Measurement: Profiling

Performance Evaluation of Computer Systems

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Outline

Profiling

Purpose

Profiling collects information about system execution connected (typically) with individual program locations, making it possible to associate performance anomalies with code.

Examples of profiling output:

- List of all executed functions annotated with percentual share of execution time
- A calling context tree depicting all function calls annotated with call counts in each context
- A map of all program locations annotated with the likelihood that a memory access in that location causes a cache miss

Collecting Profile Data

Profiler can collect profile data in one of two ways

- Sampling on asynchronous events
- Instrumentation in locations of interest

Sampling

Interrupts program execution at (ideally) random locations and records metric of interest together with location.

- Enough random samples should provide representative information
- Overhead depends on sampling frequency (hence can be regulated)

Instrumentation

Inserts probes for collecting metric of interes in important locations such as function entry and exit points or basic block boundaries.

- Accuracy determined only by probe location (no sampling involved)
- Overhead depends on execution patterns (cannot be helped)

Outline

Profiling With Sampling

System configured to interrupt the application when some event occurs. The sample is collected on each interrupt.

The event can be generated for example by:

- Periodic timers (hardware interrupt)
- Hardware counter overflow (hardware interrupt)
- Software callback (JVMTI, kernel signal, network stack, ...)

Robustness

For sampling to be useful, the event occurrence should be independent of the metric sampled (unless the events are the metric).

The sample typically consists of:

- Sampled program location
- Possibly sampled metric

Outline

Sampling Program Location

Program Counter

Program counter value is typically available on interrupt
(because that is where the program execution will resume).

The uses of program counter in profiling:

- Identifies (binary) instruction as sample location
(but interrupt can be delayed after sampled event)
- Debug information can convert address to source code location
(but debug info not always available and mapping not trivial)
- Stack trace information can provide calling context information
(but stack frames are not always in standard format)

Sampling location alone already gives *hotness profile*.

Example: Delayed Branch Event Samples

```
> perf record -e branch-misses <file>
...
> perf annotate --no-source --stdio
...
    0.00 :   4010cd: cmpb   $0x0,0x404180(%rdx)
    6.79 :   4010d4: je     4010c0 <main+0x20>
    0.11 :   4010d6: lea    (%rdx,%rdx,1),%eax
   44.23 :   4010d9: add    $0x1,%ebp
    7.95 :   4010dc: cmp    $0x7ffffff,%eax
    0.00 :   4010e1: ja     4010c0 <main+0x20>
   32.12 :   4010e3: lea    (%rdx,%rdx,1),%rax
    0.00 :   4010e7: nopw   0x0(%rax,%rax,1)
    2.61 :   4010f0: movb   $0x0,0x404180(%rax)
    4.85 :   4010f7: add    %rdx,%rax
    0.06 :   4010fa: cmp    $0x7ffffff,%eax
    0.00 :   4010ff: jle    4010f0 <main+0x50>
...
```

The only branch instructions in the listing are `ja`, `je` and `jle`, yet most samples are recorded for add and `lea`.

Example: DWARF Debug Information

```
> readelf --debug-dump=rawline <file>
...
Line Number Statements:
  [0x0000031d]  Extended opcode 2: set Address to 0x4008c6
  [0x00000328]  Advance Line by 17 to 18
  [0x0000032a]  Copy
  [0x0000032b]  Special opcode 103: advance Address by 7 to 0x4008cd and Line by 0 to
  [0x0000032c]  Special opcode 230: advance Address by 16 to 0x4008dd and Line by 1 to
  [0x0000032d]  Special opcode 103: advance Address by 7 to 0x4008e4 and Line by 0 to
  [0x0000032e]  Advance PC by constant 17 to 0x4008f5
...
> readelf --debug-dump=decodedline <file>
Decoded dump of debug contents of section .debug_line:

CU: <file>.cc:
File name                              Line number    Starting address
<file>.cc                                       18            0x4008cd
<file>.cc                                       19            0x4008dd
<file>.cc                                       19            0x4008e4
<file>.cc                                       21            0x400901
<file>.cc                                       22            0x40090c
<file>.cc                                       23            0x400919
...
```

Source Line Mapping

Ideal

Each source code line corresponds to distinct code block

- Each code block is characterized by program counter range
- Direct mapping between program counter and source trivial

Real

Source code line is not an execution unit
Optimizations create complex mapping

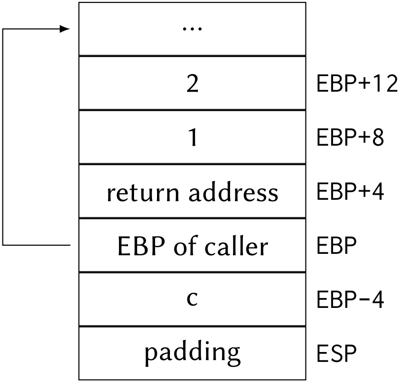
- Matching to lines with multiple statements loses information
- Macros expanded before compilation not visible to compiler
- Optimizations can change execution order
  (for example invariant code motion)
- Optimizations can break one to one mapping
  (for example common subexpression elimination)

... how does all this impact profiling ?

Example: Standard Stack Frame

```
x = f (1,2);
...
int f (int a, int b) {
    int c = a + b;
    ...
}


        push 2
        push 1
        call f
...
f:      push ebp
        mov  ebp, esp
        sub  esp, 16
        mov  eax, [ebp+8]
        add  eax, [ebp+12]
        mov  [ebp-4], eax
...
```



Example: libunwind Stack Walk

```c
#define UNW_LOCAL_ONLY
#include <libunwind.h>

void print_stack () {
    unw_context_t context;      // Machine register context.
    unw_cursor_t cursor;        // Stack frame reference.
    unw_word_t ip, sp, offset;
    char name [256];

    unw_getcontext (&context);
    unw_init_local (&cursor, &context);

    while (unw_step (&cursor) > 0) {
        unw_get_reg (&cursor, UNW_REG_IP, &ip);
        unw_get_reg (&cursor, UNW_REG_SP, &sp);
        unw_get_proc_name (&cursor, name, sizeof (name), &offset);
        printf ("%s+%lx IP %lx SP %lx\n", name, offset, ip, sp);
    }
}
```

Based on code from libunwind documentation

Stack Walk

Ideal

Location sample includes top stack frame address
All stack frames in standard format

- Frame walk as simple as linked list traversal

Real

Top stack frame address not always available
Some stack frames not in standard format
Some calls do not have stack frames

- Samples close to function entry and exit
  may not have frame pointer ready
- Handwritten assembly code may use stack in many inventive ways
- Tail call optimizations do not create frames
- Stack may not be continous

... how does all this impact profiling ?

Stack Frame Information I

Compiler Information

Compilers know how the code uses stack, can they help ?

```
> cat <file.c>
void function () { ... }

> objdump --disassemble <file.o>
...
0000000000000000 <function>:
   0:   55                      push   %rbp
   1:   48 89 e5                mov    %rsp,%rbp
...

> readelf --debug-dump=frames-interp <file.o>
...
   LOC           CFA      rbp   ra
0000000000000000 rsp+8    u     c-8
0000000000000001 rsp+16   c-16  c-8
0000000000000004 rbp+16   c-16  c-8
...
```

Stack Frame Information II

```
0000000000000000 <function>:
   0:   55                      push   %rbp
   1:   48 89 e5                mov    %rsp,%rbp
```

DWARF

```
   LOC           CFA      rbp   ra
0000000000000000 rsp+8    u     c-8
0000000000000001 rsp+16   c-16  c-8
0000000000000004 rbp+16   c-16  c-8
```

- On function entry
  - Return address at top of stack
  - Registers not yet saved
- First instruction saves RBP on stack
- Second instruction sets RBP to provide canonical frame address
- Rest of function uses canonical frame address in RBP instead of RSP

Dynamic Stack Frame Analysis

Doing More ?

What if the frame information is incomplete or incorrect ?
We can try dynamic program analysis ...

- Exported symbols point to function addresses
- More function boundaries located with heuristic analysis
  - Non conditional control transfers may terminate function
  - Conditional jumps do not cross function boundaries
  - Look for typical frame pointer manipulation
  - Look for symmetrical stack manipulation
  - ...
- Linear scan to find stack and frame pointer manipulation
- Stack frame information deducted using more heuristic
- Shown to be over 95% accurate on optimized x86 code

Based on Tallent et al.: Binary Analysis ... doi:10.1145/1543135.1542526

Outline

Sampling Managed Languages

What happens when we are sampling program location
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Just-In-Time Compiler

Naive sampling will profile the compiler together with the application.

Sampling Location in Java

JVMTI

Use JVMTI to query high level language program position (used by hprof) ?

```
jvmtiFrameInfo frames[5];
jint count;
jvmtiError err;

err = (*jvmti)->GetStackTrace (jvmti, aThread, 0, 5, &frames, &count);
if (err == JVMTI_ERROR_NONE && count >= 1) {
    char *methodName;
    err = (*jvmti)->GetMethodName (jvmti,
                                   frames [0].method,
                                   &methodName, NULL);
    if (err == JVMTI_ERROR_NONE) {
        printf ("Method␣%s.\n", methodName);
    }
}
```

Based on code from JVMTI documentation

Sampling and Safepoints

Safepoint

Program location where information needed
for garbage collection is available.

This interferes with JVMTI program location sampling:

- Stack trace query waits until all threads reach safepoints
- Safepoints at hot locations typically avoided if possible
- Samples therefore biased

Based on Mytkowicz et al.: Evaluating the Accuracy ... doi:10.1145/1809028.1806618

Sampling Location in Java

JVMTI

Use JVMTI to know about dynamically compiled code ?

JVMTI reports JIT compilation

- What method was compiled
- Where the compiled code is stored

By recording this information, we can do sampling in compiled methods. Not compiled methods are not hot anyway.

Outline

Hotness Profiling With Instrumentation

Basic Block Counting

- Counter increment inserted at the start of each basic block
- Provides exact execution count for every instruction in the code

This comes with significant overhead.
Typical basic block units to tens of instructions long,
hence overhead factors of 2 or more are easily possible.

Tool: gprof

Native code profiler integrated with the GCC compiler.

- Instrumentation at function entry.
- Periodic sampling with interval timers.

```
> g++ -pg <file.c> -o <file>
> ./<file>
...
> gprof <file>
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ns/call  ns/call  name
 33.33      3.33     3.33  1234567   123.45   123.45  frequent_function(int)
  9.99      0.99     0.99   123456    12.34    12.34  less_frequent_function(int)
...
```

Outline

1. Overview
2. Profiling With Sampling
3. Native Program Location
4. Managed Program Location
5. Profiling With Instrumentation
6. Visualizing Profiling Output

Flame Graphs