Fast and Reliable DWARF-Based Stack Unwinding

with Théophile Bastian & Stephen Kell

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$ gdb ./a.out
(gdb) run
Starting program: ./a.out

Program received signal Segmentation fault.
0x000000000040049f in bar ()

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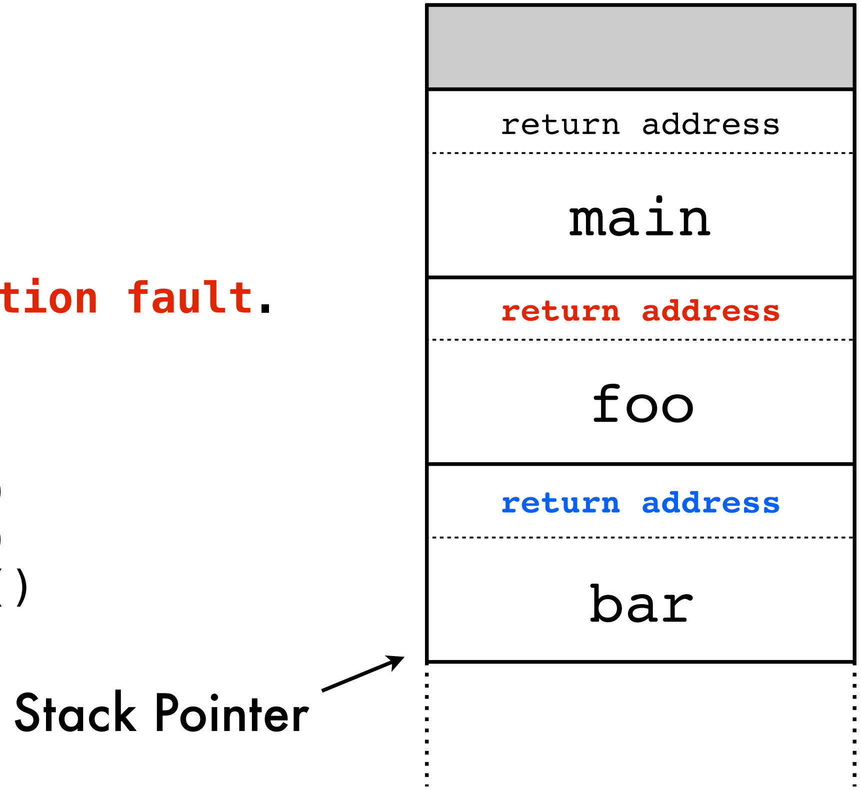

Backtrace

Call-stack in memory

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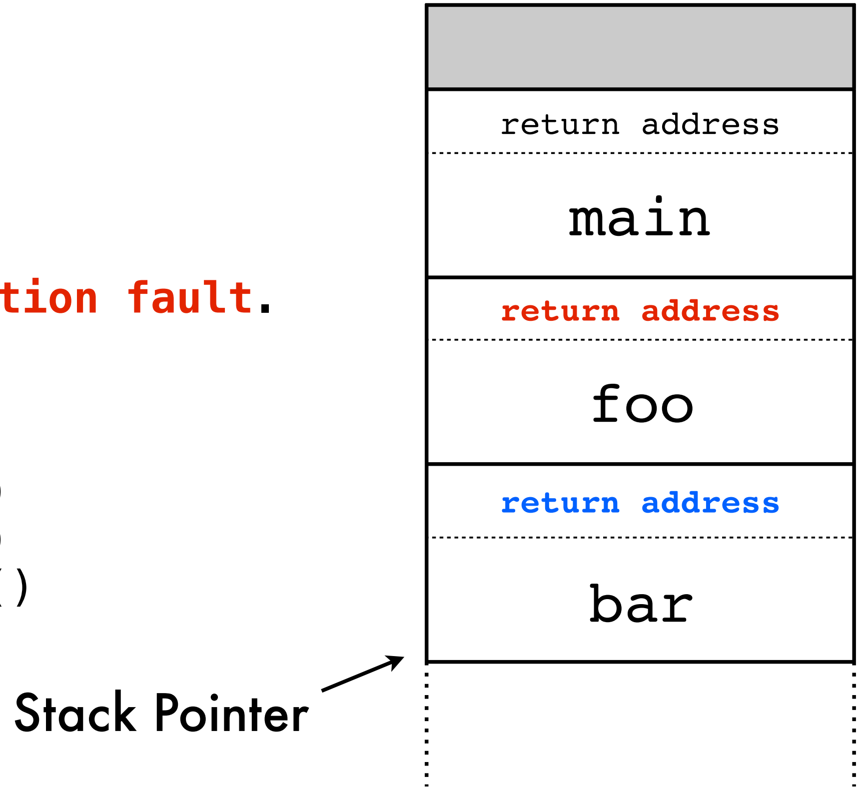


Backtrace

Call-stack in memory

Given a call-stack
is there a ***reliable*** *and* ***efficient*** way to produce a backtrace?

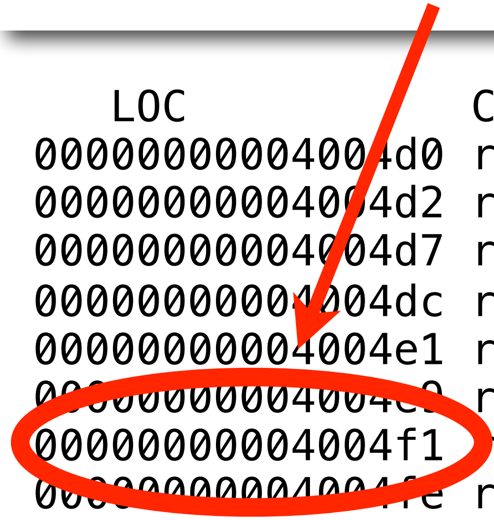
DWARF unwinding tables

```
$ readelf -Wf a.out


   LOC              CFA      rbx   rbp   r12   r13   r14   r15   ra
00000000004004d0 rsp+8    u     u     u     u     u     u     c-8
00000000004004d2 rsp+16   u     u     u     u     u     c-16  c-8
00000000004004d7 rsp+24   u     u     u     u     c-24  c-16  c-8
00000000004004dc rsp+32   u     u     u     c-32  c-24  c-16  c-8
00000000004004e1 rsp+40   u     u     c-40  c-32  c-24  c-16  c-8
00000000004004e9 rsp+48   u     c-48  c-40  c-32  c-24  c-16  c-8
00000000004004f1 rsp+56   c-56  c-48  c-40  c-32  c-24  c-16  c-8
00000000004004fe rsp+64   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040052a rsp+56   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040052b rsp+48   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040052c rsp+40   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040052e rsp+32   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400530 rsp+24   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400532 rsp+16   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400534 rsp+8    c-56  c-48  c-40  c-32  c-24  c-16  c-8
[...]
```

DWARF unwinding tables

For each instruction...
(identified by the program counter)



LOC	CFA	rbx	rbp	r12	r13	r14	r15	ra
00000000004004d0	rsp+8	u	u	u	u	u	u	c-8
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00000000004004d7	rsp+24	u	u	u	u	c-24	c-16	c-8
00000000004004dc	rsp+32	u	u	u	c-32	c-24	c-16	c-8
00000000004004e1	rsp+40	u	u	c-40	c-32	c-24	c-16	c-8
00000000004004e0	rsp+48	u	c-48	c-40	c-32	c-24	c-16	c-8
00000000004004f1	rsp+56	c-56	c-48	c-40	c-32	c-24	c-16	c-8
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000000000040052b	rsp+48	c-56	c-48	c-40	c-32	c-24	c-16	c-8
000000000040052c	rsp+40	c-56	c-48	c-40	c-32	c-24	c-16	c-8
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0000000000400530	rsp+24	c-56	c-48	c-40	c-32	c-24	c-16	c-8
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[...]

DWARF unwinding tables

For each instruction…
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…specify how to compute the location on the stack of the return address

LOC	CFA	rbx	rbp	r12	r13	r14	r15	ra
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Relied upon to implement ***stack unwinding***

By **debuggers**

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[...]
```

Relied upon to implement ***stack unwinding***

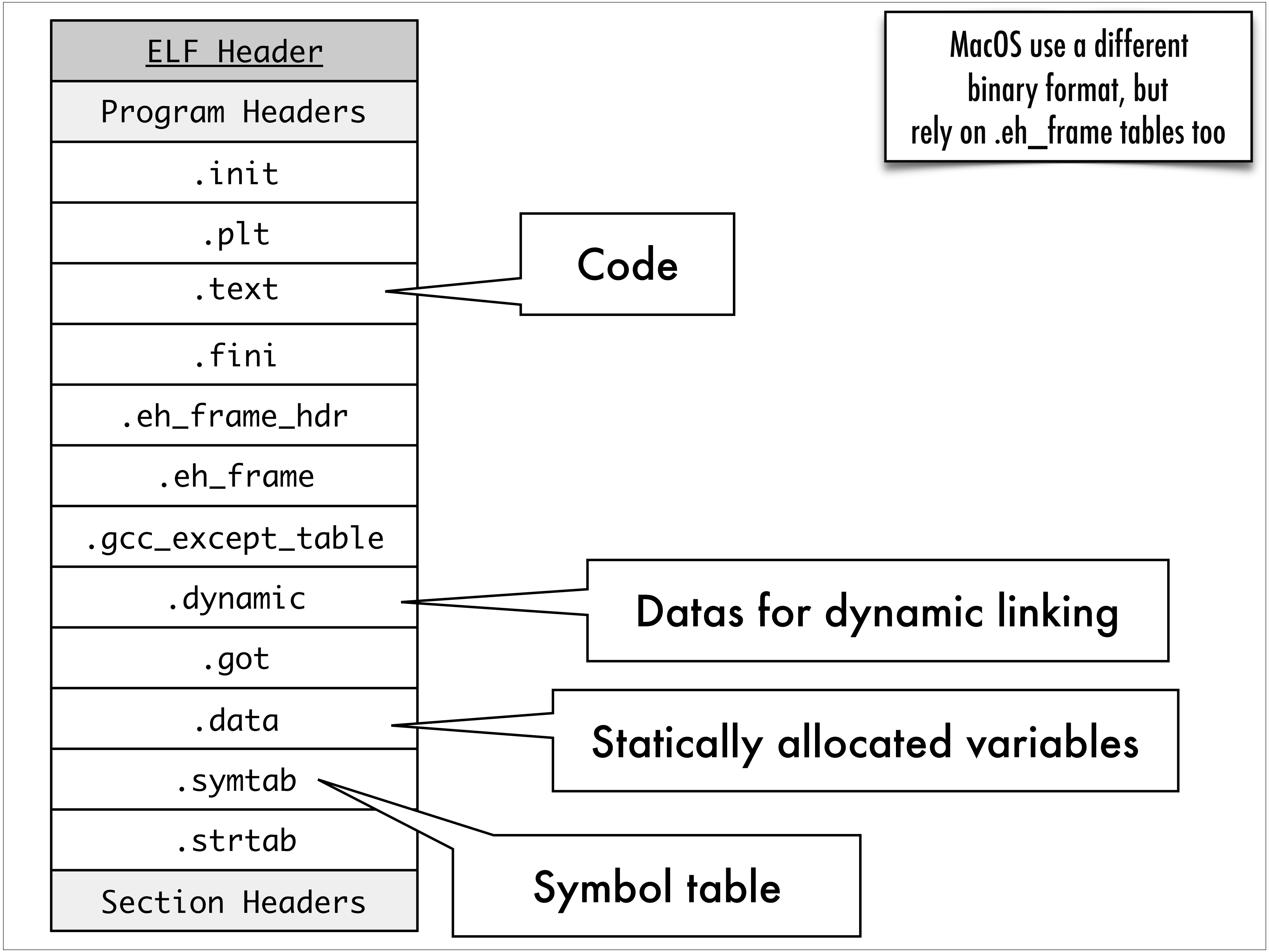
By **debuggers** but also by **program analysis tools**

And by the **C++ runtime** to implement **exceptions!!!**

Debug tables are not only for debugging

ELF Header
Program Headers
.init
.plt
.text
.fini
.eh_frame_hdr
.eh_frame
.gcc_except_table
.dynamic
.got
.data
.symtab
.strtab
Section Headers

MacOS use a different binary format, but rely on .eh_frame tables too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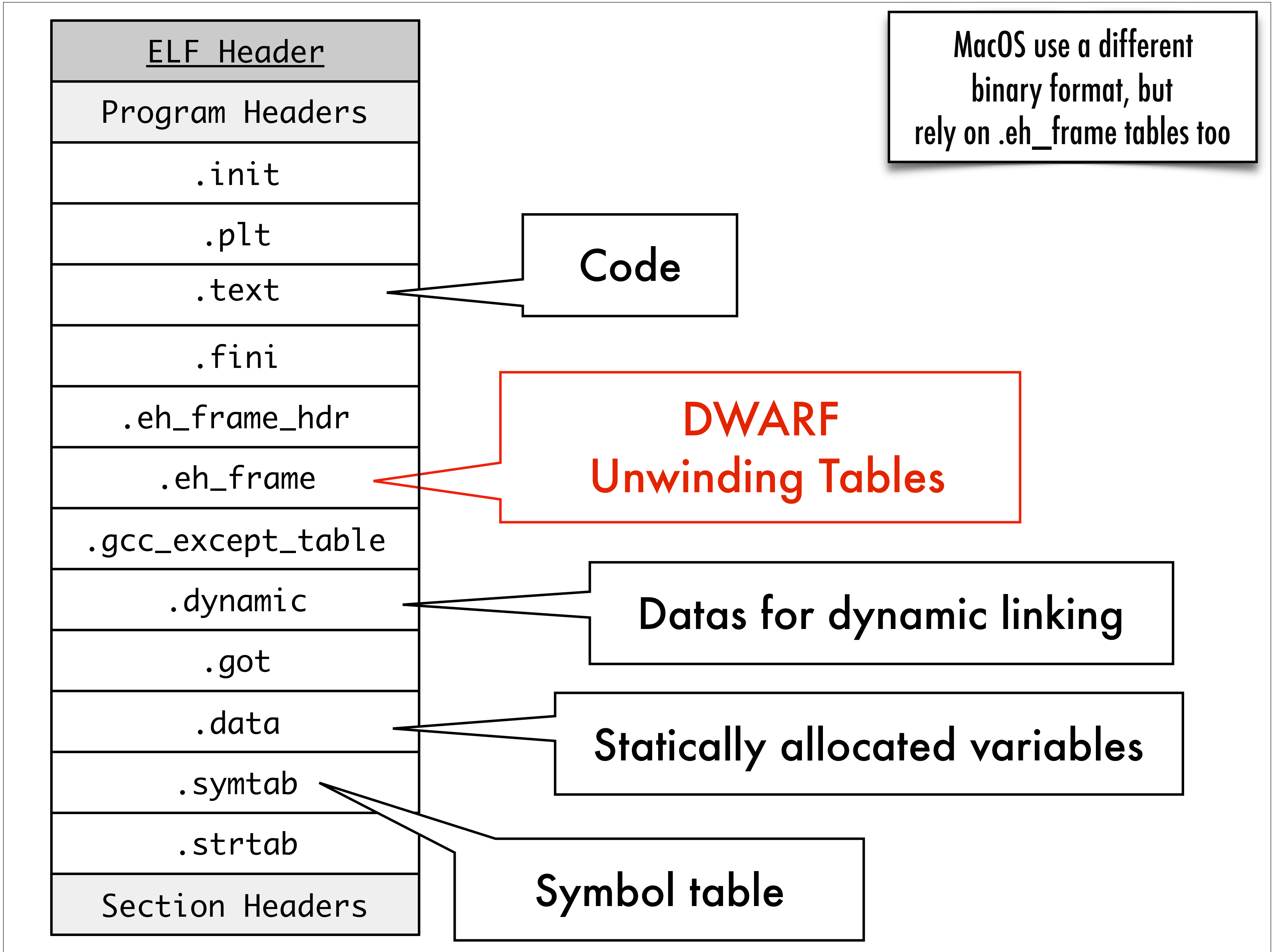
Statically allocated variables
Symbol table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Unwinding Tables on disk

```
0000f670  14 00 00 00 00 00 00 00  01 7a 52 00 01 78 10 01  |.........zR..x..|
0000f680  1b 0c 07 08 90 01 07 10  14 00 00 00 1c 00 00 00  |................|
0000f690  90 0d ff ff 2a 00 00 00  00 00 00 00 00 00 00 00  |....*...........|
0000f6a0  14 00 00 00 00 00 00 00  01 7a 52 00 01 78 10 01  |.........zR..x..|
0000f6b0  1b 0c 07 08 90 01 00 00  24 00 00 00 1c 00 00 00  |........$.......|
0000f6c0  10 0d ff ff 40 00 00 00  00 0e 10 46 0e 18 4a 0f  |....@......F..J.|
0000f6d0  0b 77 08 80 00 3f 1a 3b  2a 33 24 22 00 00 00 00  |.w...?.;*3$"....|
0000f6e0  1c 00 00 00 44 00 00 00  2e 0e ff ff 07 00 00 00  |....D...........|
0000f6f0  00 41 0e 10 86 02 43 0d  06 42 0c 07 08 00 00 00  |.A....C..B......|
0000f700  1c 00 00 00 64 00 00 00  15 0e ff ff 25 00 00 00  |....d.......%...|
0000f710  00 41 0e 10 86 02 43 0d  06 60 0c 07 08 00 00 00  |.A....C..`......|
0000f720  1c 00 00 00 84 00 00 00  1a 0e ff ff 11 00 00 00  |................|
0000f730  00 41 0e 10 86 02 43 0d  06 4c 0c 07 08 00 00 00  |.A....C..L......|
0000f740  1c 00 00 00 a4 00 00 00  0b 0e ff ff 1a 00 00 00  |................|
0000f750  00 41 0e 10 86 02 43 0d  06 55 0c 07 08 00 00 00  |.A....C..U......|
0000f760  1c 00 00 00 c4 00 00 00  05 0e ff ff 1c 00 00 00  |................|
```

Unwinding Tables on disk

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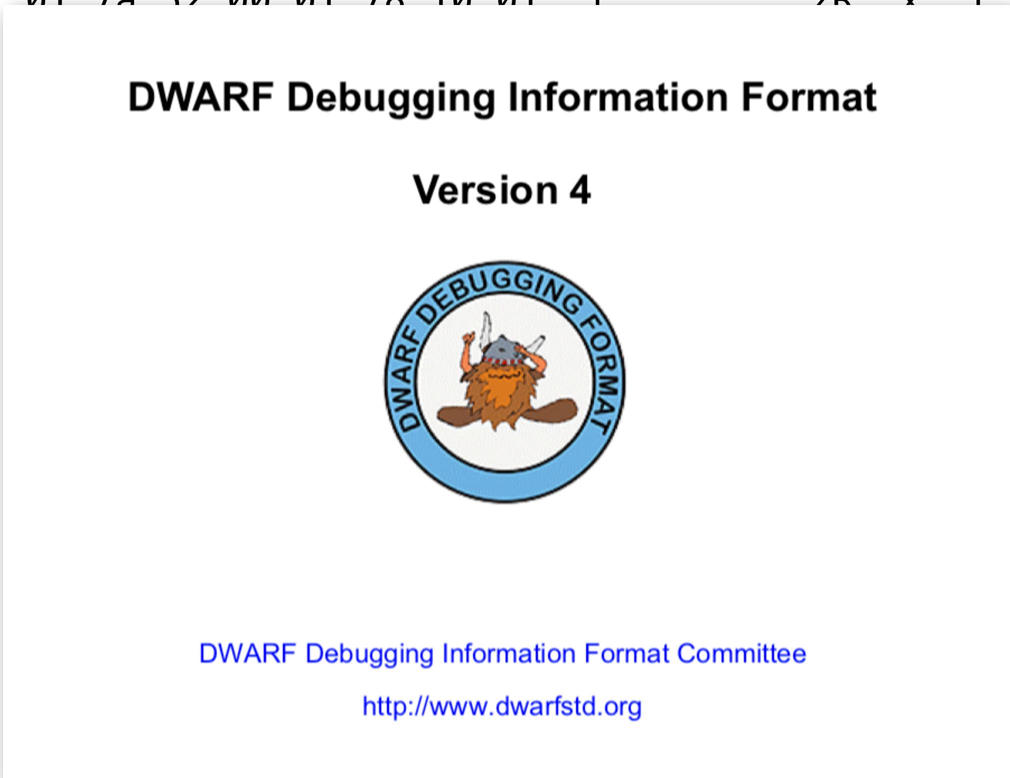
0000f700  1c 00 00 00 64 00 00 00
0000f710  00 41 0e 10 86 02 43 0d
0000f720  1c 00 00 00 84 00 00 00
0000f730  00 41 0e 10 86 02 43 0d
0000f740  1c 00 00 00 a4 00 00 00
0000f750  00 41 0e 10 86 02 43 0d
0000f760  1c 00 00 00 c4 00 00 00
```


DWARF Debugging Information Format

Version 4

DWARF Debugging Information Format Committee

http://www.dwarfstd.org

DWARF Debug Unwinding Table

```
DW_CFA_def_cfa_offset: 16
DW_CFA_advance_loc: 6 to 0000000000400376
DW_CFA_def_cfa_offset: 24
DW_CFA_advance_loc: 10 to 0000000000400380
DW_CFA_def_cfa_expression (DW_OP_breg7 (rsp): 8;
    DW_OP_breg16 (rip): 0; DW_OP_lit15;
    DW_OP_and; DW_OP_lit11; DW_OP_ge; DW_OP_lit3;
    DW_OP_shl; DW_OP_plus)
[...]
```

DWARF Debug Unwi

Bytecode instructions

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DW_CFA_def_cfa_offset: 16
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```

Arbitrary expressions accessing registers and memory locations

DWARF Debug Unwi

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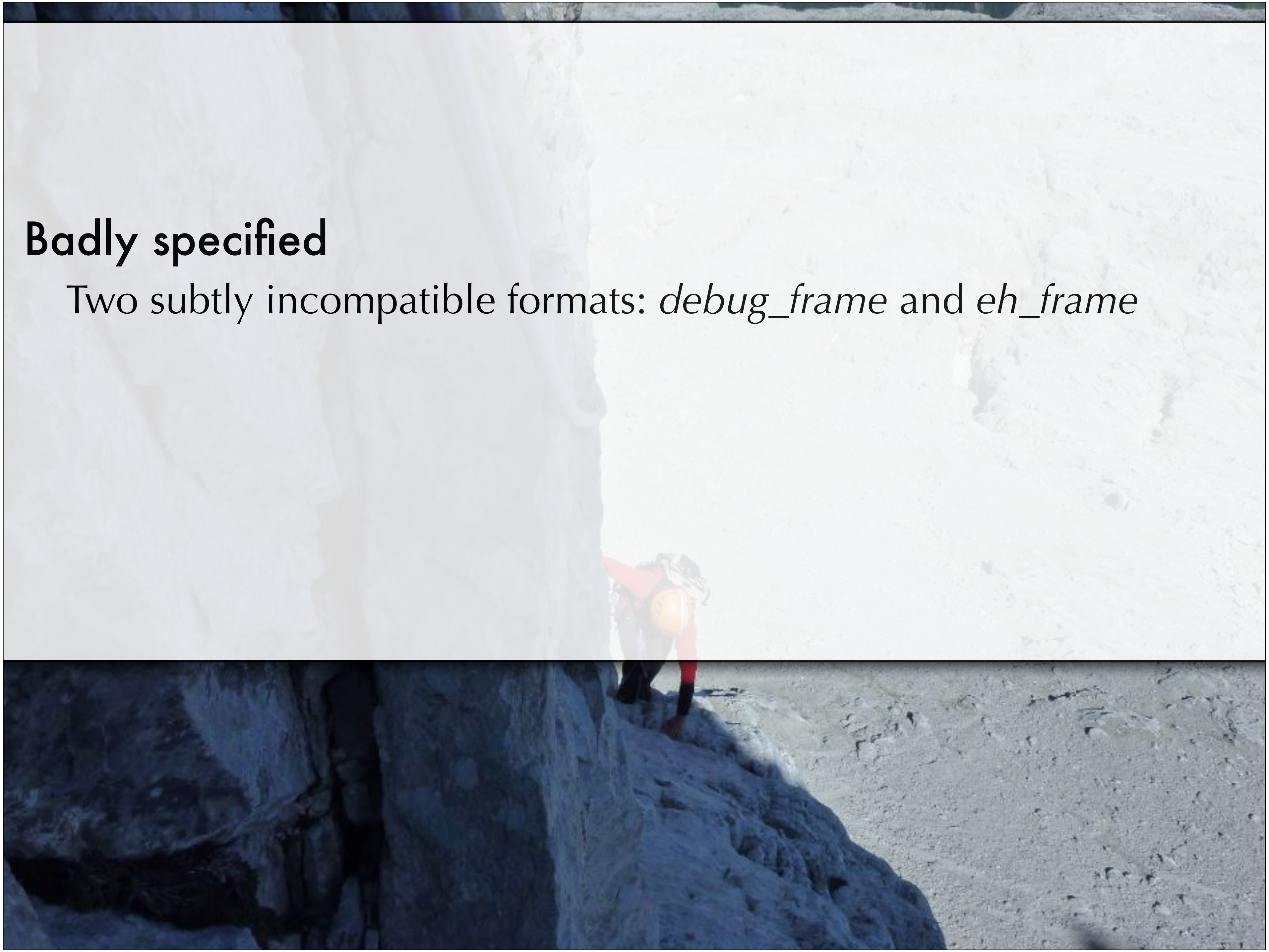
```

Interpreted on demand to inspect the call-stack

A Turing-complete stack-based machine

can dereference memory and access values in machine registers

— in a place where few expect it



Badly specified

Two subtly incompatible formats: *debug_frame* and *eh_frame*

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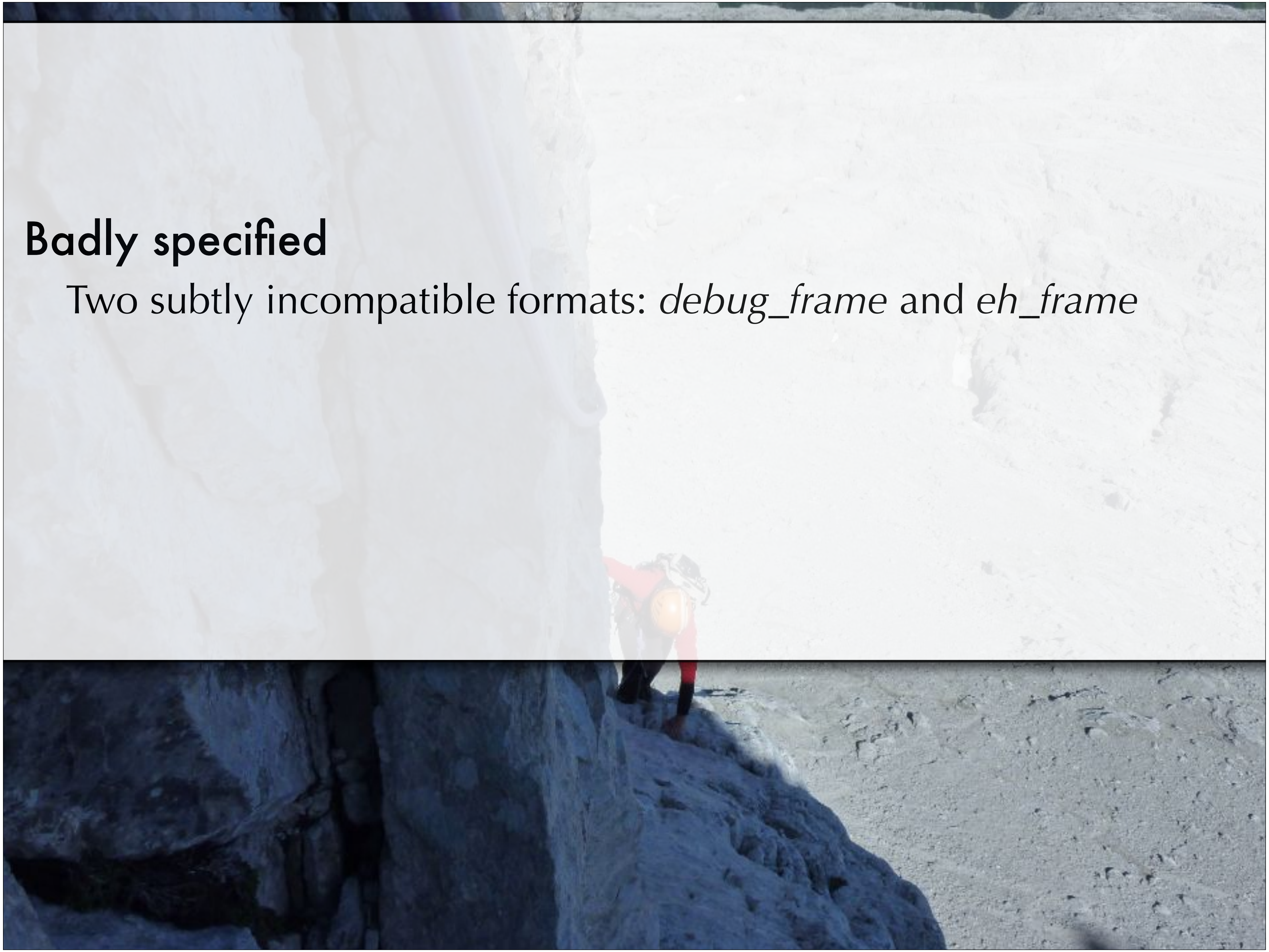
Two subtly incompatible formats: *debug_frame* and *eh_frame*

Airs – Ian Lance Taylor

.eh_frame

January 10, 2011 at 11:12 pm · Filed under Programming

When gcc generates code that handles exceptions, it produces tables that describe how to unwind the stack. These tables are found in the .eh_frame section. The format of the .eh_frame section is very similar to the format of a DWARF .debug_frame section. Unfortunately, it is not precisely identical. I don't know of any documentation which describes this format. The following should be read in conjunction with the relevant section of the DWARF standard, available from http://dwarfstd.org.



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Burden for the compiler to generate

Each compiler pass must keep the table in sync with code

```
foo:
    .cfi_startproc
    pushq   %rbp
    .cfi_def_cfa_offset 16
    .cfi_offset 6, -16
    movq    %rsp, %rbp
    .cfi_def_cfa_register 6
    movl    %edi, -4(%rbp)
    movl    %esi, -8(%rbp)
    movl    -4(%rbp), %edx
    movl    -8(%rbp), %eax
    addl    %edx, %eax
    popq    %rbp
    .cfi_def_cfa 7, 8
    ret
    .cfi_endproc
```

```
$ gcc -S foo.c
```

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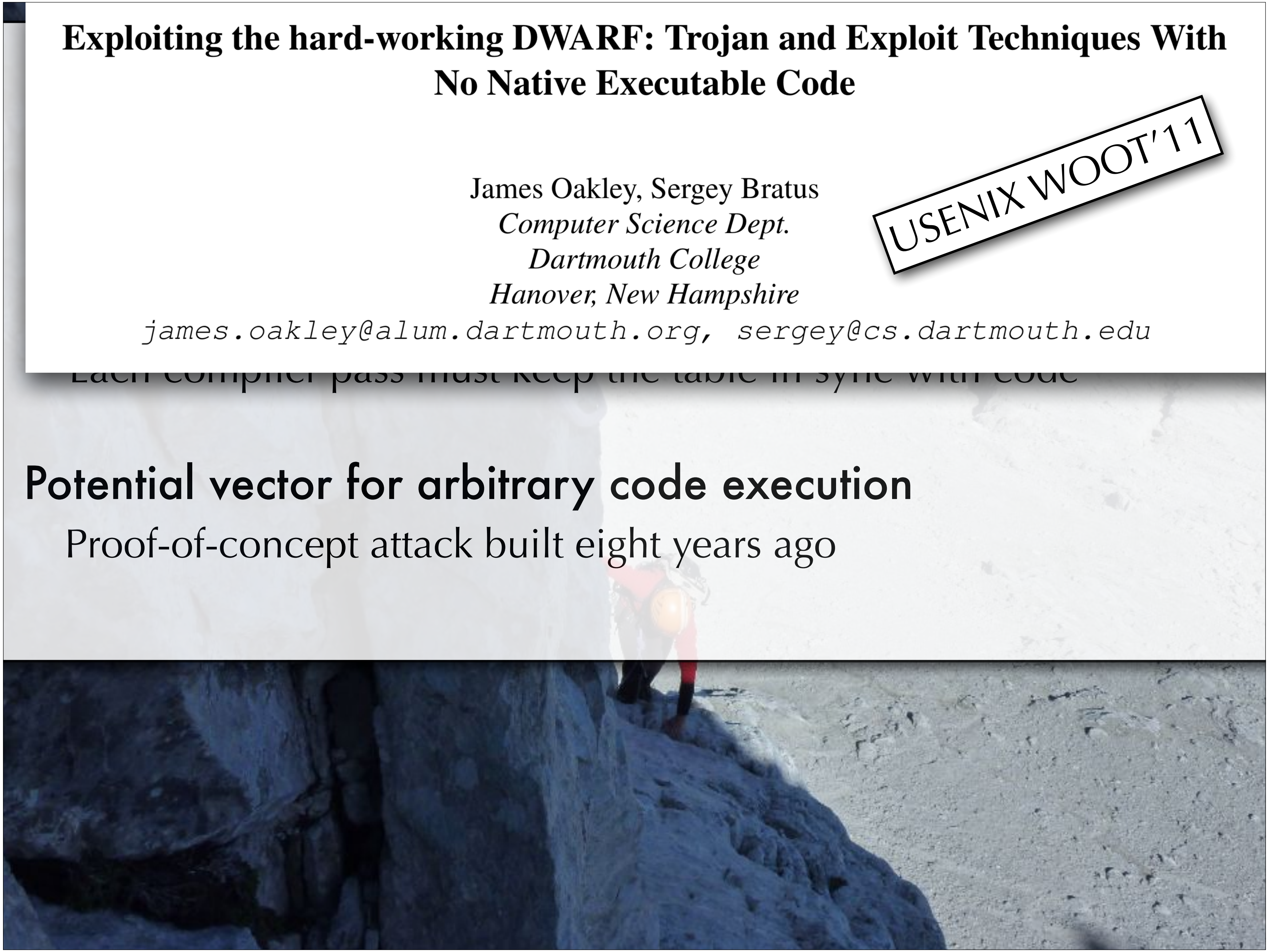
Potential vector for arbitrary code execution

Proof-of-concept attack built eight years ago


Exploiting the hard-working DWARF: Trojan and Exploit Techniques With No Native Executable Code
James Oakley, Sergey Bratus
Computer Science Dept.
Dartmouth College
Hanover, New Hampshire
james.oakley@alum.dartmouth.org, sergey@cs.dartmouth.edu
USENIX WOOT'11
Potential vector for arbitrary code execution
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Two subtly incompatible formats: *debug_frame* and *eh_frame*

Burden for the compiler to generate

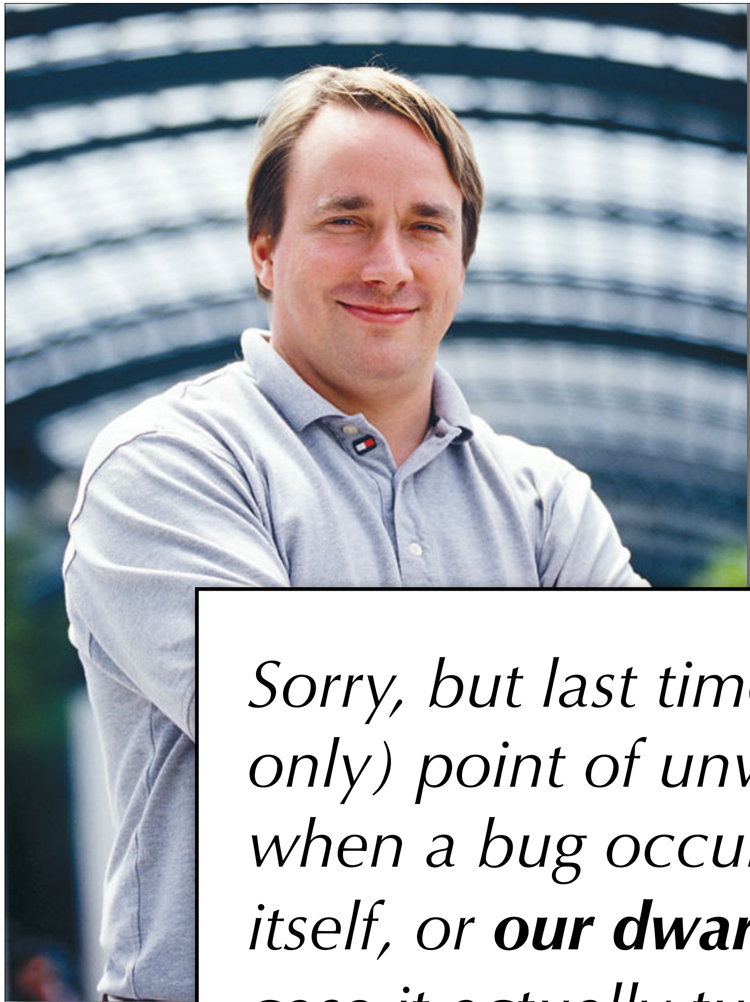
Each compiler pass must keep the table in sync with code

Potential vector for arbitrary code execution

Proof-of-concept attack built five years ago

Complex, Buggy, Untested

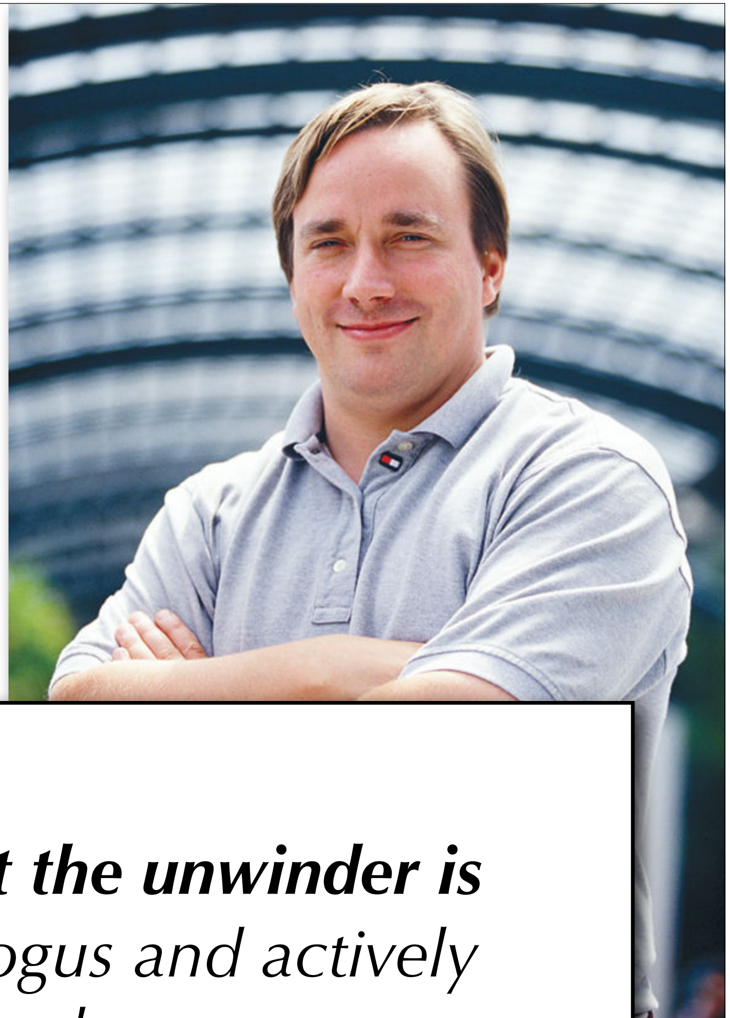
Why doesn't the Linux Kernel rely on DWARF tables?



Why doesn't the Linux Kernel rely on DWARF tables?

Sorry, but last time was too f... painful. The whole (and only) point of unwinders is to make debugging easy when a bug occurs. But ***the dwarf unwinder had bugs*** *itself, or* ***our dwarf information had bugs****, and in either case it actually turned several trivial bugs into a* ***total undebuggable hell****.*

Linus Torvalds, Kernel mailing list, 2012



*If you can **mathematically prove that the unwinder is correct** — even in the presence of bogus and actively incorrect unwinding information — and never ever follows a bad pointer, **I'll reconsider**.*

Validation of unwinding tables

```
<foo>:
  push   %r15
  push   %r14
  mov    $0x3,%eax
  push   %r13
  push   %r12
  push   %rbp
  push   %rbx
  sub    $0x68,%rsp
  cmp    $0x1,%edi
  movl   $0x0,0x14(%rsp)
  je     49e4a0
  add    $0x68,%rsp
  pop    %rbx
  pop    %rbp
```

```
<foo>:
  push   %r15
  push   %r14
  mov    $0x3,%eax
```

Assume:

- `eh_frame` table has been generated by the compiler
- we can interpret the `eh_frame` bytecode to generate the unwinding tables

```
  cmp    $0x1,%edi
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  je     49e4a0
  add    $0x68,%rsp
  pop    %rbx
  pop    %rbp
```

		CFA	ra
<foo>:			
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8

Assume:

- `eh_frame` table has been generated by the compiler
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cmp	$0x1,%edi	rsp+160	c-8
movl	$0x0,0x14(%rsp)	rsp+160	c-8
je	49e4a0	rsp+160	c-8
add	$0x68,%rsp	rsp+160	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

<foo>:		CFA	ra
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8
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push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
cmp	$0x1,%edi	rsp+160	c-8
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je	49e4a0	rsp+160	c-8
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pop	%rbx	rsp+56	c-8
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<foo>:		CFA	ra
push	%r15	rsp+8	c-8
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mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8

When `foo` is called, *before executing its first instruction:*

return address is stored at `*rsp`

pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

<foo>:		CFA	ra
push	%r15	rsp+8	c-8
push	**%r14**	**rsp+16**	**c-8**
mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

After `push %r15`, `rsp` has been decreased by 8:

return address is stored at `*(rsp+8)`

		CFA	ra
<foo>:			
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

After `push %r14`, `rsp` has been decreased by 8:

return address is stored at `*(rsp+16)`

<foo>:		CFA	ra
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

After `mov $0x3,%eax`:

return address is still stored at `*(rsp+16)`

<foo>:		CFA	ra
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8

The unwinding table is redundant wrt the binary code

It captures *some abstract execution* of the code

pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

<foo>:		CFA	ra
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
cmp	$0x1,%edi	rsp+160	c-8
movl	$0x0,0x14(%rsp)	rsp+160	c-8
je	49e4a0	rsp+160	c-8
add	$0x68,%rsp	rsp+160	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

<foo>:		CFA	ra
push	%r15	rsp+8	c-8
push	%r14	rsp+16	c-8
mov	$0x3,%eax	rsp+24	c-8
push	%r13	rsp+24	c-8
push	%r12	rsp+32	c-8
push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
cmp	$0x1,%edi	rsp+160	c-8
movl	$0x0,0x14(%rsp)	rsp+160	c-8
je	49e4a0	rsp+160	c-8
add	$0x68,%rsp	rsp+160	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

<foo>:		CFA	ra
push	%r15	rsp+8	c-8

Suppose that we know that **in an execution**:

- the return address is stored at `0xFFFF1158`

We read `%rsp` and it stores `0xFFFF1000`

push	%rbp	rsp+40	c-8
push	%rbx	rsp+48	c-8
sub	$0x68,%rsp	rsp+56	c-8
cmp	$0x1,%edi	rsp+160	c-8
movl	$0x0,0x14(%rsp)	rsp+160	c-8
je	49e4a0	rsp+160	c-8
add	$0x68,%rsp	rsp+160	c-8
pop	%rbx	rsp+56	c-8
pop	%rbp	rsp+48	c-8

<foo>:		CFA	ra
push	%r15	rsp+8	c-8

Suppose that we know that **in an execution**:

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push	%rbp	rsp+40	c-8
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sub	$0x68,%rsp	rsp+56	c-8
cmp	$0x1,%edi	rsp+160	c-8
movl	$0x0,0x14(%rsp)	rsp+160	c-8

Evaluating the **entry** on the **current register values**,

should compute the **concrete address** of the return address.

Dynamic Validation of Unwinding Tables

Abstract state

stack of concrete **addresses where return address are stored**

Abstract instruction semantics

`call`: **push** the **content of** `%rsp` on top of the abstract state
`ret`: **pop** one value from the abstract state

Validation at each instruction

evaluate the return address eh_frame entry for ip
compare with the value in abstract state

Dynamic Validation of Unwinding Ta

Abstract state

stack of concrete **addresses**

Abstract instruction sem

`call`: **push** th   top of the abstract state

`ret`: **pop**   bstract state

Valid   *ction*

urn address eh_frame entry for ip

ith the value in abstract state

callee-saved registers require some care

The eh_frame_check tool

Goal: validate eh_frame entries along one execution path

gdb:

- step-by-step binary execution, access to processor state

Python:

- parsing ELF and DWARF binary code *(building on pyelftool)*
- evaluating DWARF expressions
- scripting gdb to implement the dynamic analysis

The eh_frame_check tool

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- parsing ELF and DWARF binary code *(building on pyelftool)*
- evaluating DWARF expressions
- scripting gdb to implement the dynamic analysis

Can process *a few k asm instructions/sec*: good for now

```
short a,b,g;
long c;
char d;
int e, f;

void main() {
  for (; f; f++)
    for (; e; e++)
      for (; c; c++) {
        g = a % b;
        for (; d <= 1; d++)
          ;
      }
}
```

CSmith + Creduce + eh_frame_check.py

<main>:		CFA	ra
4004e0:	push %rbx	rsp+8	c-8
		rsp+16	c-8
[..]		[..]	
40061d:	pop %rbx	rsp+16	c-8
40061e:	retq	rsp+16	c-8

Abstract state [0xFFFF1000]

```
<main>:                              CFA      ra
  4004e0:  push  %rbx                rsp+8    c-8
                                     rsp+16   c-8
  [..]
                                     [..]

  40061d:  pop  %rbx                 rsp+16   c-8
  40061e:  retq                      rsp+16   c-8
```

Abstract state [0xFFFF1000]

%rsp 0xFFFF1000

<main>:	CFA	ra
4004e0: push %rbx	rsp+8	c-8
	rsp+16	c-8
[..]	[..]	
40061d: pop %rbx	rsp+16	c-8
40061e: retq	rsp+16	c-8

Abstract state [0xFFFF1000]

```
%rsp    0xFFFF1000

<main>:                               CFA        ra
  4004e0:  push  %rbx                 rsp+8      c-8
                                      rsp+16     c-8
  [..]
                                      [..]

  40061d:  pop   %rbx                 rsp+16     c-8
  40061e:  retq                       rsp+16     c-8
```

Abstract state [0xFFFF1000]

%rsp 0xFFFF0FF8

		CFA	ra
<main>:			
4004e0:	push %rbx	rsp+8	c-8
		rsp+16	c-8
[..]		[..]	
40061d:	pop %rbx	rsp+16	c-8
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Abstract state [0xFFFF1000]

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```
<main>:                              CFA       ra
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  [..]
                                     [..]

  40061d:  pop   %rbx                rsp+16    c-8
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<main>:                          CFA       ra
  4004e0:  push  %rbx            rsp+8     c-8
                                 rsp+16    c-8
  [..]
                                 [..]

  40061d:  pop  %rbx             rsp+16    c-8
  40061e:  retq                  rsp+16    c-8
```

Abstract state [0xFFFF1000]

```
%rsp    0xFFFF1000
```

```
<main>:                              CFA       ra
  4004e0:  push  %rbx                rsp+8     c-8
                                     rsp+16    c-8
  [..]
                                     [..]
  40061d:  pop  %rbx                 rsp+16    c-8
  40061e:  retq                      rsp+16    c-8
```

Abstract state [0xFFFF1000]

%rsp 0xFFFF1000

```
<main>:                              CFA       ra
  4004e0:   push   %rbx              rsp+8     c-8
                                     rsp+16    c-8
  [..]
                                     [..]

  40061d:  pop   %rbx                rsp+16    c-8
  40061e:  retq                      rsp+16    c-8
```

0xFFFF1000+16-8 != 0xFFFF1000

At -O0, -O2, or -Os. *Not at* -O1.

```
<main>:                          CFA       ra
  4004e0:  push  %rbx            rsp+8     c-8
                                 rsp+16    c-8
  [..]
                                 [..]

  40061d:  pop  %rbx             rsp+16    c-8
  40061e:  retq                  rsp+16    c-8
```

At -O0, -O2, or -Os. *Not at* -O1.

<main>:			CFA	ra
4004e0:	push	%rbx	rsp+8	c-8
			rsp+16	c-8
[..]			[..]	
40061d:	pop	%rbx	rsp+16	c-8
40061e:	retq		rsp+16	c-8

Just a coincidence: at `-O1` `rbx` is not saved.

Validation of unwinding tables is effective

The sad truths

Generating `eh_frame` is a *burden* for the compiler

Some compilers do not generate `eh_frame` at all

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To enable binary profilers!!!

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Did you ever attempt **debugging**
jit-generated assembly gone wrong?

The sad truths

Generating `eh_frame` is a *burden* for the compiler

Some compilers do not generate `eh_frame` at all

OCaml `eh_frame` code was contributed by JaneStreet

Did you ever attempt **debugging**
jit-generated assembly gone wrong?

Or manually code **unwinding instructions** in **inline asm**?

```
#define LLL_STUB_UNWIND_INFO_START
    ".section  .eh_frame,\"a\",@progbits\n"
"5:\t" ".long 7f-6f                # Length of Common Information Entry\n”
"6:\t" ".long 0x0                  # CIE Identifier Tag\n\t"
    ".byte 0x1                     # CIE Version\n\t"
    ".ascii \"zR\\0\"              # CIE Augmentation\n\t"
    ".uleb128 0x1                  # CIE Code Alignment Factor\n\t”
    ".sleb128 -4                   # CIE RA Column\n\t”
    ".byte 0x8                     # Augmentation size\n\t"
    ".uleb128 0x1                  # FDE Encoding (pcrel sdata4)\n\t”
    ".byte 0x1b                    # DW_CFA_def_cfa\n\t"
    ".byte 0xc
    ".uleb128 0x4\n\t"
    ".uleb128 0x0\n\t"
    ".align 4\n"
"7:\t" ".long 17f-8f               # FDE Length\n"
"8:\t" ".long 8b-5b                # FDE CIE offset\n\t”
    ".long 1b-.                    # FDE initial location\n\t"
    ".long 4b-1b                   # FDE address range\n\t"
    ".uleb128 0x0                  # Augmentation size\n\t”
    ".byte 0x16                    # DW_CFA_val_expression\n\t”
    ".uleb128 0x8\n\t"
    ".uleb128 10f-9f\n"
"9:\t" ".byte 0x78                 # DW_OP_breg8\n\t"
    ".sleb128 3b-1b\n"
```

glibc: lowlevellock.h

```
#define LLL_STUB_UNWIND_INFO_START
    ".section  .eh_frame,\"a\",@progbits\n"
"5:\t" ".long 7f-6f            # Length of Common Information Entry\n"
"6:\t" ".long 0x0              # CIE Identifier Tag\n\t"
    ".byte 0x1                 # CIE Version\n\t"
```

Despite great care, off by 1 offset error…

```
    ".byte 0x1b
    ".byte 0xc                 # DW_CFA_def_cfa\n\t"
    ".uleb128 0x4\n\t"
    ".uleb128 0x0\n\t"
    ".align 4\n"
"7:\t" ".long 17f-8f           # FDE Length\n"
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    ".uleb128 0x8\n\t"
    ".uleb128 10f-9f\n"
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    ".sleb128 3b-1b\n"
```

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    ".byte 0x1                 # CIE Version\n\t"
```

Despite great care, off by 1 offset error…

```
Breakpoint 2, 0x0000000000406c2c in _L_lock_19 ()
(gdb) disass
Dump of assembler code for function _L_lock_19:
=> 0x0000000000406c2c <+0>:     lea    0x2ba13d(%rip),%rdi        # 0x6c0d70 <lock>
   0x0000000000406c33 <+7>:     sub    $0x80,%rsp
   0x0000000000406c3a <+14>:    callq  0x436d10 <__lll_lock_wait_private>
   0x0000000000406c3f <+19>:    add    $0x80,%rsp
   0x0000000000406c46 <+26>:    jmpq   0x4069c6 <abort+70>
End of assembler dump.
(gdb) bt
#0  0x0000000000406c2c in _L_lock_19 ()
#1  0x0000000000406c3f in _L_lock_19 ()
#2  0x00000000004069c6 in abort ()
#3  0x0000000000401017 in main () at foo1.c:4
(gdb)
```

```
"9:\t" ".byte 0x78             # DW_OP_breg8\n\t"
    ".sleb128 3b-1b\n"
```

glibc: lowlevellock.h

Synthesis of unwinding tables

Synthesis Strategy

Upon entering a function:

CFA = `rsp` - 8   RA = CFA + 8

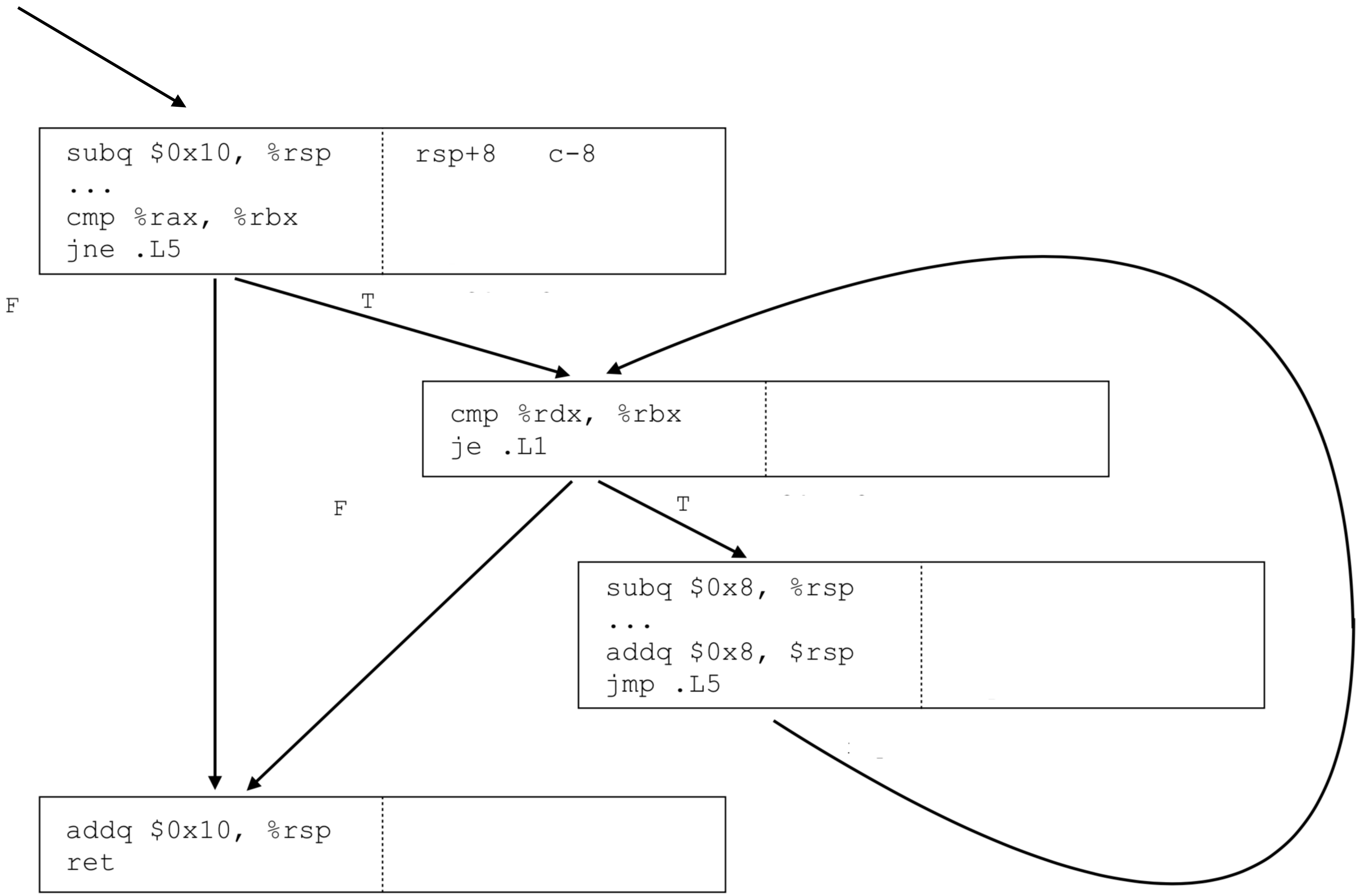
Check the semantics of each instruction in each basic block:

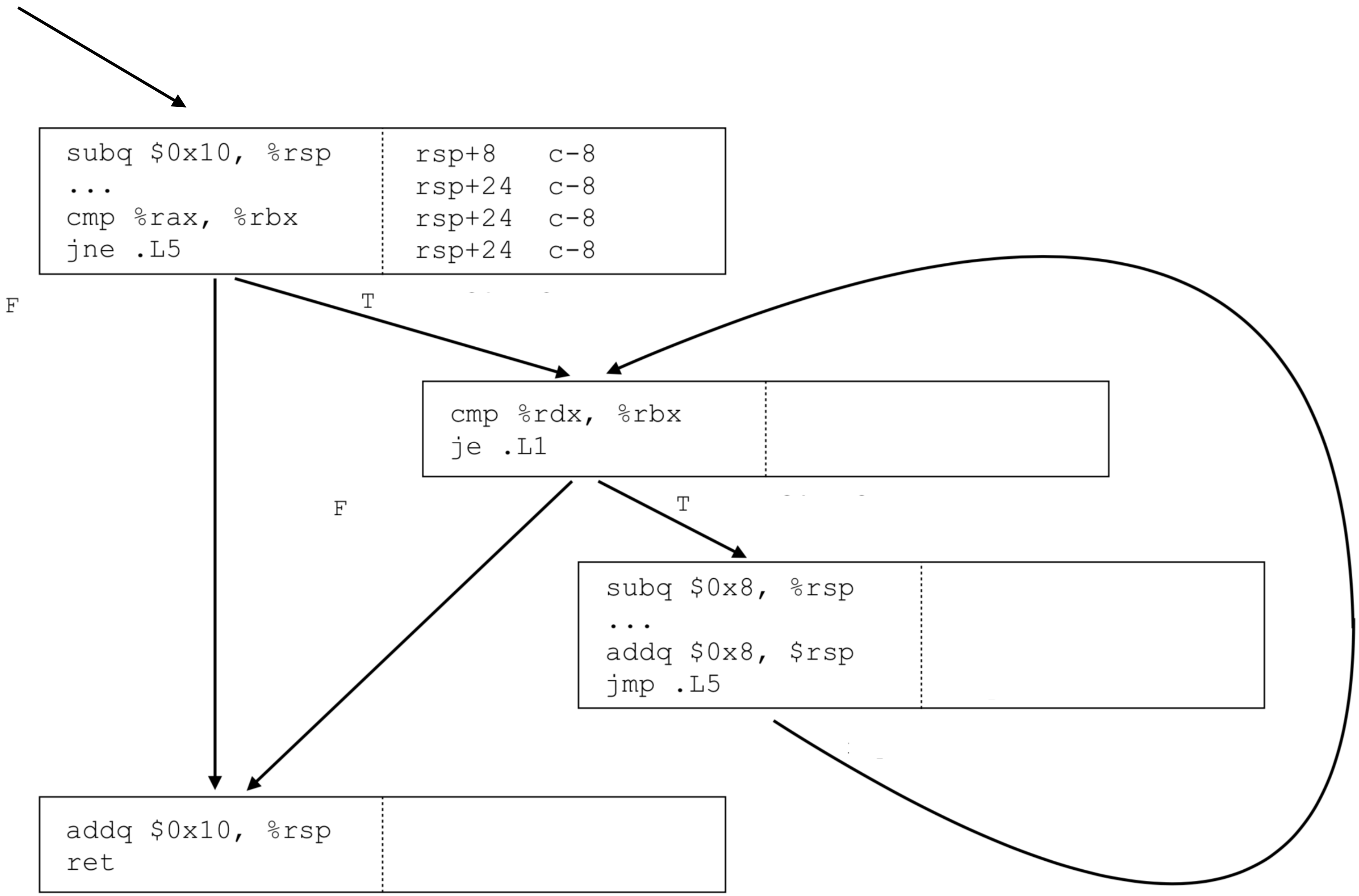
— Is `rbp` used as a base pointer?

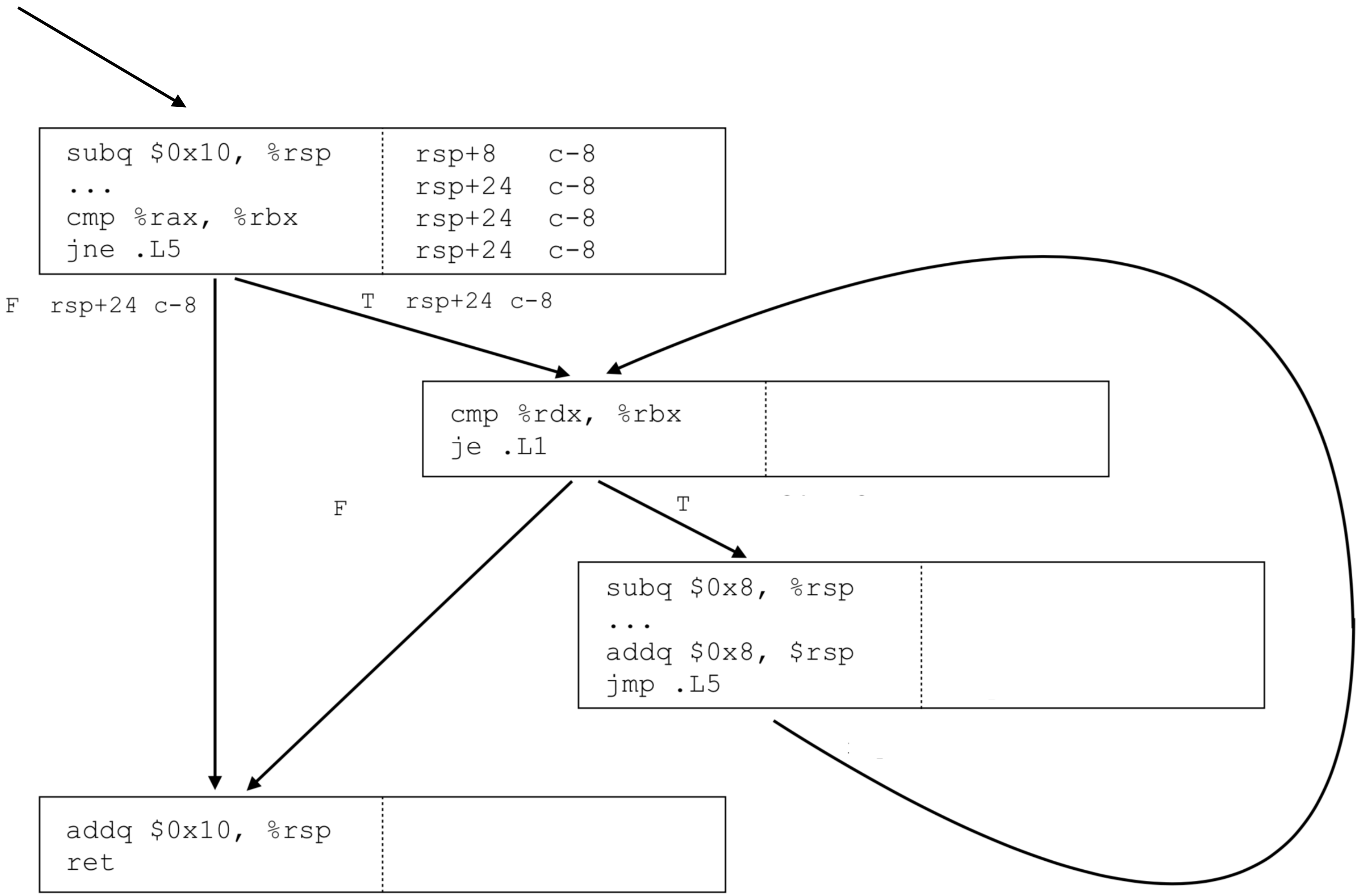
— Is `rsp` modified?

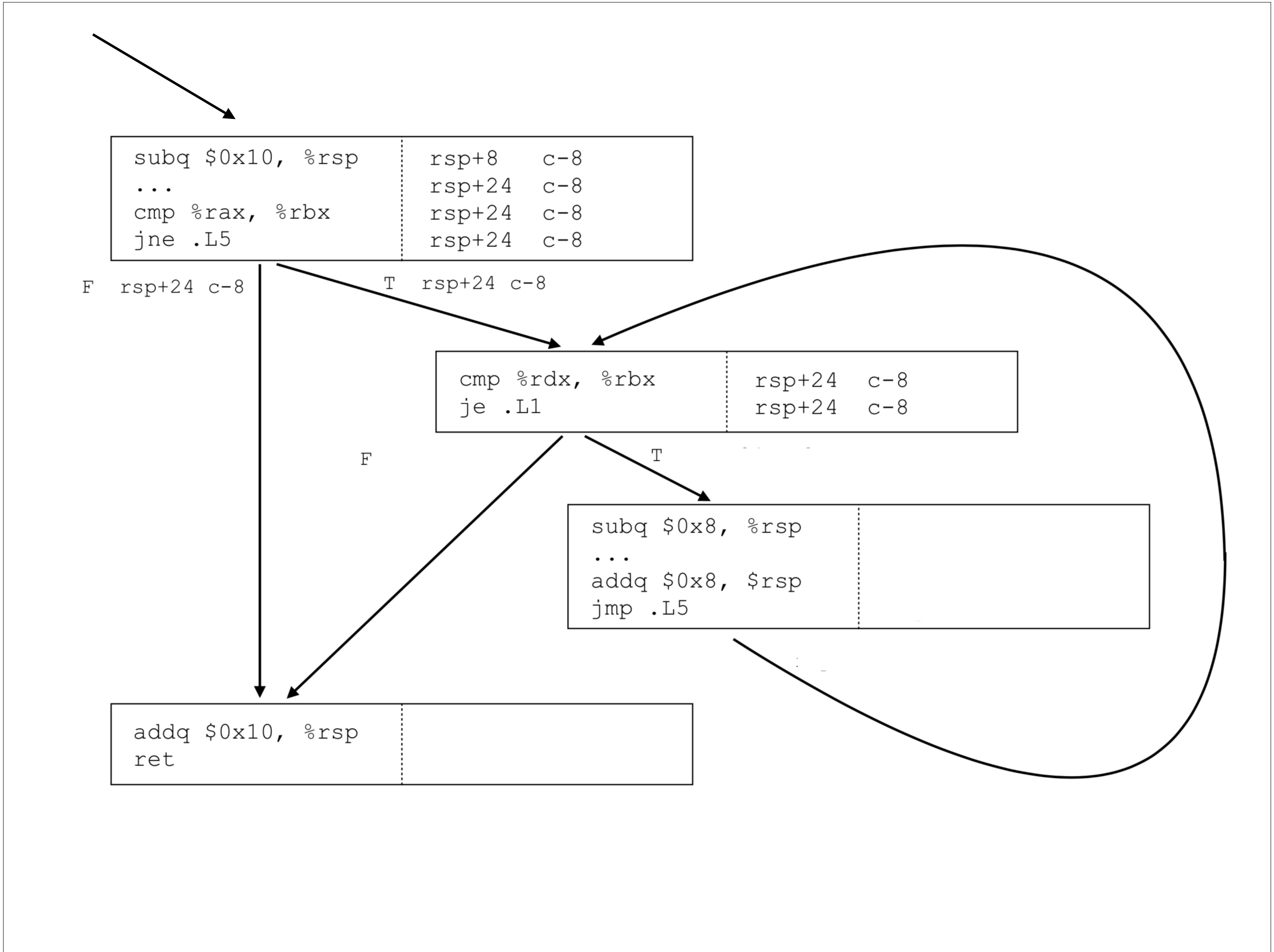
    — update the computation of CFA accordingly

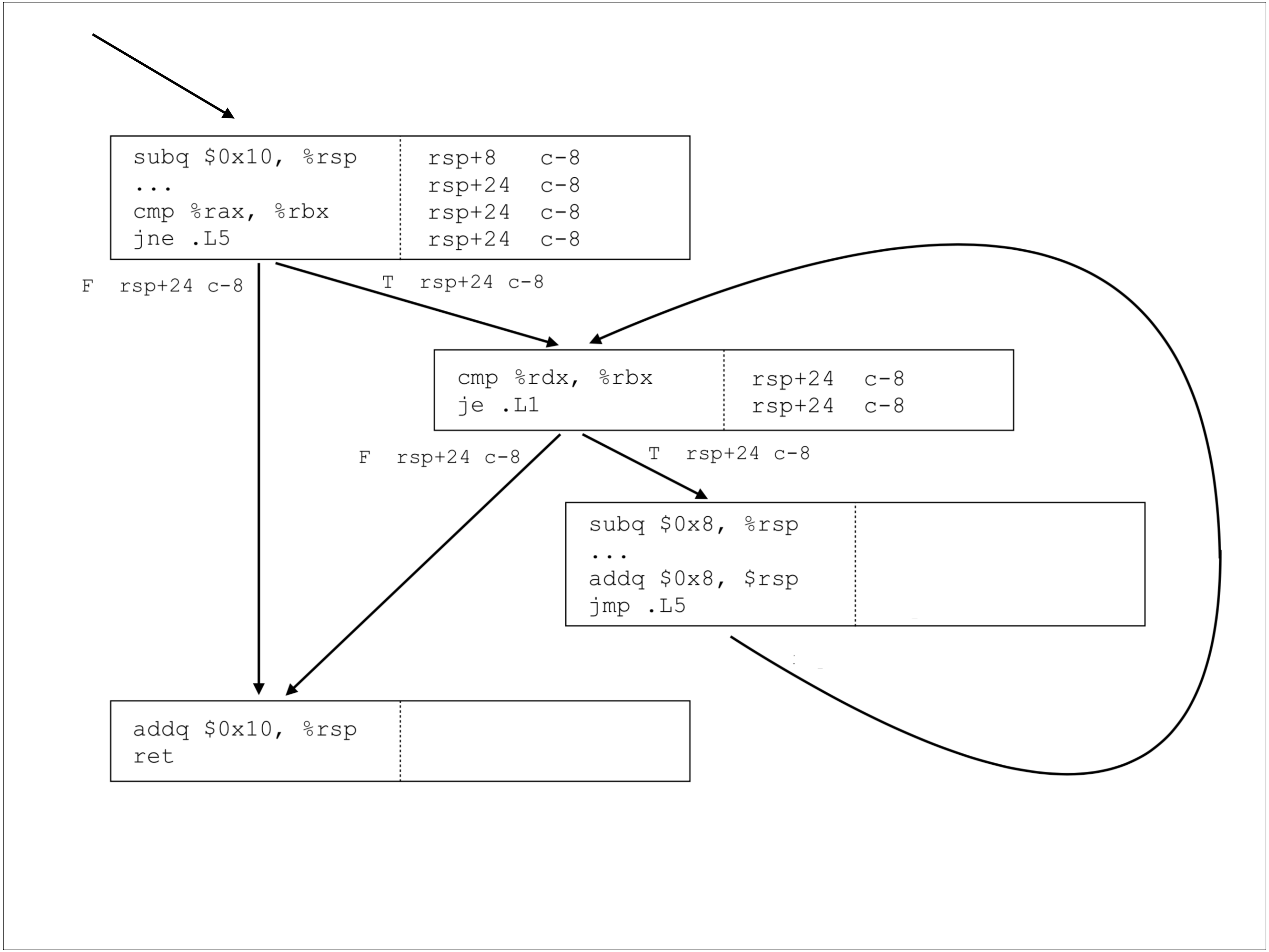
Chain across basic blocks following the control-flow graph.

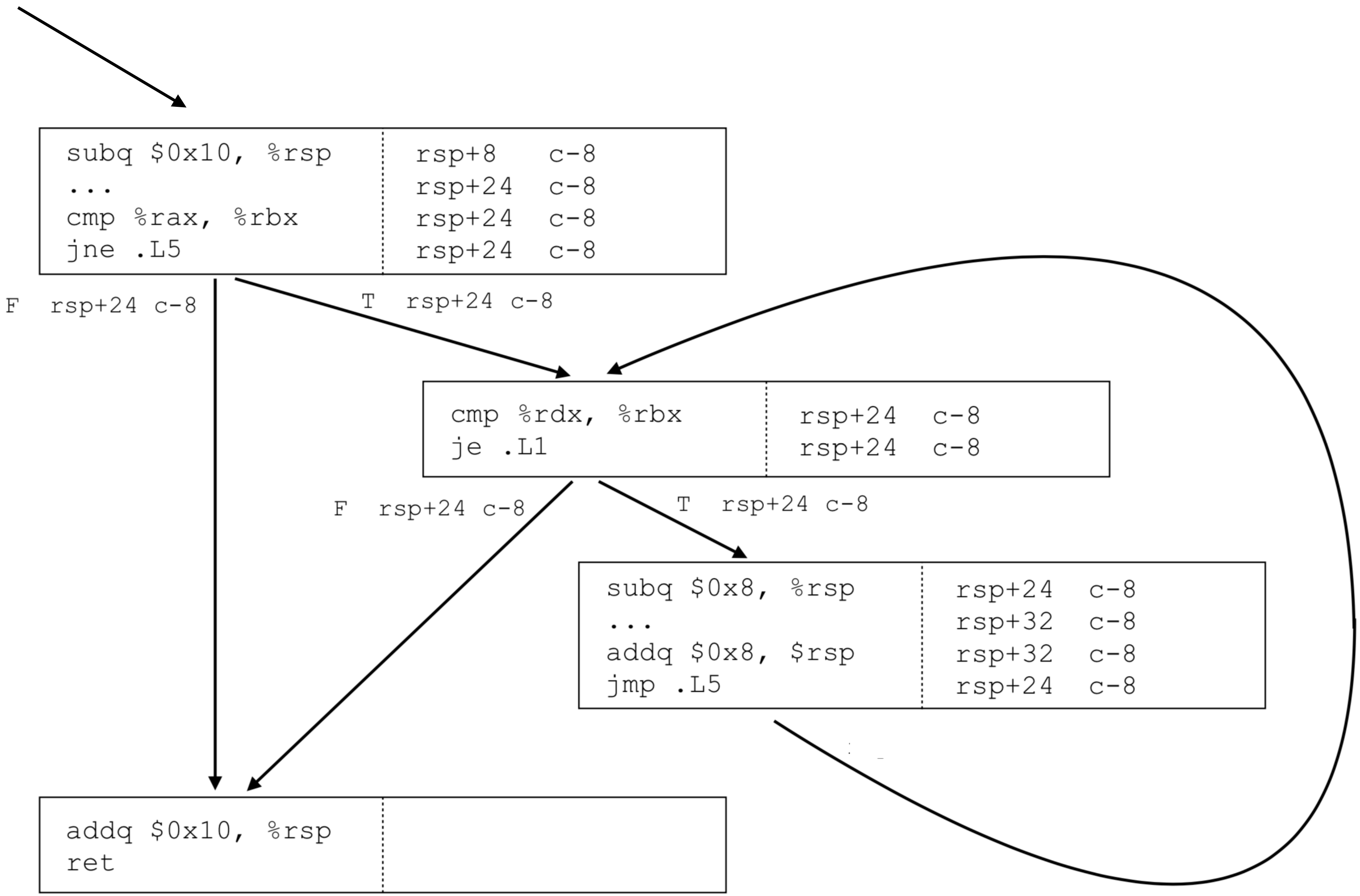

subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
F
T
cmp %rdx, %rbx
je .L1
F
T
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
addq $0x10, %rsp
ret

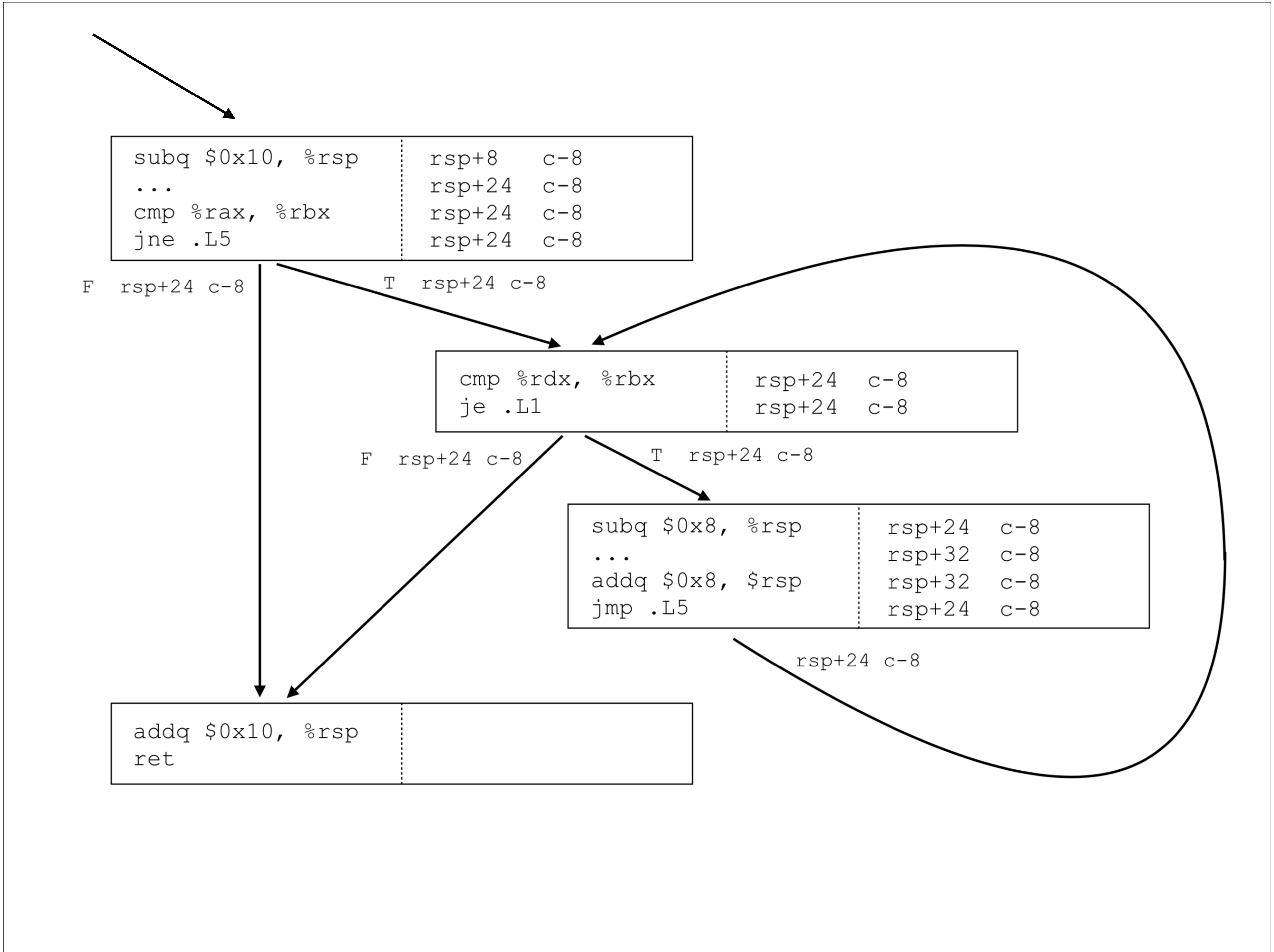

subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F
T
cmp %rdx, %rbx
je .L1
F
T
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
addq $0x10, %rsp
ret


subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
cmp %rdx, %rbx
je .L1
F
T
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
addq $0x10, %rsp
ret


subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
cmp %rdx, %rbx
je .L1
rsp+24 c-8
rsp+24 c-8
F
T
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
addq $0x10, %rsp
ret


subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
cmp %rdx, %rbx
je .L1
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
addq $0x10, %rsp
ret


subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
cmp %rdx, %rbx
je .L1
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
rsp+24 c-8
rsp+32 c-8
rsp+32 c-8
rsp+24 c-8
addq $0x10, %rsp
ret


subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
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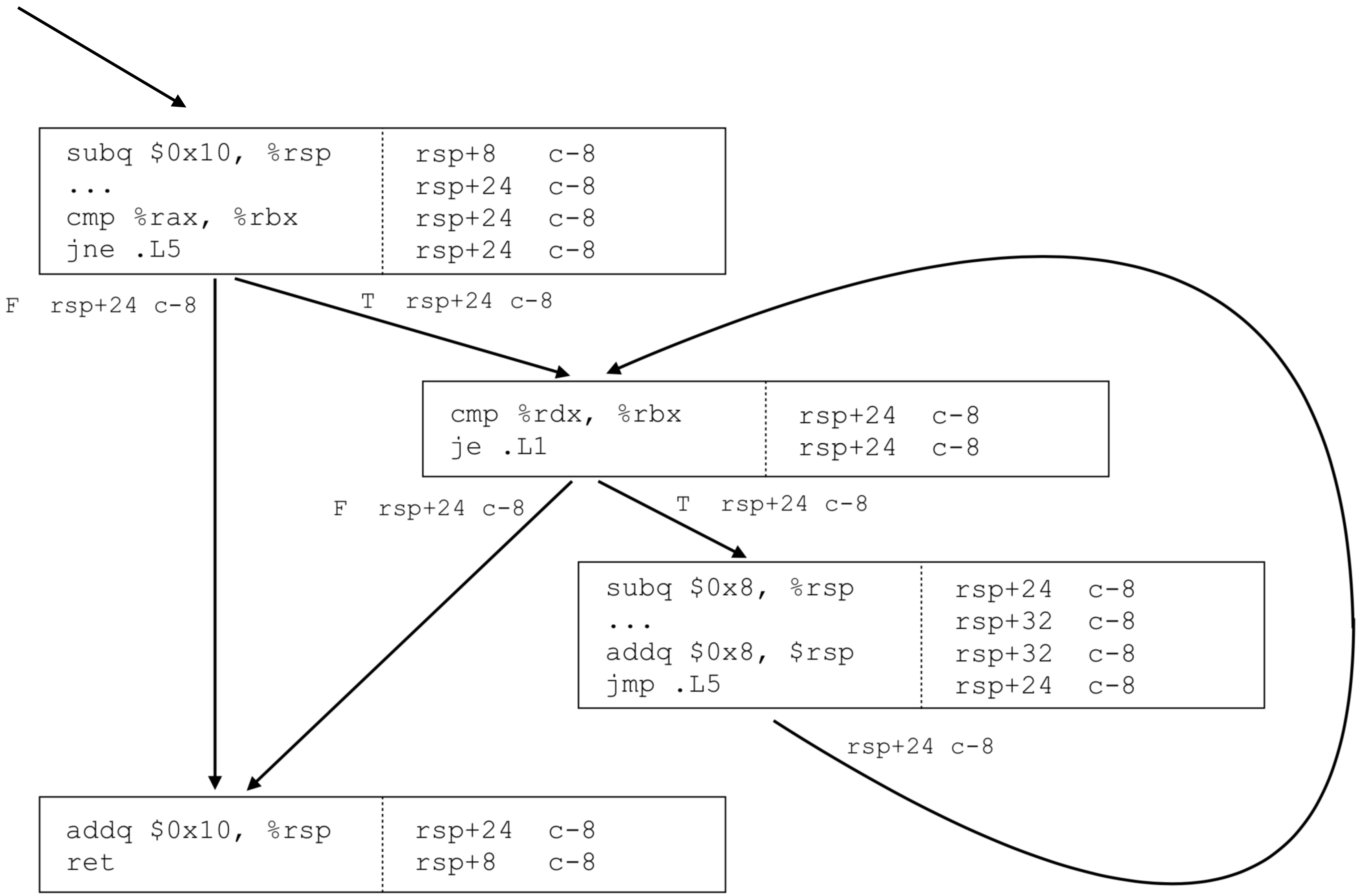
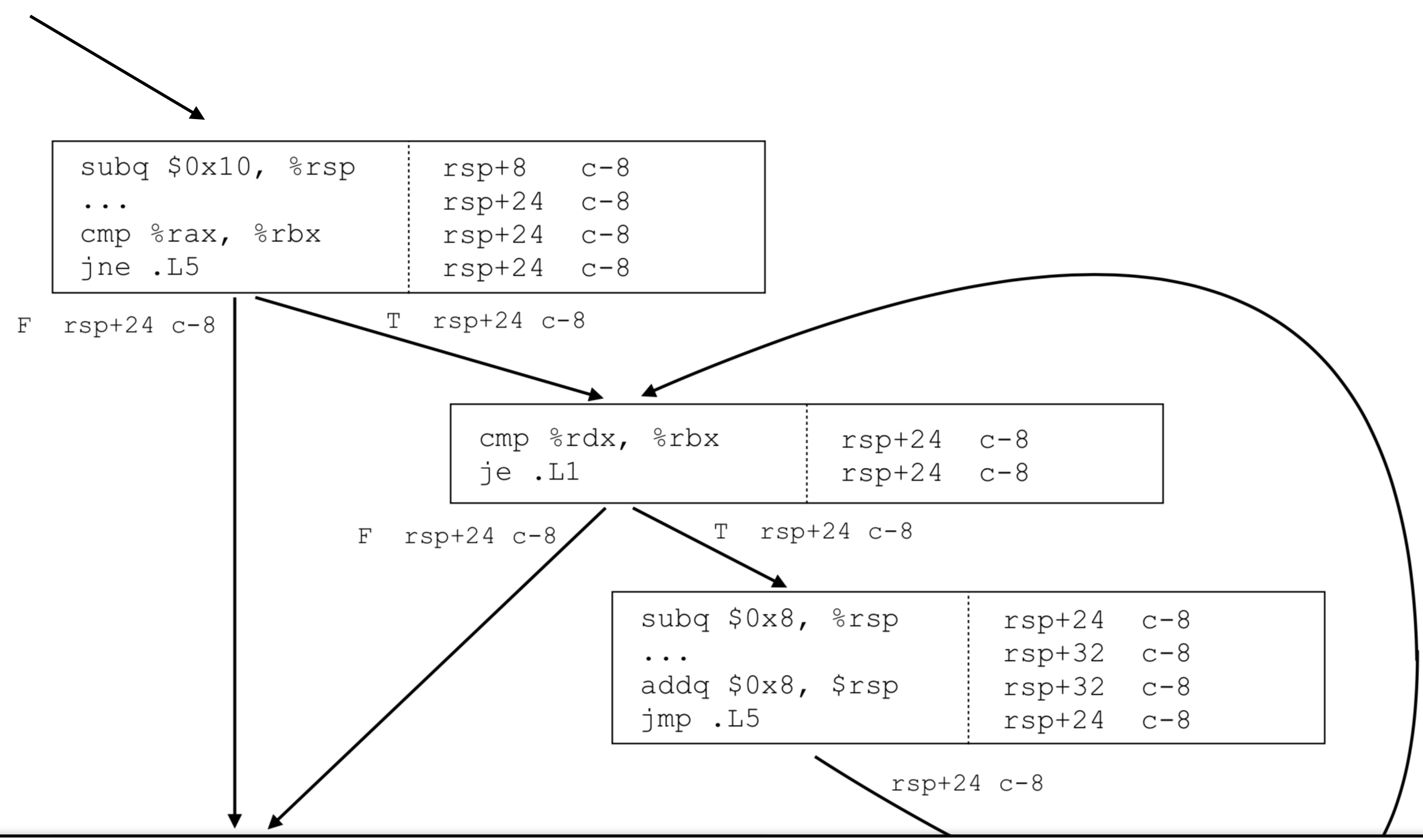
je .L1
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
rsp+24 c-8
rsp+32 c-8
rsp+32 c-8
rsp+24 c-8
rsp+24 c-8
addq $0x10, %rsp
ret



subq $0x10, %rsp
...
cmp %rax, %rbx
jne .L5
rsp+8 c-8
rsp+24 c-8
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
cmp %rdx, %rbx
je .L1
rsp+24 c-8
rsp+24 c-8
F rsp+24 c-8
T rsp+24 c-8
subq $0x8, %rsp
...
addq $0x8, $rsp
jmp .L5
rsp+24 c-8
rsp+32 c-8
rsp+32 c-8
rsp+24 c-8
rsp+24 c-8
addq $0x10, %rsp
ret
rsp+24 c-8
rsp+8 c-8



Fixpoint immediate!

Fixpoint fallback

Compiler relies on base pointer even if -fomit-frame-pointer is specified

```
int main() {

 read_integer(z_max);

 for(int z=0; z < z_max; z++) {
   int x[z];
   …do something with x...
 }
}
```

LOC	CFA	rbx	rbp	r12	r13	r14	r15	ra
0000000000400526	rsp+8	u	u	u	u	u	u	c-8
0000000000400527	rsp+16	u	c-16	u	u	u	u	c-8
000000000040052a	rbp+16	u	c-16	u	u	u	u	c-8
0000000000400537	rbp+16	c-56	c-16	c-48	c-40	c-32	c-24	c-8
00000000004005cf	rsp+8	c-56	c-16	c-48	c-40	c-32	c-24	c-8

Fixpoint fallback

Compiler relies on base pointer

Implementation on top of CMU's Binary Analysis Platform

Theory: symbolic evaluation of ASM, tracking registers

Practice: heuristics aware of few ASM patterns

0000000000400526	rsp+8	u	u	u	u	u	u	c-8
0000000000400527	rsp+16	u	c-16	u	u	u	u	c-8
000000000040052a	rbp+16	u	c-16	u	u	u	u	c-8
0000000000400537	rbp+16	c-56	c-16	c-48	c-40	c-32	c-24	c-8
00000000004005cf	rsp+8	c-56	c-16	c-48	c-40	c-32	c-24	c-8

Validate unwinding tables against the binary code

Synthesise unwinding tables from the binary/ASM code

Identify bugs in generation of tables

Make unwinding tables available to other systems
- integrate with compiler's inline assembly extensions?
- run on demand on JITted code?

Interpreting DWARF bytecode is **slooooow**…

…despite libunwind aggressive caching

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The **perf** profiler cannot unwind the stack in an interrupt handler

Interpreting DWARF bytecode is **slooooow**…

…despite libunwind aggressive caching

The **perf** profiler cannot unwind the stack in an interrupt handler

During profiling stack copies are recorded for offline unwinding

Ahead-of-time compilation of DWARF unwind tables

```
DW_CFA_advance_loc: 0 to 0x615
DW_CFA_def_cfa: r7 (rsp) ofs 8
DW_CFA_offset: r16 (rip) at cfa-8
DW_CFA_advance_loc: 5 to 0x620
DW_CFA_def_cfa_offset: 48
...
```

```
DW_CFA_advance_loc: 0 to 0x615
DW_CFA_def_cfa: r7 (rsp) ofs 8
DW_CFA_offset: r16 (rip) at cfa-8
DW_CFA_advance_loc: 5 to 0x620
DW_CFA_def_cfa_offset: 48
...
```

→

LOC	CFA	ra
0x615	rsp+8	c-8
0x620	rsp+48	c-8
0x659	rsp+8	c-8

```
DW_CFA_advance_loc: 0 to 0x615
DW_CFA_def_cfa: r7 (rsp) ofs 8
DW_CFA_offset: r16 (rip) at cfa-8
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...
```

LOC	CFA	ra
0x615	rsp+8	c-8
0x620	rsp+48	c-8
0x659	rsp+8	c-8

```
unwind_context_t _eh_elf(unwind_context_t ctx, uintptr_t pc) {
  unwind_context_t out_ctx;
  switch(pc) {
  ...
  case 0x615 ... 0x618:
      out_ctx.rsp = ctx.rsp + 8;
      out_ctx.rip = *((uintptr_t*)(out_ctx.rsp - 8));
      out_ctx.flags = 3u;
      return out_ctx;
  ...
  }
}
```

eh_elfs

Dwarf unwind bytecode compiled to ASM

Each .eh_table is compiled to a separate eh_elfs .so file

```
    unwind_context_t out_ctx;
    switch(pc) {
    ...
    case 0x615 ... 0x618:
        out_ctx.rsp = ctx.rsp + 8;
        out_ctx.rip = *((uintptr_t*)(out_ctx.rsp - 8));
        out_ctx.flags = 3u;
        return out_ctx;
    ...
    }
}
```

eh_elfs

Dwarf unwind bytecode compiled to ASM

Each .eh_table is compiled to a separate eh_elfs .so file

```
unwind_context_t out_ctx;
```

libunwind-eh_elf

Alternative libunwind implementation based on eh_elf tables

Same API as libunwind: (almost) relink-and-play replacement

eh_elfs

Dwarf unwind bytecode compiled to ASM

Implementation tricks:

Code outlining performed at compile time

eg. on libc, 20827 entries but only 302 *unique* entries

Explicit binary search rather than switch/case

Same API as libunwind: (almost) relink-and-play replacement

13x speedup on
libunwind calls made by “perf gzip”

25x speedup on
libunwind calls made by “perf hackbench”

2.5x space overhead

Wider horizons

.debug_type: A Model of Data Types

```
 Compilation Unit @ offset 0x0:
  Length:        0x7e (32-bit)
  Version:       4
  Abbrev Offset: 0x0
  Pointer Size:  8
<0><b>: Abbrev Number: 1 (DW_TAG_compile_unit)
   <c>   DW_AT_producer    : Apple LLVM v9.0.0
   <10>   DW_AT_language    : 12  (ANSI C99)
   <12>   DW_AT_name        : hand.c
   <16>   DW_AT_stmt_list   : 0x0
   <1a>   DW_AT_comp_dir    : /Users/zappa/tmp
   <1e>   DW_AT_low_pc      : 0x0
   <26>   DW_AT_high_pc     : 0x1b
<1><2a>: Abbrev Number: 2 (DW_TAG_subprogram)
   <2b>   DW_AT_low_pc      : 0x0
   <33>   DW_AT_high_pc     : 0x1b
   <37>   DW_AT_frame_base  : (DW_OP_reg6 (rbp))
   <39>   DW_AT_name        : foo
   <3d>   DW_AT_decl_file   : 1
   <3e>   DW_AT_decl_line   : 1
   <3f>   DW_AT_prototyped  : 1
   <3f>   DW_AT_type        : <0x6e>
   <43>   DW_AT_external    : 1
<2><43>: Abbrev Number: 3 (DW_TAG_formal_parameter)
   <44>   DW_AT_location    :(DW_OP_fbreg: -4)
   <47>   DW_AT_name        : x
   <4b>   DW_AT_decl_file   : 1
   <4c>   DW_AT_decl_line   : 1
   <4d>   DW_AT_type        : <0x6e>
<2><51>: Abbrev Number: 3 (DW_TAG_formal_parameter)
   <52>   DW_AT_location    : (DW_OP_fbreg: -6)
   <55>   DW_AT_name        : y
   <59>   DW_AT_decl_file   : 1
   <5a>   DW_AT_decl_line   : 1
   <5b>   DW_AT_type        : <0x75>
<2><5f>: Abbrev Number: 3 (DW_TAG_formal_parameter)
   <60>   DW_AT_location    : (DW_OP_fbreg: -16)
   <63>   DW_AT_name        : z
   <67>   DW_AT_decl_file   : 1
   <68>   DW_AT_decl_line   : 1
   <69>   DW_AT_type        : <0x7c>
<2><6d>: Abbrev Number: 0
<1><6e>: Abbrev Number: 4 (DW_TAG_base_type)
   <6f>   DW_AT_name        : int
   <73>   DW_AT_encoding    : 5   (signed)
   <74>   DW_AT_byte_size   : 4
<1><75>: Abbrev Number: 4 (DW_TAG_base_type)
   <76>   DW_AT_name        : short
   <7a>   DW_AT_encoding    : 5   (signed)
   <7b>   DW_AT_byte_size   : 2
<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
   <7d>   DW_AT_type        : <0x6e>
<1><81>: Abbrev Number: 0
```

```
<2><5f>: Abbrev Number: 3 (DW_TAG_formal_parameter)
    <60>   DW_AT_location    : (DW_OP_fbreg: -16)
    <63>   DW_AT_name        : z
    <67>   DW_AT_decl_file   : 1
    <68>   DW_AT_decl_line   : 1
    <69>   DW_AT_type        : <0x7c>
    <2><6d>: Abbrev Number: 0

<1><6e>: Abbrev Number: 4 (DW_TAG_base_type)
    <6f>   DW_AT_name        : int
    <73>   DW_AT_encoding    : 5(signed)
    <74>   DW_AT_byte_size   : 4

<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
 <7d>   DW_AT_type        : <0x6e>
```

```
<44>    DW_AT_location     :(DW_OP_fbreg: -4)
<47>    DW_AT_name         : x
<4b>    DW_AT_decl_file    : 1
<4c>    DW_AT_decl_line    : 1
<4d>    DW_AT_type         : <0x6e>
```

```
  <7a>   DW_AT_encoding    : 5   (signed)
  <7b>   DW_AT_byte_size   : 2
<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
  <7d>   DW_AT_type        : <0x6e>
<1><81>: Abbrev Number: 0
```

```
<2><5f>: Abbrev Number: 3 (DW_TAG_formal_parameter)
    <60>   DW_AT_location    : (DW_OP_fbreg: -16)
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    <67>   DW_AT_decl_file   : 1
    <68>   DW_AT_decl_line   : 1
    <69>   DW_AT_type        : <0x7c>
    <2><6d>: Abbrev Number: 0

<1><6e>: Abbrev Number: 4 (DW_TAG_base_type)
    <6f>   DW_AT_name        : int
    <73>   DW_AT_encoding    : 5(signed)
    <74>   DW_AT_byte_size   : 4

<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
 <7d>   DW_AT_type        : <0x6e>
```

```
<44>    DW_AT_location    :(DW_OP_fbreg: -4)
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  <7a>   DW_AT_encoding    : 5   (signed)
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    <2><6d>: Abbrev Number: 0

<1><6e>: Abbrev Number: 4 (DW_TAG_base_type)
    <6f>   DW_AT_name        : int
    <73>   DW_AT_encoding    : 5(signed)
    <74>   DW_AT_byte_size   : 4

<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
 <7d>   DW_AT_type        : <0x6e>
```

```
<44>   DW_AT_location    :(DW_OP_fbreg: -4)
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    <67>   DW_AT_decl_file    : 1
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    <2><6d>: Abbrev Number: 0

<1><6e>: Abbrev Number: 4 (DW_TAG_base_type)
    <6f>   DW_AT_name         : int
    <73>   DW_AT_encoding     : 5(signed)
    <74>   DW_AT_byte_size    : 4

<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
 <7d>   DW_AT_type         : <0x6e>
```

```
<44>    DW_AT_location      :(DW_OP_fbreg: -4)
<47>    DW_AT_name          : x
<4b>    DW_AT_decl_file     : 1
<4c>    DW_AT_decl_line     : 1
<4d>    DW_AT_type          : <0x6e>
```

```
   <7a>    DW_AT_encoding     : 5    (signed)
   <7b>    DW_AT_byte_size    : 2
<1><7c>: Abbrev Number: 5 (DW_TAG_pointer_type)
   <7d>    DW_AT_type         : <0x6e>
<1><81>: Abbrev Number: 0
```

.debug_line: synchronising source and object

```
CU: /Users/zappa/tmp/hand.c:
File name                Line number    Starting address
hand.c                          5         0x8048604
hand.c                          6         0x804860a
hand.c                          9         0x8048613
hand.c                         10         0x804861c
hand.c                          9         0x8048630
hand.c                         11         0x804863c
hand.c                         15         0x804863e
hand.c                         16         0x8048647
hand.c                         17         0x8048653
hand.c                         18         0x8048658
```

Column numbers are also supported

If DWARF tables are correct

by combining informations in different tables

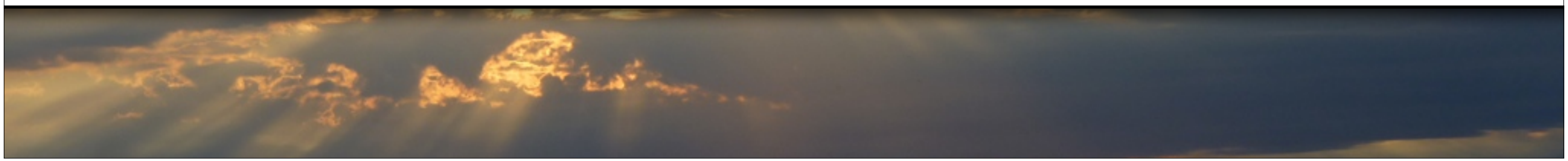
1. *we have metadata about computation at runtime*

Example: type information for all stack/register allocated variables

Outcome: identify roots for a ***precise* garbage collector** for C
runtime type-checking for C

2. *we can relate source and machine code*

Outcome: ***precise provenance informations***
translation validation for existing C compilers



If DWARF tables are correct

by combining informations in different tables

1. *we hav*

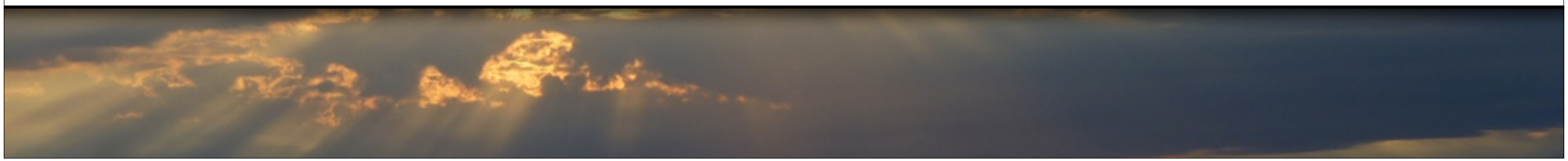
Example: t

Outcome:

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker, (struct commit *)iobj))
    return -1;
  return 0;
  }
}
```

2. *we car*

Outcome:



Dynamically Diagnosing Type Errors in Unsafe Code

Stephen Kell

OOPSLA'16

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Example: t

Outcome:

2. we can

Outcome:

check this at run-time

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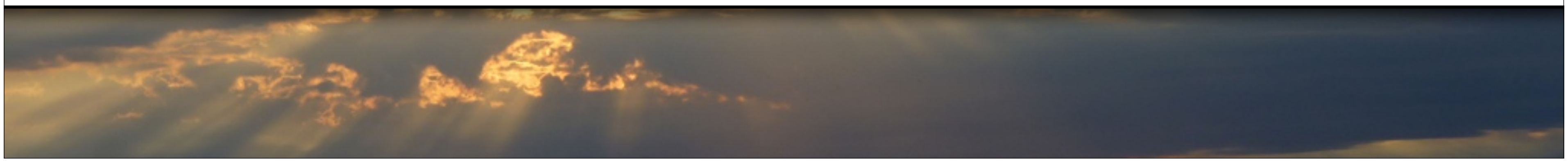


Dynamically Diagnosing Type Errors in Unsafe Code

Stephen Kell

OOPSLA'16

1. *we hav*

Example: t

Outcome:

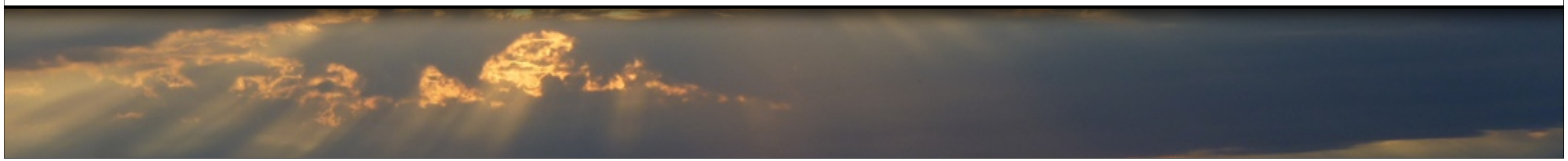
2. *we car*

Outcome:

check this at run-time

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker, (struct commit *)iobj))
    return -1;
  return 0;
  }
}
```

binary compatible
source compatible
reasonable performance
not C-specific



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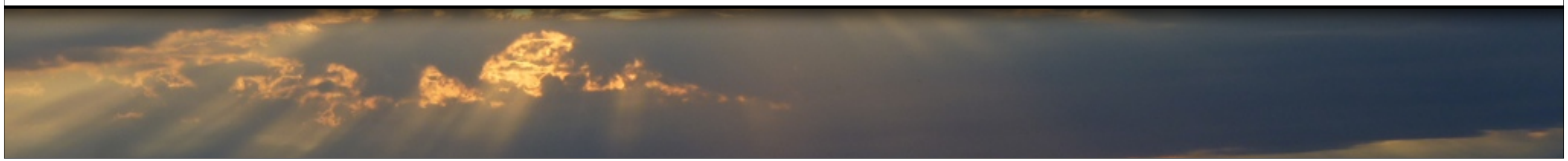

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Ongoing on Cheri-C

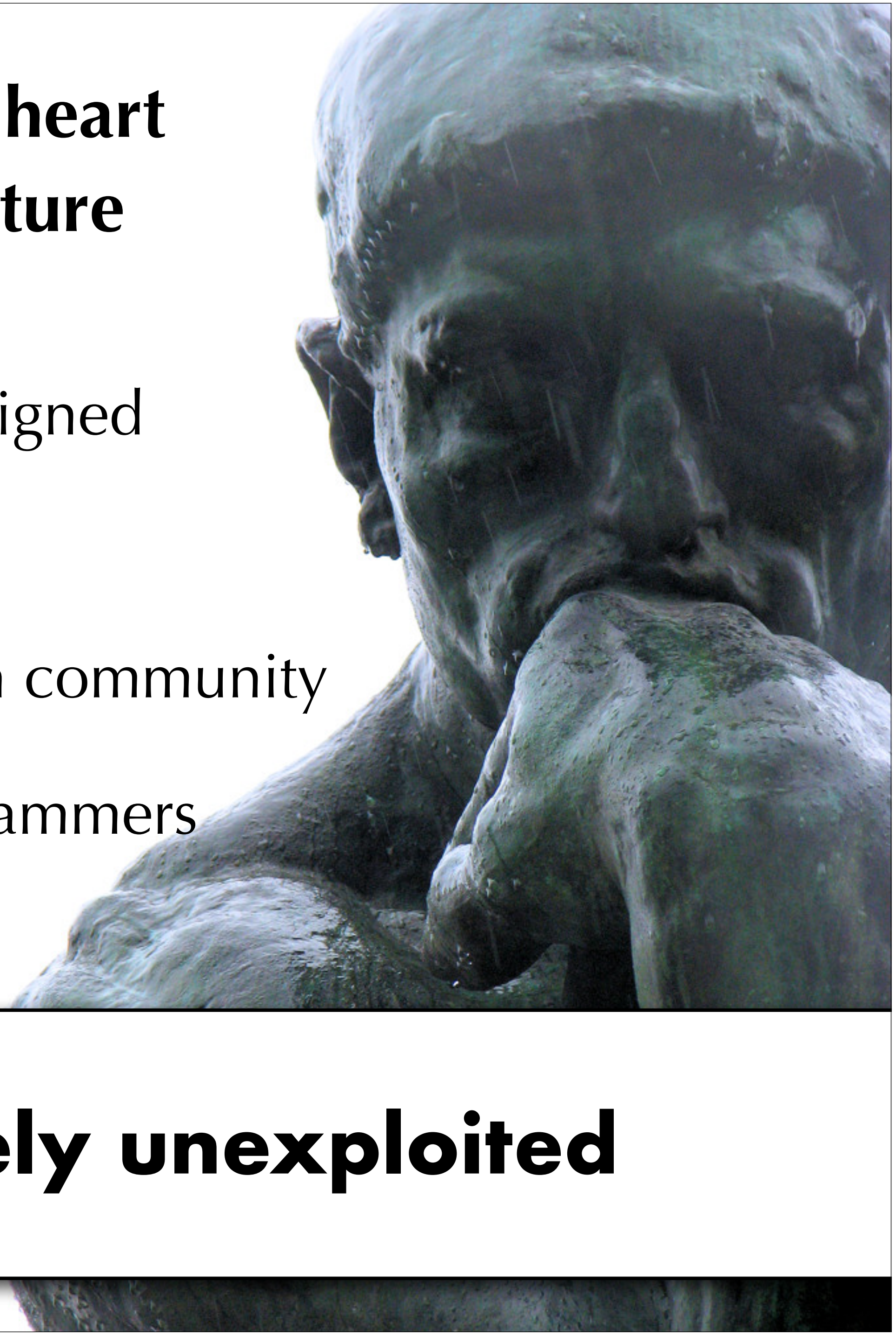
DWARF tables hide at the heart our computing infrastructure

Poorly specified and badly designed

Pervaded by subtle bugs

Mostly ignored by the research community

Not understood by most programmers



Potential largely unexploited

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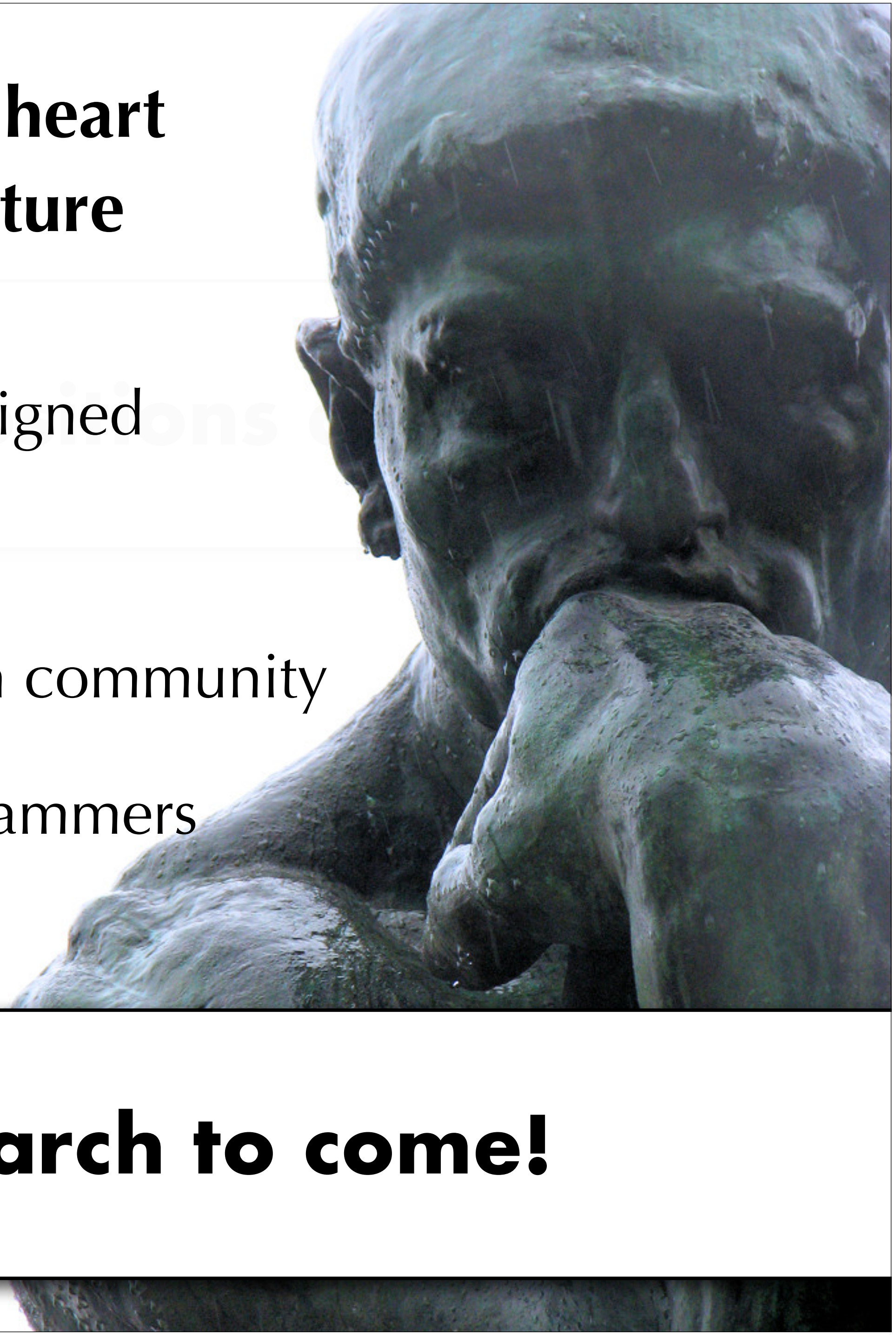

Exciting research to come!