Towards Data Type Profiling

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Google
Data type profiling

● Goal
  ○ Precise memory access profile with type info
  ○ Help memory layout optimization
  ○ No changes in the target code

● How?
  ○ PMU\textsuperscript{1} precise sampling (by Linux perf tools)
  ○ DWARF\textsuperscript{2} location description

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1. PMU: Performance Monitoring Unit in CPU cores (or other units)
2. DWARF: Debugging With Arbitrary Record Formats. The standard debug format in Linux
Existing memory profilers

- PMU sample based
  - perf mem - utilize data source (and more) in the PMU sample
  - perf c2c - dedicate to check data (false) sharing

- Heap allocation based
  - Heaptrack - leak check, heap usage, temporary allocation, ...
  - Valgrind - leak/undefined access check, cache simulation, heap usage, ...
PMU precise memory sampling

- Modern Processors provide precise memory access information like
  - Instruction address
  - Data address
  - Data source (L1$, L2$, L3$, memory, ...)
  - Latency
  - ...

- Supported vendors: Intel (PEBS\textsuperscript{1}), AMD (IBS\textsuperscript{2}), ARM (SPE\textsuperscript{3}), ...
PMU precise memory events

Each vendor has different capabilities:

- **Intel (PEBS)**
  - Sample memory operations (load or store) only
  - Loads can have a latency filter (threshold)

- **AMD (IBS)**
  - Sample any operations (uops) without filtering
  - Only memory u-ops will have meaningful info

- **ARM (SPE)**
  - Sample any operations with filtering
  - Can filter load and/or store operations, with latency filter too
Recording PMU precise memory samples

- Simply use `perf mem record`

- For advanced users

  ```
  perf mem record -t load  # load operation only (Intel, ARM)
  perf mem record --ldlat=10  # load latency filter (Intel, ARM)
  perf mem record -K  # for kernel only (Intel, ARM)
  perf record -e $EVENT  # if know what you do
  ```
Getting memory location

`perf mem record $PROG`

`perf annotate`
- register
- offset

```
3.92 25: movzbl 4(%rdi),%edx
   decb %dl
   movb %dl,4(%rdi)
   movq 8(%rdi),%rcx
   leaq -1(%rcx),%r8
   movq %r8,8(%rdi)
   movsbl %dl,%edx
   addl %edx,%ecx
   movl (%rdi),%edx
   leal -1(%rdx),%r8d
   movl %r8d,(%rdi)
   imull %edx,%ecx

4b:  incl 8(%rsi)
   incl -4(%rbp)
   addl %ecx,%eax

4.94 movl -4(%rbp),%ecx
   cmpl 1040(%rsi),%ecx
   jae 8e

91.13 5e: testl $1,%rsi
   je 25
```
Location expression

Readelf `-wi`

Debug info in
- variable
- parameter

```
<1><431542>: Abbrev Number: 68 (DW_TAG_subprogram)
<431543> DW_AT_low_pc : 0xfffffffff81ed860
<431544> DW_AT_high_pc : 0x98
<431545> DW_AT_frame_base : 1 byte block: 56 (DW_OP_reg6 (reg))
<431551> DW_AT_stmt_start : 1
<431553> DW_AT_stmt_end : 1
<431555> DW_AT_decl_file : 1
<431556> DW_AT_decl_line : 75
<431557> DW_AT_type : <0x41c732>
<431558> DW_AT_external : 1

<2><431550>: Abbrev Number: 61 (DW_TAG_formalParameter)
<431555> DW_AT_location : 1 byte block: 55 (DW_OP_reg5 (rdi))
<431556> DW_AT_name : (Indirect string, offset: 0x4803a7): n1
<431557> DW_AT_decl_file : 1
<431558> DW_AT_decl_line : 75
<431559> DW_AT_type : <0x41d9dc>

<2><431568>: Abbrev Number: 61 (DW_TAG_formalParameter)
<431569> DW_AT_location : 1 byte block: 54 (DW_OP_reg4 (rsi))
<43156b> DW_AT_name : (Indirect string, offset: 0x1d53c): n2
<43156c> DW_AT_decl_file : 1
<43156d> DW_AT_decl_line : 75
<43156e> DW_AT_type : <0x41d9e1>

<2><431575>: Abbrev Number: 62 (DW_TAG_variable)
<431576> DW_AT_location : 2 byte block: 91 7c (DW_OP_fbreg: -4)
<431579> DW_AT_name : (Indirect string, offset: 0x2c00c9): 1
<431576> DW_AT_decl_file : 1
<431577> DW_AT_decl_line : 75
<431578> DW_AT_type : <0x41d9d7>

<2><431583>: Abbrev Number: 63 (DW_TAG_variable)
<431584> DW_AT_location : 0x1ed8e8 (location list)
<431586> DW_AT_name : (Indirect string, offset: 0x18c9b2): ret
<431587> DW_AT_decl_file : 1
<431588> DW_AT_decl_line : 77
<431589> DW_AT_type : <0x41c732>

<2><431592>: Abbrev Number: 0
```
DWARF location description

- Location expression
  - Stack machine to specify a location
  - Register / mem / arithmetic operations / stack operations / ...

- Location list
  - When a variable is moving around different places (e.g. stack spill)
  - List of (code range + location expression)
Getting DWARF info

- Tree-like structure:
  - Find nested scopes using instruction address

- Each scope entry would have
  - Low PC and High PC attributes for the containing address range
  - Or, range list for scattered ranges

```
0x123456: mov %rax, 0x10(%rcx)
```
Debug info of a variable entry

- Location list has
  - Code range
  - Location (reg/mem)

- Type info has
  - Name, kind
  - Member type / offset

```
0x123456: mov %rax, 0x10(%rcx)
```
Result: perf report -s type

What it does:
1. Identify an instruction from a sample
2. Extract a register from the instruction
3. Find a variable for matching register
4. Get the type of the variable
5. Aggregate the result for the type

<table>
<thead>
<tr>
<th>Overhead</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.23%</td>
<td>(unknown)</td>
</tr>
<tr>
<td>14.20%</td>
<td>struct rq</td>
</tr>
<tr>
<td>11.39%</td>
<td>unsigned long</td>
</tr>
<tr>
<td>4.34%</td>
<td>(stack operation)</td>
</tr>
<tr>
<td>3.94%</td>
<td>unsigned int</td>
</tr>
<tr>
<td>2.21%</td>
<td>unsigned long long</td>
</tr>
<tr>
<td>1.83%</td>
<td>struct task_struct</td>
</tr>
<tr>
<td>1.62%</td>
<td>struct hlist_bl_head</td>
</tr>
<tr>
<td>1.23%</td>
<td>struct dentry</td>
</tr>
<tr>
<td>1.13%</td>
<td>struct cpuidle_device</td>
</tr>
<tr>
<td>1.11%</td>
<td>int</td>
</tr>
<tr>
<td>1.10%</td>
<td>struct k_sigaction</td>
</tr>
<tr>
<td>0.89%</td>
<td>struct kfs_node</td>
</tr>
<tr>
<td>0.83%</td>
<td>struct mm_struct</td>
</tr>
<tr>
<td>0.77%</td>
<td>struct xt_counters</td>
</tr>
<tr>
<td>0.70%</td>
<td>struct qspinlock</td>
</tr>
<tr>
<td>0.63%</td>
<td>struct hlist_bl_node*</td>
</tr>
<tr>
<td>0.63%</td>
<td>struct sched_entity</td>
</tr>
</tbody>
</table>
Result: `perf annotate --data-type`

- Same approach + Use offset info to identify the field
  - `perf report` also has ‘typeoff’ sort key to show per-field overheads

```
Annotate type: 'struct rb_node' in [kernel.kallsyms] (6 samples):

<table>
<thead>
<tr>
<th>samples</th>
<th>offset</th>
<th>size</th>
<th>field</th>
</tr>
</thead>
</table>
| 6       | 0      | 24   | struct rb_node {
| 3       | 0      | 8    |   long unsigned int __rb_parent_color;
| 1       | 8      | 8    |   struct rb_node* rb_right;
| 2       | 16     | 8    |   struct rb_node* rb_left;
|         |        |      |   
```
Issues

- No variables
- Compiler optimizations
- Struct layout randomization
- Per-cpu (kernel) or TLS\(^1\) (user) access
- Split DWARF support
- Languages
- Performance
- And more...?
No variables: chain of pointers

```c
int foo(struct foo_data *ptr)
{
    int val = ptr->another->pointer->var;
    /* do something with val */
    return 0;
}
```

DWARF (.debug_info)

- DW_TAG_subprogram (foo)
- DW_TAG_formal_parameter (ptr)
- DW_AT_location (%rdi)
- DW_TAG_variable (val)
- DW_AT_location (fbreg -4)

What’s in %rcx?
No variables: Possible solutions #1

- Build a full location table (in perf tool)
  - Go through the instructions and propagate the variable types
  - Follow pointer dereferences (a->b->c …)

<table>
<thead>
<tr>
<th>pc1</th>
<th>type1</th>
<th>reg2</th>
<th>reg3</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc1</td>
<td>N/A</td>
<td>type2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pc2</td>
<td>same</td>
<td>type3</td>
<td>same</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
No variables: Possible solutions #2

- Compiler can generate more information
  - Insert an artificial debug entry (short term)
    - For chains of pointers (and type casts too?)
    - With proper location expression and type info
  - Inverted location list (long term)
    - suggested in the DWARF discuss list
    - https://lists.dwarfstd.org/pipermail/dwarf-discuss/2023-June/002278.html
Compiler optimizations

- Compilers can change struct layouts
  - SROA for local variables (pointer not taken?)
  - Currently perf rejects complex location expressions

- What can it accept?
  - a pointer variable is in a register
  - static memory location for global variables
  - stack location from the frame base for local variables

1. SROA: Scalar Replacement of Aggregates
Struct layout randomization

- Sounds scary!
  - compiler plugin to randomize some structures
    - CONFIG_RANDSTRUCT
    - basically for structs with function pointers only?
  - hope it’d update DWARF location expression
    - Haven’t tested it yet
Language support

- The first target is C
  - Kernel on x86
  - C issues: union, array, bitfield, type cast, return value, ...

- For userspace support
  - Support for other languages: C++, Rust, Go, ...
  - Never tried yet
Per-cpu variables in kernel

- Per-cpu variable in the kernel
  - Each cpu has its own copy of the variable
  - TLS\(^1\) for user binaries would have similar concerns

- Variables can have complex(?) location expressions
  - __per_cpu_offset[cpu] + variable address
  - %gs: variable address (for this cpu)

1. TLS: Thread Local Storage
Split DWARF

- DWARF4 + fission or DWARF5
  - How well is it supported?
  - perf uses elfutils/libdw
Performance issues

- Objdump on kernel
  - To get assembly code
  - GNU objdump with debug info is very slower than LLVM
  - LLVM objdump without debug info is slightly slower then GNU

- Use in-kernel instruction decoder (x86)
  - To extract location info from the instruction
Summary

- Perf tools implement data type profiling using PMU and DWARF
- Need more toolchain supports to produce better DWARF
- Let’s make it more useful and easy to use!

Links
- v1: https://lore.kernel.org/lkml/20231012035111.676789-1-namhyung@kernel.org/
- v2: https://lore.kernel.org/lkml/20231110000012.3538610-1-namhyung@kernel.org/
LPC 2023 - Overview

Conference Details

The Linux Plumbers Conference is the premier event for developers working at all levels of the plumbing layer and beyond.

Taking place on Monday 13th, Tuesday 14th and Wednesday 15th of November, this year we will be both in person and remote (hybrid). However to minimize technical issues, we’d appreciate most of the content presenters being in-person.

The in-person venue is the Omni Richmond Hotel, Richmond, VA.

100 S 12th St, Richmond, VA 23219, United States

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