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                             dfs_traversal.part.0
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                             dfs_traversal.part.0
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                             dfs_traversal.part.0
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                             dfs_traversal.part.0
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                             memmove
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         pthread_mutex_unlock@@GLIBC_2.2.5
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_call_fini
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                             __do_global_dtors_aux
foo (/home/pfeifer/foo                                 )                                 __cxa_finalize@plt
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                                     __unregister_atfork
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                                     __unregister_atfork
foo (/home/pfeifer/foo                                 )                                 deregister_tm_clones
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_audit_objclose
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_call_fini
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_audit_objclose
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_call_fini
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_audit_objclose
foo (/usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2    )                         _dl_audit_activity_nsid
foo (/usr/lib/x86_64-linux-gnu/libc.so.6               )                 __run_exit_handlers
```

Disassembly Trace

```
7fd27a799d72 __libc_start_call_main+0x32 (/usr/lib/x86_64-linux-gnu/libc.so.6)    testl %eax, %eax
7fd27a799d74 __libc_start_call_main+0x34 (/usr/lib/x86_64-linux-gnu/libc.so.6)    jne __libc_start_call_main+0x81
7fd27a799d76 __libc_start_call_main+0x36 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq %fs:0x300, %rax
7fd27a799d7f __libc_start_call_main+0x3f (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq %rax, 0x68(%rsp)
7fd27a799d84 __libc_start_call_main+0x44 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq %fs:0x2f8, %rax
7fd27a799d8d __libc_start_call_main+0x4d (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq %rax, 0x70(%rsp)
7fd27a799d92 __libc_start_call_main+0x52 (/usr/lib/x86_64-linux-gnu/libc.so.6)    leaq 0x20(%rsp), %rax
7fd27a799d97 __libc_start_call_main+0x57 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq %rax, %fs:0x300
7fd27a799da0 __libc_start_call_main+0x60 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq 0x1b2209(%rip), %rax
7fd27a799da7 __libc_start_call_main+0x67 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq 0x18(%rsp), %rsi
7fd27a799dac __libc_start_call_main+0x6c (/usr/lib/x86_64-linux-gnu/libc.so.6)    movl 0x14(%rsp), %edi
7fd27a799db0 __libc_start_call_main+0x70 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq (%rax), %rdx
7fd27a799db3 __libc_start_call_main+0x73 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq 8(%rsp), %rax
7fd27a799db8 __libc_start_call_main+0x78 (/usr/lib/x86_64-linux-gnu/libc.so.6)    callq *%rax
55ae54c7f129 main+0x0  (/home/pfeifer/foo)    pushq %rbp
55ae54c7f12a main+0x1  (/home/pfeifer/foo)    movq %rsp, %rbp
55ae54c7f12d main+0x4  (/home/pfeifer/foo)    movl %edi, -0x14(%rbp)
55ae54c7f130 main+0x7  (/home/pfeifer/foo)    movq %rsi, -0x20(%rbp)
55ae54c7f134 main+0xb  (/home/pfeifer/foo)    movl $0x23, -4(%rbp)
55ae54c7f13b main+0x12 (/home/pfeifer/foo)    movl -4(%rbp), %eax
55ae54c7f13e main+0x15 (/home/pfeifer/foo)    f3 0f ae e0
55ae54c7f142 main+0x19 (/home/pfeifer/foo)    cmpl $0, -4(%rbp)
55ae54c7f146 main+0x1d (/home/pfeifer/foo)    je main+0x25
55ae54c7f148 main+0x1f (/home/pfeifer/foo)    addl $1, -4(%rbp)
55ae54c7f14c main+0x23 (/home/pfeifer/foo)    jmp main+0x29
55ae54c7f152 main+0x29 (/home/pfeifer/foo)    movl $0x666, %eax
55ae54c7f157 main+0x2e (/home/pfeifer/foo)    f3 0f ae e0
55ae54c7f15b main+0x32 (/home/pfeifer/foo)    movl -4(%rbp), %eax
55ae54c7f15e main+0x35 (/home/pfeifer/foo)    popq %rbp
55ae54c7f15f main+0x36 (/home/pfeifer/foo)    retq
7fd27a799dba __libc_start_call_main+0x7a (/usr/lib/x86_64-linux-gnu/libc.so.6)    movl %eax, %edi
7fd27a799dbc __libc_start_call_main+0x7c (/usr/lib/x86_64-linux-gnu/libc.so.6)    callq exit+0x0
7fd27a7b1b90 exit+0x0 (/usr/lib/x86_64-linux-gnu/libc.so.6)   subq $8, %rsp
7fd27a7b1b94 exit+0x4 (/usr/lib/x86_64-linux-gnu/libc.so.6)   movl $1, %ecx
7fd27a7b1b99 exit+0x9 (/usr/lib/x86_64-linux-gnu/libc.so.6)   movl $1, %edx
7fd27a7b1b9e exit+0xe (/usr/lib/x86_64-linux-gnu/libc.so.6)   leaq 0x19aadb(%rip), %rsi
7fd27a7b1ba5 exit+0x15 (/usr/lib/x86_64-linux-gnu/libc.so.6)    callq __run_exit_handlers+0x0
7fd27a7b1920 __run_exit_handlers+0x0 (/usr/lib/x86_64-linux-gnu/libc.so.6)    pushq %r15
7fd27a7b1922 __run_exit_handlers+0x2 (/usr/lib/x86_64-linux-gnu/libc.so.6)    pushq %r14
7fd27a7b1924 __run_exit_handlers+0x4 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movq %rsi, %r14
7fd27a7b1927 __run_exit_handlers+0x7 (/usr/lib/x86_64-linux-gnu/libc.so.6)    pushq %r13
7fd27a7b1929 __run_exit_handlers+0x9 (/usr/lib/x86_64-linux-gnu/libc.so.6)    movl %edi, %r13d
7fd27a7b192c __run_exit_handlers+0xc (/usr/lib/x86_64-linux-gnu/libc.so.6)    pushq %r12
7fd27a7b192e __run_exit_handlers+0xe (/usr/lib/x86_64-linux-gnu/libc.so.6)    pushq %rbp
7fd27a7b192f __run_exit_handlers+0xf (/usr/lib/x86_64-linux-gnu/libc.so.6)    pushq %rbx
7fd27a7b1930 __run_exit_handlers+0x10 (/usr/lib/x86_64-linux-gnu/libc.so.6)   subq $0x28, %rsp
7fd27a7b1934 __run_exit_handlers+0x14 (/usr/lib/x86_64-linux-gnu/libc.so.6)   movl %edx, 0x1c(%rsp)
```

Note: Intel XED is no longer required; starting from version v6.8-rc1-303-g8b767db33095, libcapstone is used as the disassembly engine

Custom Tooling

Using perf with Intel PT for Control Flow Analysis

Post-Processing Needs: sometimes, custom post-processing or integration with other tools is required. Two options exist

- **Parse perf script Output:** simple and effective for basic tasks, but can be time-consuming and computationally intensive
- **Integrate directly with perf script:** for more complex analyses, it's recommended to connect directly within perf script using mechanisms like dlfilter (and dlarg).

```
$ cat filter.c
int filter_event(void *data, const struct perf_dlfilter_sample *sample, void *ctx)
{
    if (sample->ip) {
        printf("IP: 0x%" PRIx64 "\n", sample->ip);
    }
    return 0;
}
$ gcc -o filter.so -shared -fPIC filter.c -ldl
$ perf script --dlfilter=filter.so
```

Tips for Overcoming Common Challenges

Using perf with Intel PT for Control Flow Analysis

%RIP Filter: limit tracing to specific areas

- `perf record -e intel_pt//u --filter 'start 0x1149 @ foo' -- foo`
- `perf record -e intel_pt//u --filter 'filter main @ foo' -- foo`

Disable Return Compression: use `/noretcomp/` to trace all "ret" instructions, helpful for obfuscated code

Limit Recording: restrict to specific processes, CPUs or use snapshot mode to manage data size

Adjust Cycle Threshold: increase `cyc_thresh` if cycle accuracy isn't critical to reduce data

PTWRITE for Custom Markers: add PTWRITE instructions to tag and track key events in the trace

Use PEBS: combine with PEBS (if supported) to capture memory access patterns alongside control flow. Technically works, but combining tracing and sampling is somehow awkward

Tips for Overcoming Common Challenges - II

Using perf with Intel PT for Control Flow Analysis

Decoding is intensive: decoding traces can produce significant output files and decoding time

```
$ perf record -a -e intel_pt// -o perf.data -- sleep 0.01  (10ms on 32 core system)
$ perf script --itrace=i0ns --ns > report.txt
$ ls -lh report.txt perf.data
-rw------- 1 pfeifer pfeifer 2.7M Nov  2 14:17 perf.data
-rw-rw-r-- 1 pfeifer pfeifer 862M Nov  2 14:18 report.txt   (--> ~330)
```

Limit Decoding Timeframe: use `--time <start>,<stop>` to reduce both data size and decoding time by focusing on specific sections

Exclude Unneeded Fields: Use: `perf script --call-trace -F -cpu,-tid,-time` to skip unnecessary fields, reducing report size and processing load

Mitigate Record Overloads: increase buffer size, limit recording, switch recording setup

Limitations of Intel PT in Control Flow Analysis

Conclusions

Limited Instruction Visibility: Intel PT captures only metadata (branches, timestamps) rather than actual instructions. For JIT-compiled code, self-modifying applications or loaded shellcode the decoder will fail as it relies on the available ELF objects

No Data Capture: captures instruction flow but lacks functionality to track data flow or data manipulation and transformations

High Data Volume: Intel PT generates vast amounts of data, making it essential to use filtering or snapshot mode to manage size and processing time

Platform Limitations:

- **ARM Alternative:** Intel PT's counterpart on ARM is CoreSight ETM, which has different configurations and features
- **No AMD Equivalent:** AMD lacks an equivalent tracing tool; → exec on Intel(R)

Thank you very much!

Let’s Tackle Your Questions!

Got more questions? Feel free to catch me at the event or email me!
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Correlate Dynamically Mapped DSO

Appendix

Linux will map DSO pseudo-randomly, see ELF and Address Space Layout Randomization

- Addresses like 0x5583ca2fa2a1 or 7f4180447792 becoming meaningless

Luckely: perf will record mmap events:

```
$ perf script --no-itrace --show-mmap-events
cms  108632 [023] 124501.882184: PERF_RECORD_MMAP2 108632/108632: [0x5583ca2fa000(0x1000) @ 0x1000 103:02
25874047 2058819998]: r-xp cms
cms  108632 [023] 124501.882202: PERF_RECORD_MMAP2 108632/108632: [0x7f4180604000(0x27000) @ 0x1000 103:02
27829660 3107761507]: r-xp /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
cms  108632 [023] 124501.882211: PERF_RECORD_MMAP2 108632/108632: [0x7f4180601000(0x2000) @ 0 00:00 0 0]:
r-xp [vdso]
cms  108632 [023] 124501.882297: PERF_RECORD_MMAP2 108632/108632: [0x7f4180419000(0x15a000) @ 0x28000 103:02
27829672 2718021217]: r-xp /usr/lib/x86_64-linux-gnu/libc.so.6
```

```
file-offset = [address] - start + offset
       4769 = 0x5583ca2fa2a1 - 0x5583ca2fa000 + 0x1000
```