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Hotpatching ClickHouse in production with XRay

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$ whoami

- Pablo Marcos Oltra
- Software Engineer @ ClickHouse's Core Team
- Systems Developer
- Passionate about videogame development
- Interested in compilers, build systems and new programming languages

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Who knows what hotpatching/hot reloading is?

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Who knows what LLVM's XRay is?

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Who's had to debug something in production and wished they had added an extra log to know what's happening?

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01 What is hotpatching

Hotpatching: The basics

- Change the code while the process is running
- Allows faster iteration
- Often done in videogame development
  - Hot reloading rather than hotpatching
  - Client-server architecture where the lightweight client loads a new version of the game (in a shared library)
  - Examples
    - http://runtimecompiledcplusplus.blogspot.com.es
    - https://fungos.github.io/cr-simple-c-hot-reload
    - https://liveplusplus.tech

Hotpatching: Adding instrumentation

- -finstrument-functions : Generates instrumentation code for every function entry/exit

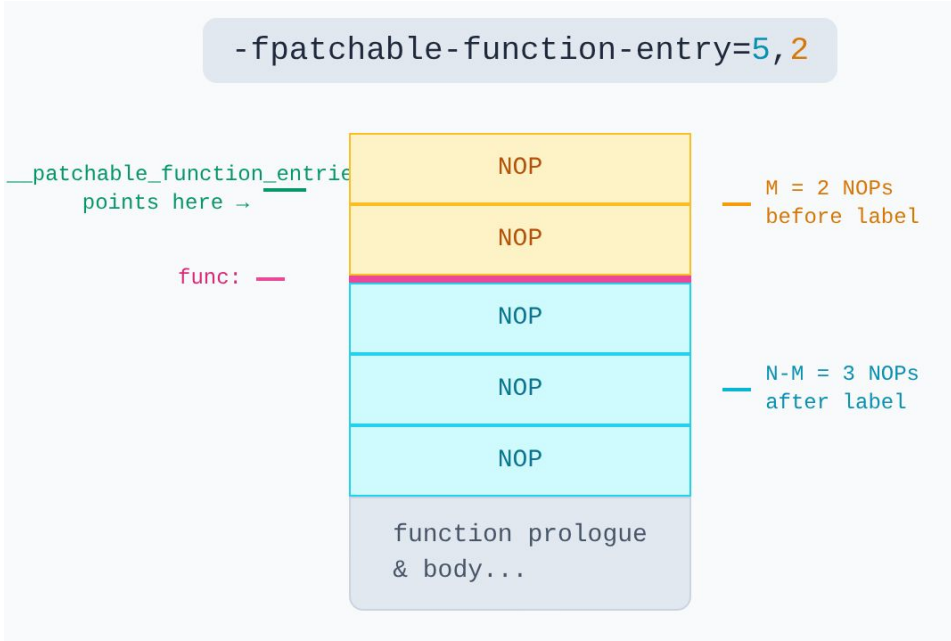
```
void __cyg_profile_func_enter(void *this_fn, void *call_site);
void __cyg_profile_func_exit(void *this_fn, void *call_site);
```

https://gcc.gnu.org/onlinedocs/gcc/Instrumentation-Options.html#index-finstrument-functions

Hotpatching: Adding instrumentation

- -fpatchable-function-entry=N[,M]:

  Generate M NOPs before function entry and N-M NOPs after function entry



https://gcc.gnu.org/onlinedocs/gcc/Instrumentation-Options.html#index-fpatchable-function-entry

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02 XRay

XRay

XRay consists of three main parts:

1. Compiler-inserted instrumentation points.
2. A runtime library for enabling/disabling tracing at runtime.
3. A suite of tools for analysing the traces.

As of July 25, 2018, XRay is only available for the following architectures running Linux:

x86_64, arm7 (no thumb), aarch64, powerpc64le, mips, mipsel, mips64, mips64el, NetBSD: x86_64, FreeBSD: x86_64 and OpenBSD: x86_64.

https://llvm.org/docs/XRay.html

XRay: Example

```
15  int main()
16  {
17      __xray_init();
18      __xray_patch();
19      __xray_set_handler(my_handler);
20
21      foo();
22
23      __xray_remove_handler();
24      __xray_unpatch();
25
26      return 0;
27  }
```

XRay: Example

```
#include <stdint.h>
#include <stdio.h>
#include <xray/xray_interface.h>

[[clang::xray_never_instrument]] void my_handler(int32_t fid, XRayEntryType type)
{
    printf("FuncID: %d, Type: %d\n", fid, type);
}

void foo()
{
    printf("Foo!\n");
}
```

XRay: Example

```
$ clang++ -o test_xray test_xray.cpp -fxray-instrument
-fxray-instruction-threshold=1


$ ./test_xray
FuncID: 1, Type: 0
Foo!
FuncID: 1, Type: 1
```

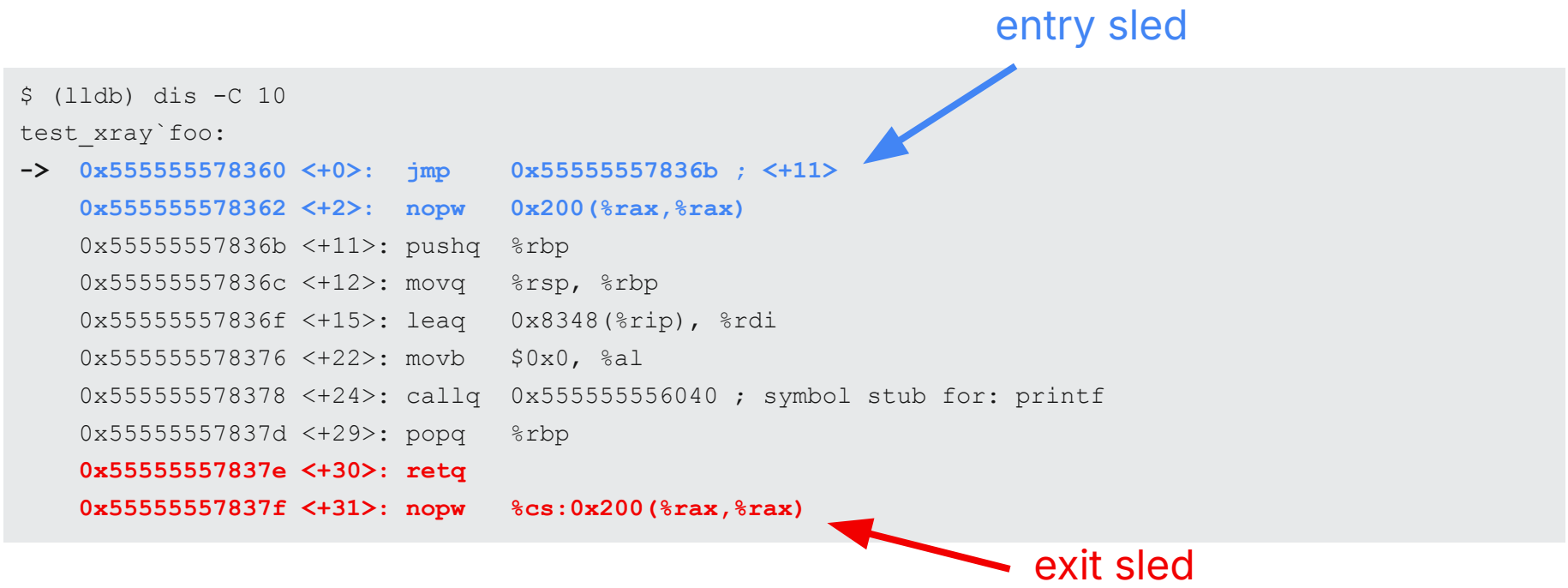
XRay: xray_instr_map

```
$ objdump -h -j xray_instr_map test_xray

test_xray:     file format elf64-x86-64

Sections:
Idx Name          Size      VMA               LMA               File off  Algn
 17 xray_instr_map 00000080  000000000002c6c4  000000000002c6c4  0002c6c4
2**0
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
```

XRay: Before patching foo



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XRay: After patching foo

```
$ (lldb) dis -C 10
test_xray`foo:
->  0x555555578370 <+0>:  movl   $0x1, %r10d
    0x555555578376 <+6>:  callq  0x555555574340 ; __xray_FunctionEntry
    0x55555557837b <+11>: pushq  %rbp
    0x55555557837c <+12>: movq   %rsp, %rbp
    0x55555557837f <+15>: leaq   0x8338(%rip), %rdi
    0x555555578386 <+22>: movb   $0x0, %al
    0x555555578388 <+24>: callq  0x555555556040 ; symbol stub for: printf
    0x55555557838d <+29>: popq   %rbp
    0x55555557838e <+30>: movl   $0x1, %r10d
    0x555555578394 <+36>: jmp    0x555555574480 ; __xray_FunctionExit
```

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03 Integration into ClickHouse

What’s ClickHouse

- Fast OLAP DBMS
- Started in 2009 at Yandex.Metrica by Alexey Milovidov
- Open sourced in 2016 under Apache 2.0 license
- Developed in C++
- Strong focus in performance
- Lots of dogfooding
    - CI results, observability, pastila, c.house, etc

https://clickhouse.com

https://benchmark.clickhouse.com

Integrating XRay into ClickHouse

- Use XRay's instrumentation to have negligible overhead in production when disabled
- Use XRay's runtime library to enable in production only the symbols we want to instrument
- Use SQL statements to enable/disable instrumentation points at runtime
- Kudos to our intern Alina Badakhova for doing the POC to prove it was feasible

https://github.com/ClickHouse/ClickHouse/issues/74249

Integrating XRay into ClickHouse

- Landed in ClickHouse 25.12 (December 25)
- Minor improvements since then, all backported

https://github.com/ClickHouse/ClickHouse/pull/89173

Hotpatching using SQL: Cheatsheet

```
-- Check symbols to add instrumentation points
SELECT * FROM system.symbols WHERE function_id IS NOT NULL

-- Add or remove instrumentation points
SYSTEM INSTRUMENT [ADD|REMOVE] 'SYMBOL' HANDLER [ENTRY|EXIT] [PARAMS]

-- Check the enabled instrumentation points
SELECT * FROM system.instrumentation

-- Check the instrumented points hit
SELECT * FROM system.trace_log WHERE trace_type = 'Instrumentation'
```

Hotpatching using SQL: Inspecting symbols

```
SET allow_introspection_functions=1

-- Check symbols to add instrumentation points
SELECT
    function_id, symbol_demangled
FROM
    system.symbols
WHERE
    symbol_demangled ILIKE '%QueryMetricLog::start%'
```

Hotpatching using SQL: Inspecting symbols

```
Row 1:
──────

function_id:      202915

symbol_demangled: DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock,
std::__1::chrono::duration<long long, std::__1::ratio<1l, 10000001>>>, unsigned long)


Row 2:
──────

function_id:      202933

symbol_demangled: void std::__1::__function::__policy_func<void
()>::__call_func[abi:ne210105]<DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock, std::__1::chrono::duration<long
long, std::__1::ratio<1l, 10000001>>>, unsigned
long)::$_0>(std::__1::__function::__policy_storage const*)
```

Hotpatching using SQL: Adding instrumentation

```
-- Add a log with stacktrace at function entry
SYSTEM INSTRUMENT ADD 'QueryMetricLog::startQuery'  LOG ENTRY 'FOSDEM 26';

-- Add a random sleep [0, 0.5] secs at function exit
SYSTEM INSTRUMENT ADD 'QueryMetricLog::startQuery'  SLEEP EXIT 0 0.5;

-- Profile deterministically
SYSTEM INSTRUMENT ADD 'QueryMetricLog::startQuery'  PROFILE;
```

Hotpatching using SQL: Adding instrumentation

```
SELECT * FROM system.instrumentation


Row 1:
──────
id:             0
function_id:    202915
function_name:  QueryMetricLog::startQuery
handler:        log
entry_type:     Entry
symbol:         DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock,
std::__1::chrono::duration<long long, std::__1::ratio<1l, 1000000l>>>,
unsigned long)
parameters:     ['FOSDEM 26']
```


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Hotpatching using SQL: Adding instrumentation

```
Row 2:
──────
id:              1
function_id:     202915
function_name:   QueryMetricLog::startQuery
handler:         sleep
entry_type:      Exit
symbol:
DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock,
std::__1::chrono::duration<long long, std::__1::ratio<1l,
1000000l>>>, unsigned long)
parameters:      [0,0.5]
```

Hotpatching using SQL: Adding instrumentation

```
Row 3:
──────
id:             2
function_id:    202915
function_name:  QueryMetricLog::startQuery
handler:        profile
entry_type:     EntryAndExit
symbol:
DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock,
std::__1::chrono::duration<long long, std::__1::ratio<1l,
1000000l>>>, unsigned long)
parameters:     []
```

Hotpatching using SQL: Removing instrumentation

```
-- Remove all instrumented points
SYSTEM INSTRUMENT REMOVE ALL;

-- Remove a specific instrumented point with id 2
SYSTEM INSTRUMENT REMOVE 2;

-- Remove all entry points for function 'QueryMetricLog::startQuery'
SYSTEM INSTRUMENT REMOVE 'QueryMetricLog::startQuery';
```

Hotpatching using SQL: Checking trace_log

```
SELECT
    event_time_microseconds,
    function_id,
    function_name,
    handler,
    entry_type,
    duration_nanoseconds
FROM system.trace_log
WHERE trace_type = 'Instrumentation'
```

Hotpatching using SQL: Checking trace_log

```
Row 1:
──────
event_time_microseconds: 2026-01-29 11:55:20.553718
function_id:             202915
function_name:
DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock,
std::__1::chrono::duration<long long, std::__1::ratio<1l,
1000000l>>>, unsigned long)
handler:                 profile
entry_type:              Entry
duration_nanoseconds:    □□□□
```

Hotpatching using SQL: Checking trace_log

```
Row 2:
──────
event_time_microseconds: 2026-01-29 11:55:20.553758
function_id:             202915
function_name:
DB::QueryMetricLog::startQuery(std::__1::basic_string<char,
std::__1::char_traits<char>, std::__1::allocator<char>> const&,
std::__1::chrono::time_point<std::__1::chrono::system_clock,
std::__1::chrono::duration<long long, std::__1::ratio<1l,
1000000l>>>, unsigned long)
handler:                 profile
entry_type:              Exit
duration_nanoseconds:    40059
```

Hotpatching using SQL: Visualizing the profile

- Use Chrome's Trace Event Format with different visualizers

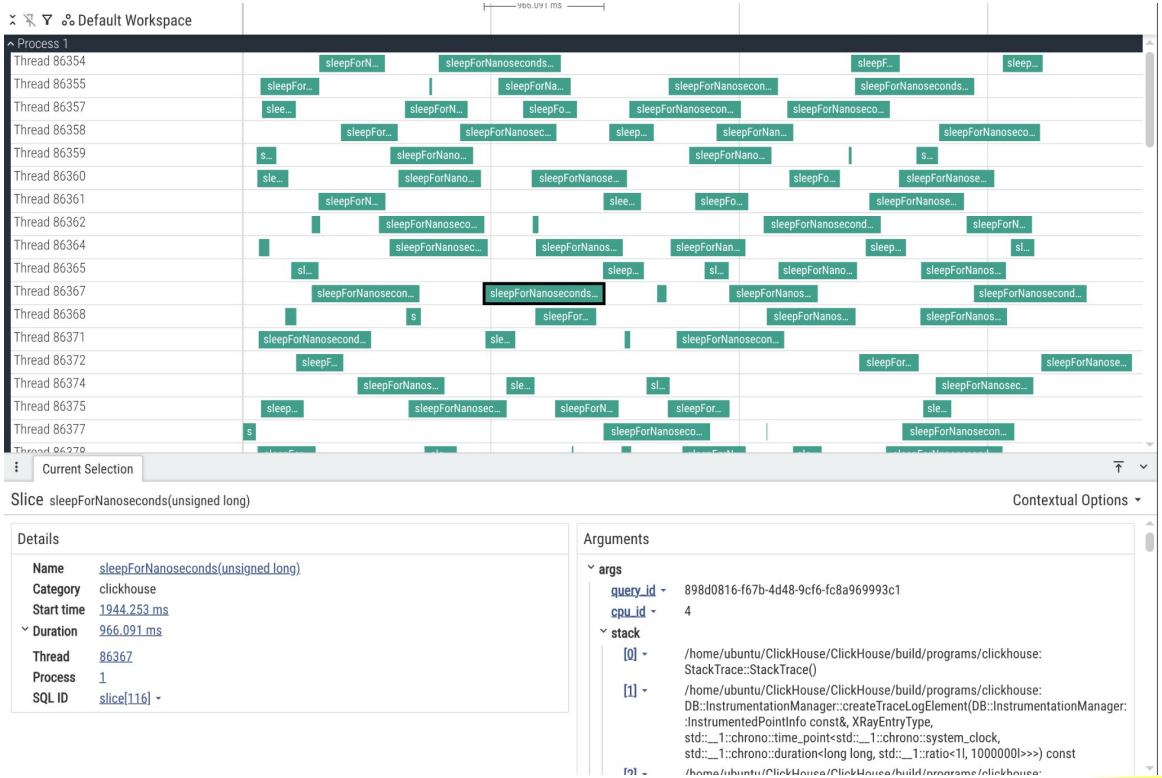
```
[
  {"name": "Asub", "cat": "PERF", "ph": "B", "pid": 22630,
"tid": 22630, "ts": 829},
  {"name": "Asub", "cat": "PERF", "ph": "E", "pid": 22630,
"tid": 22630, "ts": 833}
]
```

https://docs.google.com/document/d/1CvAClvFfyA5R-PhYUmn5OOQtYMH4h6I0nSsKchNAySU/preview?tab=t.0

Hotpatching using SQL: Converting the data

```
WITH traces AS (
    SELECT * FROM system.trace_log
    WHERE event_date >= today() AND trace_type = 'Instrumentation' AND handler = 'profile'
    ORDER BY event_time, entry_type
)
SELECT
    format(
        '{{"traceEvents": [{}\n]}}',
        arrayStringConcat(
            groupArray(
                format(
                    '\n{{"name": "{}", "cat": "clickhouse", "ph": "{}", "ts": {}, "pid": 1, "tid": {}, "args": {{"query_id": "{}", "cpu_id": {},
"stack": [{}]}}}},',
                    function_name, if(entry_type = 0, 'B', 'E'), timestamp_ns/1000,
                    toString(thread_id), query_id, cpu_id,
                    arrayStringConcat(arrayMap((x, y) -> concat('"', x, ': ', y, '"'), lines, symbols))
                )
            )
        )
    )
FROM traces;
```

Hotpatching using SQL: Visualizing in Perfetto



Future work

- Add more handlers as we see the need for them
- Add some VM to allow scripting? Wren, Lua
- Educate others that this exists so that they use it. Collect their feedback

Caveats

- Can’t mix XRay and sanitized builds due to symbols clashing in libclang_rt

```
ld.lld-19: error: duplicate symbol: __sanitizer::internal_allocator()
>>> defined at
sanitizer_allocator.cpp.o:(__sanitizer::internal_allocator()) in
archive
/usr/lib/llvm-19/lib/clang/19/lib/linux/libclang_rt.ubsan_standalone-
x86_64.a
>>> defined at
sanitizer_allocator.cpp.o:(.text._ZN11__sanitizer18internal_allocator
Ev+0x0) in archive
/usr/lib/llvm-19/lib/clang/19/lib/linux/libclang_rt.xray-x86_64.a
```

- If you mess something with this, you do it big time cause it’s in production
- Profiling a function doesn’t profile all functions underneath. That’s very difficult

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- Download open source

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- Blogs / YouTube

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- Monthly Community calls
- Meetups / events

We are Hiring. Come Work with Us!

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Q&A

All links from the slides

https://c.house/links