On the Self in Selfie

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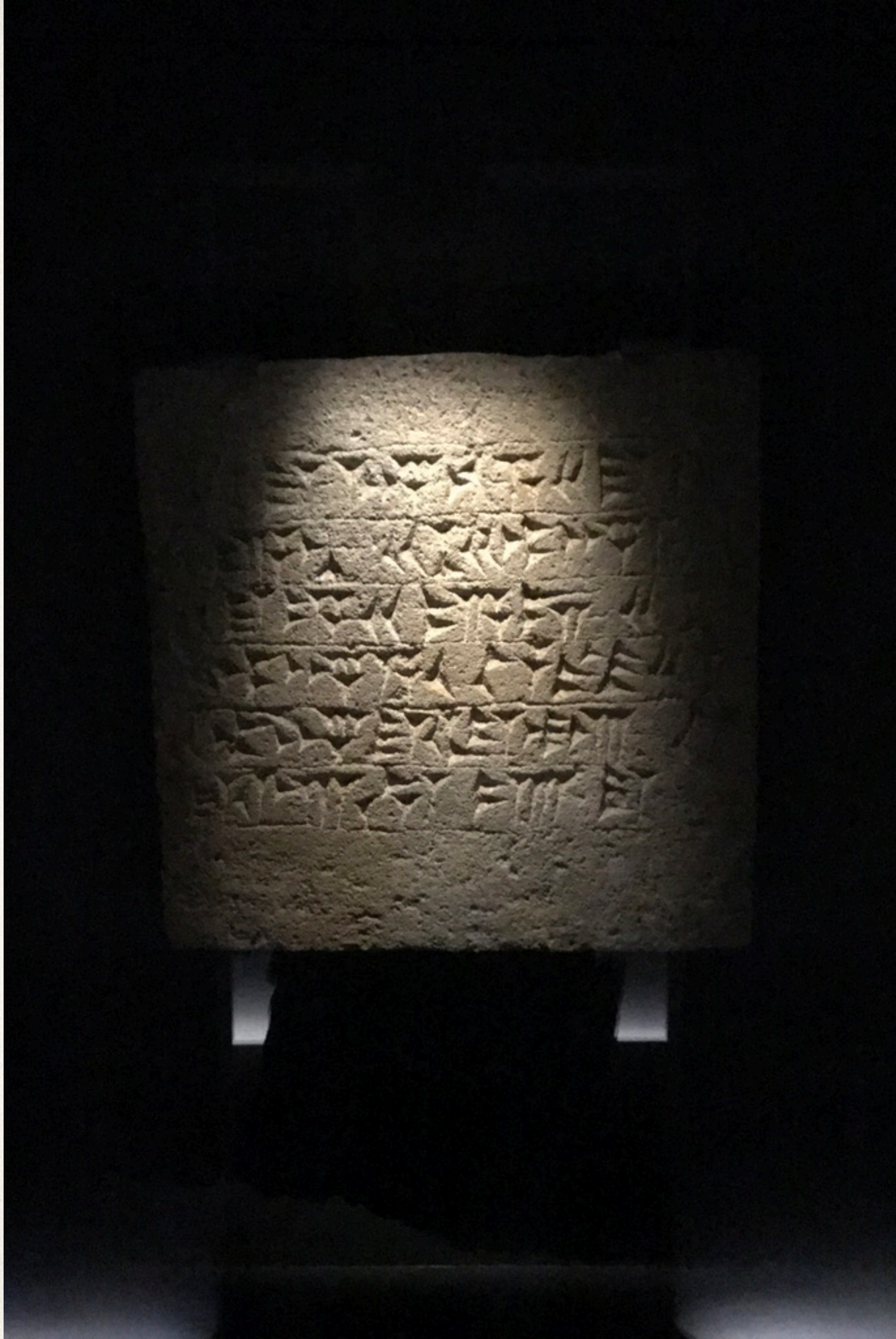
What is the meaning of this sentence?

Selfie as in self-referentiality



Interpretation

Compilation

Teaching the Construction of Semantics of Formalisms

Virtualization

Verification

Joint Work

- Alireza Abyaneh
- Martin Aigner
- Sebastian Arming
- Christian Barthel
- Simon Bauer
- Thomas Hütter
- Alexander Kollert
- Michael Lippautz
- Cornelia Mayer
- Philipp Mayer
- Christian Moesl
- Simone Oblasser
- Clement Poncelet
- Sara Seidl
- Ana Sokolova
- Manuel Widmoser

Inspiration

- Armin Biere: SAT/SMT Solvers
- Donald Knuth: Art
- Jochen Liedtke: Microkernels
- Hennessy/Patterson: RISC
- Niklaus Wirth: Compilers

Selfie: Teaching Computer Science [selfie.cs.uni-salzburg.at]

- *Selfie* is a self-referential 10k-line C implementation (in a single file) of:

  1. a self-compiling compiler called ***starc*** that compiles a tiny subset of C called C Star (C*) to a tiny subset of RISC-V called RISC-U,

  2. a self-executing emulator called ***mipster*** that executes RISC-U code including itself when compiled with starc,

  3. a self-hosting hypervisor called ***hypster*** that virtualizes mipster and can host all of selfie including itself,

  4. a self-executing symbolic execution engine called ***monster*** that executes RISC-U code symbolically when compiled with starc which includes all of selfie,

  5. a self-translating model generator called ***modeler*** that translates RISC-U code including itself to BTOR2 models for checking (memory) safety properties, and

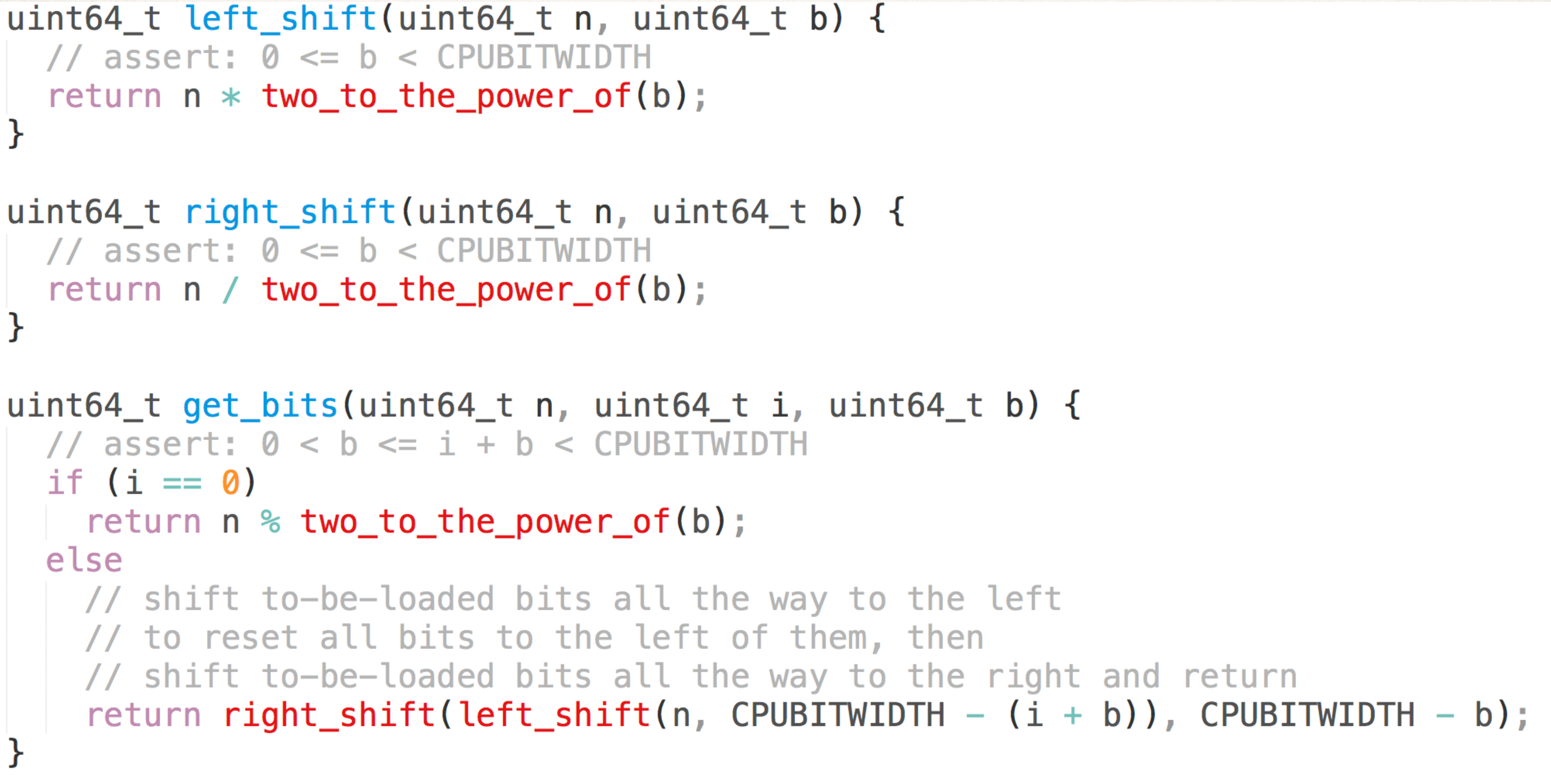
  6. a tiny C* library called ***libcstar*** utilized by all of selfie.

Selfie runs on 64-bit RISC-V QEMU and supports the official 64-bit RISC-V toolchain

Also, there is a…

- linker (in-memory only)
- disassembler (w/ source code line numbers)
- debugger (tracks full machine state w/ rollback)
- profiler (#proc-calls, #loop-iterations, #loads, #stores)
- ELF boot loader (same code for mipster/hypster)

Code as Prose



```c
uint64_t left_shift(uint64_t n, uint64_t b) {
  // assert: 0 <= b < CPUBITWIDTH
  return n * two_to_the_power_of(b);
}

uint64_t right_shift(uint64_t n, uint64_t b) {
  // assert: 0 <= b < CPUBITWIDTH
  return n / two_to_the_power_of(b);
}

uint64_t get_bits(uint64_t n, uint64_t i, uint64_t b) {
  // assert: 0 < b <= i + b < CPUBITWIDTH
  if (i == 0)
    return n % two_to_the_power_of(b);
  else
    // shift to-be-loaded bits all the way to the left
    // to reset all bits to the left of them, then
    // shift to-be-loaded bits all the way to the right and return
    return right_shift(left_shift(n, CPUBITWIDTH - (i + b)), CPUBITWIDTH - b);
}
```

Discussion of Selfie reached 3rd place on Hacker News

news.ycombinator.com

Website

selfie.cs.uni-salzburg.at

Code + Self-Grader

github.com/cksystemsteaching/selfie

Slides

selfie.cs.uni-salzburg.at/slides

Book (draft)

leanpub.com/selfie

5 statements:
assignment
while
if
return
procedure()

```
uint64_t atoi(uint64_t *s) {
          uint64_t i;
          uint64_t n;
          uint64_t c;

          i = 0;
          n = 0;
          c = *(s+i);

          while (c != 0) {
                    n = n * 10 + c - '0';
                    if (n < 0)
                              return -1;

                    i = i + 1;
                    c = *(s+i);
          }

          return n;
}
```

no data types other than `uint64_t` and `uint64_t*` and dereferencing: the * operator

character literals
string literals

integer arithmetics
pointer arithmetics

no bitwise operators
no Boolean operators

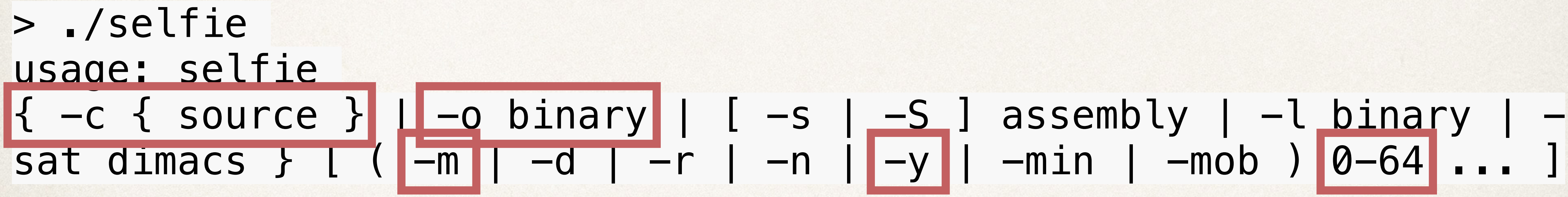
library: `exit`, `malloc`, `open`, `read`, `write`

Minimally complex, maximally self-contained system

Programming languages vs systems engineering?

```
> make
cc -w -O3 -m64 -D'main(a,b)=main(int argc, char** argv)' \
-Duint64_t=‘unsigned long long' selfie.c -o selfie
```

bootstrapping `selfie.c` *into x86* `selfie` *executable*
using standard C compiler



```
> ./selfie
usage: selfie
{ -c { source } | -o binary | [ -s | -S ] assembly | -l binary | -
sat dimacs } [ ( -m | -d | -r | -n | -y | -min | -mob ) 0-64 ... ]
```

selfie usage

```
> ./selfie -c selfie.c

selfie compiling selfie.c with starc

289095 characters read in 10034 lines and 1335 comments
with 170555(58.99%) characters in 43772 actual symbols
341 global variables, 438 procedures, 411 string literals
2517 calls, 1139 assignments, 86 while, 874 if, 391 return
symbol table search time was 2 iterations on average and
48795 in total

170504 bytes generated with 39496 instructions and 12520 bytes of data

init:    lui: 2296(5.81%), addi: 13595(34.40%)
memory:  ld: 7106(17.98%), sd: 5884(14.89%)
compute: add: 3422(8.65%), sub: 704(1.78%), mul: 807(2.40%),
         divu: 78(0.19%), remu: 35(0.80%)
control: sltu: 624(1.57%), beq: 964(2.43%),
         jal: 3555(8.99%), jalr: 438(1.10%), ecall: 8(0.20%)
```

compiling `selfie.c` *with x86* `selfie` *executable*

(takes seconds)

```
> ./selfie -c selfie.c -m 3 -c selfie.c
selfie compiling selfie.c with starc
...
selfie executing selfie.c with 3MB physical memory on mipster
selfie compiling selfie.c with starc
...
selfie.c exiting with exit code 0 and 2.11MB mallocated memory
...
summary: 285261695 executed instructions and 2.10MB mapped memory
init:    lui: 836418(0.29%), addi: 120536779(42.25%)
memory:  ld: 61562613(21.58%), sd: 39713446(13.92%)
compute: add: 7234823(2.53%), sub: 5903746(2.60%), mul:
6878318(2.41%), divu: 2100676(0.73%), remu: 2016943(0.70%)
control: sltu: 4436689(1.55%), beq: 6011381(2.10%), jal:
18600397(6.52%), jalr: 9118787(3.19%), ecall: 310679(0.10%)
profile: total,max(ratio%)@addr(line#),2max,3max
calls:   9118787,2492778(27.33%)@0x282C(~1671),...
loops:   500189,164040(32.79%)@0x355C(~1859),...
loads:   61562613,2492778(4.40%)@0x2840(~1671),...
stores:  39713446,2492778(6.27%)@0x2830(~1671),...
```

compiling `selfie.c` *with x86* `selfie` *executable into a RISC-U executable*

and

then running that RISC-U executable to compile `selfie.c` *again*

(takes a minute)

```
> ./selfie -c selfie.c -o selfie1.m -m 3 -c selfie.c -o selfie2.m

selfie compiling selfie.c with starc
...
170632 bytes with 39496 instructions and 12520 bytes of data written
into selfie1.m

selfie executing selfie1.m with 3MB physical memory on mipster
selfie compiling selfie.c with starc

...
170632 bytes with 39496 instructions and 12520 bytes of data written
into selfie2.m

selfie1.m exiting with exit code 0 and 2.11MB mallocated memory
...
summary: 285338515 executed instructions and 2.10MB mapped memory
```

compiling `selfie.c` *into a RISC-U executable* `selfie1.m`

and

then running `selfie1.m` *to compile* `selfie.c`

into another RISC-U executable `selfie2.m`

(takes a minute)

```
> ./selfie -c selfie.c -m 6 -c selfie.c -m 3 -c selfie.c
```

compiling `selfie.c` *with x86* `selfie` executable

and

then running that executable to compile `selfie.c` *again*

and

then running that executable to compile `selfie.c` *again*

*(**takes hours**)*

```
> ./selfie -c selfie.c -m 6 -c selfie.c -y 3 -c selfie.c
```

compiling `selfie.c` *with x86* `selfie` *executable*

and

then running that executable to compile `selfie.c` *again*

and

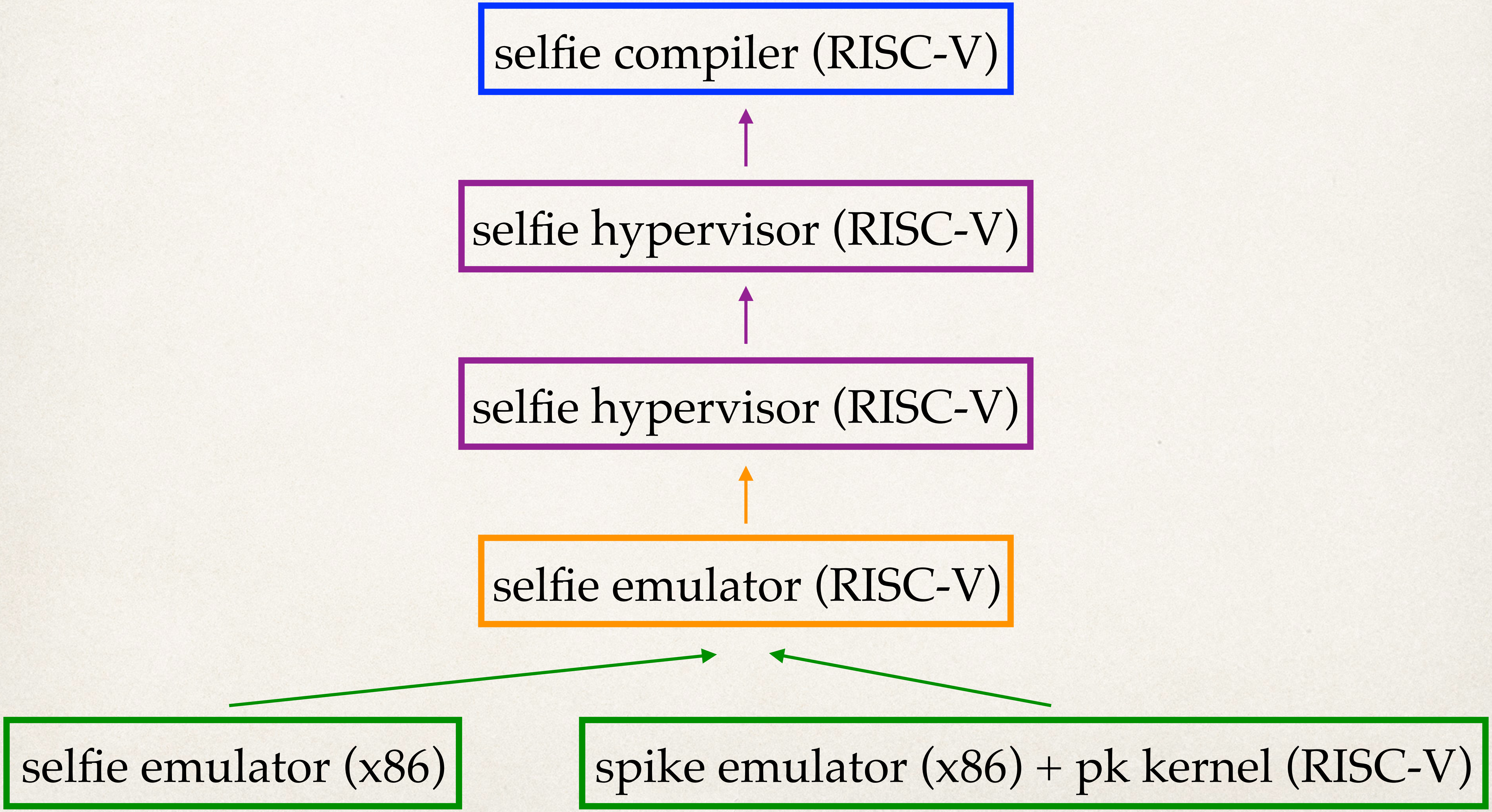
then ***hosting*** *that executable in a virtual machine to compile* `selfie.c` *again*

*(**takes 2 minutes**)*

On the Self in Selfie

How does self-referentiality work in selfie?

Selfie Stick!



selfie compiler (RISC-V)

selfie hypervisor (RISC-V)

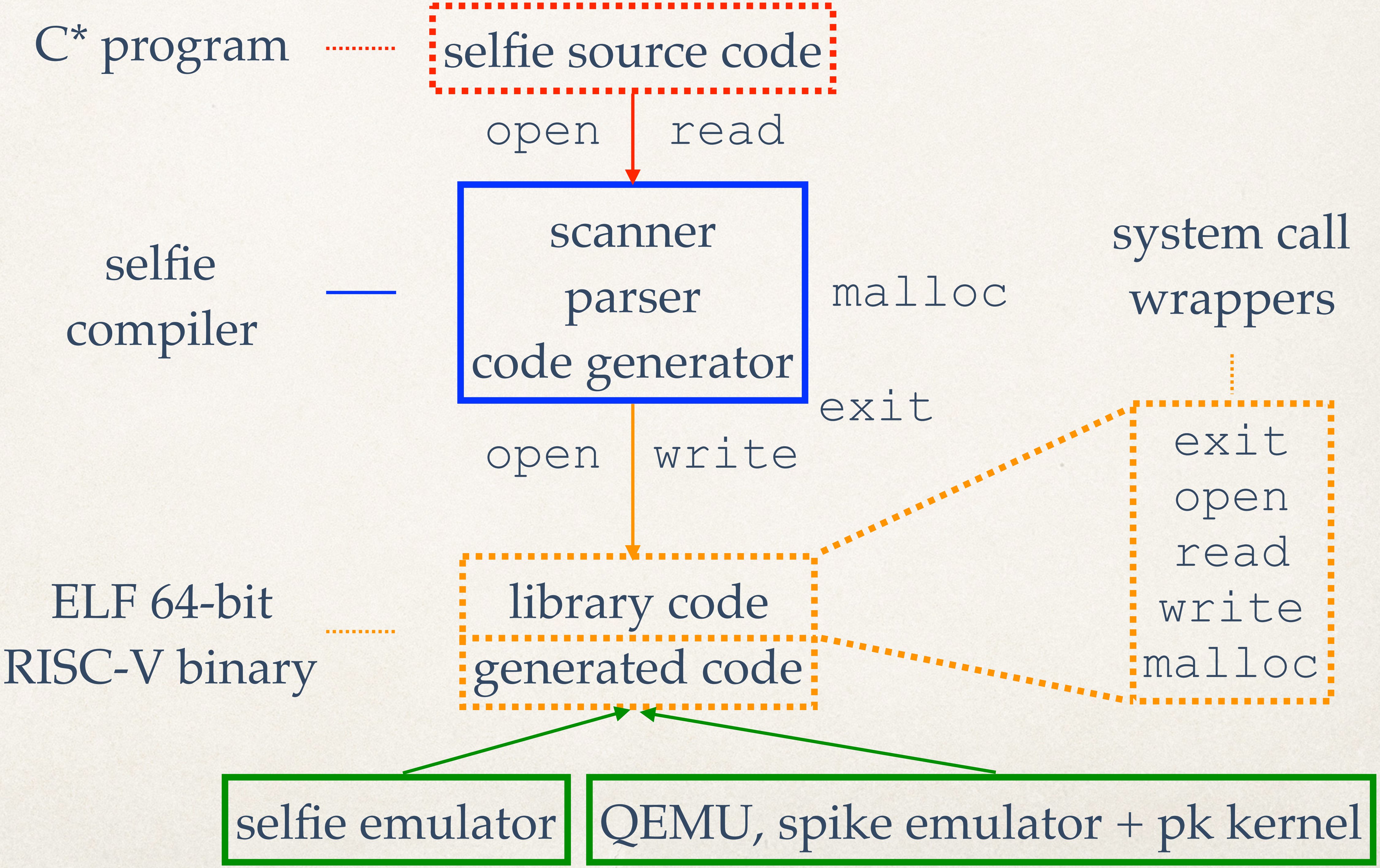
selfie hypervisor (RISC-V)

selfie emulator (RISC-V)

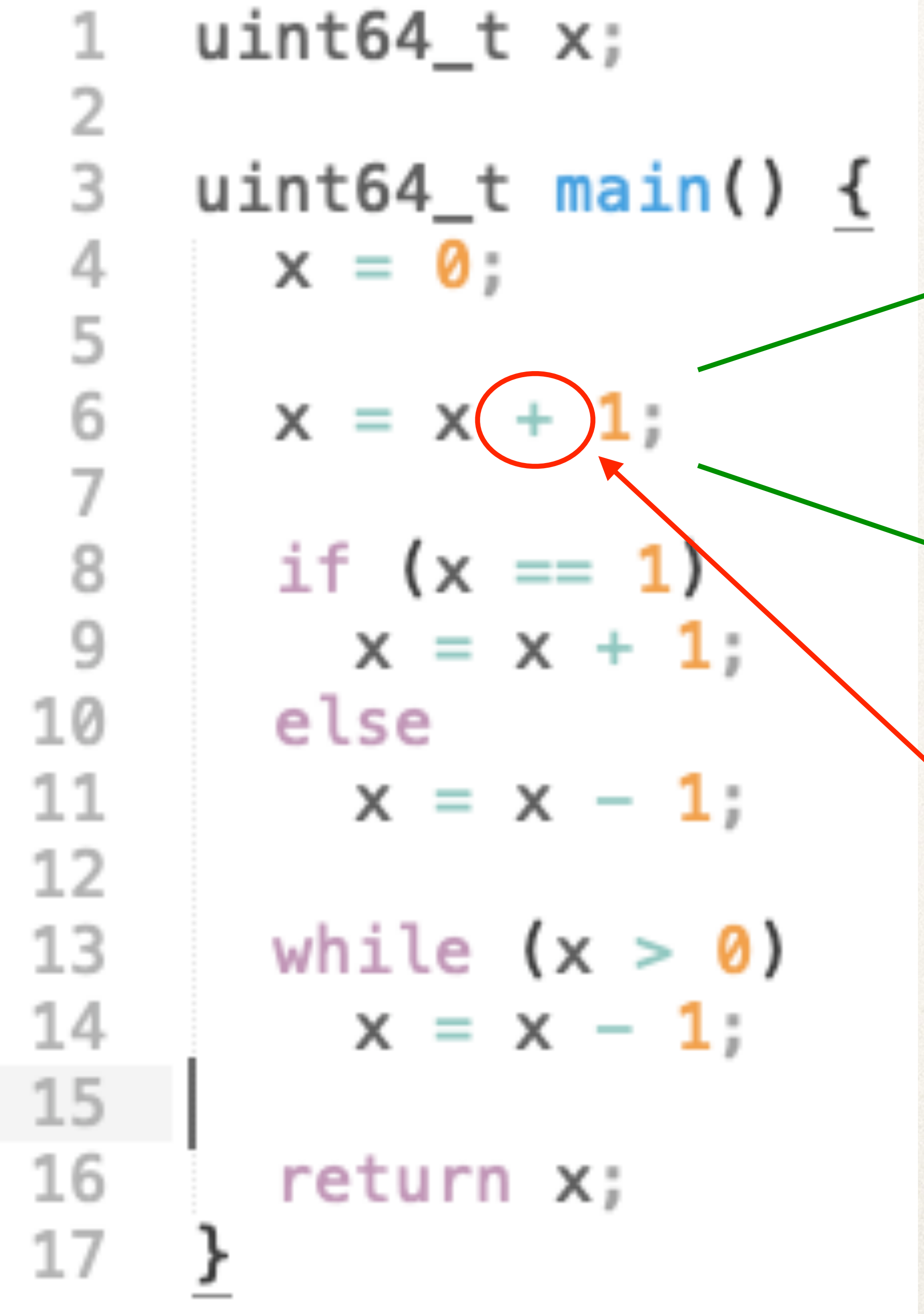
selfie emulator (x86)

spike emulator (x86) + pk kernel (RISC-V)

Self-Compilation



Generated Code: unsigned + code



```
uint64_t x;

uint64_t main() {
  x = 0;

  x = x + 1;

  if (x == 1)
    x = x + 1;
  else
    x = x - 1;

  while (x > 0)
    x = x - 1;

  return x;
}
```

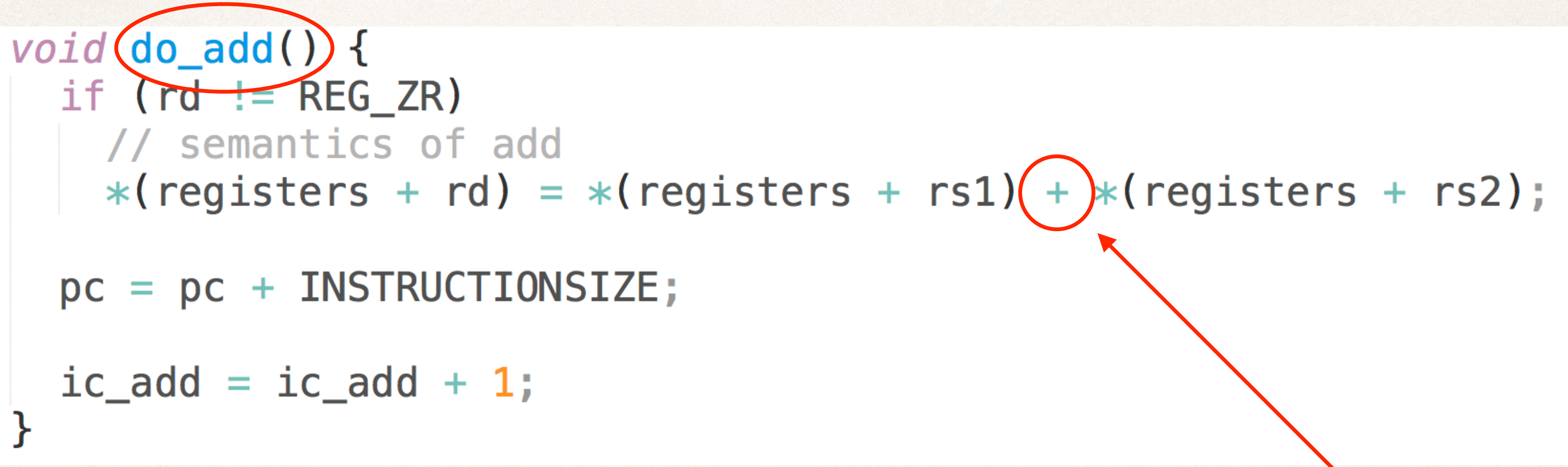
64-bit RISC-V `add` instruction

```
0x150(~6): ld $t0,-16($gp)
0x154(~6): addi $t1,$zero,1
0x158(~6): add $t0,$t0,$t1
0x15C(~6): sd $t0,-16($gp)
```

C code for unsigned 64-bit integer addition

add implementation in selfie emulator

64-bit RISC-V add instruction



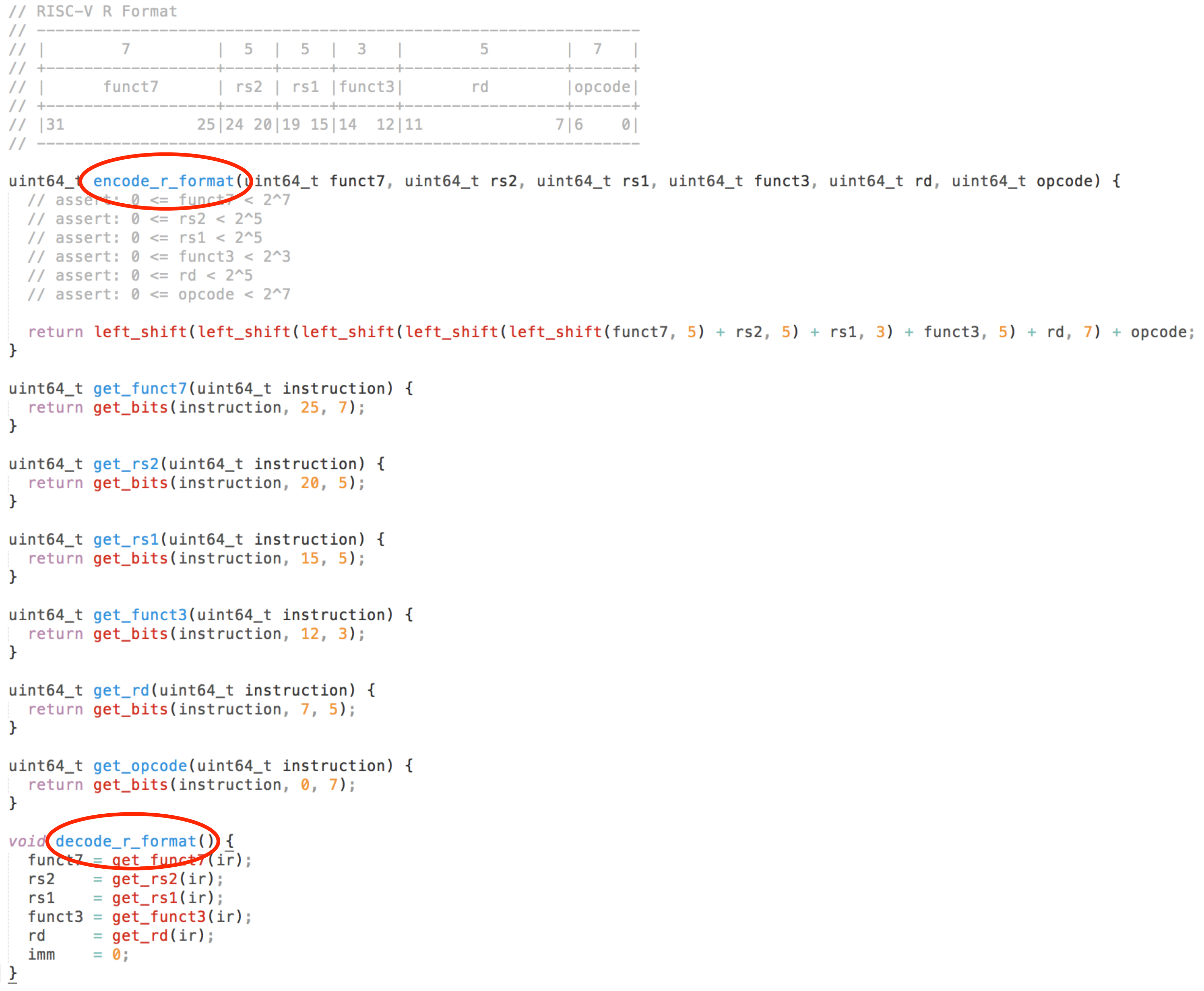
```
void do_add() {
  if (rd != REG_ZR)
    // semantics of add
    *(registers + rd) = *(registers + rs1) + *(registers + rs2);

  pc = pc + INSTRUCTIONSIZE;

  ic_add = ic_add + 1;
}
```

C code for unsigned 64-bit integer addition

selfie compiler

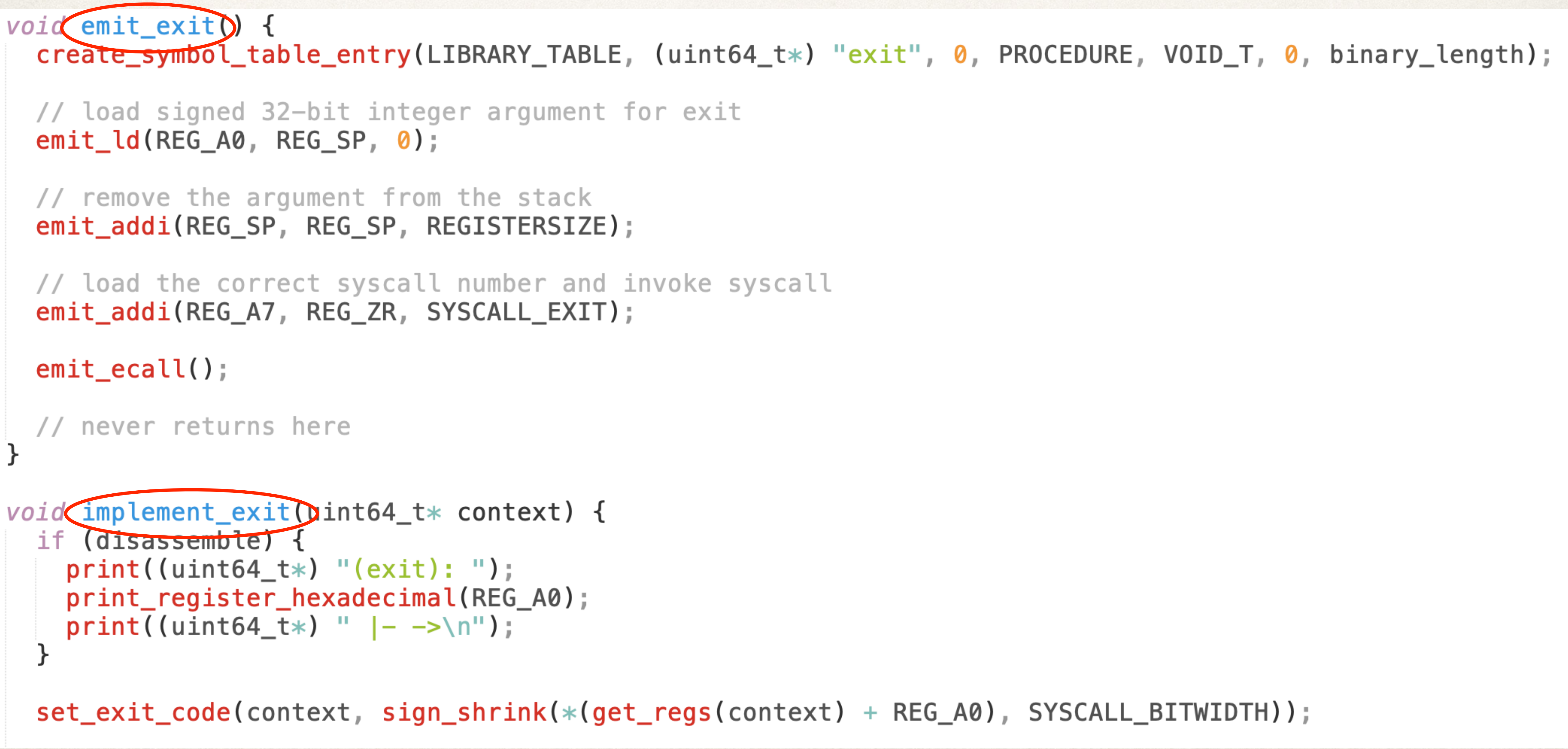
gcc/ clang

Synergy of Compiler & Emulator



```
// RISC-V R Format
// ----------------------------------------------------------------
// |        7         |  5  |  5  |  3   |        5        |  7   |
// +------------------+-----+-----+------+-----------------+------+
// |      funct7      | rs2 | rs1 |funct3|       rd        |opcode|
// +------------------+-----+-----+------+-----------------+------+
// |31              25|24 20|19 15|14  12|11              7|6    0|
// ----------------------------------------------------------------

uint64_t encode_r_format(uint64_t funct7, uint64_t rs2, uint64_t rs1, uint64_t funct3, uint64_t rd, uint64_t opcode) {
  // assert: 0 <= funct7 < 2^7
  // assert: 0 <= rs2 < 2^5
  // assert: 0 <= rs1 < 2^5
  // assert: 0 <= funct3 < 2^3
  // assert: 0 <= rd < 2^5
  // assert: 0 <= opcode < 2^7

  return left_shift(left_shift(left_shift(left_shift(left_shift(funct7, 5) + rs2, 5) + rs1, 3) + funct3, 5) + rd, 7) + opcode;
}

uint64_t get_funct7(uint64_t instruction) {
  return get_bits(instruction, 25, 7);
}

uint64_t get_rs2(uint64_t instruction) {
  return get_bits(instruction, 20, 5);
}

uint64_t get_rs1(uint64_t instruction) {
  return get_bits(instruction, 15, 5);
}

uint64_t get_funct3(uint64_t instruction) {
  return get_bits(instruction, 12, 3);
}

uint64_t get_rd(uint64_t instruction) {
  return get_bits(instruction, 7, 5);
}

uint64_t get_opcode(uint64_t instruction) {
  return get_bits(instruction, 0, 7);
}

void decode_r_format() {
  funct7 = get_funct7(ir);
  rs2    = get_rs2(ir);
  rs1    = get_rs1(ir);
  funct3 = get_funct3(ir);
  rd     = get_rd(ir);
  imm    = 0;
}
```

Synergy of Compiler & Emulator & Hypervisor



```
void emit_exit() {
  create_symbol_table_entry(LIBRARY_TABLE, (uint64_t*) "exit", 0, PROCEDURE, VOID_T, 0, binary_length);

  // load signed 32-bit integer argument for exit
  emit_ld(REG_A0, REG_SP, 0);

  // remove the argument from the stack
  emit_addi(REG_SP, REG_SP, REGISTERSIZE);

  // load the correct syscall number and invoke syscall
  emit_addi(REG_A7, REG_ZR, SYSCALL_EXIT);

  emit_ecall();

  // never returns here
}

void implement_exit(uint64_t* context) {
  if (disassemble) {
    print((uint64_t*) "(exit): ");
    print_register_hexadecimal(REG_A0);
    print((uint64_t*) " |- ->\n");
  }

  set_exit_code(context, sign_shrink(*(get_regs(context) + REG_A0), SYSCALL_BITWIDTH));
```

Library Code: open wrapper

parameters

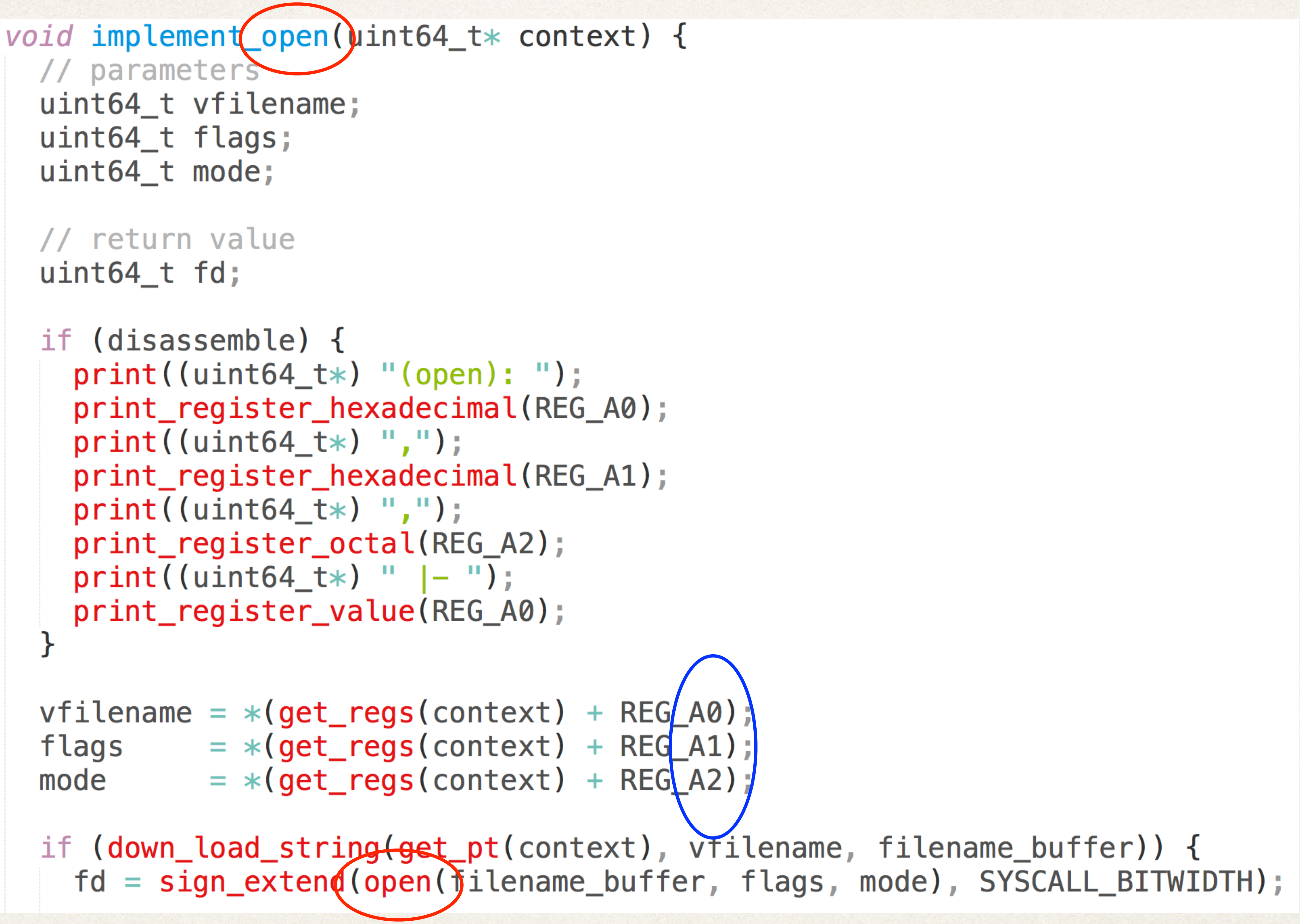
```
0xA8(~1): 0x00013603: ld $a2,0($sp)
0xAC(~1): 0x00810113: addi $sp,$sp,8
0xB0(~1): 0x00013583: ld $a1,0($sp)
0xB4(~1): 0x00810113: addi $sp,$sp,8
0xB8(~1): 0x00013503: ld $a0,0($sp)
0xBC(~1): 0x00810113: addi $sp,$sp,8
0xC0(~1): 0x40000893: addi $a7,$zero,1024
0xC4(~1): 0x00000073: ecall
0xC8(~1): 0x00008067: jalr $zero,0($ra)
```

syscall ID

selfie emulator

QEMU, spike emulator + pk kernel

open implementation in selfie emulator



```
void implement_open(uint64_t* context) {
  // parameters
  uint64_t vfilename;
  uint64_t flags;
  uint64_t mode;

  // return value
  uint64_t fd;

  if (disassemble) {
    print((uint64_t*) "(open): ");
    print_register_hexadecimal(REG_A0);
    print((uint64_t*) ",");
    print_register_hexadecimal(REG_A1);
    print((uint64_t*) ",");
    print_register_octal(REG_A2);
    print((uint64_t*) " |- ");
    print_register_value(REG_A0);
  }

  vfilename = *(get_regs(context) + REG_A0);
  flags     = *(get_regs(context) + REG_A1);
  mode      = *(get_regs(context) + REG_A2);

  if (down_load_string(get_pt(context), vfilename, filename_buffer)) {
    fd = sign_extend(open(filename_buffer, flags, mode), SYSCALL_BITWIDTH);
```

selfie compiler

C library call

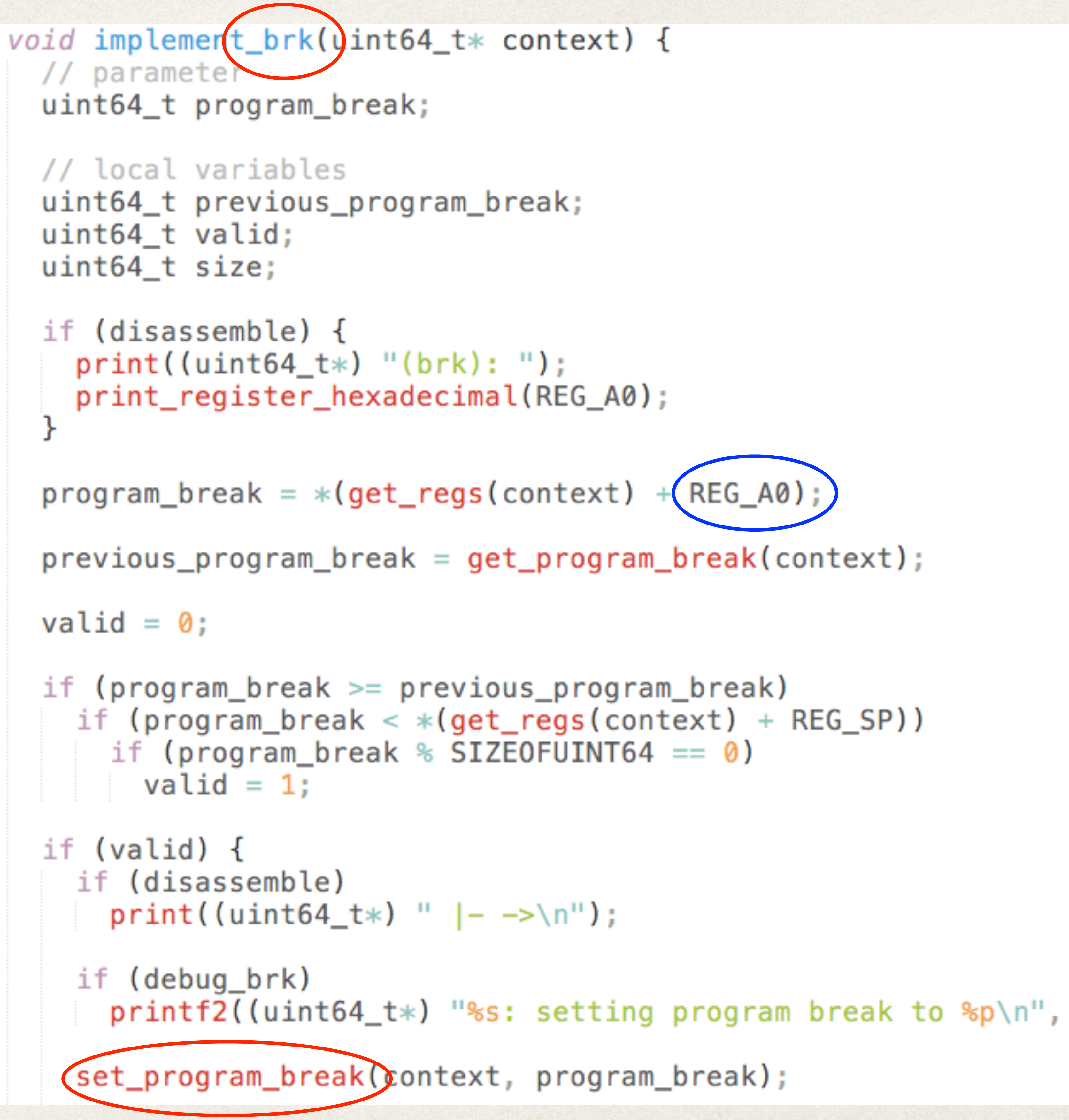
gcc/clang

`malloc` is different!

`malloc` invokes
the `brk` system call

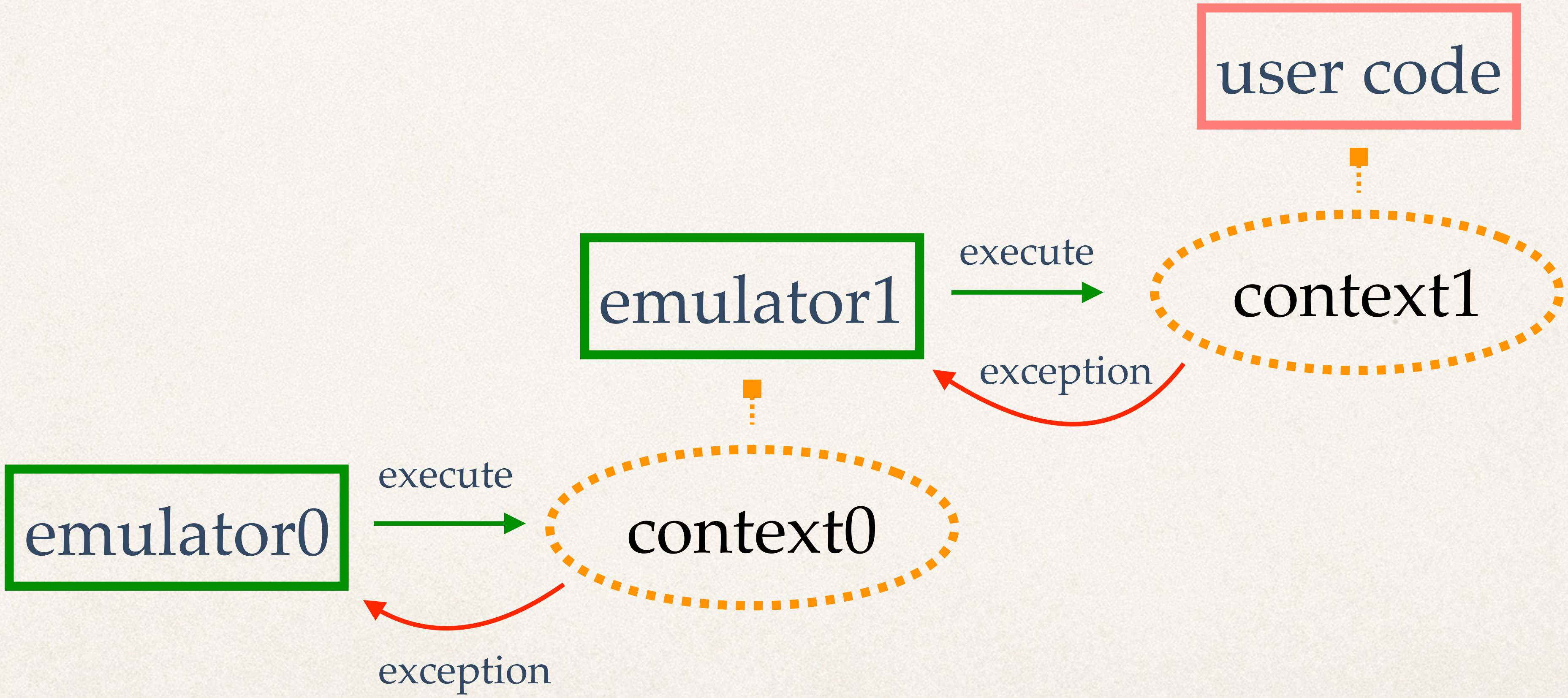
both manage pure
address spaces

actual memory
storage is done
in the paging system

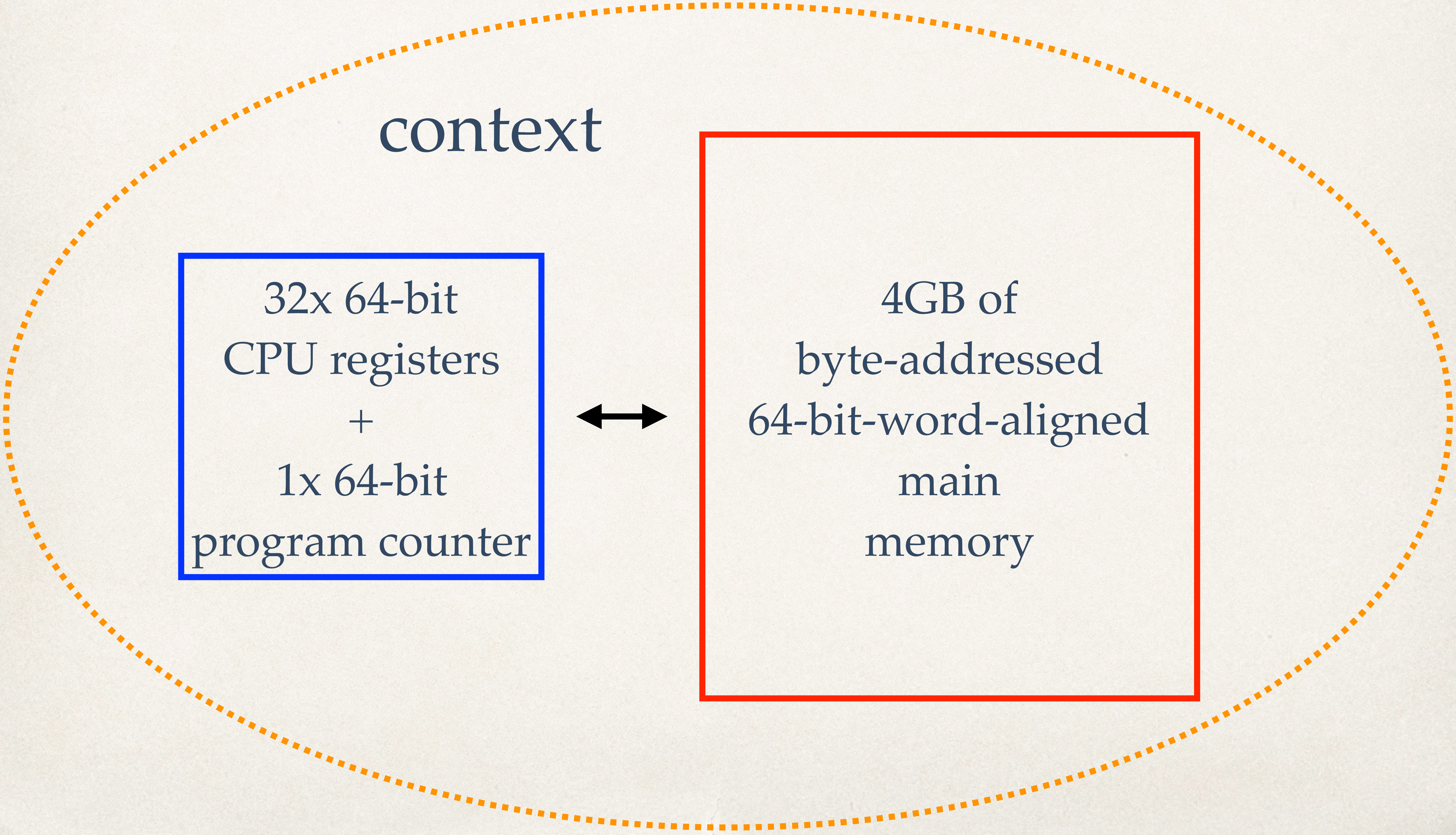


```
void implement_brk(uint64_t* context) {
  // parameter
  uint64_t program_break;

  // local variables
  uint64_t previous_program_break;
  uint64_t valid;
  uint64_t size;

  if (disassemble) {
    print((uint64_t*) "(brk): ");
    print_register_hexadecimal(REG_A0);
  }

  program_break = *(get_regs(context) + REG_A0);

  previous_program_break = get_program_break(context);

  valid = 0;

  if (program_break >= previous_program_break)
    if (program_break < *(get_regs(context) + REG_SP))
      if (program_break % SIZEOFUINT64 == 0)
        valid = 1;

  if (valid) {
    if (disassemble)
      print((uint64_t*) " |- ->\n");

    if (debug_brk)
      printf2((uint64_t*) "%s: setting program break to %p\n",

    set_program_break(context, program_break);
```

Self-Execution



RISC-U Machine State

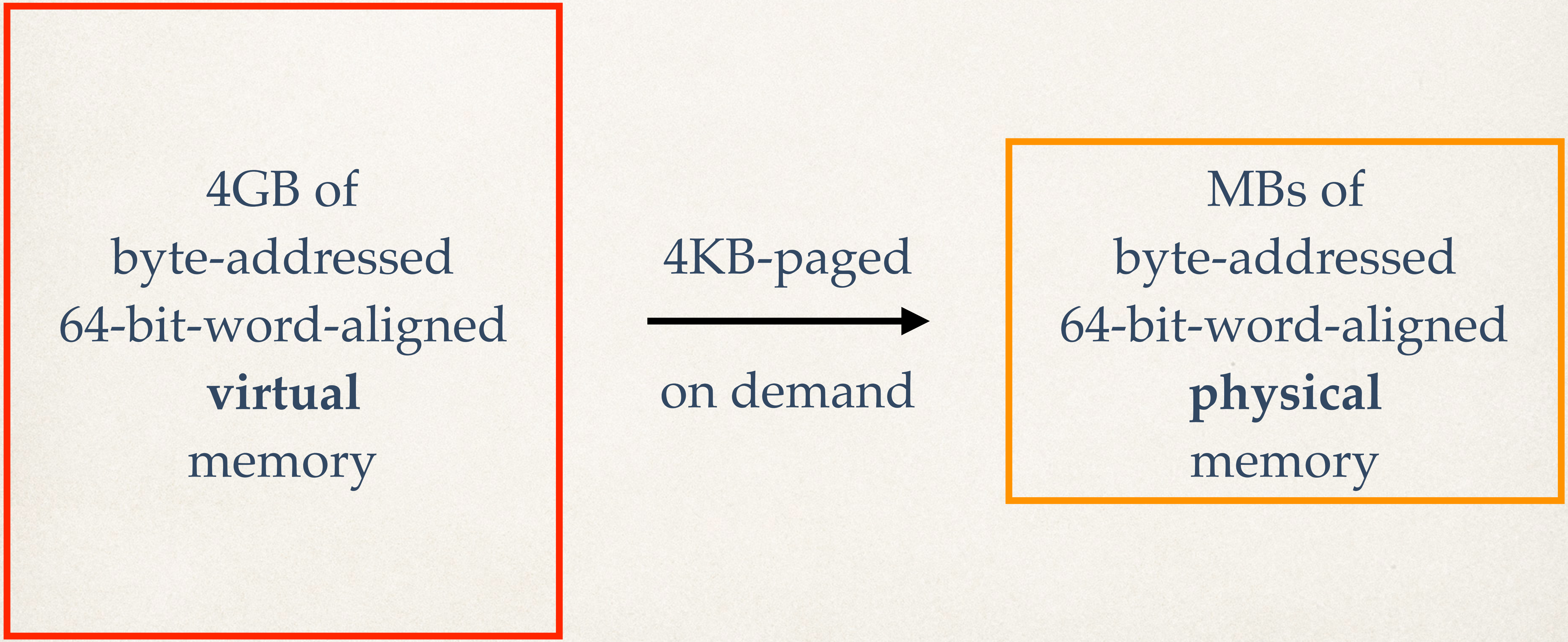


context

32x 64-bit
CPU registers
+
1x 64-bit
program counter

4GB of
byte-addressed
64-bit-word-aligned
main
memory

Virtual Memory in Selfie



4GB of
byte-addressed
64-bit-word-aligned
virtual
memory

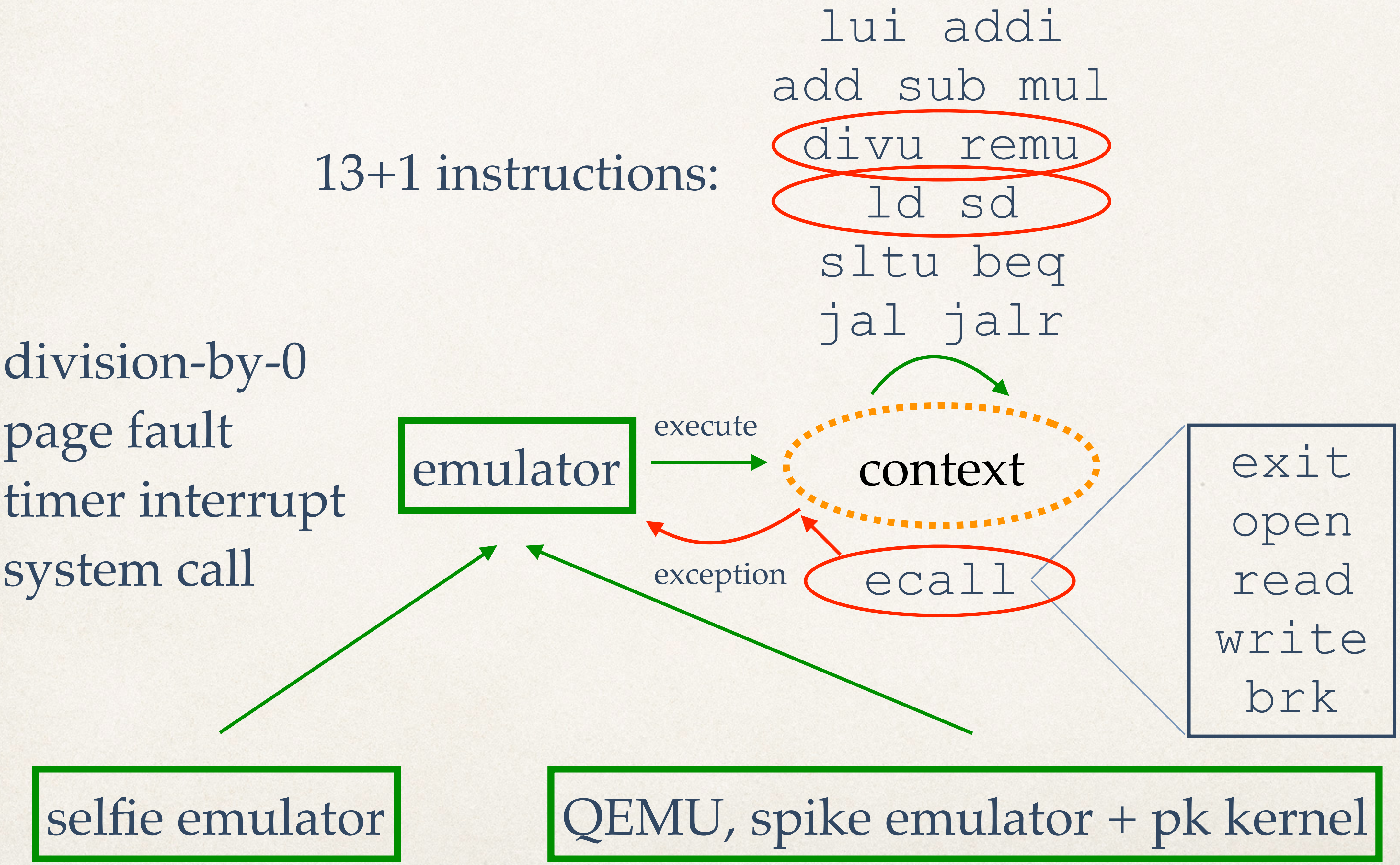
4KB-paged

on demand

MBs of
byte-addressed
64-bit-word-aligned
physical
memory

Code Execution and Exceptions

1. division-by-0
2. page fault
3. timer interrupt
4. system call



13+1 instructions:

```
lui addi
add sub mul
divu remu
ld sd
sltu beq
jal jalr
```

emulator

execute

context

exception

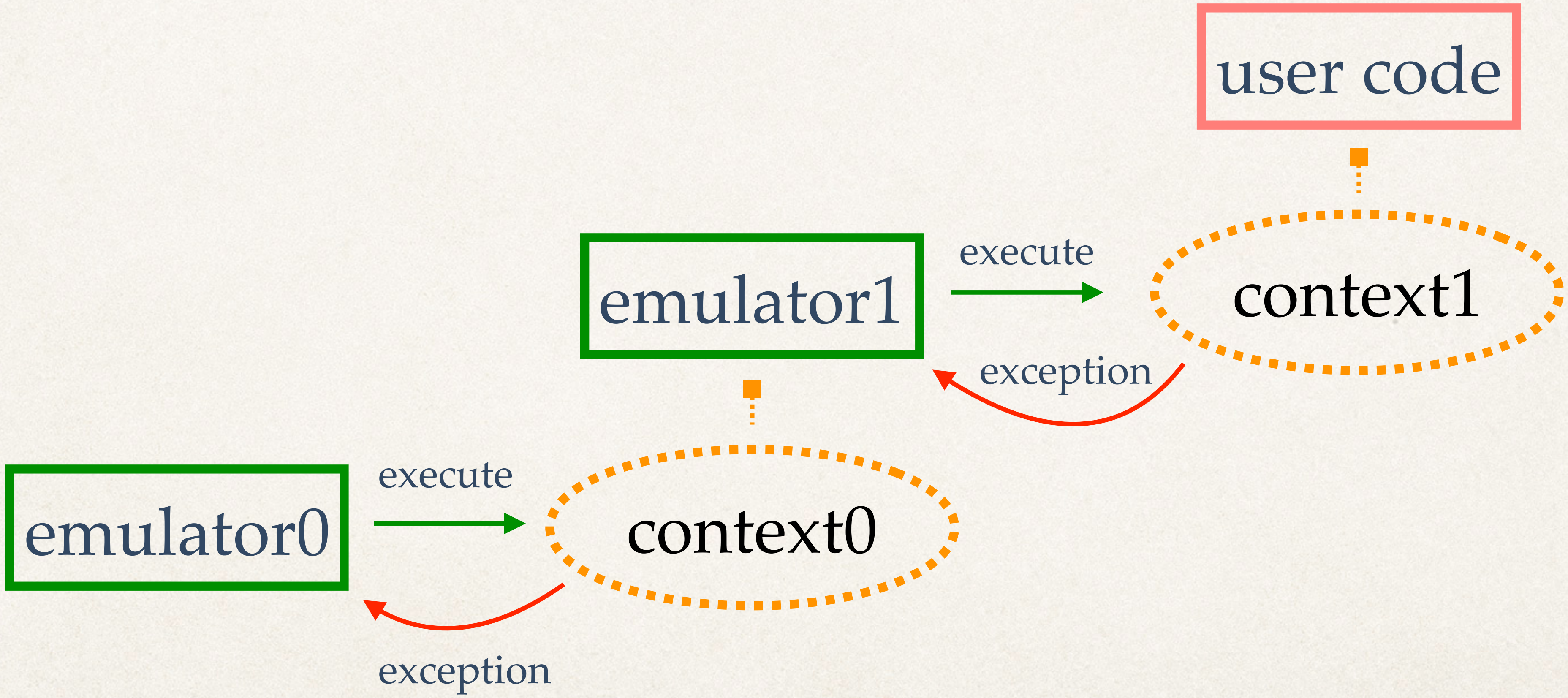
ecall

```
exit
open
read
write
brk
```

selfie emulator

QEMU, spike emulator + pk kernel

Self-Execution Revisited



user code

emulator1

execute

context1

exception

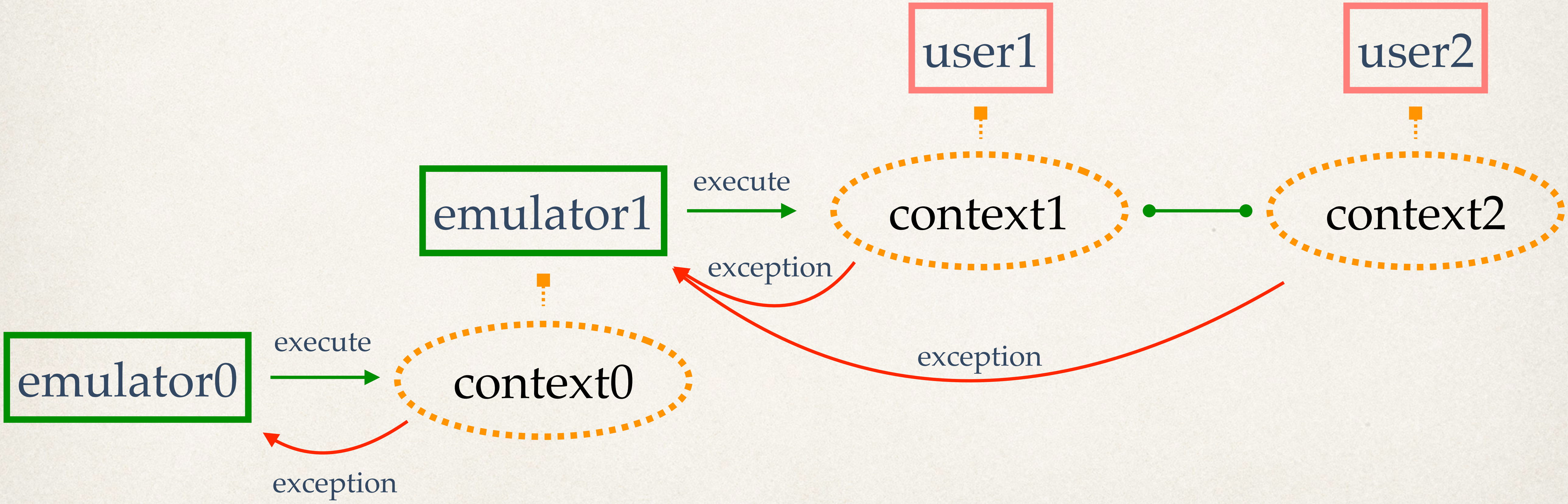
emulator0

execute

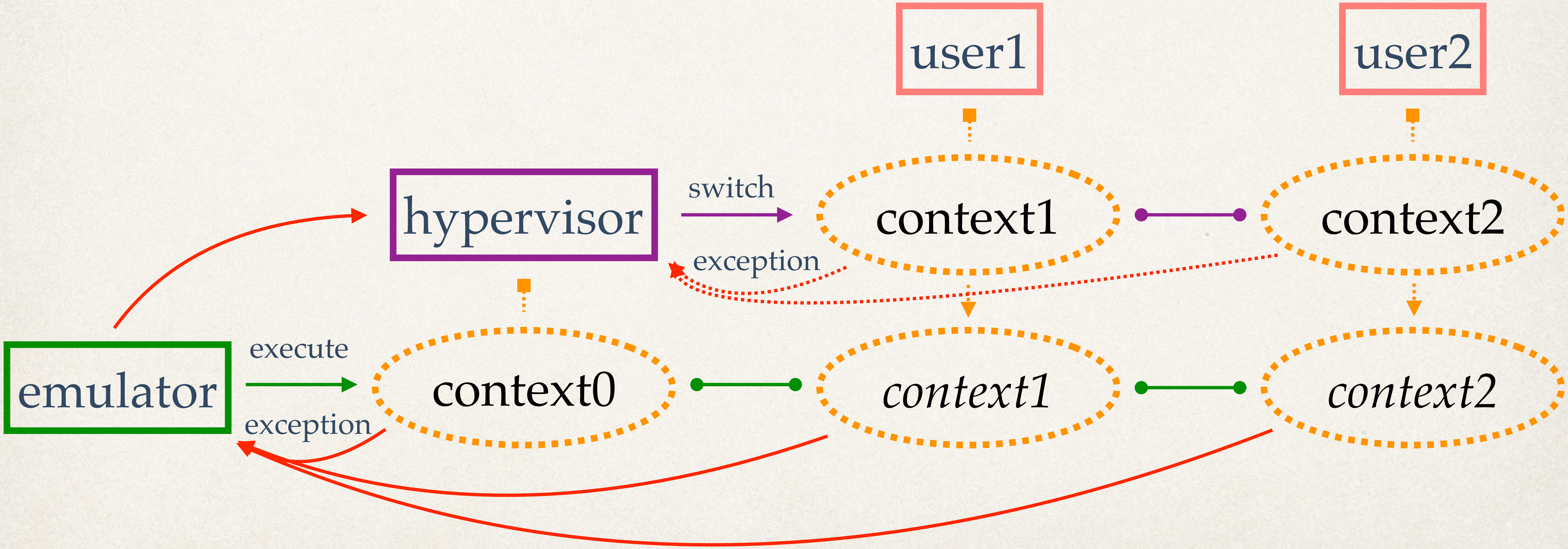
context0

exception

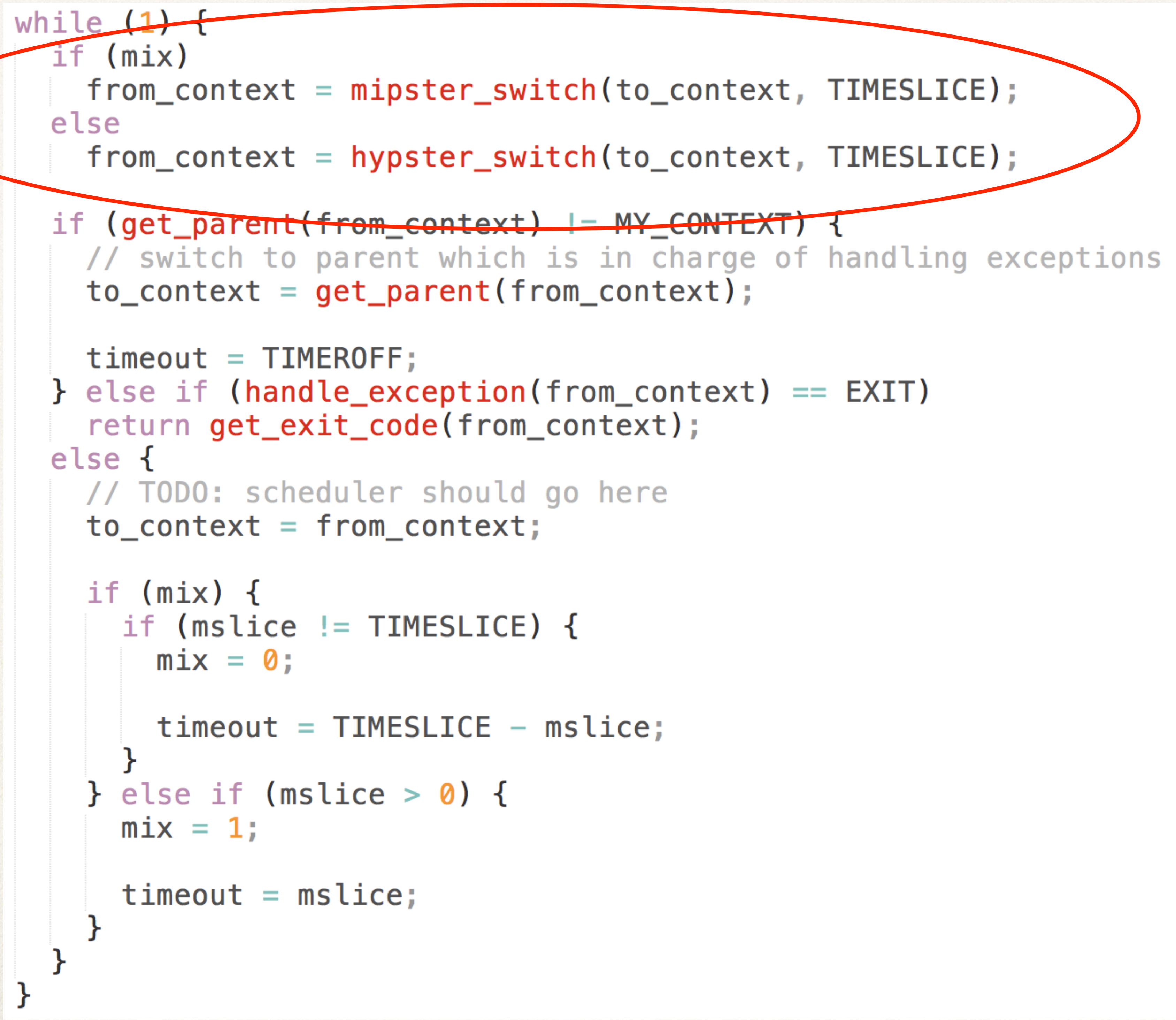
Self-Execution: Concurrency



Hosting: Concurrency

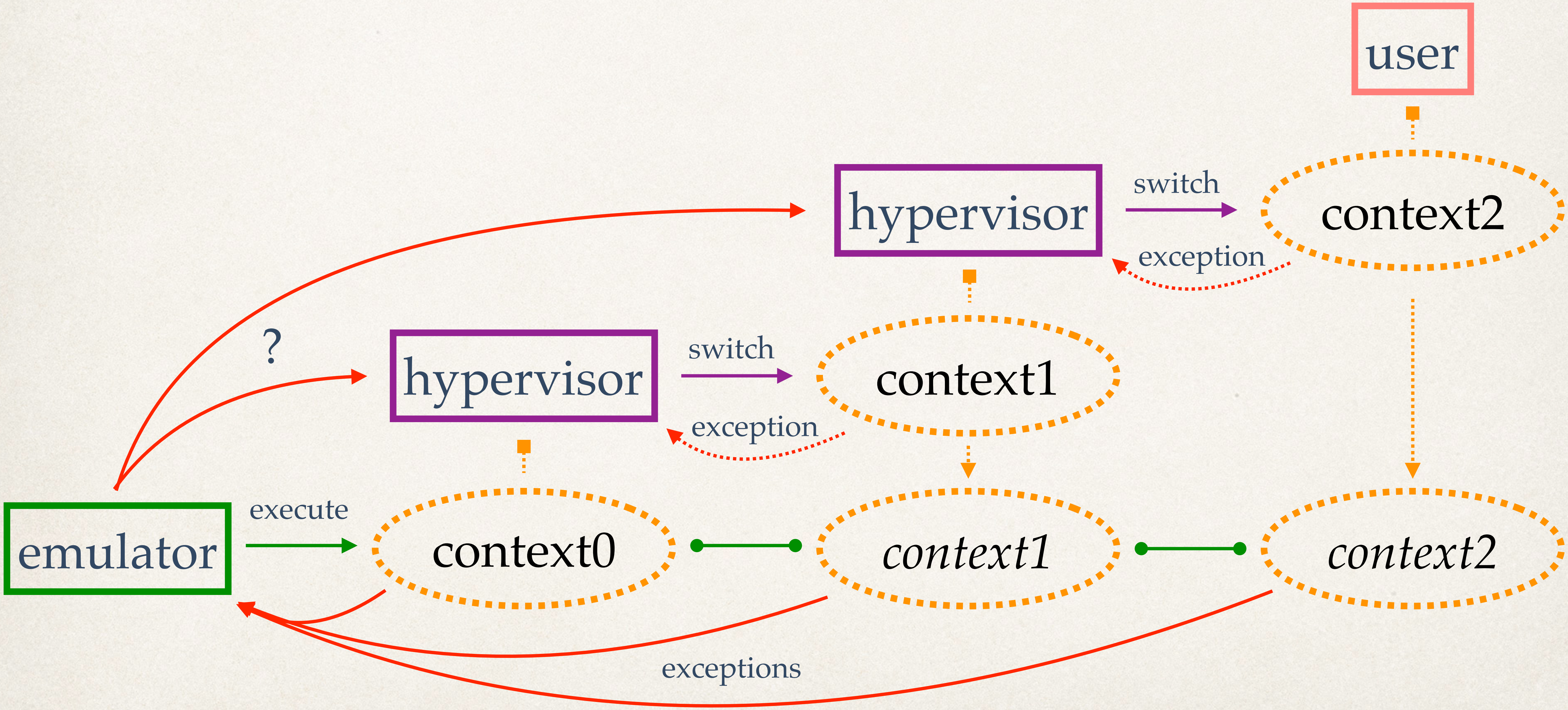


Emulation versus Virtualization



```
while (1) {
  if (mix)
    from_context = mipster_switch(to_context, TIMESLICE);
  else
    from_context = hypster_switch(to_context, TIMESLICE);

  if (get_parent(from_context) != MY_CONTEXT) {
    // switch to parent which is in charge of handling exceptions
    to_context = get_parent(from_context);

    timeout = TIMEROFF;
  } else if (handle_exception(from_context) == EXIT)
    return get_exit_code(from_context);
  else {
    // TODO: scheduler should go here
    to_context = from_context;

    if (mix) {
      if (mslice != TIMESLICE) {
        mix = 0;

        timeout = TIMESLICE - mslice;
      }
    } else if (mslice > 0) {
      mix = 1;

      timeout = mslice;
    }
  }
}
```

Self-Hosting: Hierarchy



Bit-precise Symbolic Exploration?

What exactly is needed to explore the bit-precise execution of systems code like selfie's symbolically?

Selfie
Symbolic
Execution
monster
(beast)

Selfie
Model
Generator
modeler
(beauty)

Replay vs. Symbolic Execution

- Selfie supports replay of RISC-U execution upon detecting runtime errors such as division by zero

- Selfie first rolls back *n* instructions (undo (!) semantics, system calls?) and then re-executes them but this time printed on the console

- We use a cyclic buffer for replaying *n* instructions

- That buffer is logically also used in symbolic execution but then for recording symbolic execution of up to *n* instructions

Symbolic Execution: Status

- We fuzz input read from files
- Symbolic execution proceeds by generating SMT-LIB formulae that are satisfiable iff there is an input that leads to a (memory) safety violation
- Exponential in the size of the input and the binary
- Ongoing bachelor project: a hybrid symbolic execution and bounded model checking engine

Model Generation: Status

- We fuzz input read from files

- Model generation proceeds by generating BTOR2 formulae that are satisfiable iff there is an input that leads to a (memory) safety violation

- Key difference to symbolic execution:

  It's translation, not execution, linear in time and space in the size of the binary.

- Selfie representation:

  300KB (source), 200KB (binary), 1MB (assembly), 13MB (BTOR2)

What's next?

Finding bugs and teaching verification!

selfie.cs.uni-salzburg.at

Got Research and Teaching Ideas?

- Selfie is a simple but still realistic sandbox
- You control everything!
- Want to play with an idea that requires compiler/operating systems/architecture support?
- We are glad to help you get started!

Thank you!