Compiler Construction

Lecture 11: The Jargon VM

Jeremy Yallop

jeremy.yallop@cl.cam.ac.uk

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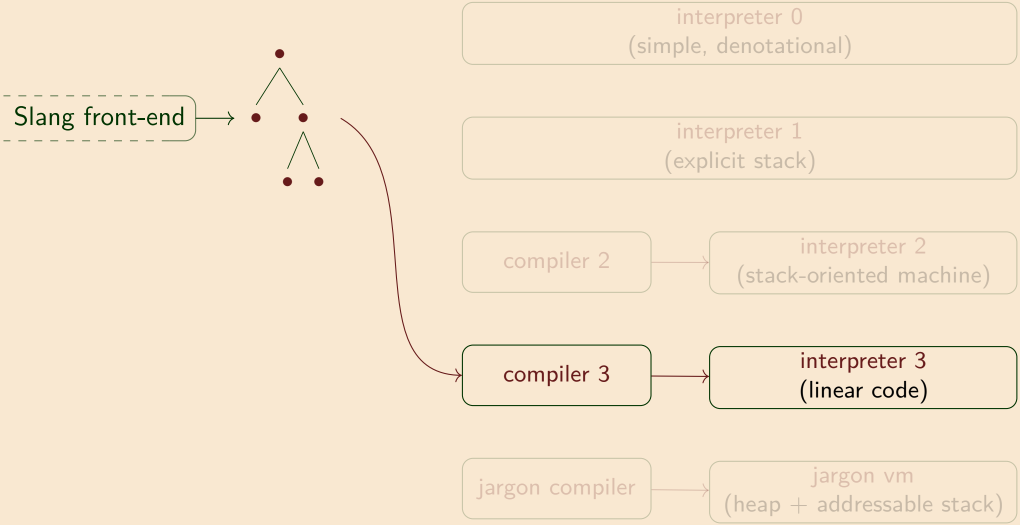
Reminder: the derivation



Slang front-end

interpreter 0
(simple, denotational)

interpreter 1
(explicit stack)

compiler 2

interpreter 2
(stack-oriented machine)

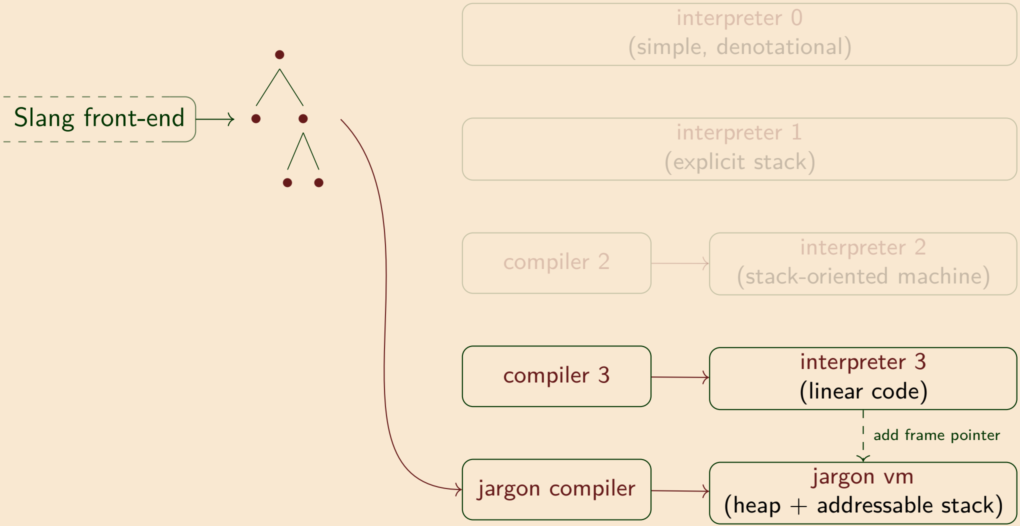
compiler 3

interpreter 3
(linear code)

jargon compiler

jargon vm
(heap + addressable stack)

Reminder: the derivation



Jargon VM

Deriving the Jargon VM (interpreter 4)

Three changes to interpreter 3:

Addressable stack

Replace variable lookup by a static offset from a **frame pointer** or closure

Closure representation

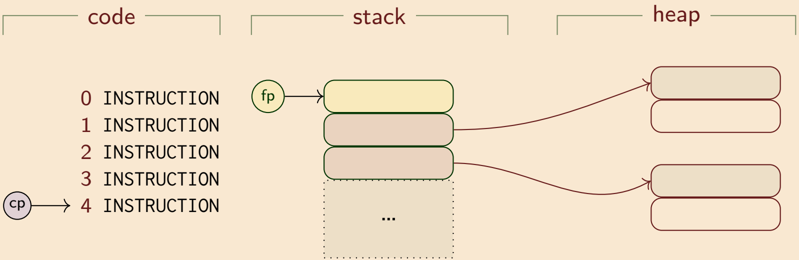
Optimise the **representation of closures** to contain only a code pointer and values for the free variables of the closure

Simple stack values

Restrict values on stack to be simple (ints, bools, heap addresses, etc).
Move complex data to the **heap**

(How might things look different in a language without first-class functions? or in a language with multiple arguments to function calls?)

Jargon Virtual Machine



cp code pointer (to next instruction)

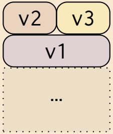
fp frame pointer (to current activation frame)

not shown: stack pointer, heap limit

The stack in interpreter 3

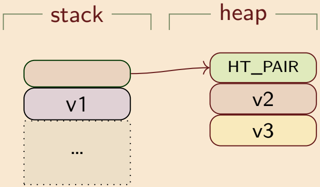
> *All problems in computer science can be solved by another level of indirection, except of course for the problem of too many indirections.*
>
> — *David Wheeler*

Problem: Interpreter 3 stack elements not fixed size



Virtual machines (JVM, etc) typically restrict stack elements to have fixed size

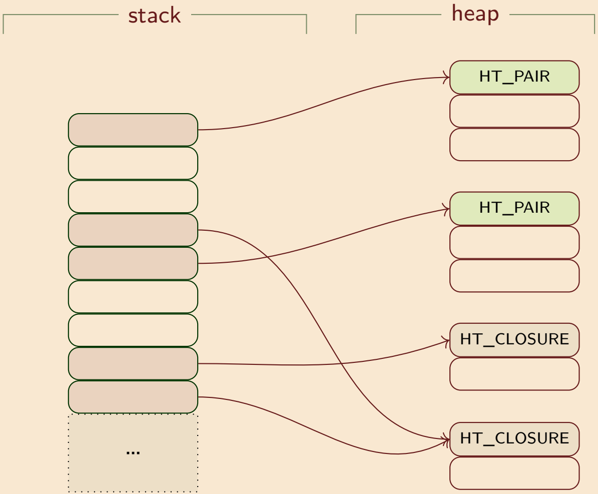
Solution: put the data in the **heap**



Place pointers to heap on stack

Jargon VM: the stack and the heap

Some stack elements represent pointers into the heap:



Instructions

Small changes to instructions

Interpreter 3

```
type instruction =
| PUSH of value
| LOOKUP of Ast.var
| UNARY of Ast.unary_oper
| OPER of Ast.oper
| SWAP
| POP
| BIND of Ast.var
| FST
| SND
| APPLY
| RETURN
| MK_PAIR
| MK_CLOSURE of location
| TEST of location
| GOTO of location
| LABEL of label
| HALT
...
```

Jargon VM

```
type instruction =
| PUSH of stack_item
| LOOKUP of value_path
| UNARY of Ast.unary_oper
| OPER of Ast.oper
| SWAP
| POP

| FST
| SND
| APPLY
| RETURN
| MK_PAIR
| MK_CLOSURE of location * int
| TEST of location
| GOTO of location
| LABEL of label
| HALT
...
and value_path =
   | STACK_LOCATION of offset
   | HEAP_LOCATION of offset
```

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and value_path =
    | STACK_LOCATION of offset
    | HEAP_LOCATION of offset
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Value, stack and heap data types

Interpreter 3

```
type value =
  | REF of address
  | INT of int
  | BOOL of bool
  | UNIT
  | PAIR of value * value
  | INL of value
  | INR of value
  | CLOSURE of location * env
type env_or_value =
  | EV of env
  | V of value
  | RA of address
type env_value_stack =
    env_or_value list
```

Stack contains structured values

Jargon VM

```
type stack_item = STACK_INT of int
                | STACK_BOOL of bool
                | STACK_UNIT
                | STACK_HI of heap_index
                | STACK_RA of code_index
                | STACK_FP of stack_index
```

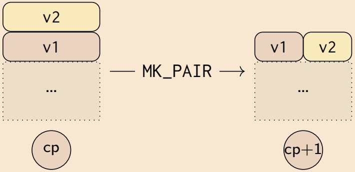
Stack contains integers, heap addresses, code addresses, & stack addresses

```
type heap_type =  HT_PAIR
                | HT_INL
                | HT_INR
                | HT_CLOSURE
type heap_item =  HEAP_INT of int
                | HEAP_BOOL of bool
                | HEAP_UNIT
                | HEAP_HI of heap_index
                | HEAP_CI of code_index
                | HEAP_HEADER of int
                                 * heap_type
```

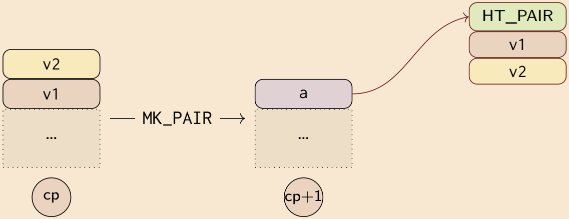
Heap contains integers, addresses & code addresses
(The headers will be essential for garbage collection)

MK_PAIR

In interpreter 3:



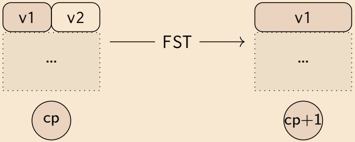
In Jargon VM:



The pair is freshly allocated on the heap

FST (similar for SND)

In interpreter 3:



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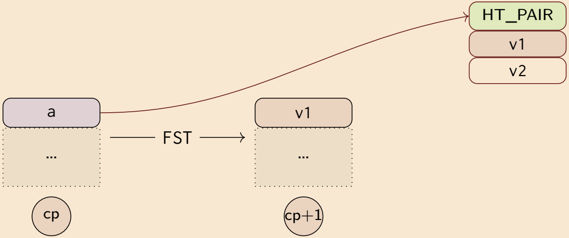
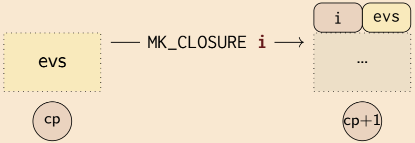


Note: v1 might be a simple value (`int` or `bool`) or another heap address

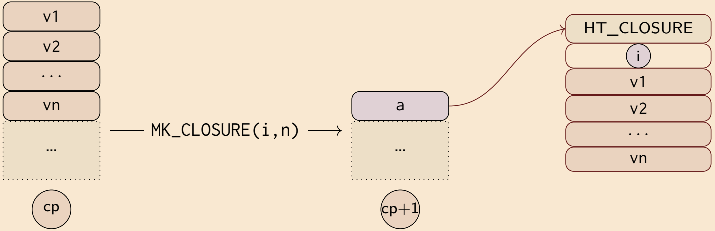
Functions

MK_CLOSURE (c,n)

In interpreter 3:

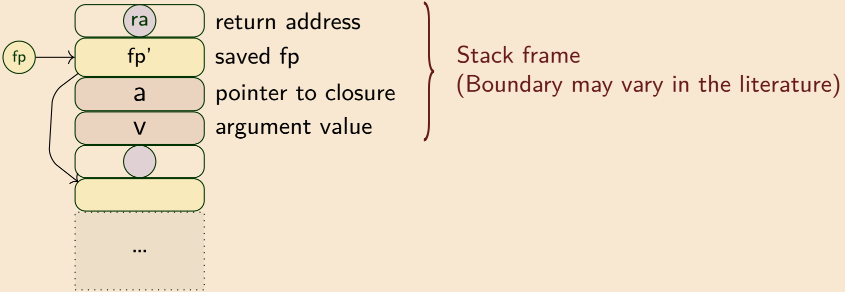


In Jargon VM:



i = code location of start of instructions for closure
n = number of free variables in the body of closure.
Put values associated with **free variables** on stack, then construct the closure on the heap

A stack frame

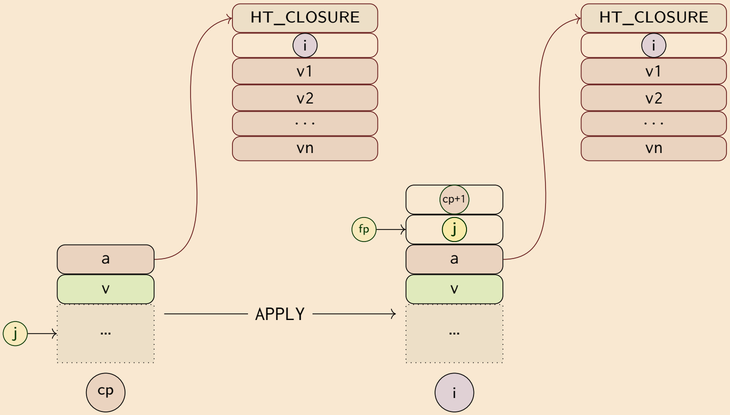


return address
saved fp
pointer to closure
argument value

Stack frame
(Boundary may vary in the literature)

Executing code for closure at heap address a after it was applied to argument v.

APPLY

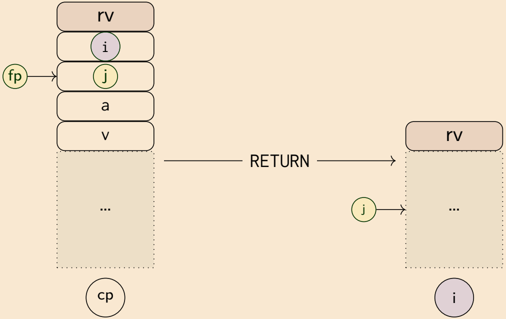


Push stack frame

Save return address (code pointer)

Save and update frame pointer

RETURN



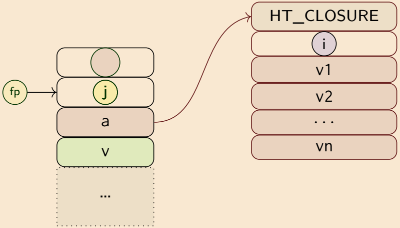
Discard stack frame

Update code pointer to return address

Restore frame pointer

Variables

Finding a variable’s value at runtime

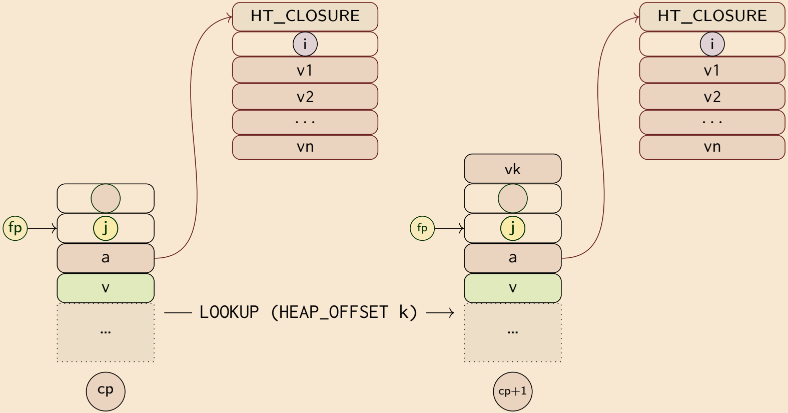


Suppose we are executing code associated with this closure. Then:

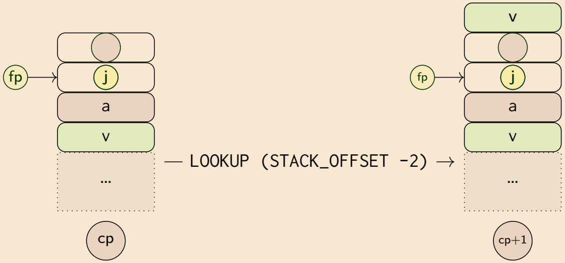
The **argument** can be found at a fixed offset from fp

The **free variables** in the closure body can be found at fixed offsets from the closure a

LOOKUP (HEAP_OFFSET k)

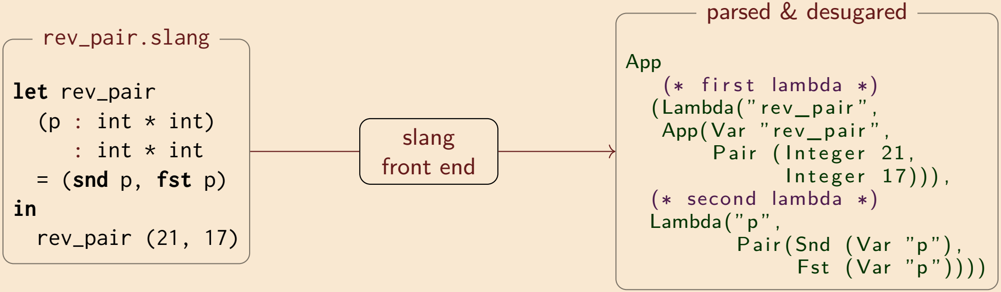


LOOKUP (STACK_OFFSET -2)



Example

Example: compiling rev_pair.slang (front end)



rev_pair.slang

```
let rev_pair
  (p : int * int)
     : int * int
  = (snd p, fst p)
in
  rev_pair (21, 17)
```

parsed & desugared

```
App
   (* first lambda *)
  (Lambda("rev_pair",
   App(Var "rev_pair",
       Pair (Integer 21,
             Integer 17))),
  (* second lambda *)
  Lambda("p",
         Pair(Snd (Var "p"),
              Fst (Var "p"))))
```

```
         (fun rev_pair =>
i.e.:       rev_pair (21, 17))
         (fun p => (snd p, fst p))
```

Example: compiling rev_pair.slang (back end)

Jargon VM

Instructions

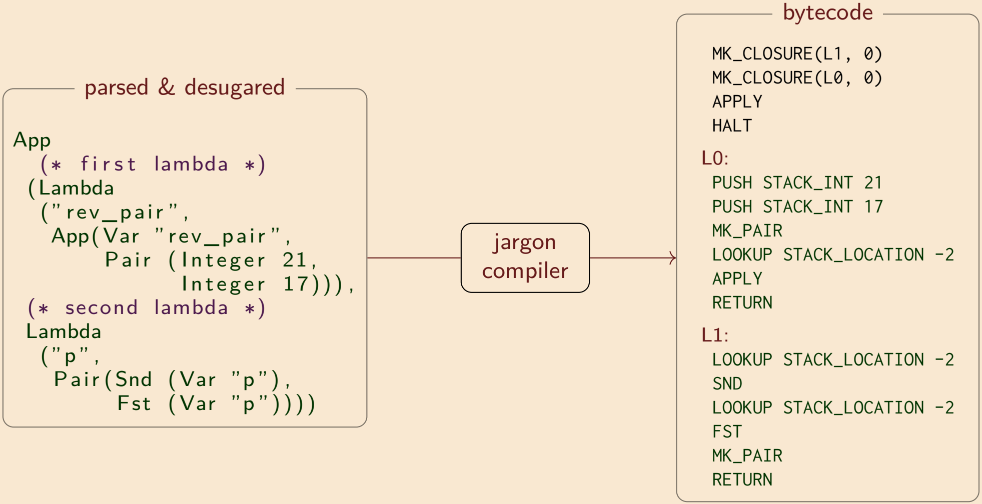
Functions

Variables

Example

● ● ○

The Gap



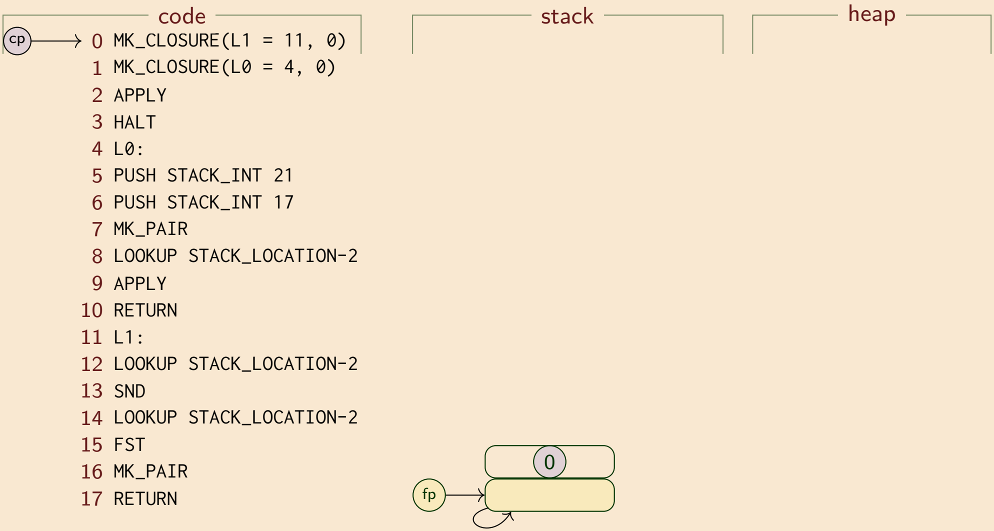
parsed & desugared

```
App
  (* first lambda *)
 (Lambda
  ("rev_pair",
   App(Var "rev_pair",
       Pair (Integer 21,
             Integer 17))),
 (* second lambda *)
 Lambda
  ("p",
   Pair(Snd (Var "p"),
        Fst (Var "p"))))
```

bytecode

```
   MK_CLOSURE(L1, 0)
   MK_CLOSURE(L0, 0)
   APPLY
   HALT
L0:
   PUSH STACK_INT 21
   PUSH STACK_INT 17
   MK_PAIR
   LOOKUP STACK_LOCATION -2
   APPLY
   RETURN
L1:
   LOOKUP STACK_LOCATION -2
   SND
   LOOKUP STACK_LOCATION -2
   FST
   MK_PAIR
   RETURN
```

Example: executing rev_pair.slang



```
 0 MK_CLOSURE(L1 = 11, 0)
 1 MK_CLOSURE(L0 = 4, 0)
 2 APPLY
 3 HALT
 4 L0:
 5 PUSH STACK_INT 21
 6 PUSH STACK_INT 17
 7 MK_PAIR
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 9 APPLY
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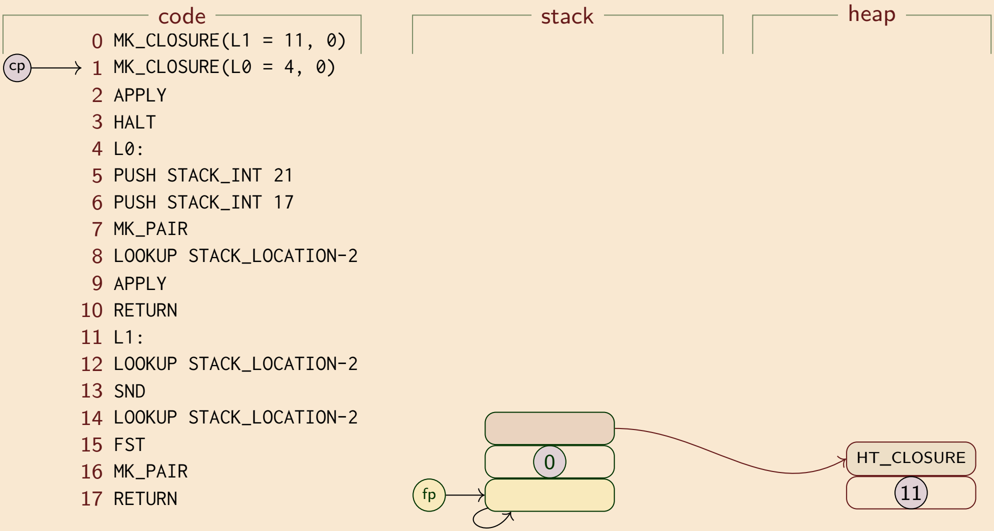

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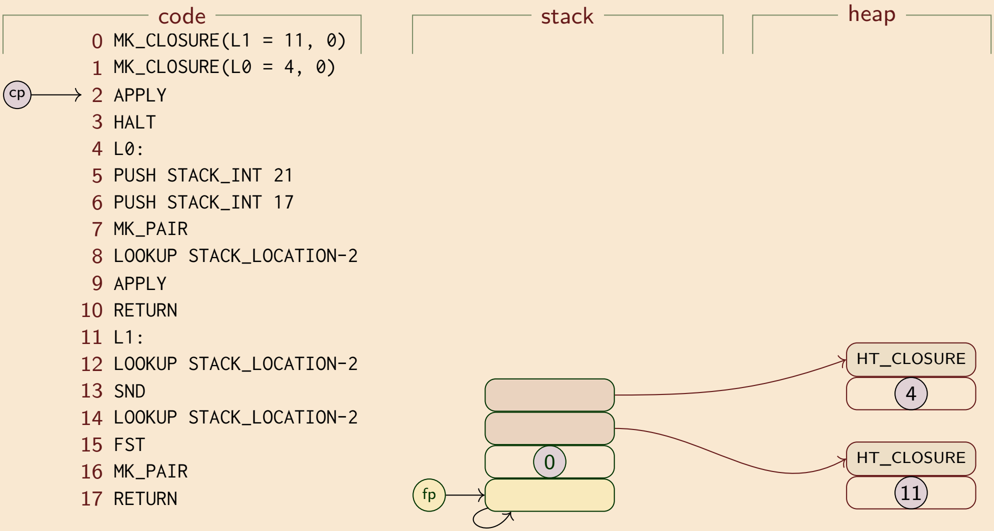

code

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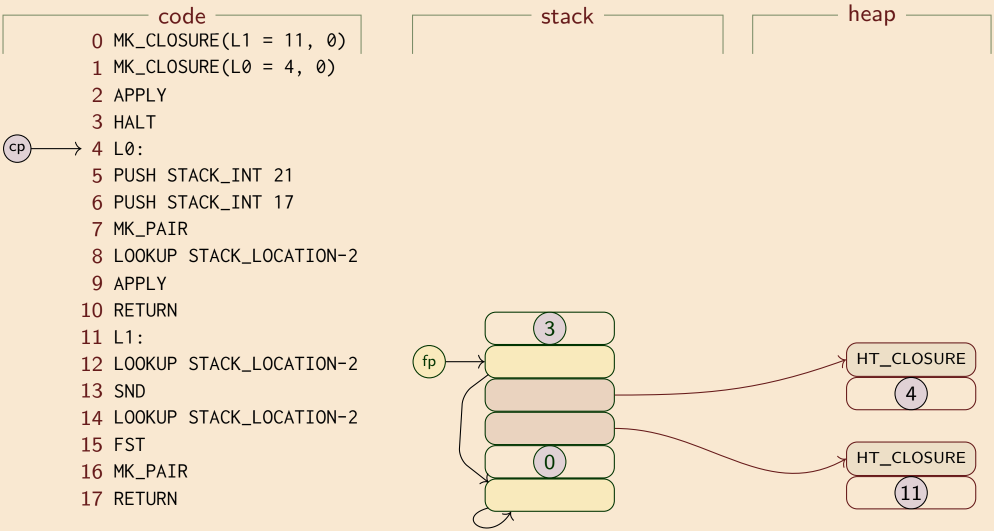

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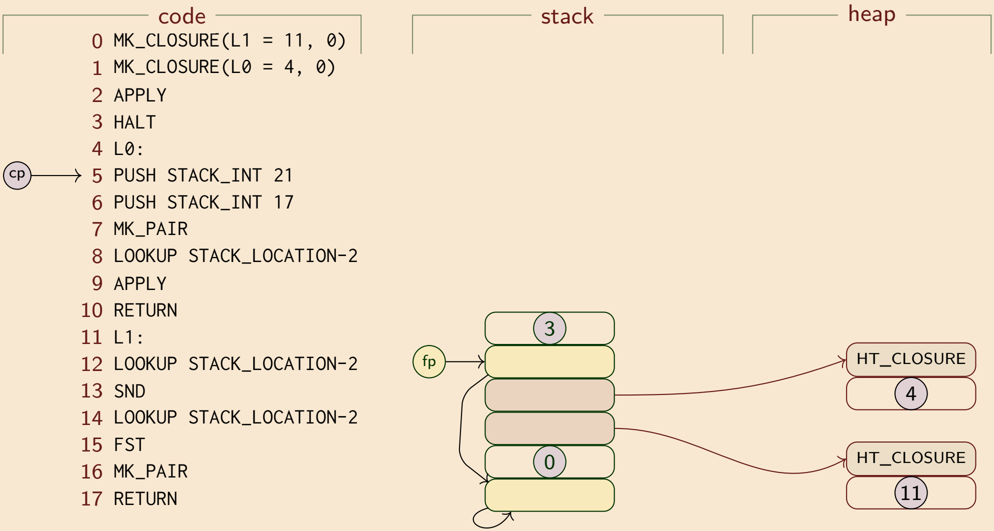

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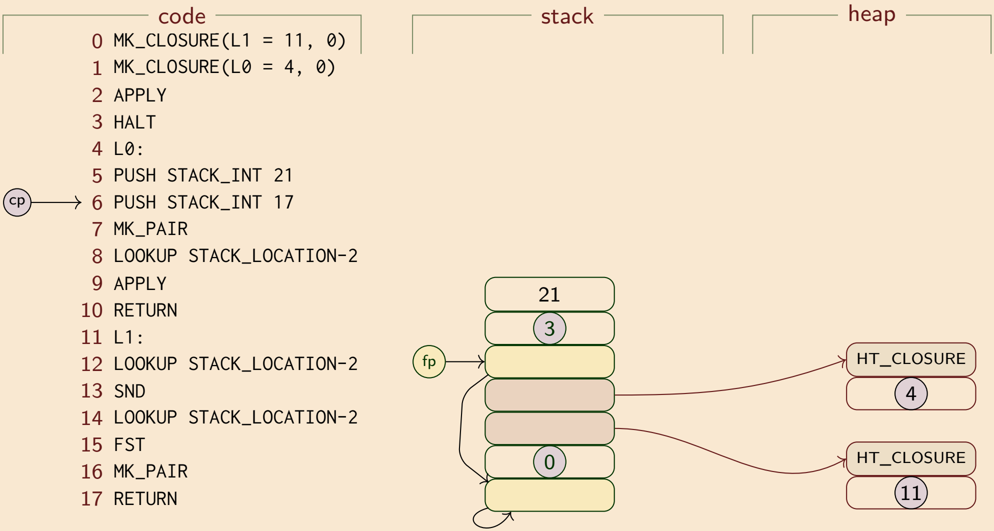

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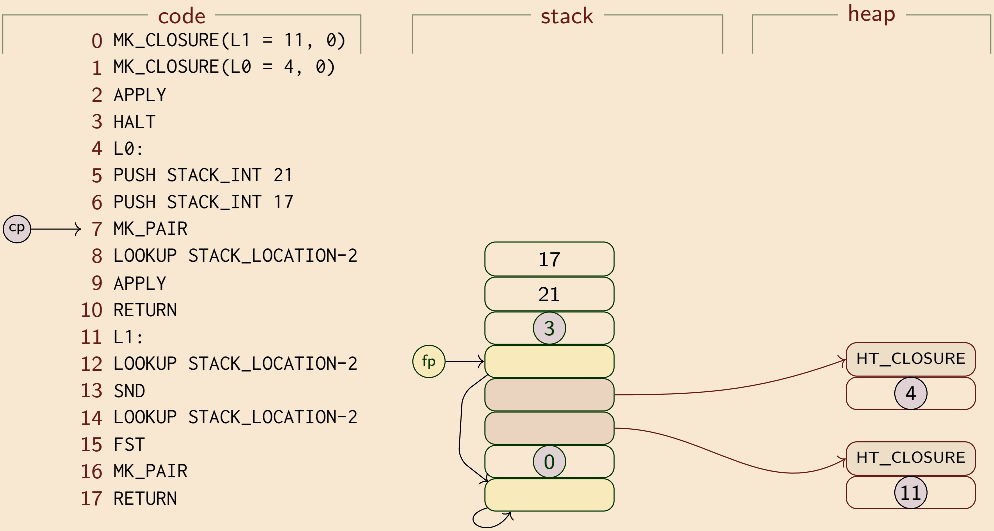

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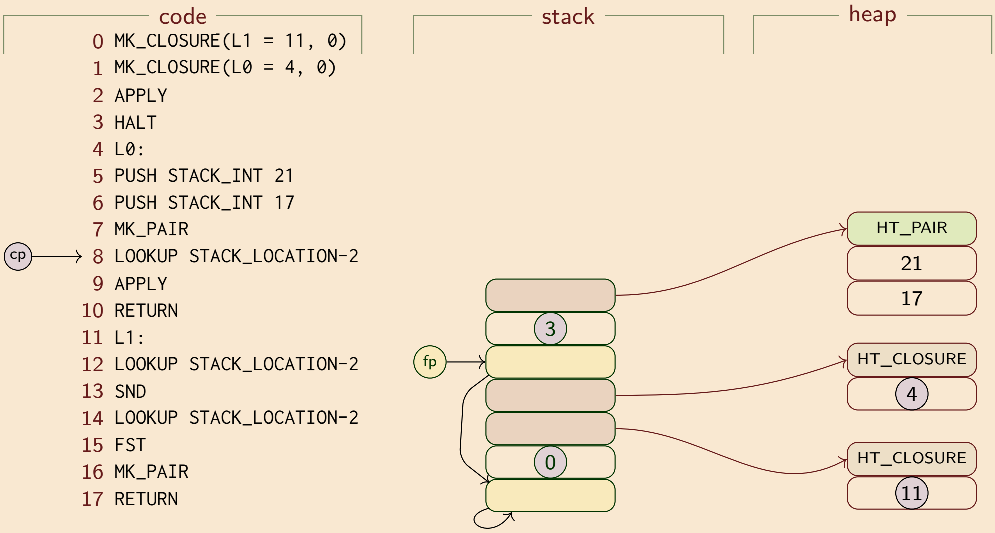

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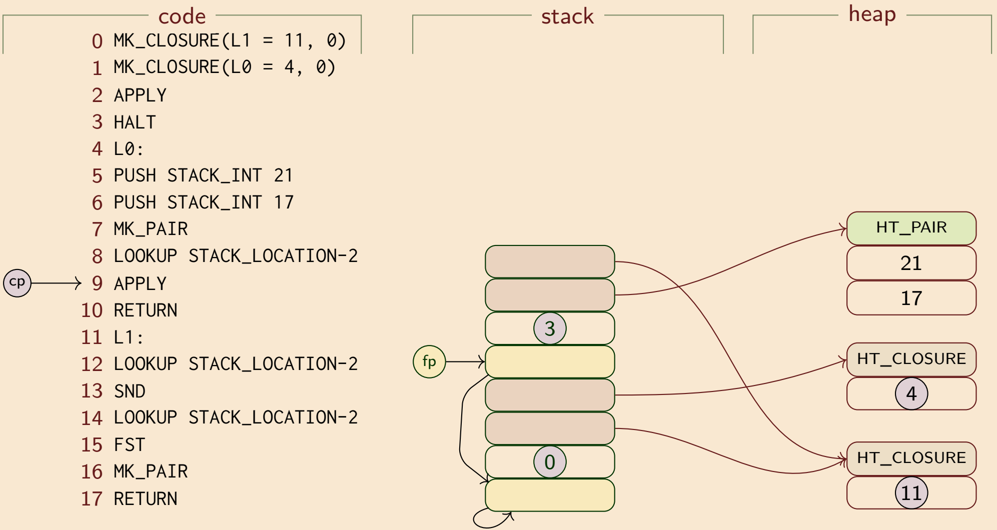

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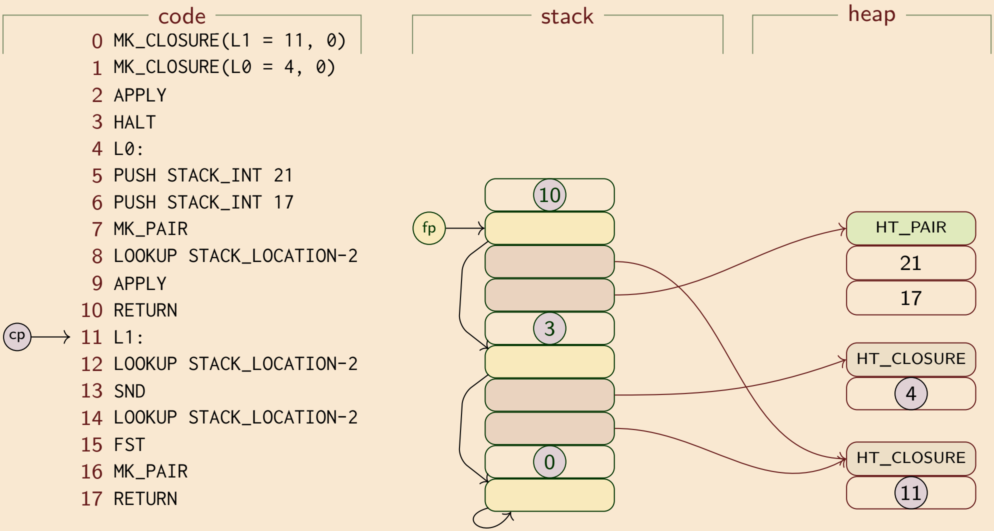

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Example: executing rev_pair.slang

code

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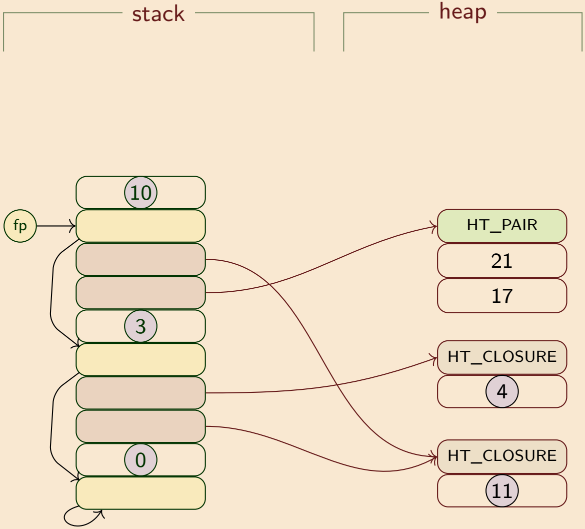
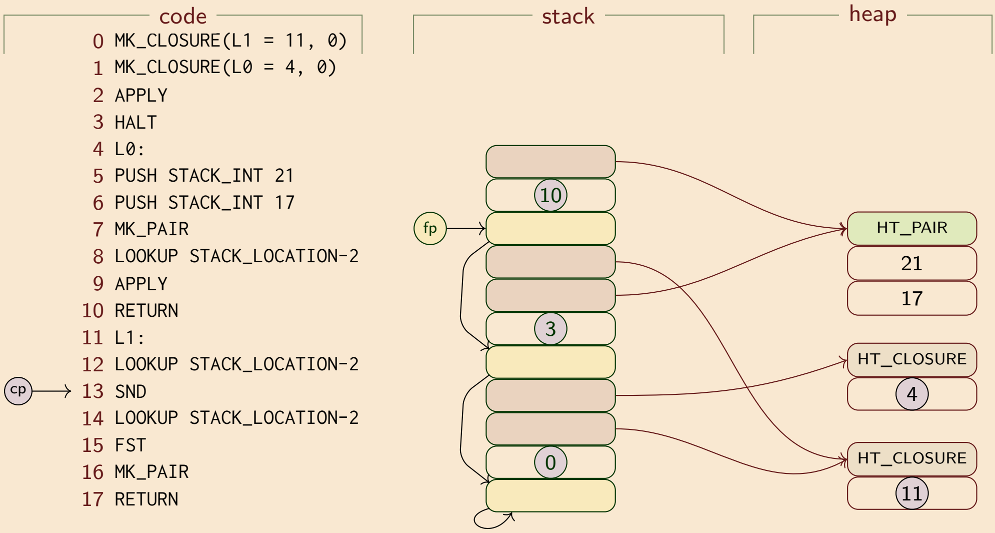
         3  HALT
         4  L0:
         5  PUSH STACK_INT 21
         6  PUSH STACK_INT 17
         7  MK_PAIR
         8  LOOKUP STACK_LOCATION-2
         9  APPLY
        10  RETURN
        11  L1:
cp →    12  LOOKUP STACK_LOCATION-2
        13  SND
        14  LOOKUP STACK_LOCATION-2
        15  FST
        16  MK_PAIR
        17  RETURN
```



Example: executing rev_pair.slang



code

```
 0 MK_CLOSURE(L1 = 11, 0)
 1 MK_CLOSURE(L0 = 4, 0)
 2 APPLY
 3 HALT
 4 L0:
 5 PUSH STACK_INT 21
 6 PUSH STACK_INT 17
 7 MK_PAIR
 8 LOOKUP STACK_LOCATION-2
 9 APPLY
10 RETURN
11 L1:
12 LOOKUP STACK_LOCATION-2
13 SND
14 LOOKUP STACK_LOCATION-2
15 FST
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```

Example: executing rev_pair.slang

code

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         0  MK_CLOSURE(L1 = 11, 0)
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cp →    14  LOOKUP STACK_LOCATION-2
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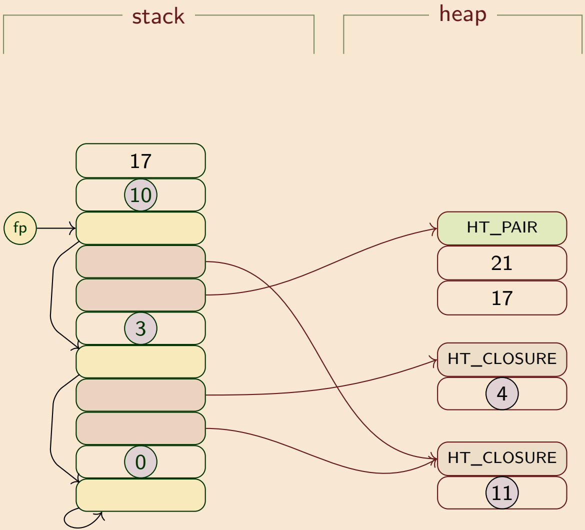
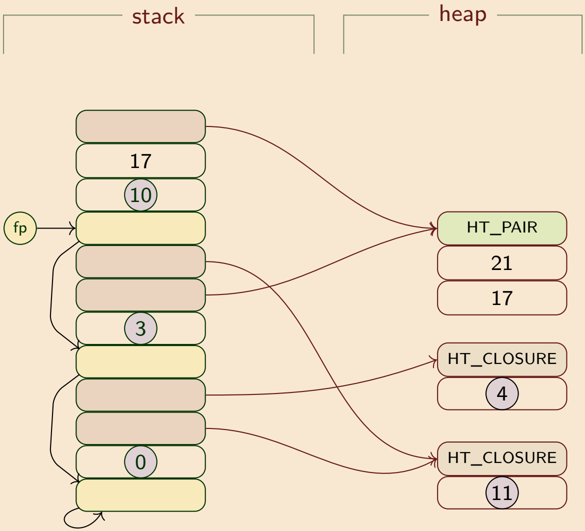
        16  MK_PAIR
        17  RETURN
```



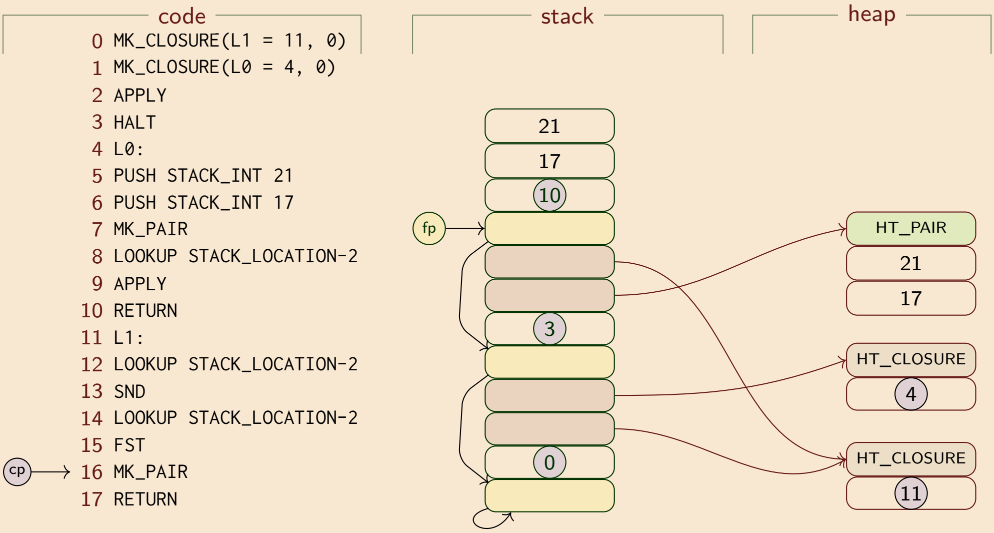
Example: executing rev_pair.slang

code

```
    0 MK_CLOSURE(L1 = 11, 0)
    1 MK_CLOSURE(L0 = 4, 0)
    2 APPLY
    3 HALT
    4 L0:
    5 PUSH STACK_INT 21
    6 PUSH STACK_INT 17
    7 MK_PAIR
    8 LOOKUP STACK_LOCATION-2
    9 APPLY
   10 RETURN
   11 L1:
   12 LOOKUP STACK_LOCATION-2
   13 SND
   14 LOOKUP STACK_LOCATION-2
cp → 15 FST
   16 MK_PAIR
   17 RETURN
```



Example: executing rev_pair.slang



```
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 1 MK_CLOSURE(L0 = 4, 0)
 2 APPLY
 3 HALT
 4 L0:
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10 RETURN
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13 SND
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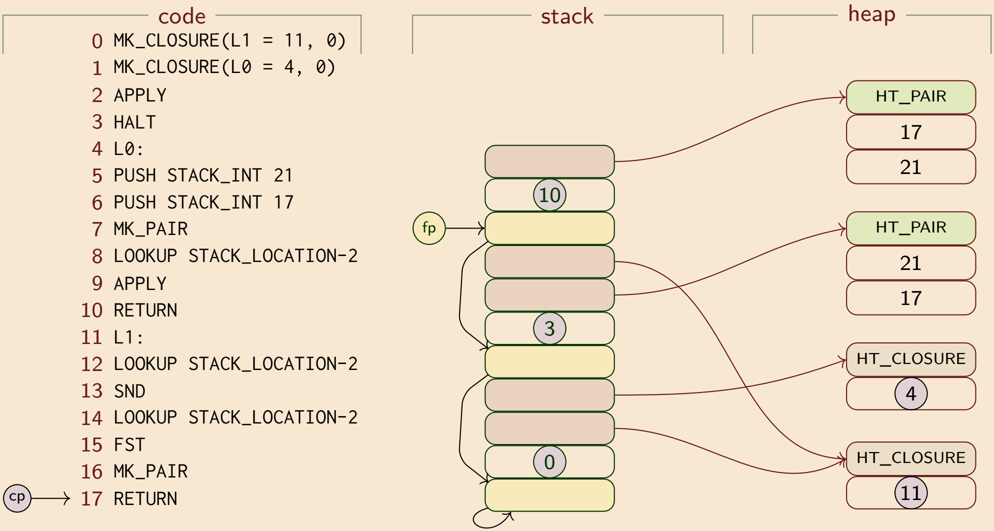
15 FST
16 MK_PAIR
17 RETURN
```

Example: executing rev_pair.slang



code

```
 0 MK_CLOSURE(L1 = 11, 0)
 1 MK_CLOSURE(L0 = 4, 0)
 2 APPLY
 3 HALT
 4 L0:
 5 PUSH STACK_INT 21
 6 PUSH STACK_INT 17
 7 MK_PAIR
 8 LOOKUP STACK_LOCATION-2
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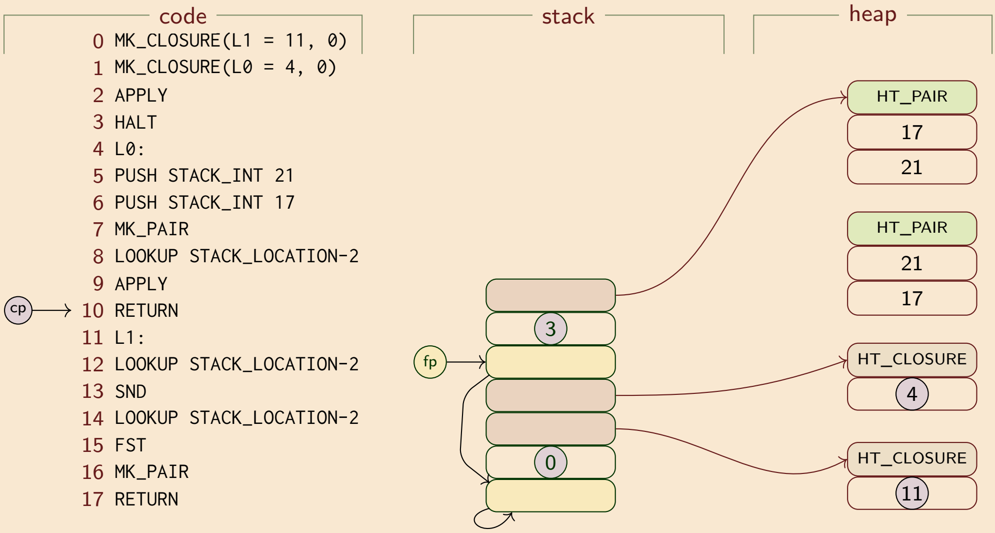
13 SND
14 LOOKUP STACK_LOCATION-2
15 FST
16 MK_PAIR
17 RETURN
```

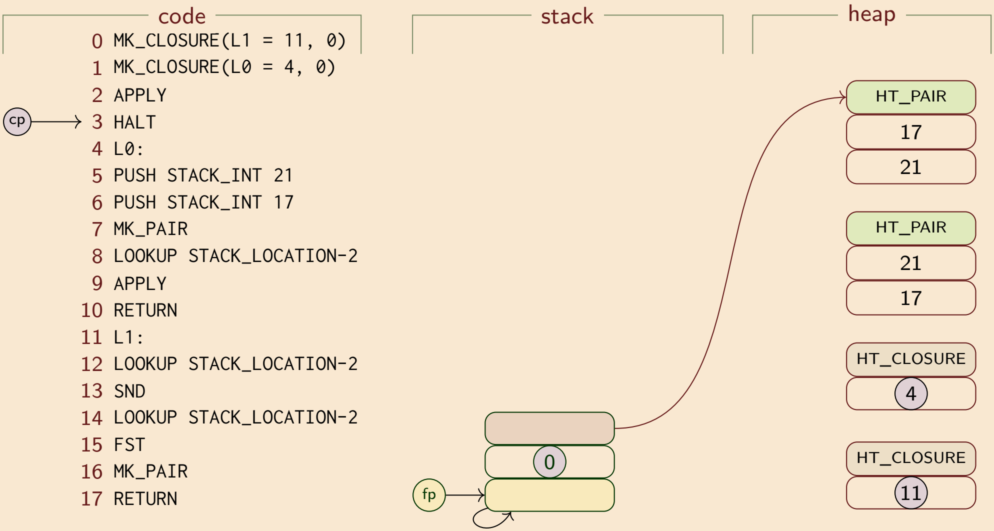
Example: executing rev_pair.slang



code

```
0  MK_CLOSURE(L1 = 11, 0)
1  MK_CLOSURE(L0 = 4, 0)
2  APPLY
3  HALT
4  L0:
5  PUSH STACK_INT 21
6  PUSH STACK_INT 17
7  MK_PAIR
8  LOOKUP STACK_LOCATION-2
9  APPLY
10 RETURN
11 L1:
12 LOOKUP STACK_LOCATION-2
13 SND
14 LOOKUP STACK_LOCATION-2
15 FST
16 MK_PAIR
17 RETURN
```

Example: executing rev_pair.slang

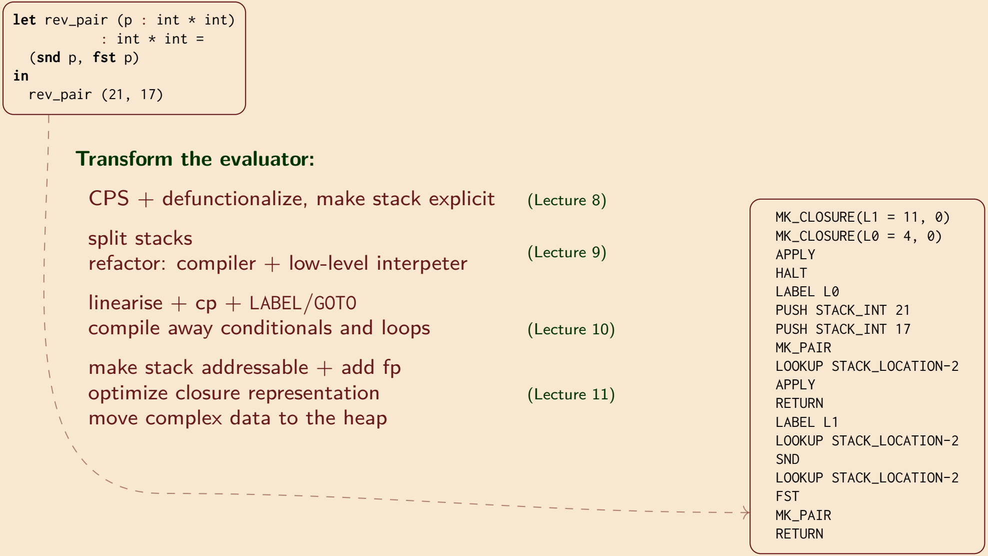


code

```
 0 MK_CLOSURE(L1 = 11, 0)
 1 MK_CLOSURE(L0 = 4, 0)
 2 APPLY
 3 HALT
 4 L0:
 5 PUSH STACK_INT 21
 6 PUSH STACK_INT 17
 7 MK_PAIR
 8 LOOKUP STACK_LOCATION-2
 9 APPLY
10 RETURN
11 L1:
12 LOOKUP STACK_LOCATION-2
13 SND
14 LOOKUP STACK_LOCATION-2
15 FST
16 MK_PAIR
17 RETURN
```

The Gap, revisited

The Gap: Slang to Jargon VM



```
let rev_pair (p : int * int)
           : int * int =
  (snd p, fst p)
in
  rev_pair (21, 17)
```

Transform the evaluator:

CPS + defunctionalize, make stack explicit (Lecture 8)

split stacks
refactor: compiler + low-level interpeter (Lecture 9)

linearise + cp + LABEL/GOTO
compile away conditionals and loops (Lecture 10)

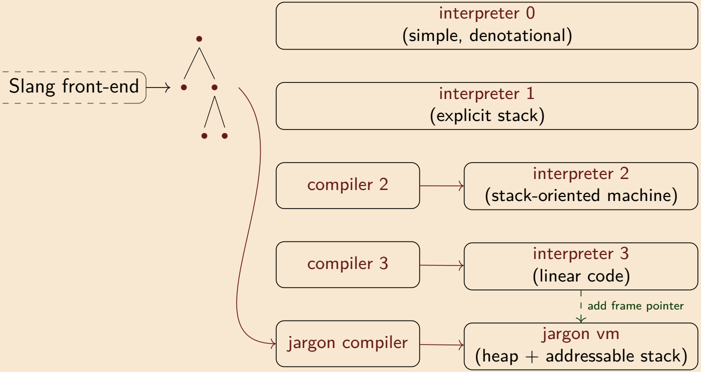
make stack addressable + add fp
optimize closure representation (Lecture 11)
move complex data to the heap

```
MK_CLOSURE(L1 = 11, 0)
MK_CLOSURE(L0 = 4, 0)
APPLY
HALT
LABEL L0
PUSH STACK_INT 21
PUSH STACK_INT 17
MK_PAIR
LOOKUP STACK_LOCATION-2
APPLY
RETURN
LABEL L1
LOOKUP STACK_LOCATION-2
SND
LOOKUP STACK_LOCATION-2
FST
MK_PAIR
RETURN
```

The derivation

Starting from a direct implementation of Slang/L3 semantics, we **derived** a virtual machine in a step-by-step manner.

The correctness of each step is easy to check.



Remarks

Semantic gap between Slang/L3 program & low-level translation (say x86/Unix) significantly reduced.

Implementing Jargon VM at a lower-level of abstraction (C?, JVM bytecode? X86/Unix? ...) now a relatively easy programming problem.

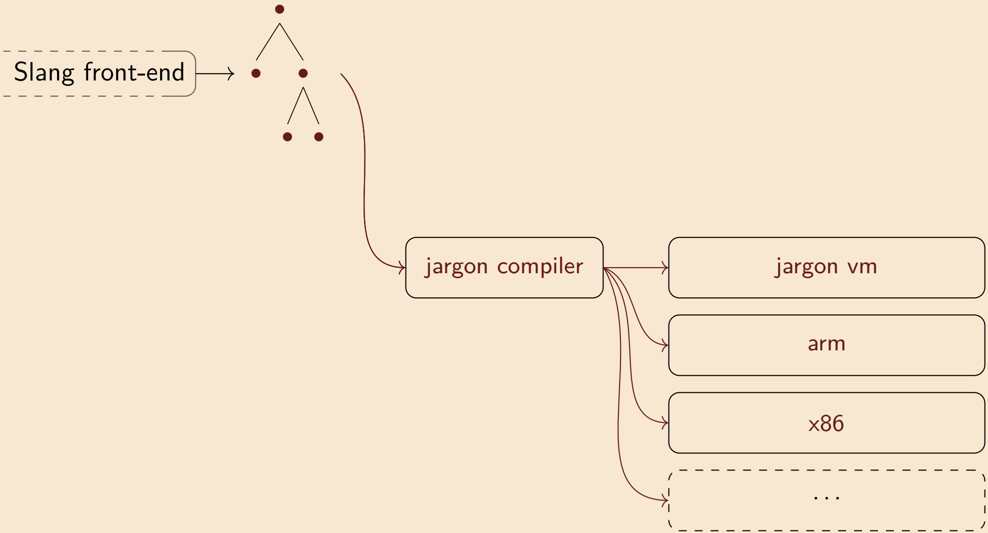
However, using a lower-level implementation (e.g. x86, exploiting fast registers) to generate very efficient code is not so easy. (See Part II Optimising Compilers).

New possibility: Jargon bytecode interpreter in C

```
...
...
void vsm_execute_instruction(vsm_state *state, bytecode instruction) {
  opcode code = instruction.code;
  argument arg1 = instruction.arg1;
  switch (code) {
    case PUSH: { state→stack[state→sp++] = arg1; state→pc++; break; }
    case GOTO: { state→pc = arg1; break; }
    case STACK_LOOKUP: {
      state→stack[state→sp++] =
      state→stack[state→fp + arg1];
      state→pc++; break;! }
    ...
  }
} ...
```

Idea: Generate compact bytecode for each Jargon instruction.
Compiler writes bytecode to a file
Implement an interpreter in C or C++ for the bytecode
Execution much faster than `jargon.ml`
Alternatively: generate assembly code from Jargon instructions

Backend could target multiple platforms



Slang front-end

jargon compiler

jargon vm

arm

x86

. . .

Next time: miscellany