C⚙mpiler
C⚙nstruction

L1

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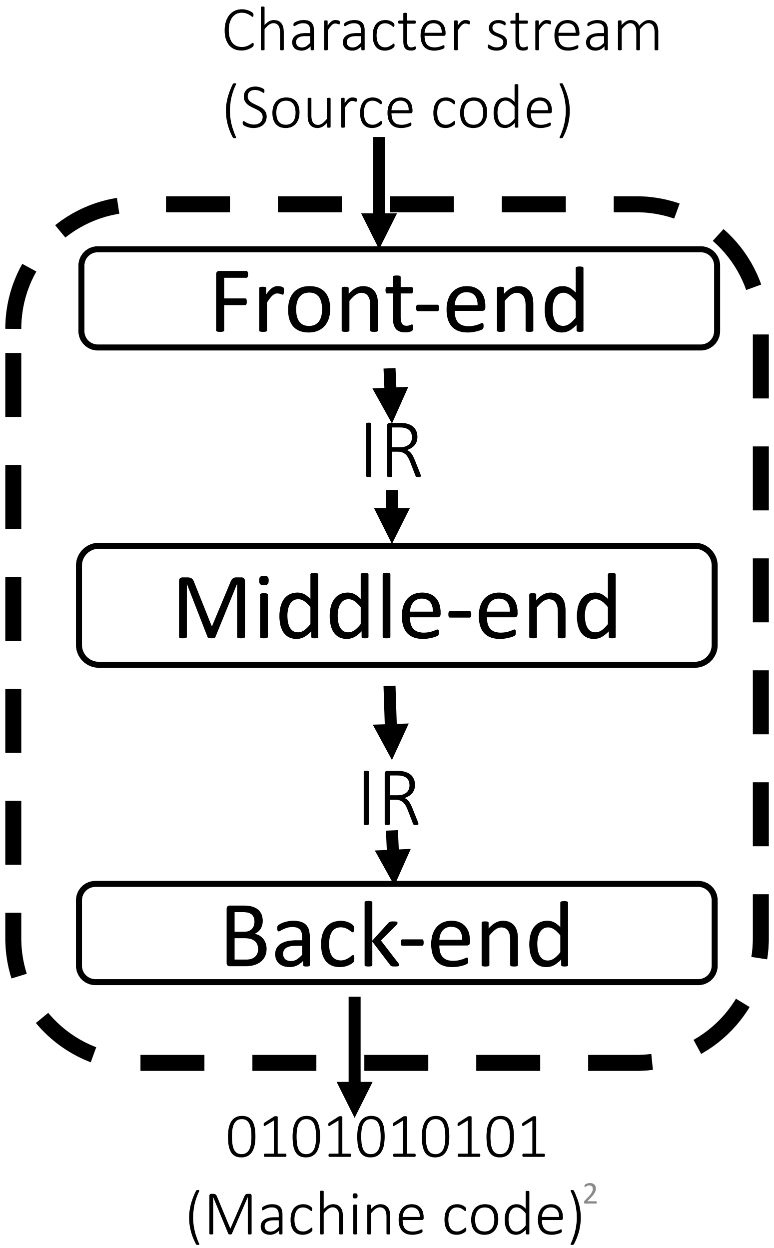
Compilers

- Compilers translate a source language (e.g., C++) to a destination language (e.g., x86_64)
  - We use them every day
  - If you understand their internals,
    you better understand (and take advantage of)
    the tools you rely on
  - Are you interested in computer architectures?
    their inputs is the outputs of a compiler


Character stream
(Source code)

Front-end

IR

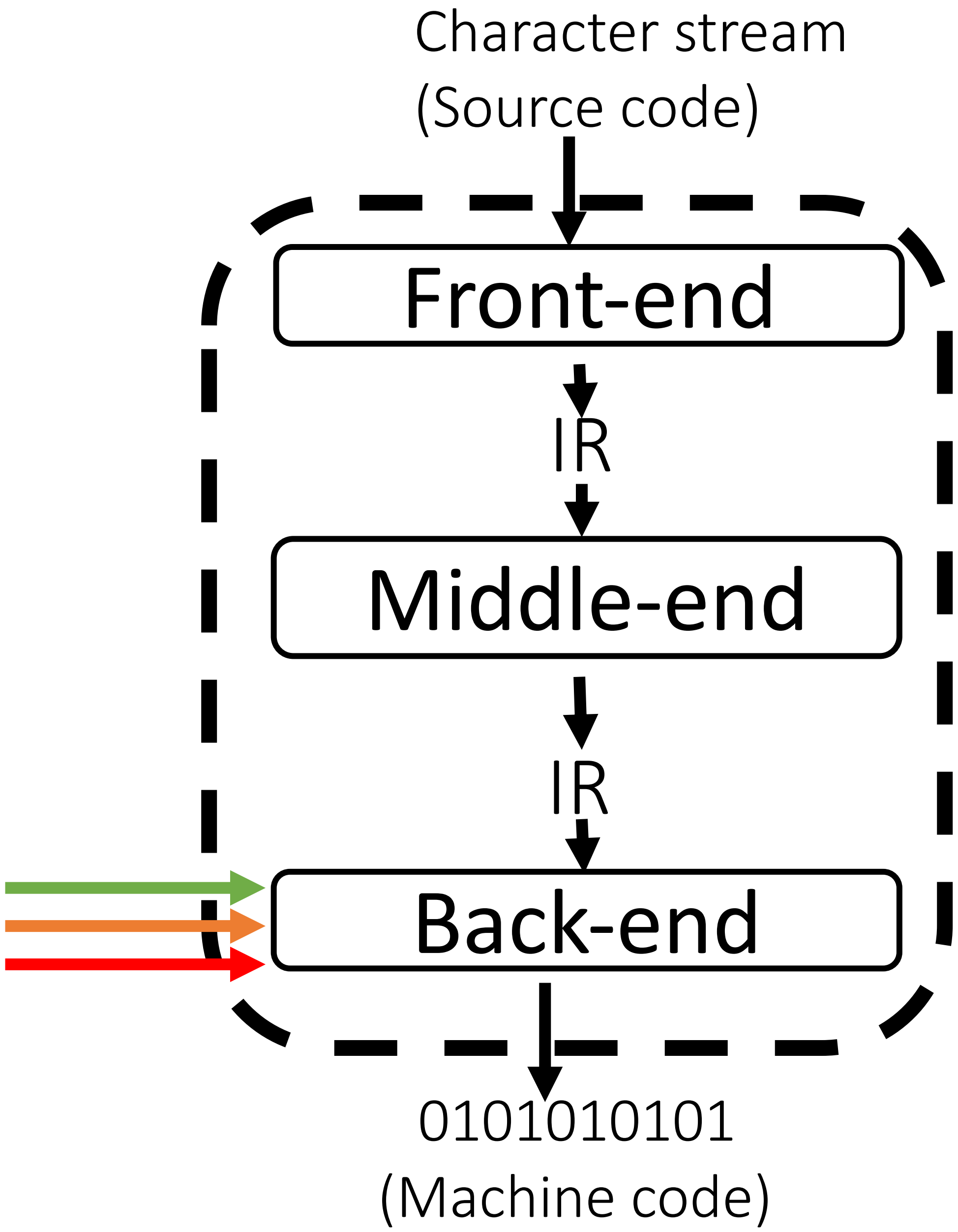
Middle-end

IR

Back-end

0101010101
(Machine code)

Compilers



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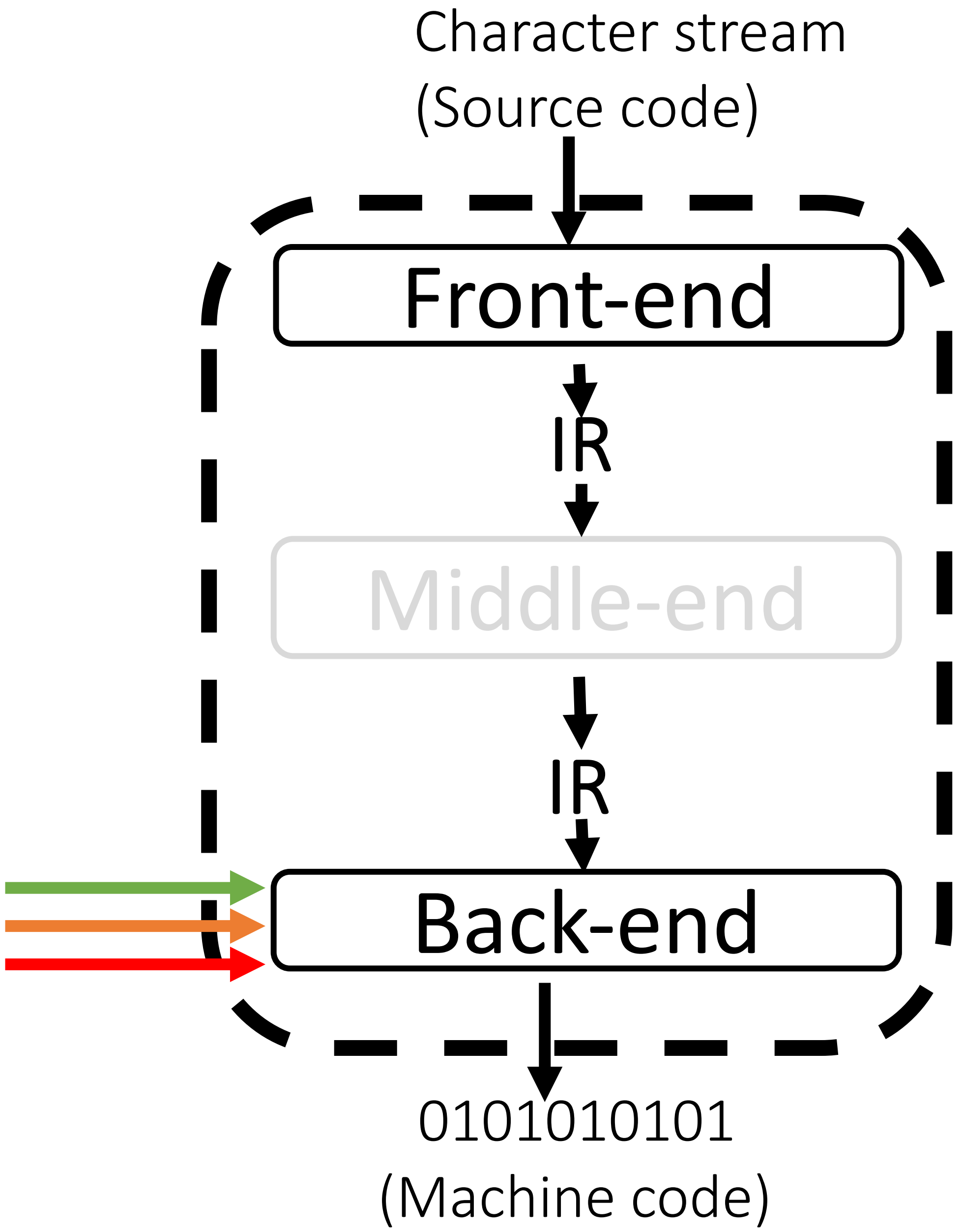

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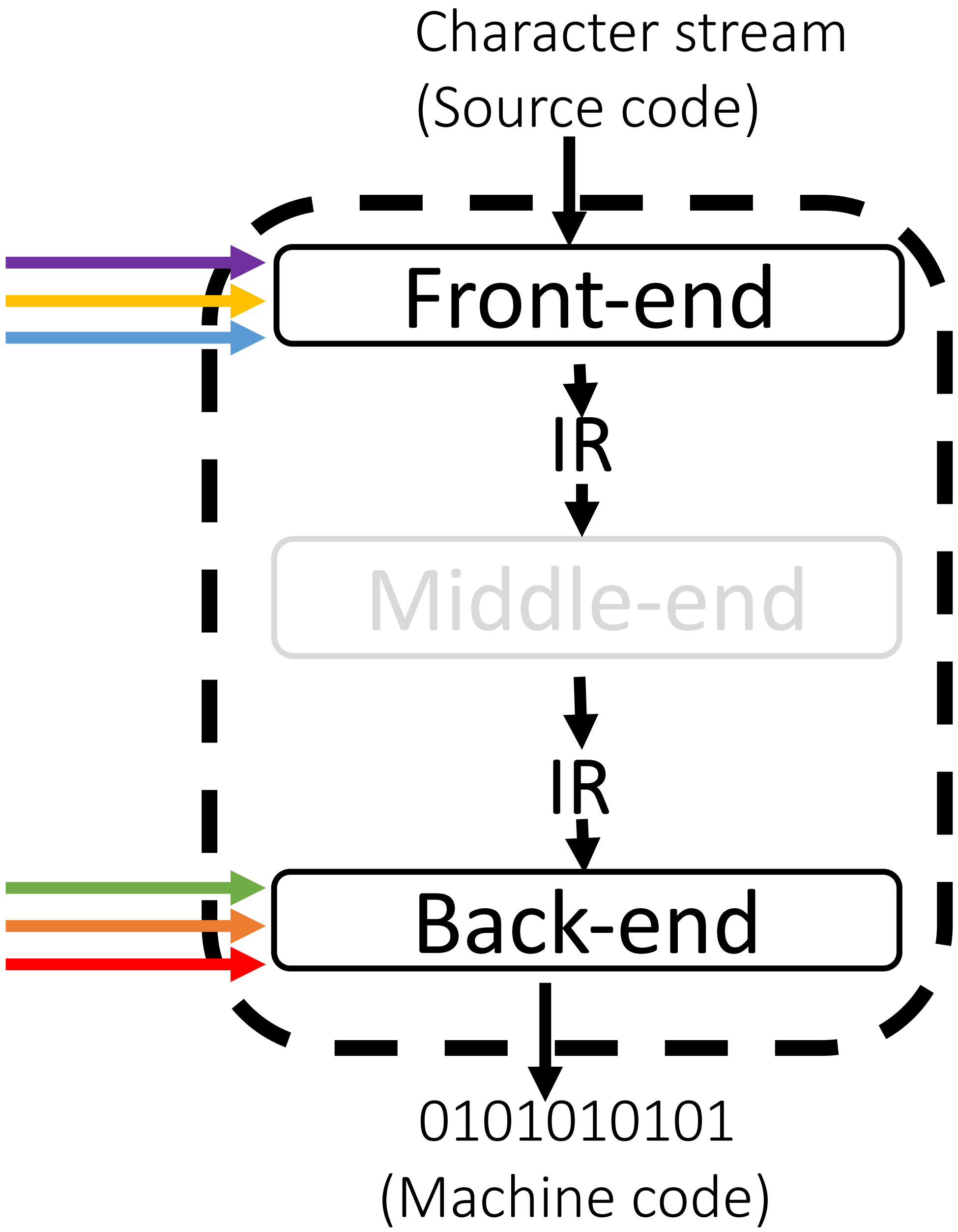

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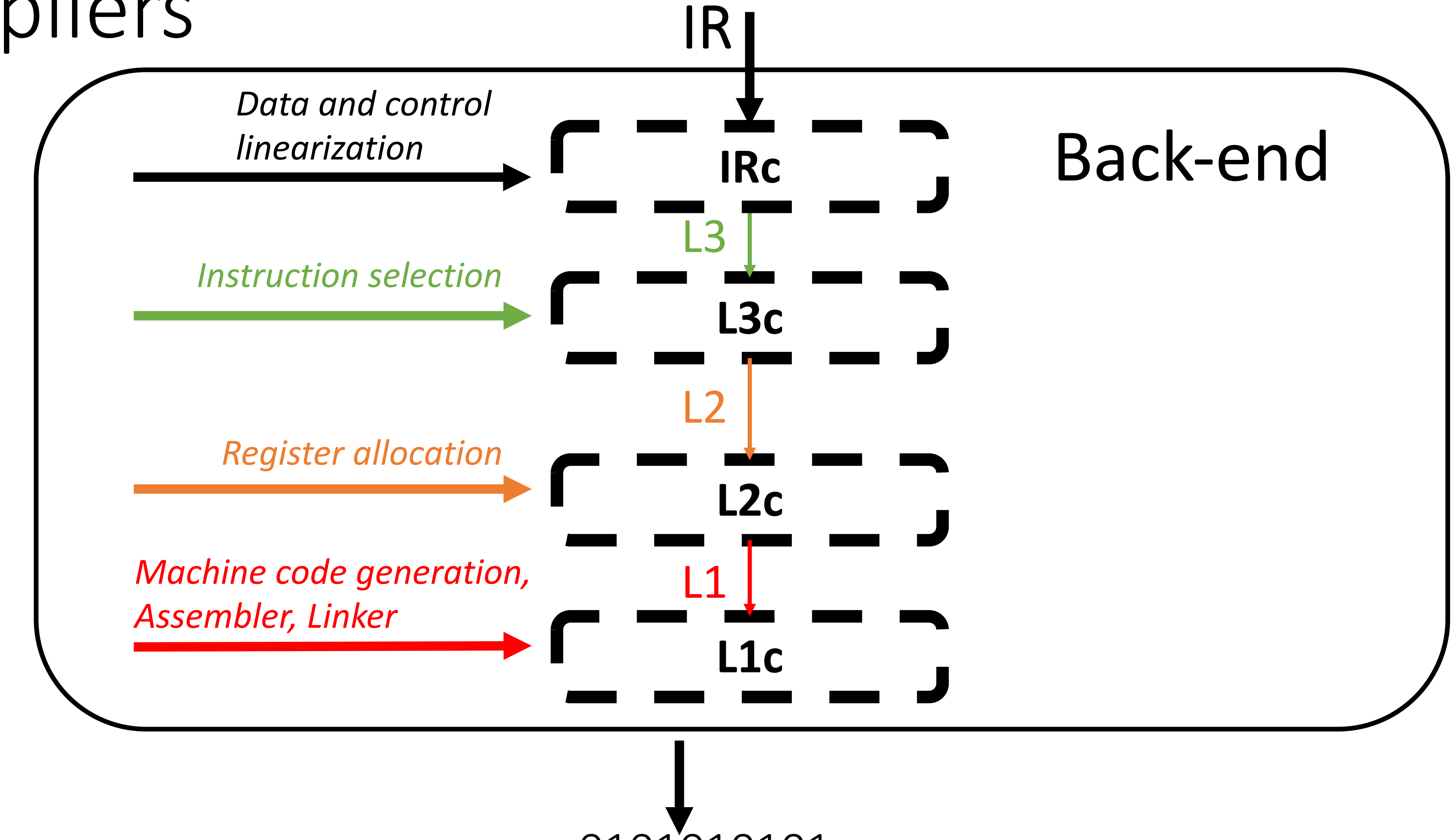


IR

Back-end

Data and control linearization

IRc

L3

Instruction selection

L3c

L2

Register allocation

L2c

Machine code generation, Assembler, Linker

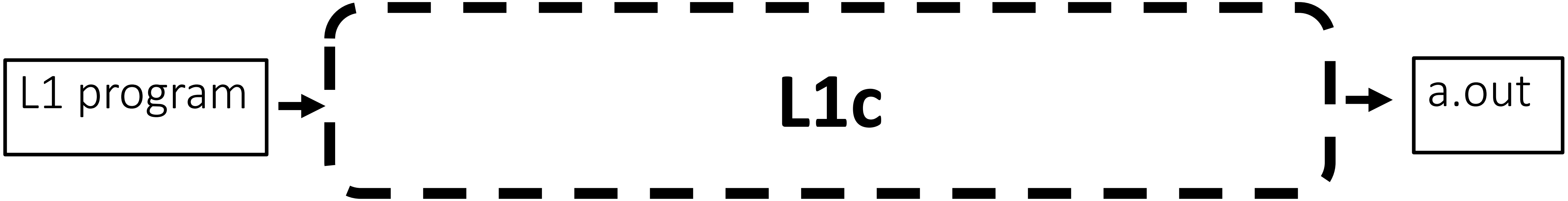
L1

L1c

0101010101
(Machine code)

The L1 source language

- L1 is going to be the input of your first compiler L1c
- The output of L1c is an executable ELF binary
  that can run on Linux-based and Intel-based systems



Outline

- L1 language
- Value encoding
- Calling convention
- Heap

From now on, we need to use the mindset of
“we want to become L1 developers”

rather than
“we want to build a compiler for L1” (this will come later)

The L1 source language

- Similar to a subset of x86_64, but with some abstractions

```
movq $1, %rax                  rax <- 1
```

- L1 only has integer values and memory addresses
  (no floating point values)

- L1 has only
  compare, call, arithmetic, branch, and memory instructions

Correct programs that can be written using a language
are specified using a grammar
and some formal specification for its semantics

A program is a sequence of characters

A grammar specifies the set of sequences of characters that are allowed

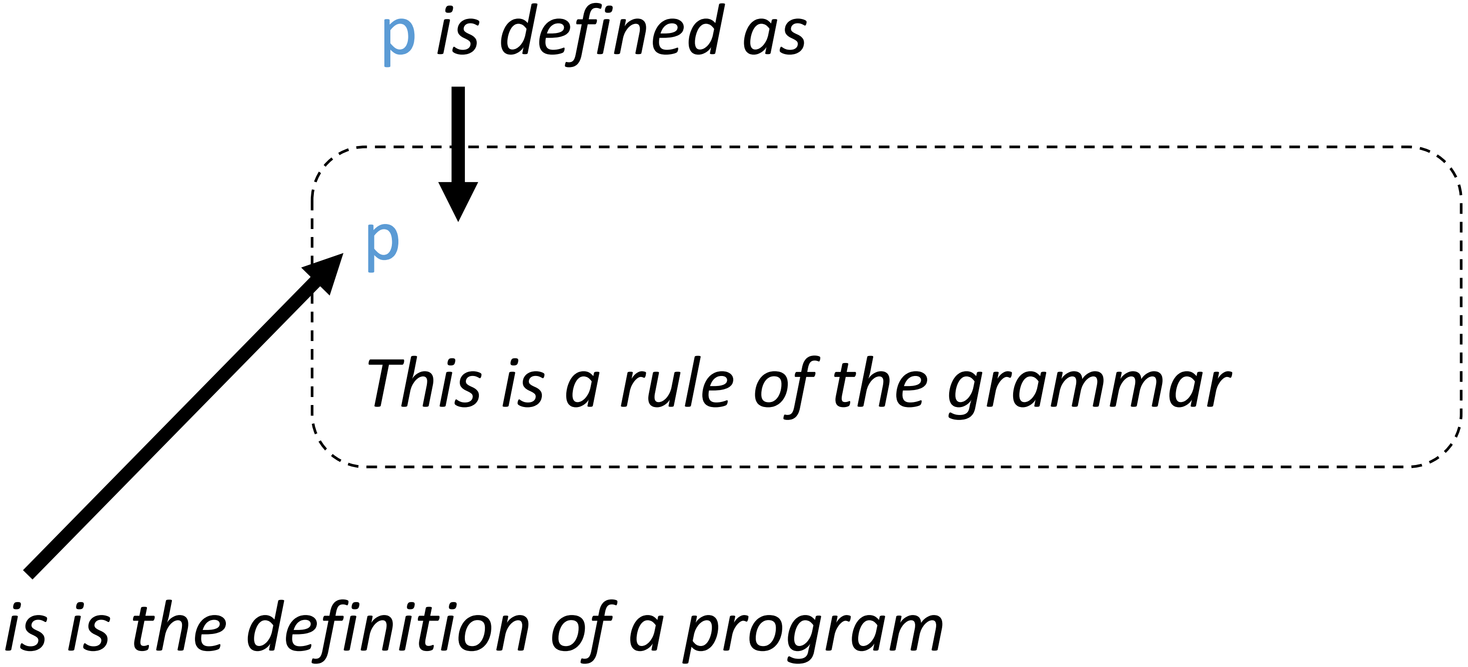
Let’s have a quick introduction to a trivial grammar

and then we’ll look at the L1 grammar

Trivial example of a grammar

Let’s assume we want a grammar that allows only the next sequences of characters:

- a
- 0
- 10
- 20
- 30



p *is defined as*

p

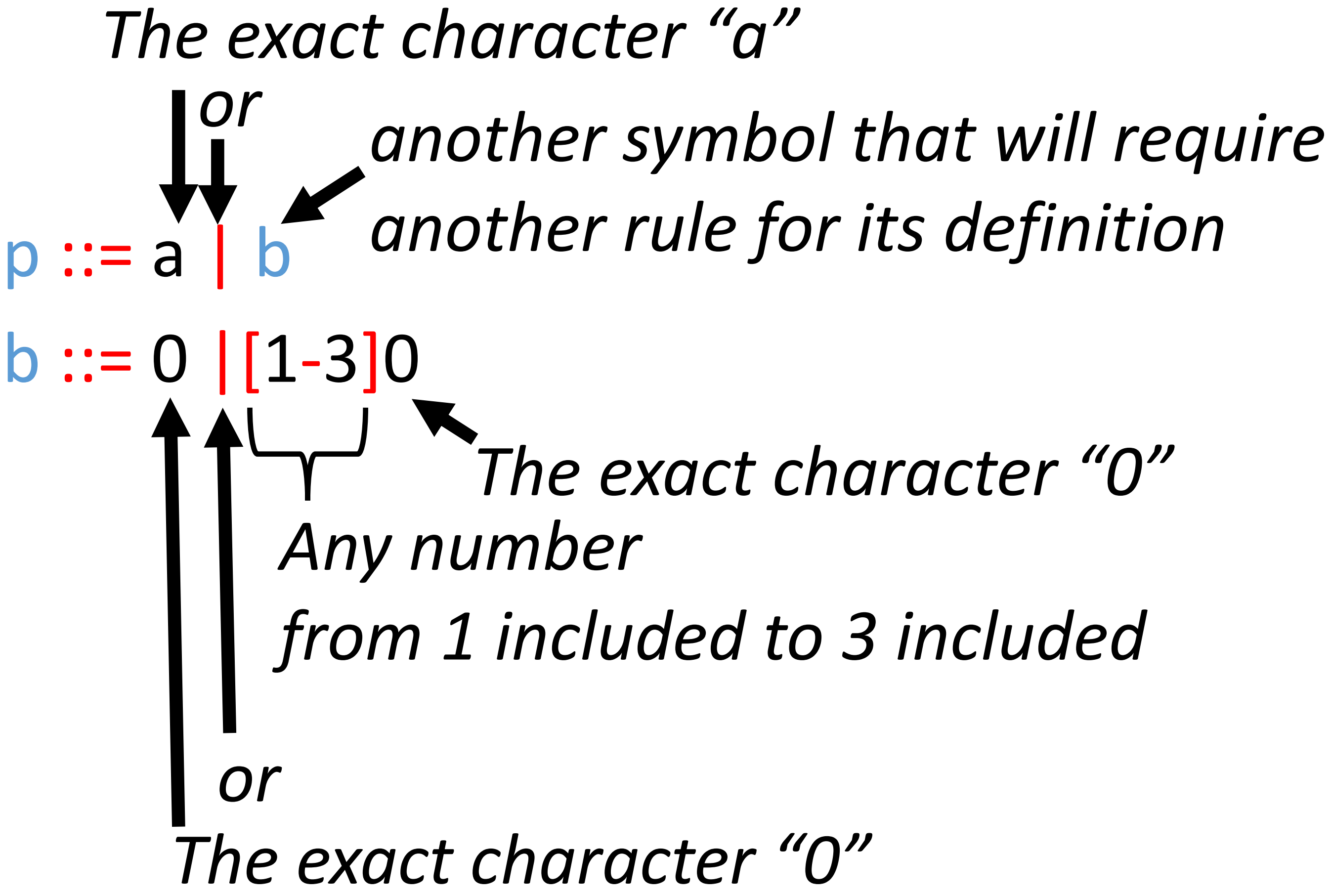
This is a rule of the grammar

This is the definition of a program

Trivial example of a grammar

Let’s assume we want a grammar that allows only the next sequences of characters:

- a
- 0
- 10
- 20
- 30



The exact character “a”

or

another symbol that will require another rule for its definition

```
p ::= a | b
b ::= 0 | [1-3]0
```

The exact character “0”

Any number from 1 included to 3 included

or

The exact character “0”

- a
- 0
- 10
- 20
- 30
- c
- +c

p ::= a | b

b ::= 0 | [1-3]0 | +? c

- a
- 0
- 10
- 20
- 30
- c
- +c
- -c

```
p ::= a | b
b ::= 0 | [1-3]0 | (+|-)? c
```

- a
- 0
- 10
- 20
- 30
- c
- +c
- -c
- Z
- …

p ::= a | b

b ::= 0 | [1-3]0 | (+ | -)? c | ([a-z] | [A-Z])

- a
- 0
- 10
- 20
- 30
- c
- +c
- -c
- Z
- …

p ::= a | b

b ::= 0 |[1-3]0 | (+|-)? c | [a-zA-Z]

- :Aaaaaabbdfsdgfdssdfdsgfs
- :A
- :ZFRDFGDFdfsfdsfsdf

p ::= a | b

b ::= 0 | [1-3]0 | (+|-)? c | :[a-zA-Z]$^{+}$

- :Aaaaaabbdfsdgfdssdfdsgfs
- :A
- :ZFRDFGDFdfsfdsfsdf
- :

p ::= a | b

b ::= 0 | [1-3]0 | (+|-)? c | :[a-zA-Z]*

Now we are ready to look at the L1 grammar

L1 name

name ::= *sequence of chars matching* [a-zA-Z_][a-zA-Z_0-9]*

go ← This is a name

3go ← This is not a name

L1 label

label ::= :name

name ::= *sequence of chars matching* [a-zA-Z_][a-zA-Z_0-9]*

:go ← This is a label

:3go ← This is not a label

L1 program

p ::= (l f^{+})
l ::= @name
name ::= *sequence of chars matching* [a-zA-Z_][a-zA-Z_0-9]*

```
(@go
  f1
  f2
)
```

The entry point of this L1 program is the function @go

One of these functions must be @go

L1 function

p ::= (l f^+)
l ::= @name
name ::= *sequence of chars matching* [a-zA-Z_][a-zA-Z_0-9]*
f ::= (l N N i^+)
N ::= (+|-)? [1-9][0-9]* | 0

```
(@go
  4 2
  i1
  i2
)
```

We now need to look at
the possible instructions that we can include
in an L1 function

L1 instruction: return

f ::= (l N N i^+)
i ::= return

L1 example

```
(@go
 (@go
    0 0
    return
  )
)
```

This is a complete and correct L1 program

L1 instruction: assignment

f ::= (l N N i^+)
i ::= … | w <- s

w ::= a | rax | rbx | rbp | r10 | r11 | r12 | r13 | r14 | r15
a ::= rdi | rsi | rdx | rcx | r8 | r9
s ::= x | N | label
x ::= w | rsp

L1 example

```
(@go
 (@go
   0 0
   rdi <- 5
   rax <- rdi
   return
  )
)
```

- The execution goes top->down, instruction after instruction
- Undefined behavior:
  if the instruction at the bottom of the function is executed and the semantics is to execute the next one, then the behavior is undefined

L1 example

```
(@go
 (@go
    0 0
    rdi <- 5
    rax <- rdi
  )
)
```

- The execution goes top->down,
  instruction after instruction
- Undefined behavior:
  if the instruction at the bottom of the function is executed
  and the semantics is to execute the next one,
  then the behavior is undefined

L1 instruction: assignment

f ::= (l N N i^+)

i ::= … | w <- s

When s is a label, then
it must be an existing function name

w ::= a | rax | rbx | rbp | r10 | r11 | r12 | r13 | r14 | r15

a ::= rdi | rsi | rdx | rcx | r8 | r9

s ::= x | N | label

x ::= w | rsp

L1 instruction: load

f ::= (l N N i^+)
i ::= … | w <- mem x M

w ::= a | rax | rbx | rbp | r10 | r11 | r12 | r13 | r14 | r15
a ::= rdi | rsi | rdx | rcx | r8 | r9
s ::= x | N | label
x ::= w | rsp
M ::= *multiplicative of 8 constant (e.g., 0, 8, 16)*

L1 example

```
(@go
 (@go
    0 0
    rdi <- 5
    rbx <- mem rdi 8
    return
  )
)
```

L1 instruction: load

f ::= (l N N i^+)
i ::= … | w <- mem x M

w ::= a | rax | rbx | rbp | r10 | r11 | r12 | r13 | r14 | r15
a ::= rdi | rsi | rdx | rcx | r8 | r9
s ::= x | N | label
x ::= w | rsp
M ::= *multiplicative of 8 constant (e.g., 0, 8, 16)*

L1 instruction: store

f ::= (l N N i^+)
i ::= … | w <- mem x M | mem x M <- s

w ::= a | rax | rbx | rbp | r10 | r11 | r12 | r13 | r14 | r15
a ::= rdi | rsi | rdx | rcx | r8 | r9
s ::= x | N | label
x ::= w | rsp
M ::= *multiplicative of 8 constant (e.g., 0, 8, 16)*

L1 instruction: arithmetic operations

f ::= (l N N i^+)
i ::= …| w aop t

aop ::= += | -= | *= | &=
t ::= x | N

L1 example

```
(@go
 (@go
   0 0
   rdi <- 5
   rdi += 2
   return
  )
)
```

L1 instruction: arithmetic operations

f ::= (l N N i^+)
i ::= … | w aop t

aop ::= += | -= | *= | &=
t ::= x | N

Integer overflow is undefined behavior

L1 instruction: shifting

f ::= (l N N i^+)

i ::= … | w aop t | w sop rcx

sop ::= <<= | >>=

rdi <<= rcx

L1 instruction: shifting

f ::= (l N N i^{+})

i ::= … | w aop t | w sop rcx | w sop N

sop ::= <<= | >>=

rdi <<= rcx

rdi <<= 3

L1 instruction: memory arithmetic operations

f ::= (l N N i^+)

i ::= …

| mem x M += t

| mem x M -= t

| w += mem x M

| w -= mem x M

Notice you cannot have both operands in memory

L1 instruction: comparison

f ::= (l N N i^+)

i ::= …

| w <- t cmp t

cmp ::= < | <= | =

Notice there is neither

\>

nor

\>=

L1 example

```
(@go
 (@go
   0 0
   rax <- 5
   rdi <- rax <= 3
   return
  )
)
```

L1 instruction: comparison

f ::= (l N N i^+)

i ::= …

| w <- t cmp t

cmp ::= < | <= | =

L1 instruction: conditional jump

f ::= (l N N i^+)

i ::= …

| w <- t cmp t

| cjump t cmp t label ← *Fall-through semantic*

cmp ::= < | <= | =

L1 example

```
(@go
 (@go
   0 0
   rax <- 5
   :true
   rdi <- rax <= 3
   cjump rdi = 1 :true
   return
  )
)
```

L1 instruction: label and jump

f ::= (l N N i^+)

i ::= …

| w <- t cmp t

| cjump t cmp t label

| label

| goto label

L1 example

```
(@go
 (@go
   0 0
   rax <- 5
   rax += 2
   cjump rax <= 3 :END
   rax += 4
   goto :END
   :END
   return
 ))
```

L1 instruction: label and jump

```
f       ::= (l N N i+)
i       ::= …
          | w <- t cmp t
          | cjump t cmp t label
          | label
          | goto label
```

The scope of labels is the program

L1 another example

```
(@F1
 (@F1
   0 0
   :L1
   return
  )
  (@F2
    0 0
    ~~:L1~~
    return
   )
)
```

L1 instruction: call

f ::= (l N N i^+)

i ::= …

| call u N

Number of arguments of the called function (a.k.a. callee)

u ::= w | l

Name of a function

Register that holds the reference (name) of the function to call

L1 example

```
(@go
  (@go
    0 0
    call @myF2 0
    return
  )
  (@myF2
    0 0
    return
  )
)
```

Why do we have redundant information in L1?
To simplify the L1 compiler (your work)

They must match

Number of parameters of the function

L1 instruction: call

f ::= (l N N i^+)

i ::= …

| call u N

| call print 1

L1 example

```
(@go
 (@go
   0 0
   rdi <- 5
   call print 1
   return
  )
)
```

The calling convention will be explained soon

L1 instruction: call

f ::= (l N N i^+)

i ::= …

| call u N

| call print 1

| call input 0

| call allocate 2

| call tensor-error F

F ::= 1 | 3 | 4

L1 instruction: misc

f ::= (l N N i^+)

i ::= …

| w++

| w--

| w @ w w E

E ::= 1 | 2 | 4 | 8

rax @ rdi rsi 4

Set rax **to** rdi + (rsi * 4)

L1

```
p     ::= (l f+)
f     ::= (l N N i+)
i     ::= w <- s | w <- mem x M | mem x M <- s |
          w aop t | w sop sx | w sop N | mem x M += t | mem x M -= t | w += mem x M | w -= mem x M |
          w <- t cmp t | cjump t cmp t label | label | goto label |
          return | call u N | call print 1 | call input 0 |  call allocate 2 | call tensor-error F |
          w ++ | w -- | w @ w w E
w     ::= a | rax | rbx | rbp | r10 | r11 | r12 | r13 | r14 | r15
a     ::= rdi | rsi | rdx | sx | r8 | r9
sx    ::= rcx
s     ::= t | label | l
t     ::= x | N
u     ::= w | l
x     ::= w | rsp
aop   ::= += | -= | *= | &=
sop   ::= <<= | >>=
cmp   ::= < | <= | =
E     ::= 1 | 2 | 4 | 8
F     ::= 1 | 3 | 4
M     ::= multiplicative of 8 constant (e.g., 0, 8, 16)
N     ::= (+|-)? [1-9][0-9]* | 0
l     ::= @name
label ::= :name
name ::= sequence of chars matching [a-zA-Z_][a-zA-Z_0-9]*
```

Outline

- L1 language
- Value encoding
- Calling convention
- Heap

High level vs. low level languages

C language

printf(“5”); $\xrightarrow{\text{You expect the output}}$ 5

Back-end languages

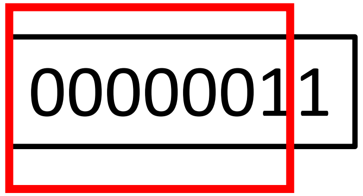
rdi <- 5
call print 1 $\xrightarrow{\text{You expect the output}}$?

It depends on
the encoding scheme
designed for correctness

Value encoding in L1

- A value is either an 8 byte integer value or a memory address
- We would like to differentiate between the two
  - Safer programming environment
  - Problem: how to do it?
  - For example:
    mem rdi 8 <- rax
    is the value in rdi a memory address?

Two’s complement



- This class solution: using the least significant bit to specify it
  0: it is a memory address
  1: it is an integer value
- **Values in L1 are all encoded**

High level vs. low level language L1

C language

printf(“5”); → 5

You expect the output

L1 language

rdi <- 5

call print 1 → 2

You expect the output

00000101 → 00000010

Decoding an encoded value

- x & 1 = 0
  x is a memory address

- x & 1 = 1
  x >> 1 is a 63 bit two’s complement integer

- Values (integer or addresses) must be encoded for runtime APIs
  - print
  - input (it returns the encoded value of the one read)
  - allocate
  - tensor-error

L1 example

```
(@go
  (@go
    0 0
    rdi <- 5
    call print 1
    return
  )
)
```

- print writes to the terminal the integer value encoded in rdi if rdi contains a number
- What is going to be the output?
  2

Outline

- L1 language
- Value encoding
- Calling convention
- Heap

Calling convention

- How many arguments a given function has?

  `call @myF 2`

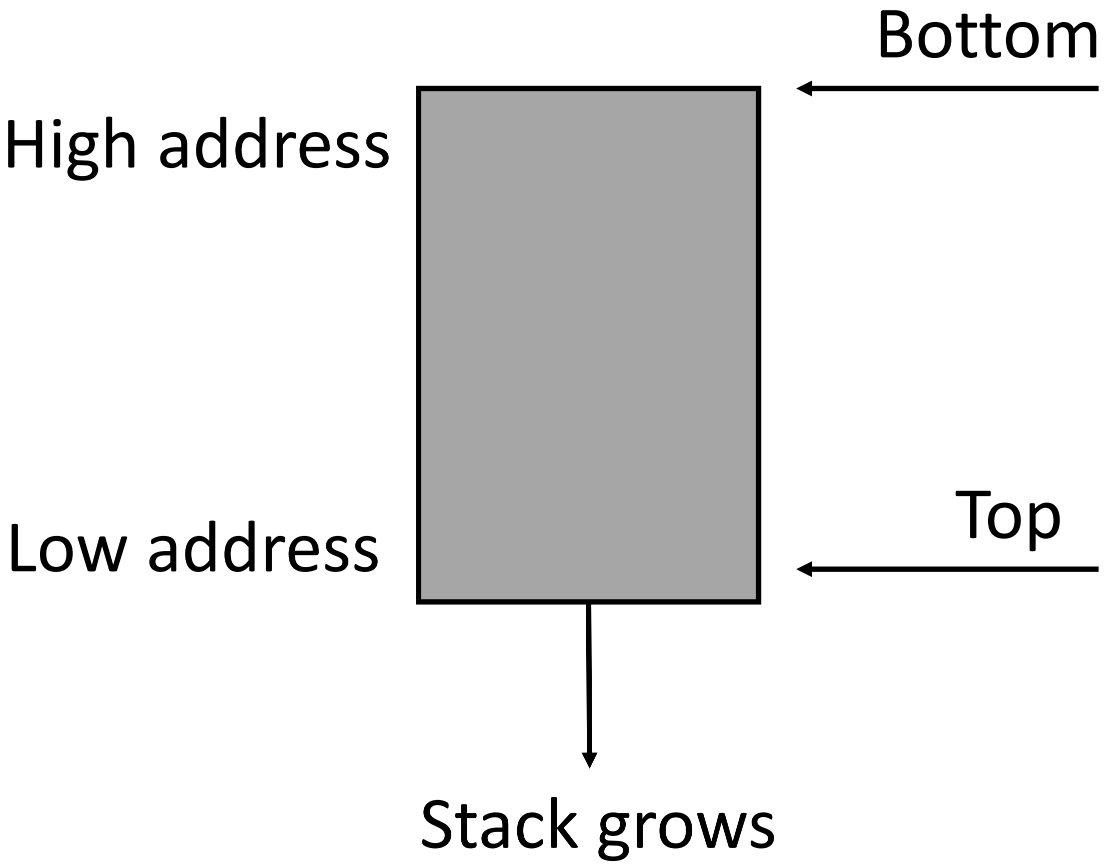
- Where are the arguments stored?

- Who (caller vs. callee) is responsible for what?

- Where is the return value stored?

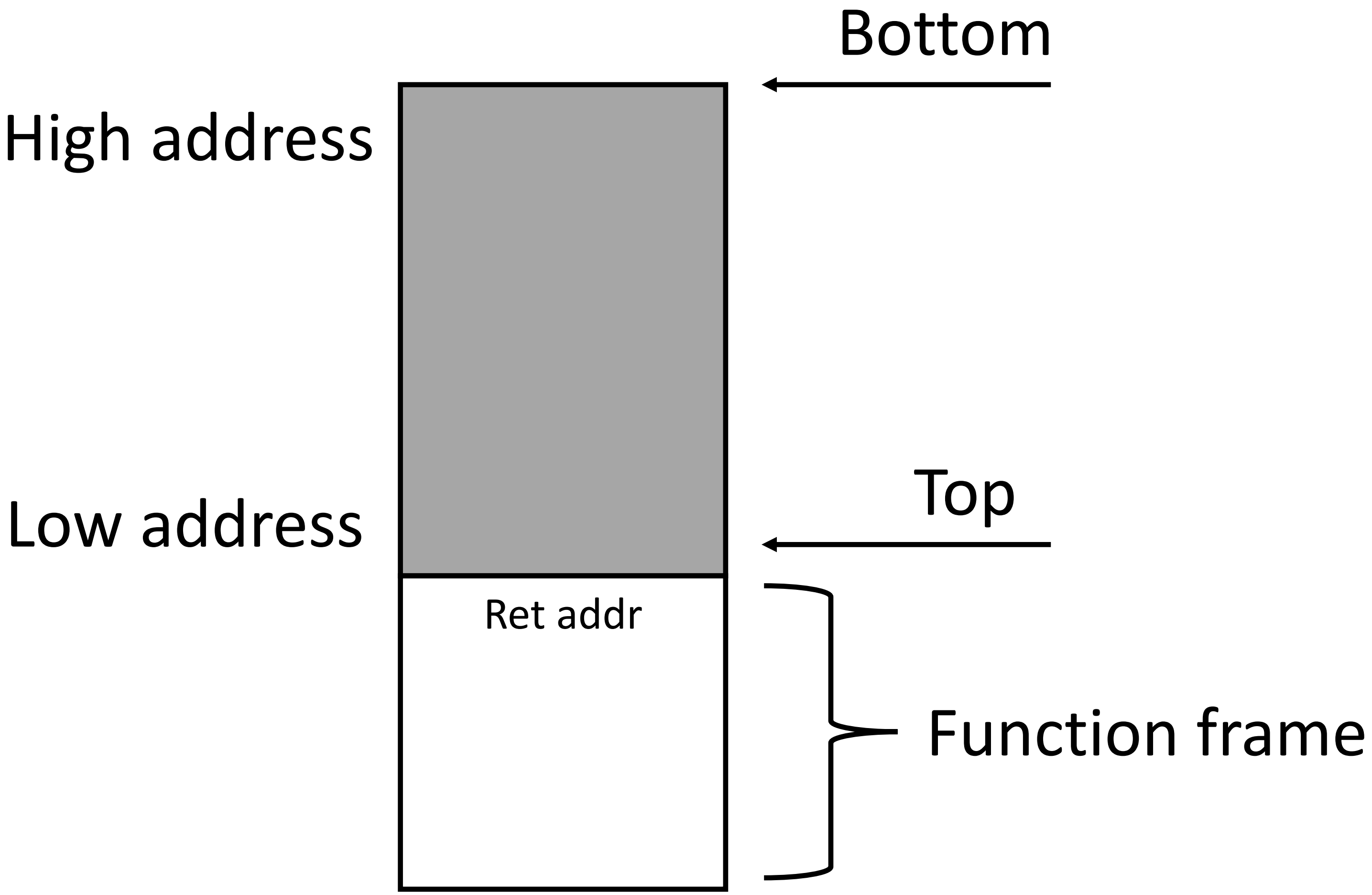
  rax

The stack in L1



- A call instruction that invokes F allocates new memory on top of the stack needed by F and to pass its arguments
- A return instruction executed in F frees that space

The stack in L1: function frame convention



So before calling a function, we need to store the return address on top of the stack

Storing the return address

Two type of calls:

- Calls to L1 functions
  - L1 code is responsible
    to store the return address on top of the stack

- Calls to runtime
  - L1 code is not responsible
    to store the return address on top of the stack

Function call example

```
(@myF
   0 0
   mem rsp -8 <- :myF2_ret
   call @myF2 0
   :myF2_ret
   return
)
```

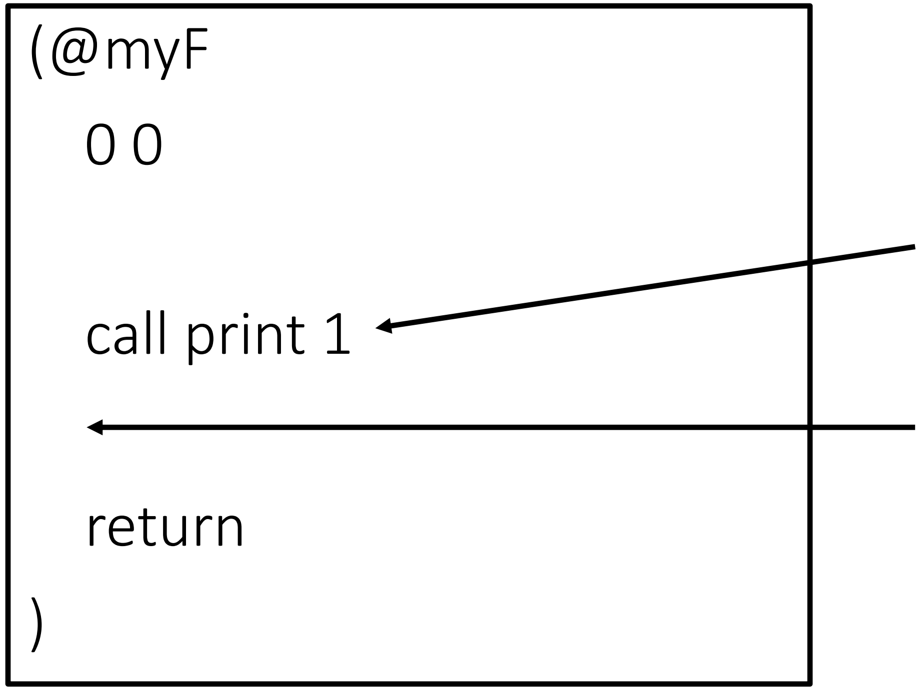
```
(@myF2
   0 0
   return
)
```

It jumps to the label read from the stack (and it frees the stack space of :myF2)

Whoever generates L1 code (developer, compiler that targets L1) is **responsible**

- to define the return label just after the call
- to store that label on top of the stack

Function call example (2)



```
(@myF
   0 0


   call print 1


   return
)
```

- The call itself writes the return address on top of the stack
- There is no need to define the label after the call

What about function parameters?

- The convention used in the L1 language is that the first 6 parameters of the callee are passed using registers

- The other parameters are passed using the function frame of the callee stored on the stack

Registers

Arguments

rdi
rsi
rdx
rcx
r8
r9

First argument

Result

rax

```
(@go
   0 1
   r10 <- 5
   …
)
```

- What about the previous value of r10?
- We want to write our function without knowing the registers used/needed by every possible caller
  - Is it possible to know them all?
- Who is responsible to save the previous value?
  - Are we (the callee)?
  - Are the callers?
  - We need to establish a convention

Registers

Arguments

rdi
rsi
rdx
rcx
r8
r9

First argument

Result

rax

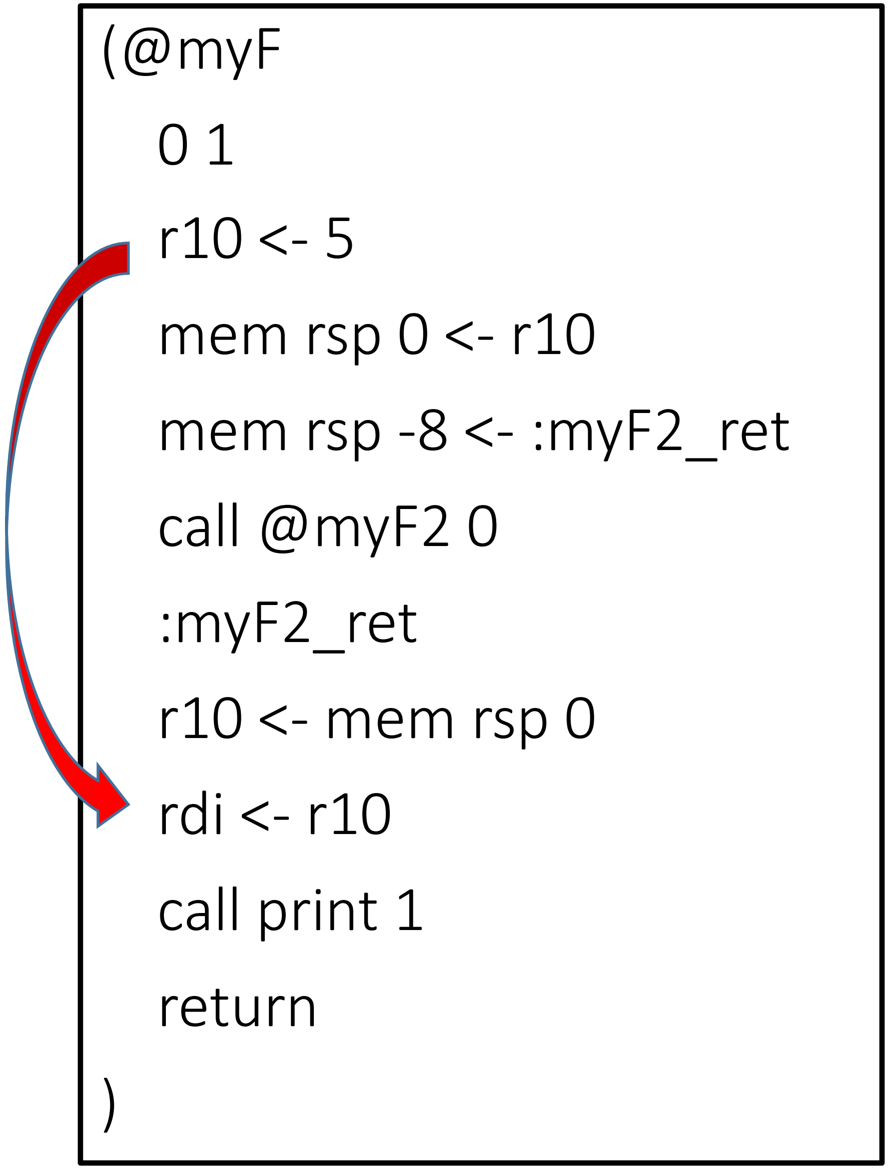
Caller save

r10
r11
r8
r9
rax
rcx
rdi
rdx
rsi

Callee save

r12
r13
r14
r15
rbp
rbx

Caller save registers (e.g., r10)



```
(@myF
   0 1
   r10 <- 5
   mem rsp 0 <- r10
   mem rsp -8 <- :myF2_ret
   call @myF2 0
   :myF2_ret
   r10 <- mem rsp 0
   rdi <- r10
   call print 1
   return
)
```

```
(@myF2
   0 0
   r10 <- 3
   return
)
```

What is the output?

Whoever generates L1 code
(developer, compiler that targets L1)
is **responsible**
to properly save caller-save registers

Caller save registers (e.g., r10)

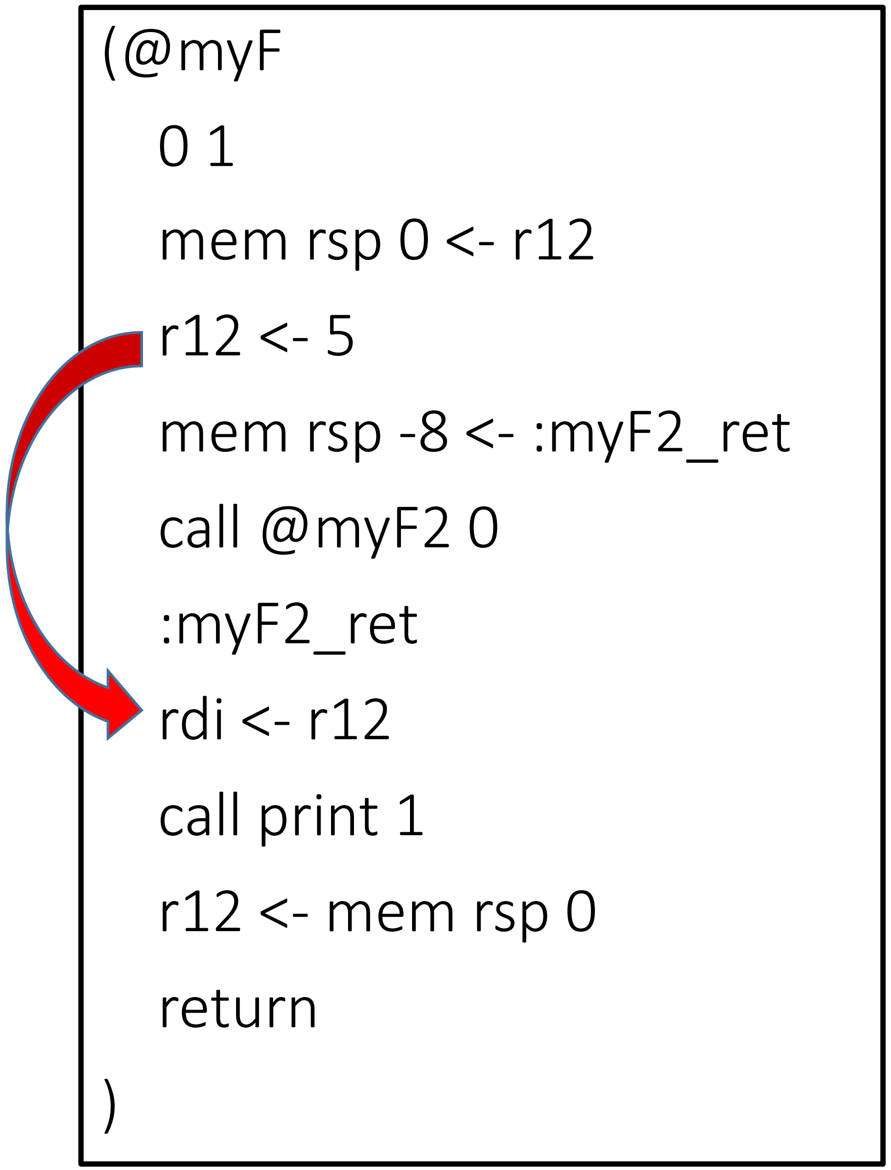
```
(@myF
   0 0
   r10 <- 5

   mem rsp -8 <- :myF2_ret
   call @myF2 0
   :myF2_ret

   rdi <- 5
   call print 1
   return
)
```

```
(@myF2
   0 0
   r10 <- 3
   return
)
```

Whoever generates L1 code
(developer, compiler that targets L1)
is **responsible**
to properly save caller-save registers

R10 is not used after the call.
Hence, we don’t need to save it

Callee save registers (e.g., r12)



```
(@myF
   0 1
   mem rsp 0 <- r12
   r12 <- 5
   mem rsp -8 <- :myF2_ret
   call @myF2 0
   :myF2_ret
   rdi <- r12
   call print 1
   r12 <- mem rsp 0
   return
)
```

```
(@myF2
   0 1
   mem rsp 0 <- r12
   r12 <- 3
   r12 <- mem rsp 0
   return
)
```

Whoever generates L1 code
(developer, compiler that targets L1)
is **responsible**
to properly save caller-save registers
as well as callee-save registers

Callee save registers (e.g., r12)

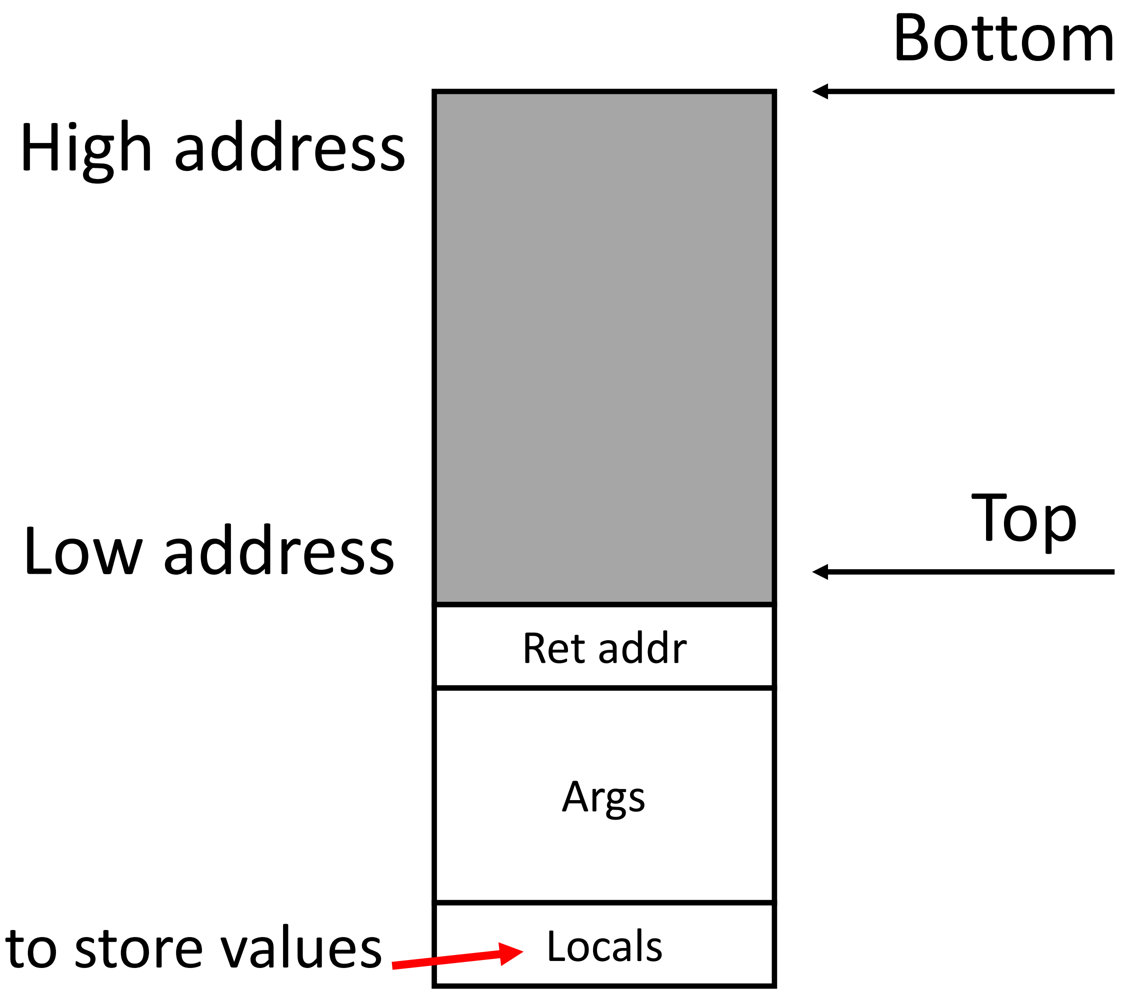
```
(@myF
   0 0



   mem rsp -8 <- :myF2_ret
   call @myF2 0
   :myF2_ret

   rdi <- 5
   call print 1
   return
)
```

```
(@myF2
   0 1
   mem rsp 0 <- r12
   r12 <- 3
   r12 <- mem rsp 0
   return
)
```

And now?

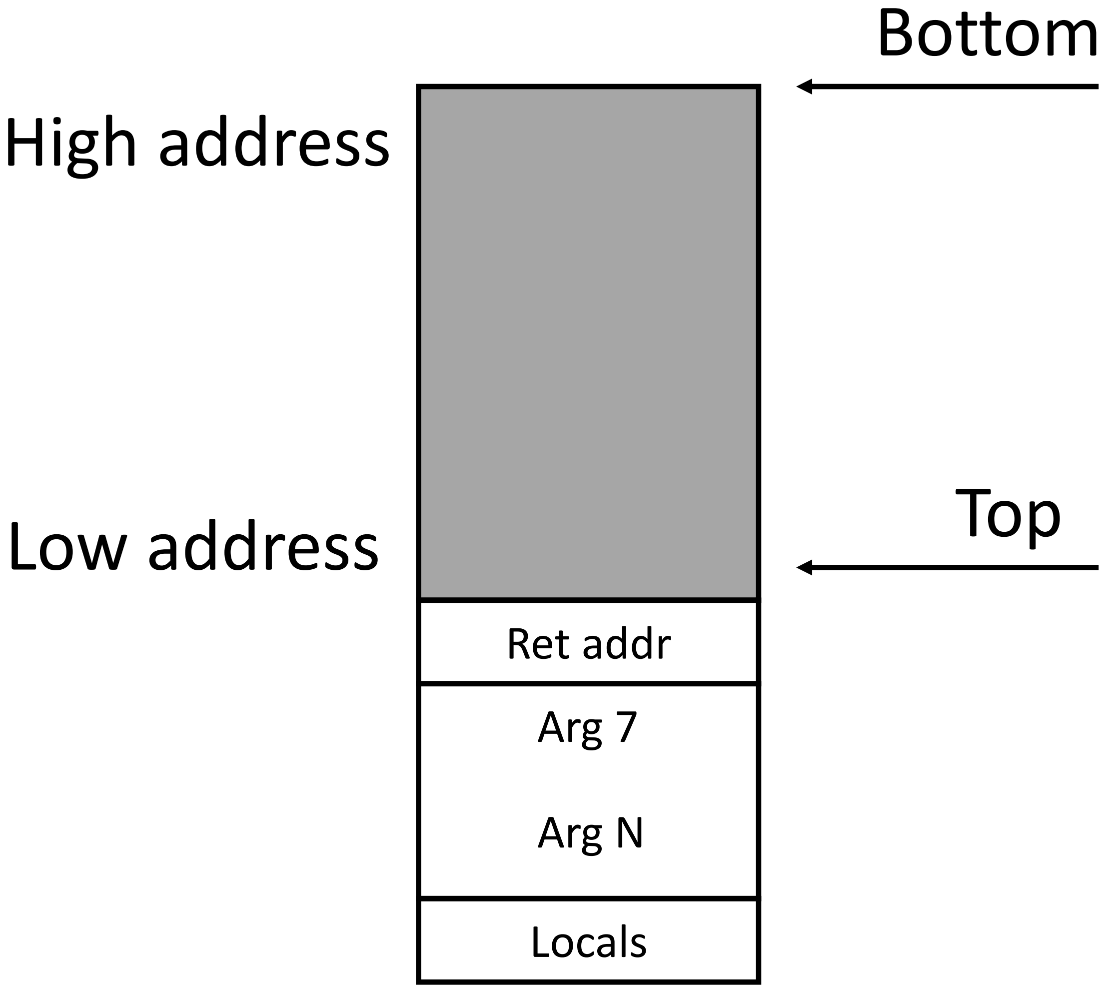
Whoever generates L1 code
(developer, compiler that targets L1)
is **responsible**
to properly save caller-save registers
as well as callee-save registers

The stack in L1



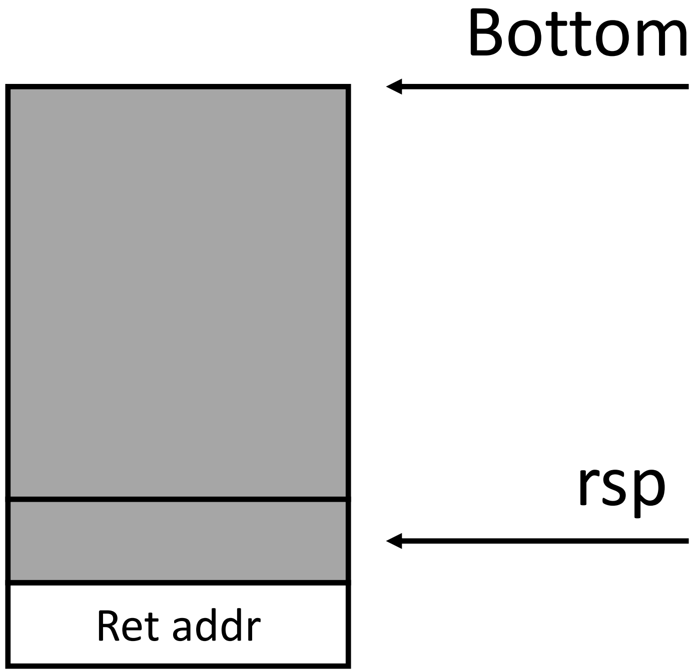
- Stack space used to store values needed by the related function
- Locals are used as function variables

The stack in L1



Stack frame: <= 6 arguments, no locals

```
(@go
  …
  rdi <- 5
  mem rsp -8 <- :f_ret
  call @f 1
  :f_ret
  …
)
(@f
  1 0
  return
)
```



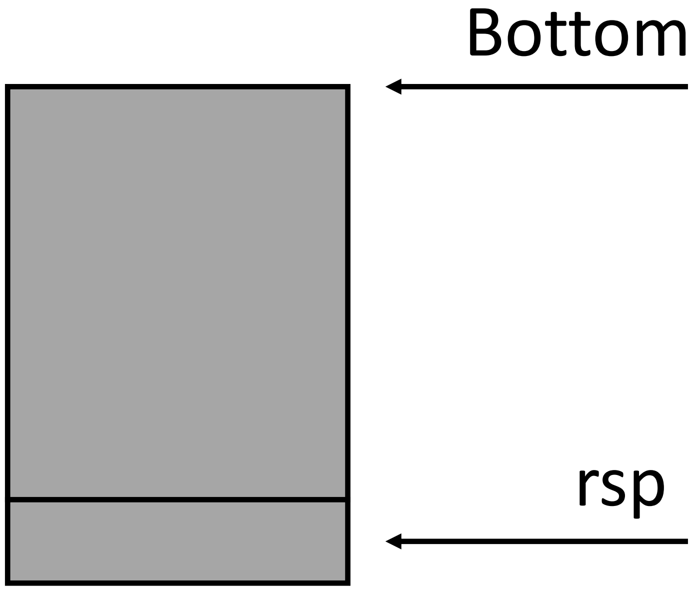
Stack frame: > 6 arguments, no locals

```
(@go
  rdi<-1
  rsi<-3
  rdx<-5
  rcx<-7
  r8<-9
  r9<-11
  …
  call @f 7
  …
)
```

Arguments

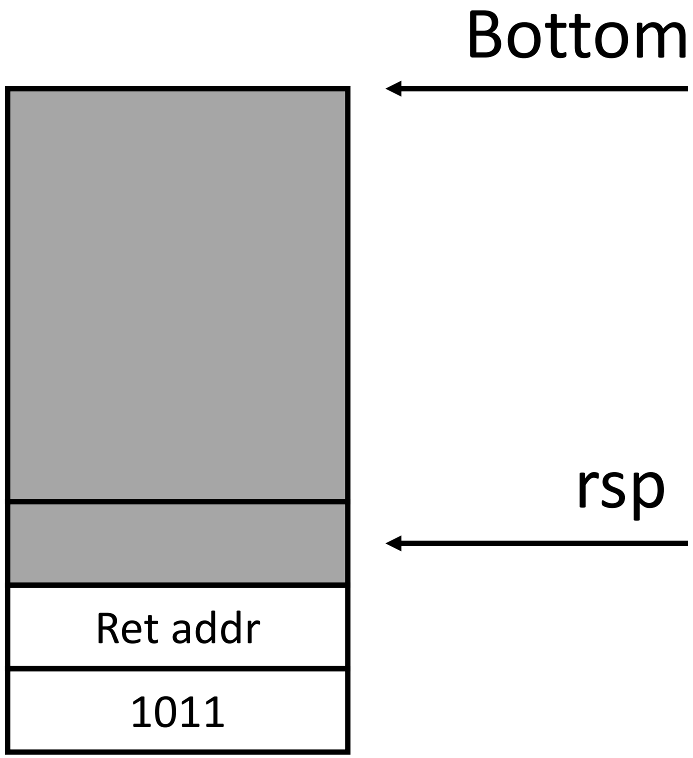
rdi
rsi
rdx
rcx
r8
r9

First argument



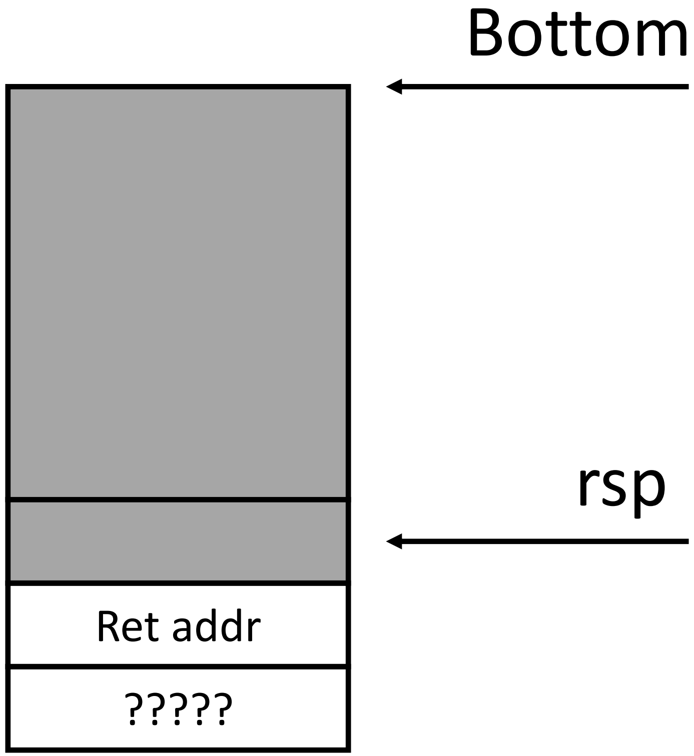
Stack frame: > 6 arguments, no locals

```
  (@go
    … //passing the first 6 arguments
→   mem rsp -8 <- :f_ret
    mem rsp -16 <- 11
→   call @f 7
    :f_ret
  )
  (@f
    7 0
→   rdi <- mem rsp 0
    call print 1
    return)
```



Stack frame: <= 6 arguments, 1 local

```
(@go
  ...
  mem rsp -8 <- :f_ret
  call @f 1
  :f_ret
  ...
)
(@f
  1 1
  return
)
```



L1 program example

Is there a bug? Where?

```
(@go
  (@go
   0 0
   rdi <- 5
   rsi <- 3
                 mem rsp -8 <- :f_ret
   call @myF 2
                 :f_ret
   return
  )
```

```
(@myF
 2 0
 call print 1
 rdi <- rsi
 call print 1
 return
)
```

What is the output?

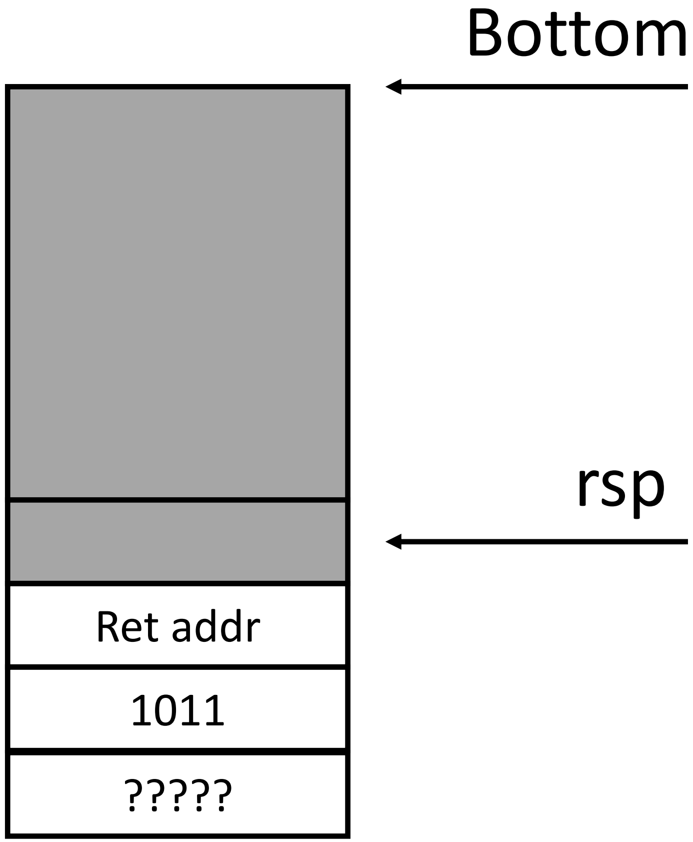
2

1

Stack frame: > 6 arguments, > 0 locals

```
  (@go
     ... //passing the first 6 arguments
→    mem rsp -8 <- :f_ret
     mem rsp -16 <- 11
→    call @f 7
     :f_ret
  )
  (@f
     7 1
→    rdi <- mem rsp 0
     call print 1
     return)
```

What does it print?



Stack pointer

- rsp (the stack pointer) is never modified directly by L1 code

- call and return instructions implicitly modify rsp to do their jobs (see the grammar)

Outline

- L1 language
- Value encoding
- Calling convention
- Heap

Heap memory in L1

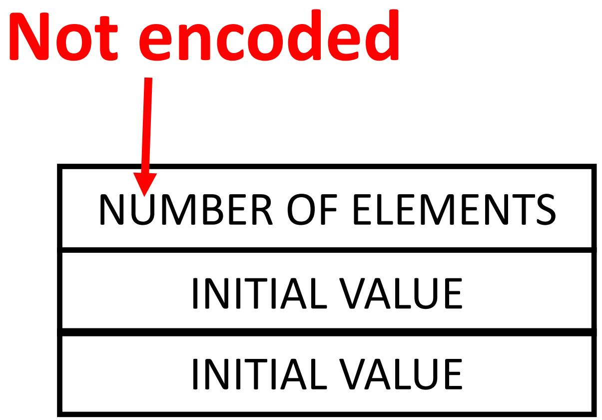
- Arrays are allocated in the heap

- No explicit deallocation
  - A garbage collector is assumed

- APIs
  - allocate:
    allocate an array of a given number of 64-bit integer elements
  - tensor-error:
    write to stdout an error message and abort the execution

Heap memory in L1

- allocate
  - Argument 1: number of array elements to allocate
  - Argument 2: 64-bit integer value used to initialize all array elements
  - Return: pointer to the array allocated and initialized



Not encoded

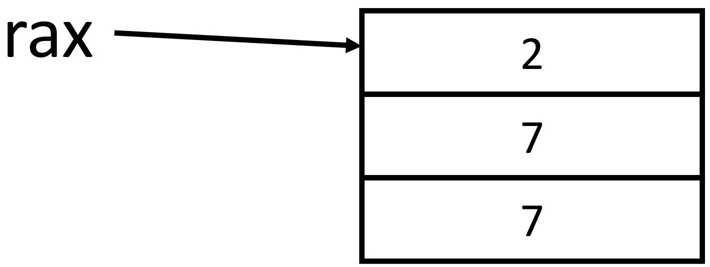
NUMBER OF ELEMENTS

INITIAL VALUE

INITIAL VALUE

Example of L1 program using heap memory

```
(@go
 (@go
   0 0
   rdi <- 5
   rsi <- 7
   call allocate 2
   return
 )
)
```

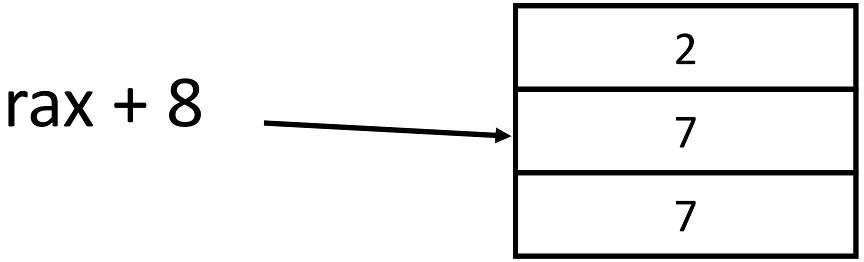


Example of L1 program using heap memory

```
(@go
  0 0
  rdi <- 5
  rsi <- 7
  call allocate 2
  rdi <- mem rax 8
  call print 1
  return
)
```

What is the output?

3

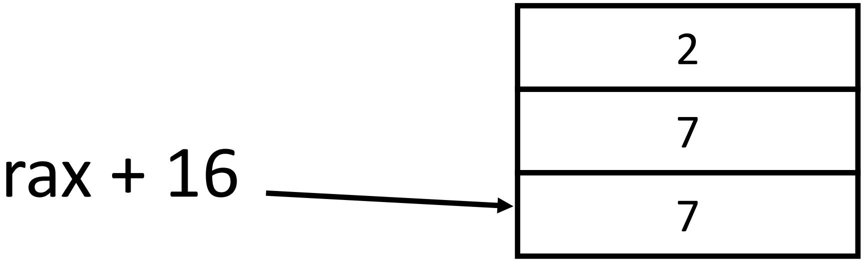


Example of L1 program using heap memory

```
(@go
 0 0
 rdi <- 5
 rsi <- 7
 call allocate 2
 rdi <- mem rax 16
 call print 1
 return
)
```

What is the output?

3



Example of L1 program using heap memory

```
(@go
  0 0
  rdi <- 5
  rsi <- 7
  call allocate 2
  rdi <- mem rax 0
  call print 1
  return
)
```

What is the output?

Segmentation fault

```
rdi <<= 1
rdi++
```

How can we fix this L1 program?

Printing an array

- The API print writes to stdout
  the whole array if its pointer is passed as argument

```
rdi <- 5
rsi <- 7
call allocate 2
rdi <- rax
call print 1
```

```
{s:2, 3, 3}
```

Tensors: array of arrays

```
(@go  0 0
  rdi <- 5
  rsi <- 7
  call allocate 2
  rdi <- 7
  rsi <- rax
  call allocate 2
  rdi <- rax
  call print 1
  return
)
```

Allocate an array of 2 integer values

Allocate an array of 3 pointers and initialize them to point to the previously allocated array

The output: {s:3, {s:2, 3, 3}, {s:2, 3, 3}, {s:2, 3, 3}}

Error messaging in L1

tensor-error 1

- Goal: report to the program’s developer a tensor access error
  and abort the execution
- Type of error: a heap object has been accessed without allocating it first
- Arguments:
    - First: line number of the program’s file where the tensor access error has occurred at run-time

Example of L1 code that uses tensor-error

```
(@myF   1 0
cjump rdi = 0 :ERROR
call print 1
:ERROR
rdi <- 5
call tensor-error 1
)
```

If this instruction executes, then no other instructions will execute

No need for a return instruction

Error messaging in L1

tensor-error 3

- Goal: report to the program’s developer an array access error and abort the execution
- Type of error: out-of-bound array access
- Arguments:
  - First: line number of the program’s file where the access error has occurred at run-time
  - Second: length of the array that has been accessed incorrectly
  - Third: index of the array used to access the array incorrectly

Error messaging in L1

tensor-error 4

- Goal: report to the program's developer a tensor access error and abort the execution
- Type of error: out-of-bound tensor access
- Arguments:
  - First: line number of the program's file where the access error has occurred at run-time
  - Second: dimension of the out-of-bound tensor access
  - Third: length of the dimension of the tensor accessed incorrectly
  - Forth: index used in the dimension that has generated the run-time error

Final notes

- The calling convention must be ALWAYS preserved

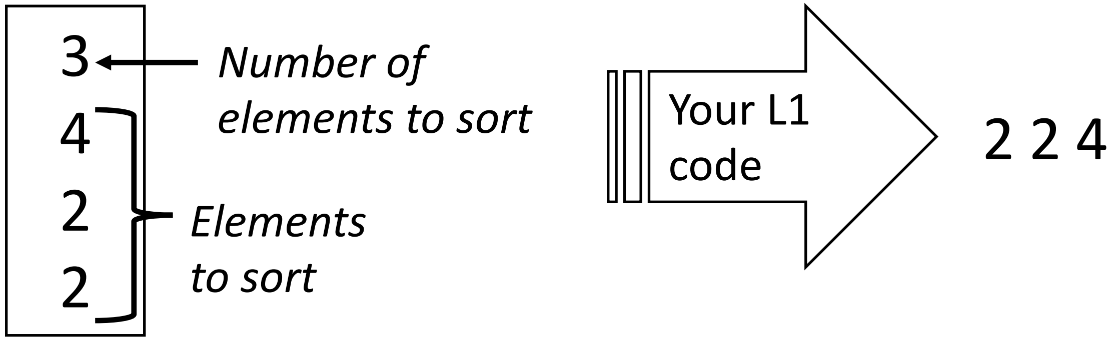
- An L1 program with undefined behavior is an incorrect L1 program

- You can write comments in L1
  - A comment starts with “//” and it comments until the end of the line
  - Example

```
// This is a comment
rdi <- 5

// this is another comment
```

Tests

- Write an L1 program that takes as input a sequence of numbers and print them in ascending order (an example of an input file is available on canvas)
  - Example of input file:



3
4
2
2

Number of elements to sort

Elements to sort

Your L1 code

2 2 4

  - The name of the L1 program file must end with .L1
  - For example: myTest1.L1
- Deadline: 2 days from today (see Canvas for the exact deadline)
- Tests and pairs
  - Submit one L1 program per pair

Always have faith in your ability

Success will come your way eventually

Best of luck!