EDAP15: Program Analysis

DYNAMIC PROGRAM ANALYSIS 2

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Welcome back!

Questions?

Gathering Dynamic Data

- Instrumentation and Software Probes
  - Example: Performance profiler
- Simulation (or Emulation)
  - Example: CPU simulator
- Hardware Probes
  - Example: Hardware Performance Counters

Automatic Performance Measurement

- **[Software Probes]** Profiler:
  - Interrupts program during execution
  - Examines call stack
- **[Software Probes]** Operating System Perf. Counters:
  - Count important system events (network accesses etc.)
- **Simulator**:
  - Simulates CPU/Memory in software
  - Tries to replicate inner workings of machine
  - Alternatively: *Emulator* (= replicate only observable functionality, not internals)
- **[Hardware Probes]** CPU:
  - Hardware performance counters count interesting events

Profiler

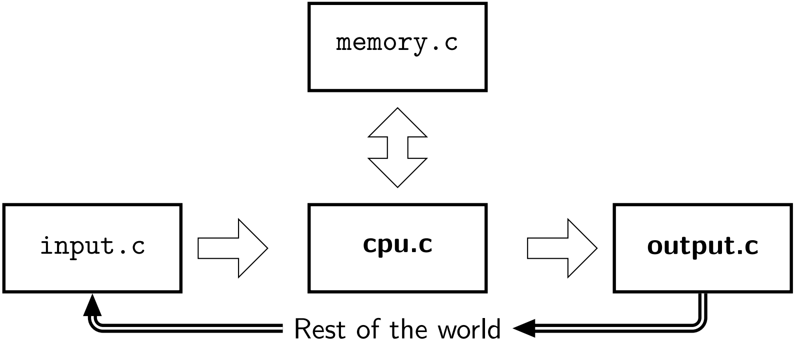
- Measures: which functions are we spending our time in?
- Approach:
  - Build stack maps
  - Execute program, interrupt regularly
  - During interrupt:
    - Examine program counter
    - Examine stack
- Infer callers from stack contents

Execution Stack

`return` (old-1)
`$fp` (old-1)
...
...
`return` (old-2)
`$fp` (old-2)
...

Source of inaccuracy: inlined functions don't track their caller on call stack

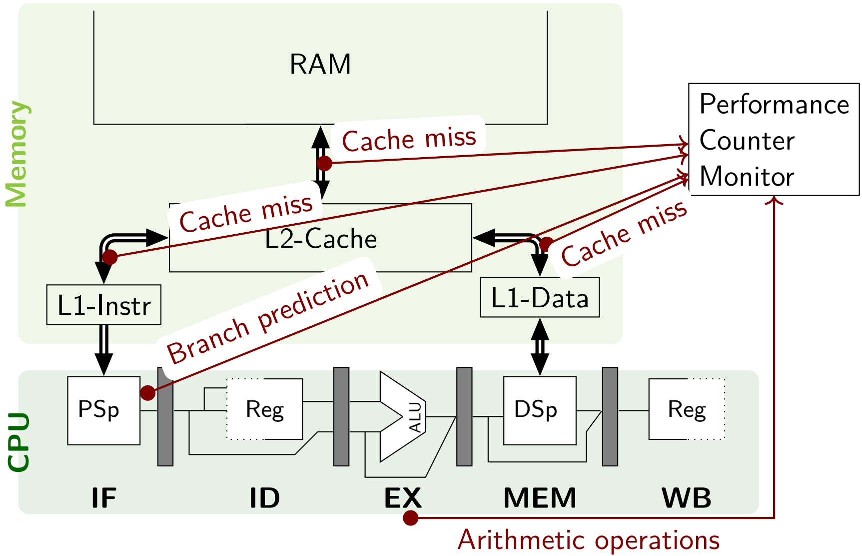
Simulator



- Software simulates hardware components
- Can count events of interest (memory accesses etc.)

Modern CPUs are very complex: Simulators are inaccurate in practice

Hardware Performance Counters (1/2)



Hardware Performance Counters (2/2)

Special CPU registers:

- Count *performance events*
- Registers must be configured to collect specific performance events
  - Number of CPU cycles
  - Number of instructions executed
  - Number of memory accesses

    ...
- #performance event types > #performance registers

May be inaccurate: not originally built for software developers

Summary

- Performance analysis may require detailed dynamic data
- **Profiler**: Probes stack contents at certain intervals
- **Simulator**:
  - Simulates hardware in software, measures
  - Tends to be inaccurate
- **Performance Counters**:
  - Software:
    - Operating System counts events of interest
  - Hardware:
    - Special registers can be configured to measure CPU-level events

Gathering Dynamic Data

- Instrumentation and Software Probes
- Simulation
- Hardware Probes

Generality of Performance Measurements?

Measured performance properties are valid for…

- Selected CPU
- Selected operating system
- Compiler version and configuration
- Operating system configuration:
  - OS setup
    (e.g., dynamic scheduler)
  - Processes running in parallel

    …
- A particular input/output setup
  - Behaviour of attached devices
  - Time of day, temperature, air pressure, …
- CPU configuration (CPU frequency etc.)

  …

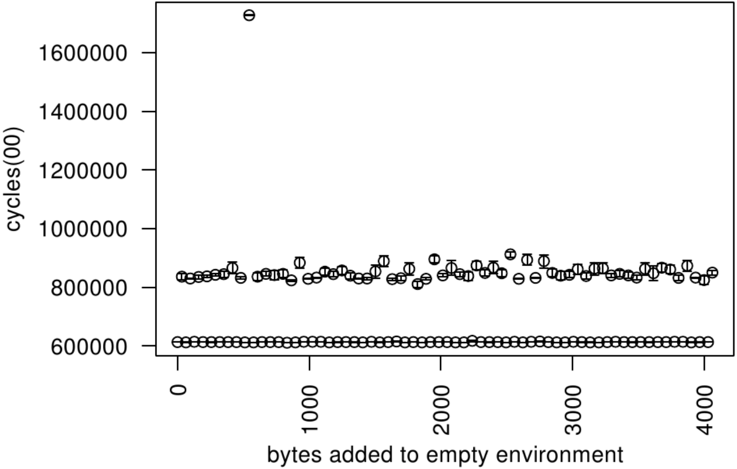
Is that all?

Unexpected Effects

- User `toddm` measures run time 0.6s
- User `amer` measures run time 0.8s
- Both measurements are stable
- Reason for discrepancy:
  - Before program start, Linux copies shell environment onto stack
  - Shell environment contains user name
  - Program is loaded into different memory addresses
    $\Rightarrow$ Memory caches can speed up memory access in one case but not the other

Changing your user name can speed up code

Unexpected Effects



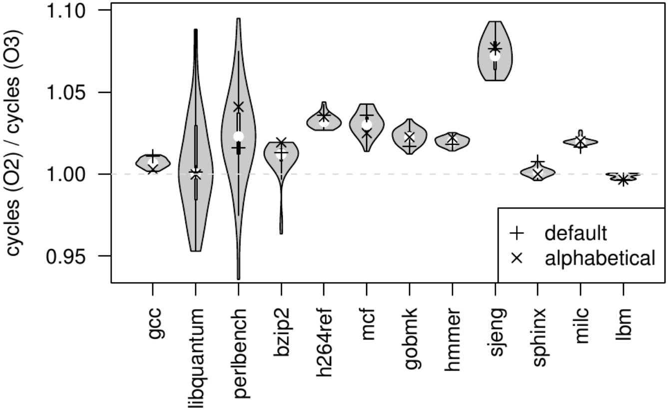
Mytkowicz, Diwan, Hauswirth, Sweeney: “Producing wrong data without doing anything obviously wrong”, in ASPLOS 2009

Linking Order

Is there a difference between re-ordering modules in RAM?

`gcc a.o b.o -o program` (Variant 1)

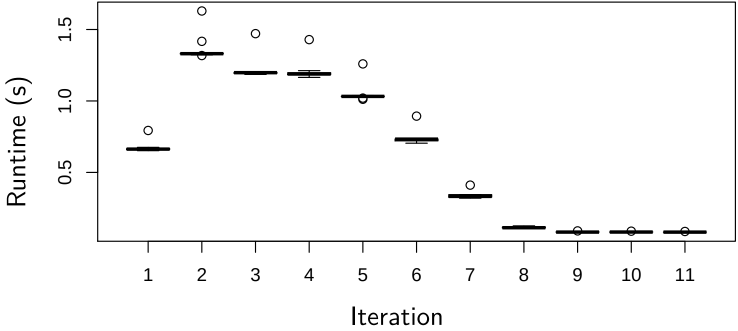
`gcc b.o a.o -o program` (Variant 2)



(Mytkowicz, Diwan, Hauswirth, Sweeney, ASPLOS'09)

Adaptive Systems

- Java program: loop *n* iterations (x axis) around simple computation that randomly samples from pre-initialised array
- Measurement: 11 runs
  - Ran each *n* 11 times, time reported below is last iteration only



Warm-up effect

Warm-Up Effects

- Performance varies during initial runs
- Eventually reaches steady state
- Reason: Adaptive Systems
  - Hardware:
    - *Cache*: Speed up some memory accesses
    - *Branch Prediction*: Speed up some jumps
    - *Translation Lookaside Buffer*
  - Software:
    - *Operating System / Page Table*
    - *Operating System / Scheduler*
    - *Just-in-Time compiler*
- Understanding performance: what to measure?
  - Latency: measure first run
    Reset system before every run
  - Throughput: later runs
    Discard initial *n* measurements

Ignored Parameters

- Performance affected by subtle effects
- Systems developers must “think like researchers” to spot potential influences

Beware of generalising measurement results!

Summary

- Modern computers are complex:
  - *Caches* make memory access times hard to predict
  - *Multi-tasking* may cause sudden interruptions
  - *CPU frequency scaling* changes speed based on temperature
  - ...
- This makes measurements difficult:
  - Must carefully consider what **assumptions** we are making
  - Must measure repeatedly to gather **distribution**
  - Must check for **warm-up effects**
  - Must try to understand causes for performance changes
- Measurements are often not normally distributed
  - Mean + Standard Deviation may not describe samples well
  - If in doubt, use **box plots** or *violin plots*

Dynamic Program Analysis: Applications

Like static analysis, dynamic analysis can help:

- *Understanding*
- *Efficiency*
- *Safety*
- *Security*

Application: Program Understanding

Approaches:

- *Performance analysis* (`gprof`, `papi`, `perf`, ...)
- *Interactive debugging* (`gdb`, `jdb`, ...)
- Tracing
  Compute sequence of actions (trace) of interest
  - Methods
  - Parameters
  - IL/assembly instructions
  - Lines of code

  ...
- Dynamic slicing
  Reduce program to parts that were actually executed
  - Remove dead code
  - Enables further optimisations (e.g., inlining)

Tracing vs. Dynamic Slicing

Source program

```
(0)int f(int x) {
(1)  return x + 1;
(2)}
(3)int g(int x) {
(4)  return x - 1;
(5)}
(6) void main() {
(7)   int x = f(1);
(8)   int y = f(2);
(9)   if (x < 0) {
(A)     puts("fail");
(B)   } else {
(C)     printf("%d",x+y);
(D)   }
(E)}
```

Trace

```
6
7
0[x=1]
1[⇒2]
8
0[x=2]
1[⇒3]
9
B
C
```

Dynamic Slice

```
(0)int f(int x) {
(1)  return x + 1;
(2)}
(6) void main() {
(7)   int x = f(1);
(8)   int y = f(2);
(C)     printf("%d",x+y);
(E)}
```

Tracing/slicing algorithms vary in output

Application: Efficiency

- Dynamic Optimisation
  - Utilise run-time knowledge to optimise
- Speculative Optimisation
  - Type or value seems to be constant?
    - Speculate: it *is* constant
    - Optimise accordingly
  - Add *guard*: is assumption correct?
  - *Deoptimise* when guard fails
  - Common example: *method inlining*
- Challenge: Dynamic analysis introduces overhead
  - Focus efforts on *hot* methods (frequently running)

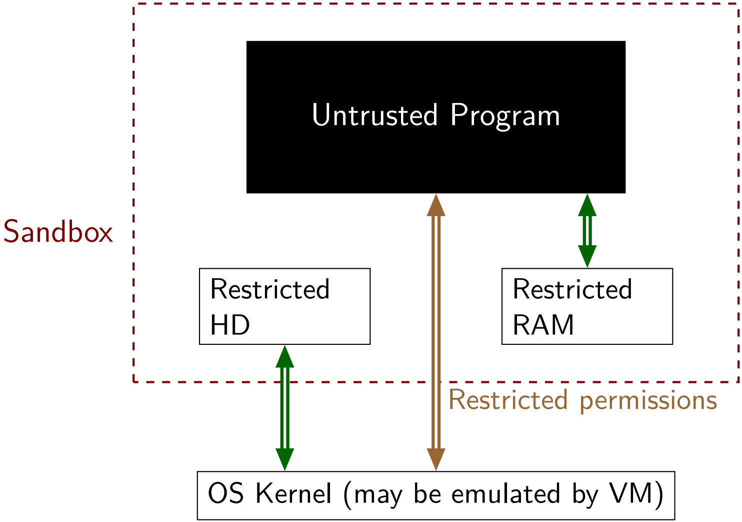
Application: Safety

- Dynamic type checking
  - Out-of-bounds checks
    `a[i]`
  - Narrowing conversions
    ```
    Object obj = ...;
    String str = (String) obj;
    ```
- Assertions
  - Preconditions
    Checked before subroutine call
  - Postconditions
    Checked at end of subroutine call
- Invariants
  Checked between subroutine calls in same module / object

Application: Security

- Which part of program are not trustworthy?
  - Externally loaded code?
  - Externally obtained data?
  - Runtime environment?
- Untrusted code:
  - Confine (containers, sandboxing)
  - Analysis mainly to detect “bad behaviour”
- Untrusted data:
  - Sanitise, track
  - Beware: can escalate to untrusted code

Sandboxing: Confining Untrusted Code



Summary

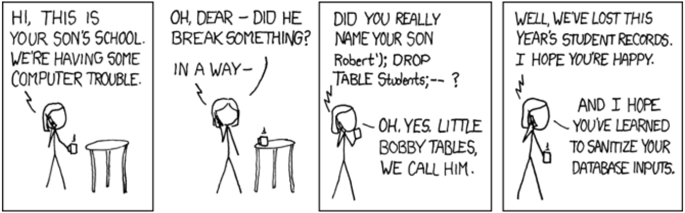
- Dynamic analysis contributes techniques to all typical clients of program analysis
- *Understanding*:
  - Interactive debugging
  - **Tracing** and **Dynamic Slicing**
- *Efficiency*:
  - **Dynamic** and **speculative optimisation**
- *Safety*:
  - **Dynamic type checking**
  - **Dynamic assertion checking**
- *Security*:
  - **Dynamic Taint analysis**
  - Alternative to analysis: **Sandboxing**, i.e., executing in restricted execution environment

Some Examples

Tainted Values (1/2)

Python

```
username = request.GET['user']
...
q = sql.query("SELECT * from Users WHERE name='"
              + username + "'")
user_data = q.run
```

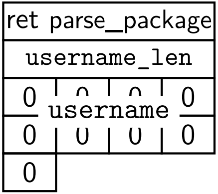


Tainted Values (2/2)

C

```c
int parse_package(s* out, uint8* data) {
  char username[9] = { 0 };
  int username_len = data[0];
  // spec says: length <= 8
  memcpy(username, data+1, username_len);
  ...
}
```

Stack



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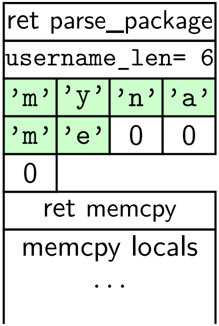

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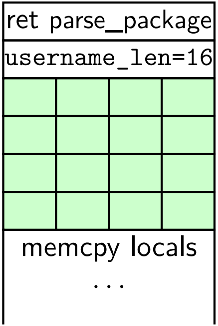


Tracing 'Tainted' Values

Taint Analysis:

- Track *tainted* values
- Remove taint if values are *sanitised*
- Detect if they reach sensitive *sinks*
- NB: Static taint analysis may also be possible

Unsafe input

- **Taint source**: Network ops
- **Sanitiser**: SQL string escape
- **Taint sink**: SQL query string

Leaking secrets

- **Taint source**: Plaintext passwd.
- **Sanitiser**: cryptographic hash
- **Taint sink**: Network ops

Dynamic Taint Analysis

`query_l = "SELECT ...'"`	`query_l` = `"SELECT ..."`$^{\epsilon}$
`query_r = "'"`	`query_r` = `"'"`$^{\epsilon}$
`username = request.GET['user']`	`username` = `"..."`^{t}
`...`	
`query_str = query_l + username`	`query_str` = `"..."`^{t}
`query_str = query_str + query_r`	`query_str` = `"..."`^{t}
`q = sql.query(query_str)`	Fault!

Dynamic Taint Analysis

Strategy:

- Annotate tainted values with *taint tags* or *shadow values*

```
s = read_network() // string in s will be tainted
t = "foo" + "bar"  // string in t will be untainted
```

- Extend operators to propagate taint:

$\oplus$	ϵ	**t**
ϵ	ϵ	t
t	t	t

$\texttt{"foo"}^v[1] = \texttt{"o"}^v$

$\texttt{"foo"}^v\texttt{+"bar"}^w = \texttt{"foobar"}^{v \oplus w}$

- Check taint sinks for tainted input
- Needs instrumentation (shadow values) or explicit support by runtime (e.g., Perl, Ruby)

Conditionals

- Should conditionals propagate taint?
- Usually such *control dependencies* don't propagate taint

Python

```
if secret_password == '':
    network_send('Account disabled, cannot log in');
```

Attackers vs. Taint Ananlysis

Is taint analysis 'sound enough' to detect attempts to expose sensitive data?

- *Attackers can subvert this analysis via control dependencies:*

C

```c
for (i = 0; i < 16; ++i) {
  for (k = 0; k < 8; ++k) {
    if (secret_password[i] & 1 << k) {
      network_send("Meaninless Message");
    } else {
      network_send("Something Else");
    }
} }
```

System Command Attack

C

```
char d_secret[1024];
strcpy(d_secret, "/tmp/");
strcat(d_secret, secret); // taint d_secret

int iopipes[2];
pipe(iopipes);
...
if (fork()) { // create child process
  // connect pipes
  execv("/bin/rm", d_secret); // call external 'rm'
}
char[1024] buf; // untained!
read(iopipes[0], ...); // read output from 'rm'
```

System call will print e.g.:

`rm: cannot remove '/tmp/mysecretstring': No such file or directory`

Side Channel Attacks

Many more attacks possible:

- Timing attacks:
  - Two threads
  - One sends signal to other, with delays
  - Delay loop length dependent on secret
- File length attack:
  - Write dummy file
  - File length (or other metadata) encodes secret
- Graphics buffer attack:
  - Write to screen
  - Read back with OCR
  - Or adjust widget position / font size to encode secret

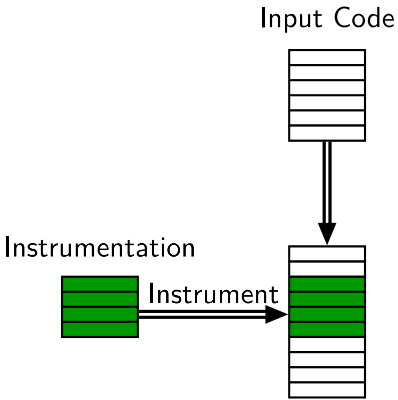
Summary

- Dynamic taint analysis tracks **tainted** values (from **taint sources**)
- Tags also referred to as **shadow values**
- Removes taint if values are **sanitised**
- Detects attempts to use tainted values in **taint sinks**
- Still many weaknesses in analysis:
  - Control-dependence attacks
  - System command attacks
  - Side-channel attacks
- Can be strengthened with *symbolic* techniques

Dynamic Binary Analysis

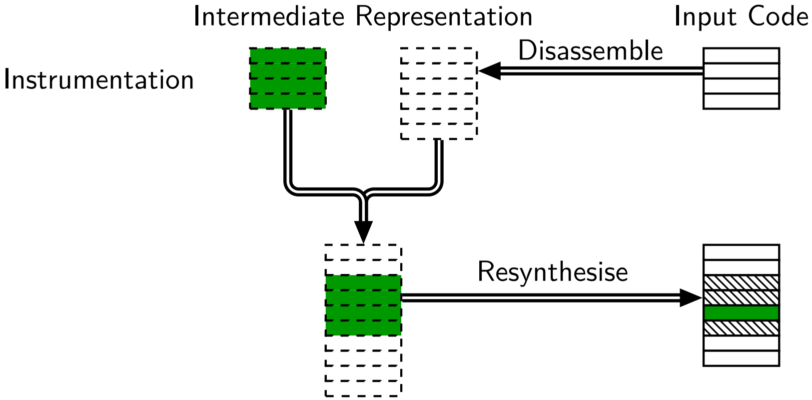
- *Binary Analysis*: Analyse binary executables
  - Applicable to any executable program
  - Only requires binary code
  - Unaware of source language
- *Dynamic Binary Analysis*
  - Analyser runs concurrently with program-under-analysis
  - Can adaptively instrument / analyse / intercede

Dynamic Binary Instrumentation (1/3)



Copy-and-Annotate

Dynamic Binary Instrumentation (2/3)



Disassemble-and-Resynthesise

Dynamic Binary Instrumentation (3/3)

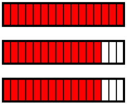
- *Copy-and-Annotate* (e.g., `pin`):
  - Inserts code into binary
  - Inserted code must maintain state (registers!)
- *Disassemble-and-Resynthesise* (e.g., `valgrind`, `qemu`):
  - Decomposes program into IR
  - Instrumentation on IR-level
  - Easier/faster to track shadow values in some cases
    - *Shadow registers*
    - *Shadow memory*
    - Must model *system calls* for proper tracking

Application: Finding Memory Errors

- Reads from uninitialised memory in C can trigger undefined behaviour
- Approach: Track information: which bits are uninitialised?
- Requires *shadow registers*, *shadow values*
- Almost every instruction must be instrumented

Shadow values   Program

x:
x:
x:



```
short x;
x |= 0x7;
if (x & 0x10) {
...
```

Example: Valgrind's Memcheck

- Valgrind is Disassemble-and-Resynthesise-style Binary Instrumentation tool
- Memcheck: tracks memory initialisation (mostly) at bit level
  - Less precise for floating point registers
- Valgrind uses dynamic translation:
  - Translate & instrument blocks of code at address until return / branch
  - Instrumented code jumps back into Valgrind core for lookup / new translation

Challenges

- System calls
  - System calls may affect shadow values (e.g., propagate taintedness)
  - Must be modelled for precision
- Self-modifying code
  - Used e.g. in GNU libc
  - Must be detected, force eviction of old code (expensive checks!)

Valgrind

- Binary instrumenter
- Open Source
- Many supported hardware / OS combinations
- Analyses (focus on *Simulation*):
  - Call analysis
  - Cache analysis
  - Memcheck

  ...

Qemu

QEMU

- Binary instrumenter and translator
- Open Source
- Focus on *emulation*
- Runs kernel + user space
- Translate from one ISA to another (e.g., run ARM on ADM64)
- Emulates system:
  - Graphics, networking, sound, input devices, USB, ...
- Almost two dozen platforms supported

Summary

- **Binary instrumentation** is a form of low-level dynamic analysis
- Two main schemes:
  - **Copy-and-Annotate**: insert new code
  - **Disassemble-and-Resynthesise**: merge analysis subject code with annotation code
- Shadow values supported through **shadow registers** and **shadow memory**

Summary: Dynamic Analysis

- Collecting *Measurements* of *Characteristics* at *Events* via *Probes*:
  - In software, hardware, or indirectly via simulation
- Applications include:
  - Purely to observe (program understanding etc.)
  - Efficiency (JIT compilation etc.)
  - Prevent undesirable behaviour (Safety, Security)
- *Sampling* to reduce overhead:
  - Finite set of inputs/workloads, hardware etc.
- Some characteristics (esp. *performance*) influenced by *sources of variability* outside of program and program input
- Can usually avoid false positives, can*not* usually avoid false negatives

Outlook

- Oral exam information / registration up on Tuesday
- Next Lecture: Review session– bring your questions!

`http://cs.lth.se/edap15`