IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Quarkslab
Securing every bit of your data

Traceability of the compilation process

CLAP-HiFi-LVP 2023

Bruno MATEU

21st of March

Introduction

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1 • Context

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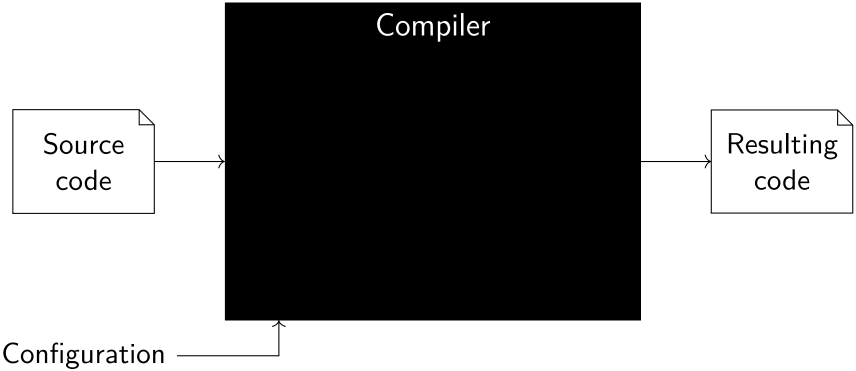
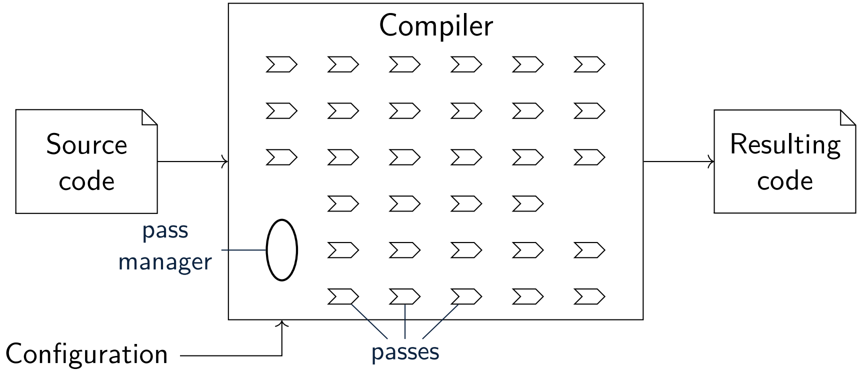
Context

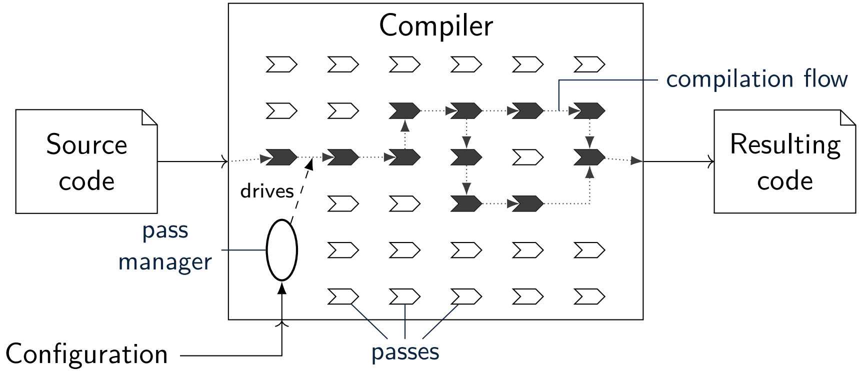
Overview



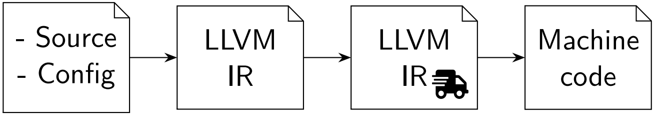
Context
LLVM Compilation and passes



Context
LLVM Compilation and passes



Motivations
Use-case: Debug



Motivations

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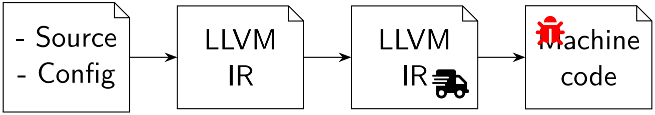
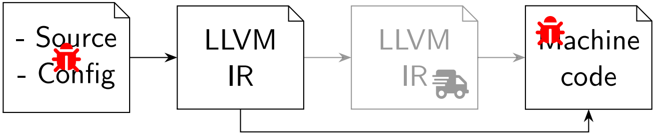


Where is the bug ?

Motivations

Use-case: Debug



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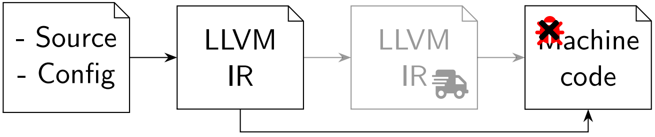

Where is the bug ?

Motivations
Traceability

Backward traceability : the story of instructions, from the produced binary to the source code

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Forward traceability : the story of instructions, from the source code to the produced binary

Goals
Traceability

Traceability inside compilers

- Create a traceability framework
- Not dedicated to a specific usage
- Implemented in LLVM, but designed with a global approach

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Trace is optional

- Enable and disable it on demand
- Partial traces are still useful
- No need to implement trace features in every compiler pass to produce useful data

2 • Existing work about traceability

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Definitions of Traceability

In software engineering

The degree to which a relationship can be established between two or more products of the development process [...][1]

[1]Ravensteijn, "Ravensteijn2011Visual Traceability across Dynamic Ordered Hierarchies".

[2]Ibid.

Definitions of Traceability

In software engineering

The degree to which a relationship can be established between two or more products of the development process [...][1]

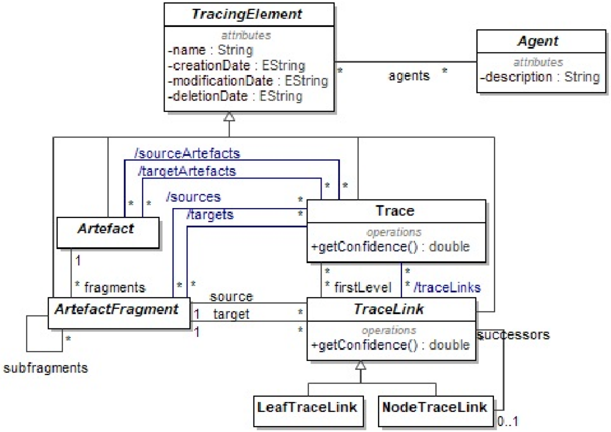
Outside of software engineering

The ability to verify the history, location, or application of an item by means of documented recorded identification. [...][2]

[1]Ravensteijn, "Ravensteijn2011Visual Traceability across Dynamic Ordered Hierarchies".

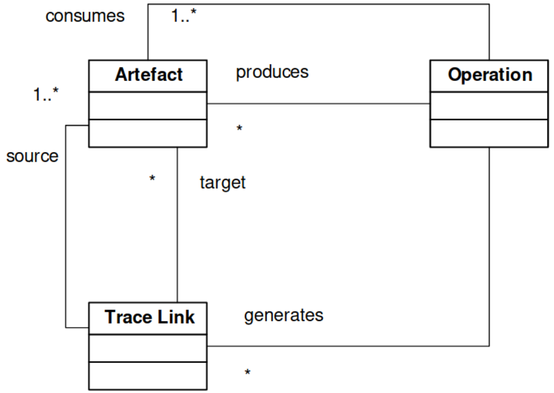
[2]Ibid.

Existing trace model
Traceα[3]



[3]Batot, Cabot, and Gerard, "(Not) Yet Another Metamodel For Traceability".

Existing trace model
TEAP[4]



[4]Paige et al., "Building Model-Driven Engineering Traceability Classifications".

Trace specification

Existing concepts

- Artefacts: The IR at a given stage of the compilation process
- Trace links: Called events in my case

Trace specification

Existing concepts

- Artefacts: The IR at a given stage of the compilation process
- Trace links: Called events in my case

Instant: Timeline information

- Has a start and an end
- Describes a time window of the compilation process
- Can be nested

3 • Implementation

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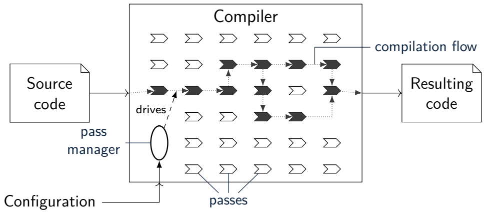
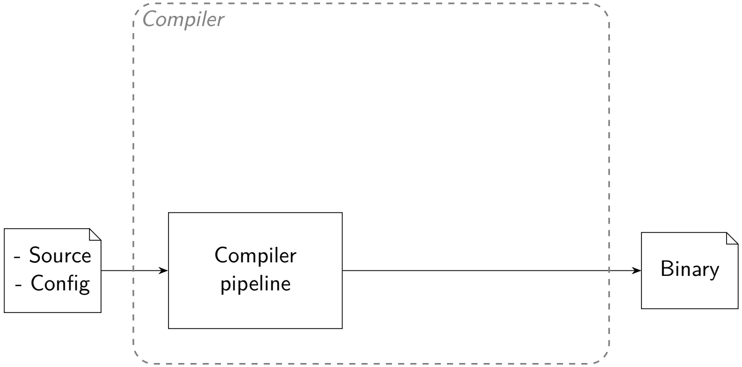
Trace monitor

The trace API

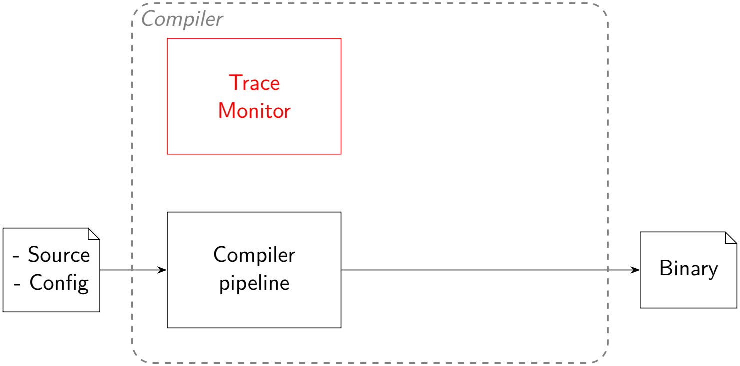




Trace monitor
The trace API

Trace Monitor

- Inside LLVMCore
- API to register Instants and Events
- Accessible from anywhere

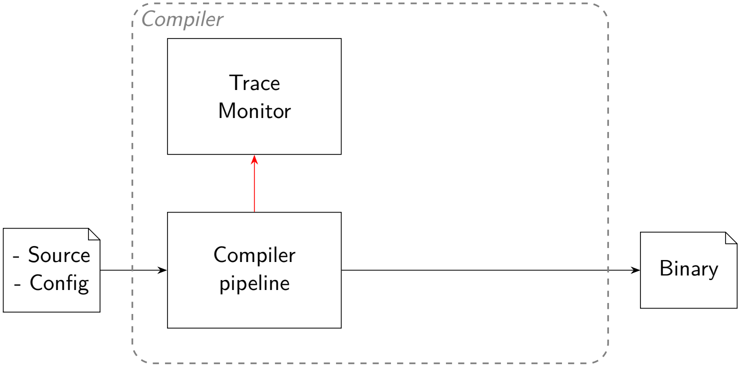


Trace monitor

The trace API

Integration with LLVM codebase

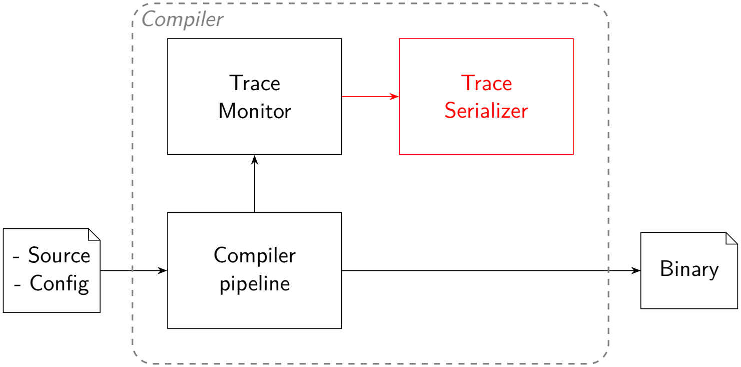
- Modifications to LLVM APIs to use trace instants and events
- New events and instants types can be created to enrich the trace



Trace monitor
The trace API

Serializer

- No pre-analysis is done by the serializer
- Easily parseable by external tools



Trace monitor
The trace API

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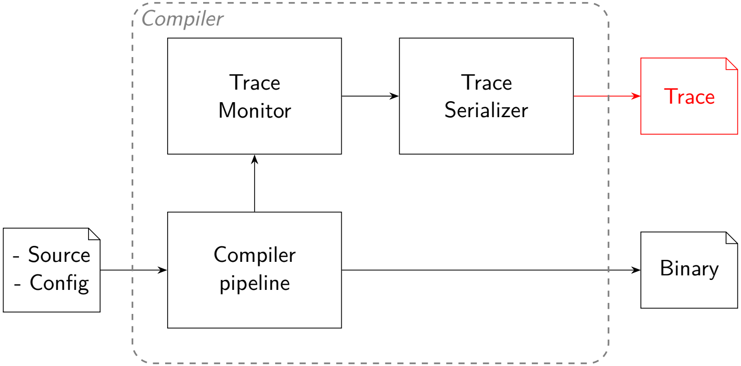
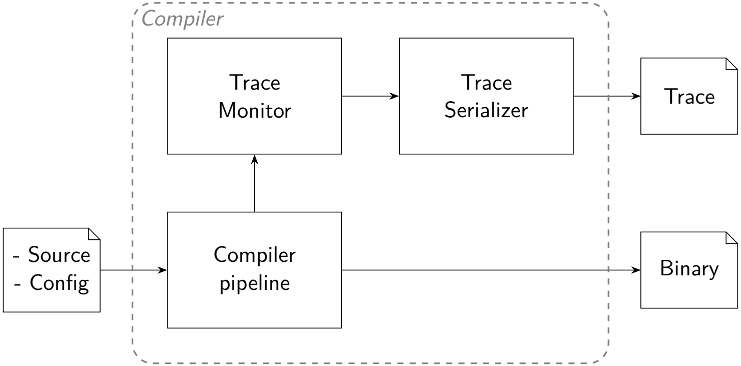


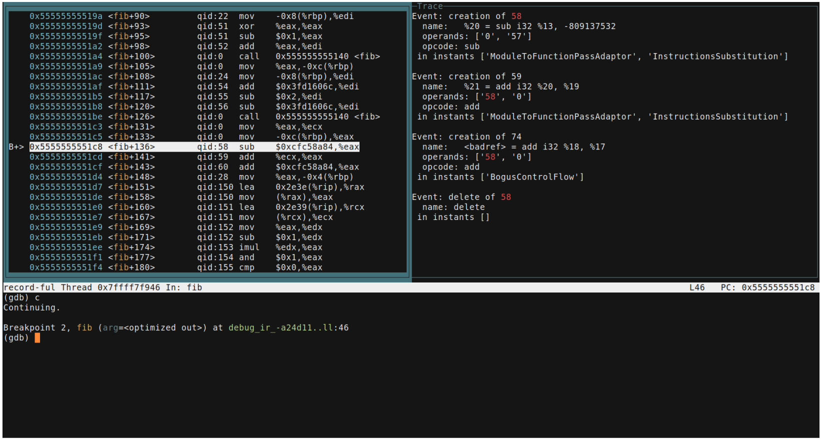
Trace monitor
The trace API

Link with the binary

- Binary and Trace are separate artifacts
- Each *Value* is uniquely identified in the trace



Using the trace



```
    0x55555555519a <fib+90>          qid:22  mov    -0x8(%rbp),%edi
    0x55555555519d <fib+93>          qid:51  xor    %eax,%eax
    0x55555555519f <fib+95>          qid:51  sub    $0x1,%eax
    0x5555555551a2 <fib+98>          qid:52  add    %eax,%edi
    0x5555555551a4 <fib+100>         qid:0   call   0x555555555140 <fib>
    0x5555555551a9 <fib+105>         qid:0   mov    %eax,-0xc(%rbp)
    0x5555555551ac <fib+108>         qid:24  mov    -0x8(%rbp),%edi
    0x5555555551af <fib+111>         qid:54  add    $0x3fd1606c,%edi
    0x5555555551b5 <fib+117>         qid:55  sub    $0x2,%edi
    0x5555555551b8 <fib+120>         qid:56  sub    $0x3fd1606c,%edi
    0x5555555551be <fib+126>         qid:0   call   0x555555555140 <fib>
    0x5555555551c3 <fib+131>         qid:0   mov    %eax,%ecx
    0x5555555551c5 <fib+133>         qid:0   mov    -0xc(%rbp),%eax
B+> 0x5555555551c8 <fib+136>         qid:58  sub    $0xcfc58a84,%eax
    0x5555555551cd <fib+141>         qid:59  add    %ecx,%eax
    0x5555555551cf <fib+143>         qid:60  add    $0xcfc58a84,%eax
    0x5555555551d4 <fib+148>         qid:28  mov    %eax,-0x4(%rbp)
    0x5555555551d7 <fib+151>         qid:150 lea    0x2e3e(%rip),%rax
    0x5555555551de <fib+158>         qid:150 mov    (%rax),%eax
    0x5555555551e0 <fib+160>         qid:151 lea    0x2e39(%rip),%rcx
    0x5555555551e7 <fib+167>         qid:151 mov    (%rcx),%ecx
    0x5555555551e9 <fib+169>         qid:152 mov    %eax,%edx
    0x5555555551eb <fib+171>         qid:152 sub    $0x1,%edx
    0x5555555551ee <fib+174>         qid:153 imul   %edx,%eax
    0x5555555551f1 <fib+177>         qid:154 and    $0x1,%eax
    0x5555555551f4 <fib+180>         qid:155 cmp    $0x0,%eax
```

```
Trace
Event: creation of 58
  name:   %20 = sub i32 %13, -809137532
  operands: ['0', '57']
  opcode: sub
 in instants ['ModuleToFunctionPassAdaptor', 'InstructionsSubstitution']

Event: creation of 59
  name:   %21 = add i32 %20, %19
  operands: ['58', '0']
  opcode: add
 in instants ['ModuleToFunctionPassAdaptor', 'InstructionsSubstitution']

Event: creation of 74
  name:   <badref> = add i32 %18, %17
  operands: ['58', '0']
  opcode: add
 in instants ['BogusControlFlow']

Event: delete of 58
  name: delete
 in instants []
```

```
record-ful Thread 0x7ffff7f946 In: fib                                   L46   PC: 0x5555555551c8
(gdb) c
Continuing.

Breakpoint 2, fib (arg=<optimized out>) at debug_ir_-a24d11..ll:46
(gdb) 
```

Summary

Trace Model

- Flexible and on-going process

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Implementation

- Limited to the middle-end for now

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Using traces

- GDB integration
- Future automated tools

Bibliography

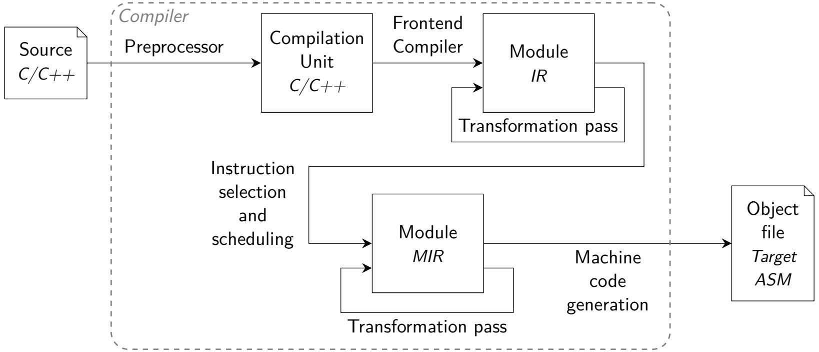
- Ravensteijn, WJP van. "Ravensteijn2011Visual Traceability across Dynamic Ordered Hierarchies". In: (2011).
- Batot, Edouard R., Jordi Cabot, and Sebastien Gerard. "(Not) Yet Another Metamodel For Traceability". In: (Oct. 2021). DOI: 10.1109/models-c53483.2021.00125.
- Paige, R. et al. "Building Model-Driven Engineering Traceability Classifications". In: (2008). URL: https://www.semanticscholar.org/paper/4d83fdf48055ee609ea7bfff0e467e6eae45e0ff.

Costs

Lua		886kB source, 300kB compiled			
Options		-O0	-O1	-O2	-O3
time (s)	Clang-14	1.16	3.81	4.24	4.42
	Clang-15 patched	17.00	22.36	23.44	23.70
Trace size (MB)		5.80	43.51	48.53	50.04

keepassxc		9.3MB source, 6.9MB compiled			
Options		-O0	-O1	-O2	-O3
time (s)	Clang-14	327.55	371.96	377.75	384.157
	Clang-15 patched	6302.95		7790.97	7721.80
Trace size (MB)		38		250	

LLVM Metamodel


Source
C/C++
Compiler
Preprocessor
Compilation Unit
C/C++
Frontend Compiler
Module
IR
Transformation pass
Instruction selection and scheduling
Module
MIR
Transformation pass
Machine code generation
Object file
Target ASM