

Compiler Construction

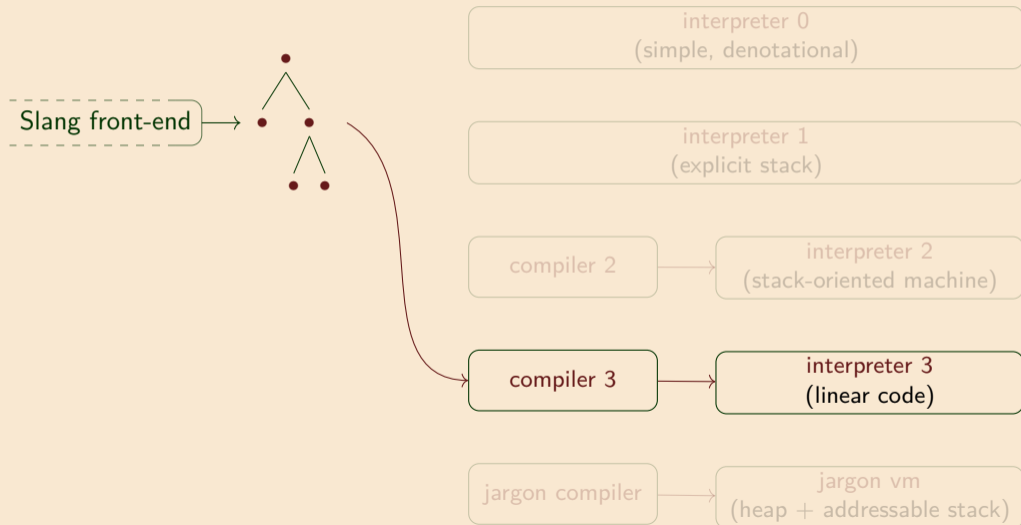
Lecture 11: The Jargon VM

Jeremy Yallop

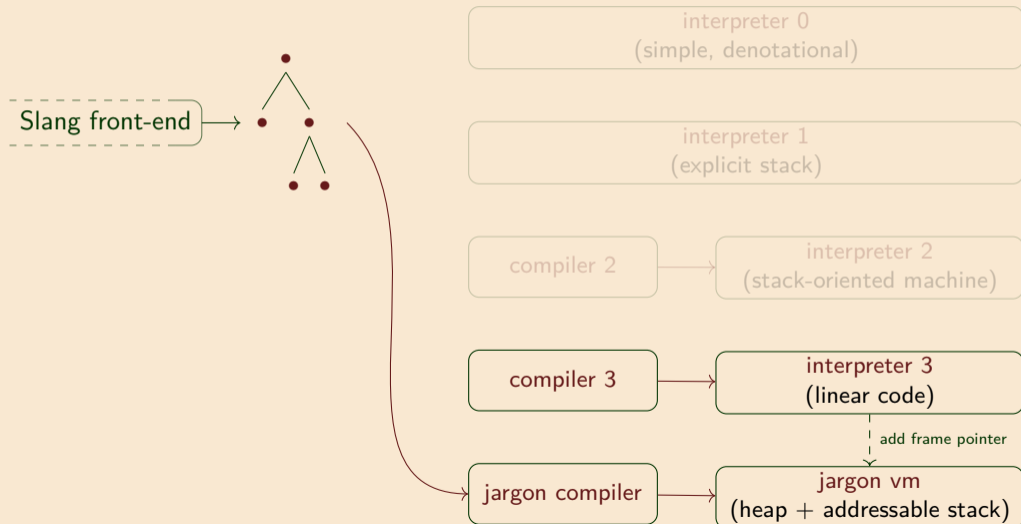
`jeremy.yallop@cl.cam.ac.uk`

Lent 2024

Reminder: the derivation



Reminder: the derivation



Jargon VM

Deriving the Jargon VM (interpreter 4)

Jargon VM



Instructions

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**

Functions

Variables

Example

The Gap

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

Jargon Virtual Machine

Jargon VM



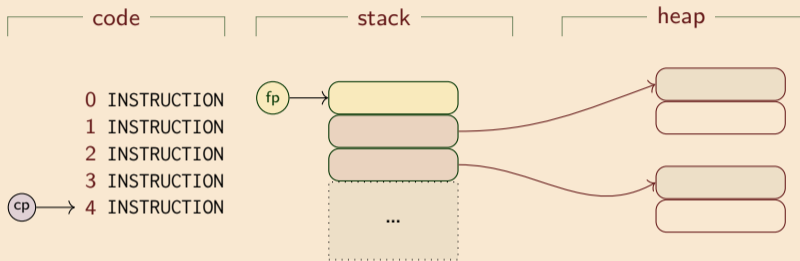
Instructions

Functions

Variables

Example

The Gap



cp code pointer (to next instruction)

fp frame pointer (to current activation frame)

not shown: stack pointer, heap limit

The stack in interpreter 3

Jargon VM



Instructions

Functions

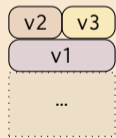
Variables

Example

The Gap

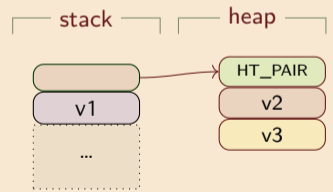
All problems in computer science can be solved by another level of indirection, except of course for the problem of too many indirections.
— David Wheeler

Problem: Interpreter 3 stack elements not fixed size



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

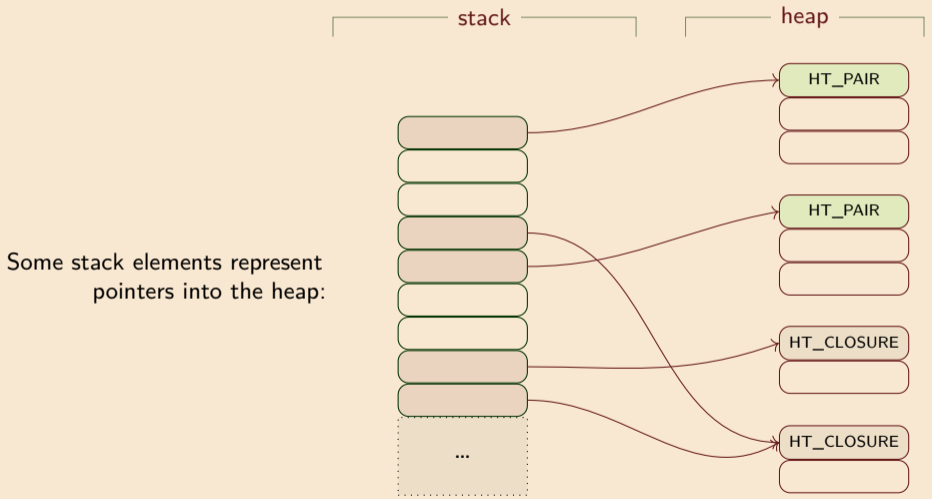
Solution: put the data in the **heap**



Place pointers to heap on stack

Jargon VM: the stack and the heap

- Jargon VM
- ● ● ●
- Instructions
- Functions
- Variables
- Example
- The Gap



Instructions

Small changes to instructions

Jargon VM

Instructions



Functions

Variables

Example

The Gap

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
```

Small changes to instructions

Jargon VM

Instructions



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Example

The Gap

Interpreter 3

```
type instruction =  
| PUSH of value  
| LOOKUP of Ast.var  
| UNARY of Ast.unary_oper  
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| 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
```

Small changes to instructions

Jargon VM

Instructions



Functions

Variables

Example

The Gap

```
Interpreter 3
type instruction =
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Jargon VM
type instruction =
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and value_path =
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Small changes to instructions

Jargon VM

Instructions



Functions

Variables

Example

The Gap

```
Interpreter 3
type instruction =
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```
Jargon VM
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| PUSH of stack_item
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| SWAP
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and value_path =
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Small changes to instructions

Jargon VM

Instructions



Functions

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Example

The Gap

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Interpreter 3
type instruction =
| PUSH of value
| LOOKUP of Ast.var
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| MK_PAIR
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| TEST of location
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| ...
```

```
Jargon VM
type instruction =
| PUSH of stack_item
| LOOKUP of value_path
| UNARY of Ast.unary_oper
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| ...
and value_path =
| STACK_LOCATION of offset
| HEAP_LOCATION of offset
```

Value, stack and heap data types

Jargon VM

Instructions



Functions

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Example

The Gap

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
```

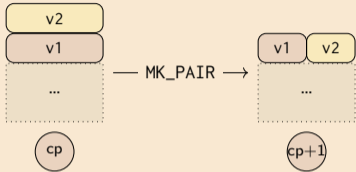
Stack contains integers, heap addresses,
code addresses, & stack addresses

```
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
```

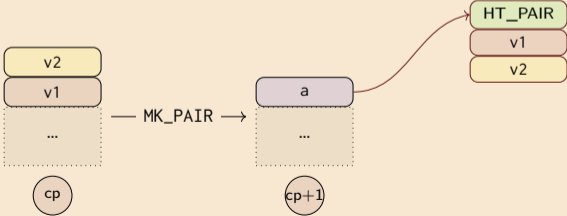
Heap contains integers, addresses & code addresses
(The headers will be essential for garbage collection)



In interpreter 3:



In Jargon VM:



The pair is freshly allocated on the heap

FST (similar for SND)

Jargon VM

Instructions



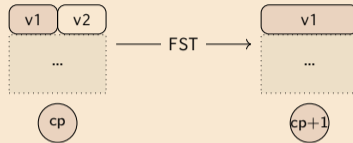
Functions

Variables

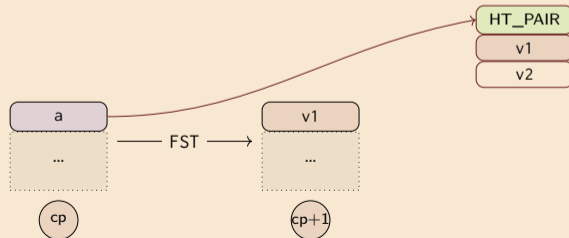
Example

The Gap

In interpreter 3:



In Jargon VM:



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

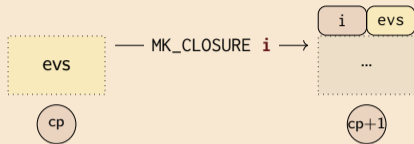
Functions

MK_CLOSURE (c,n)

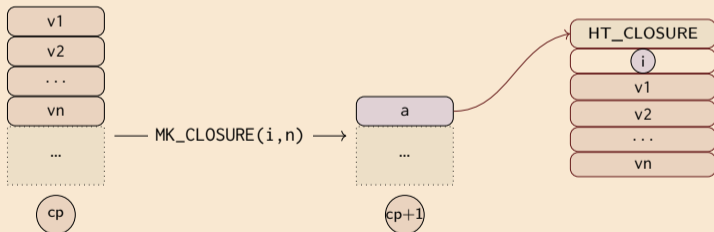
Jargon VM

Instructions

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

Functions



Variables

Example

The Gap

A stack frame

Jargon VM

Instructions

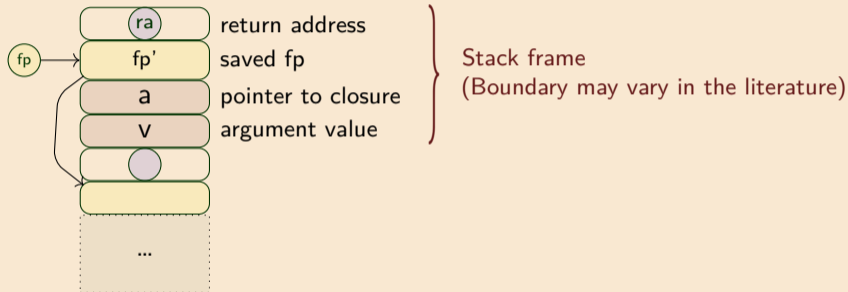
Functions



Variables

Example

The Gap



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

Jargon VM

Instructions

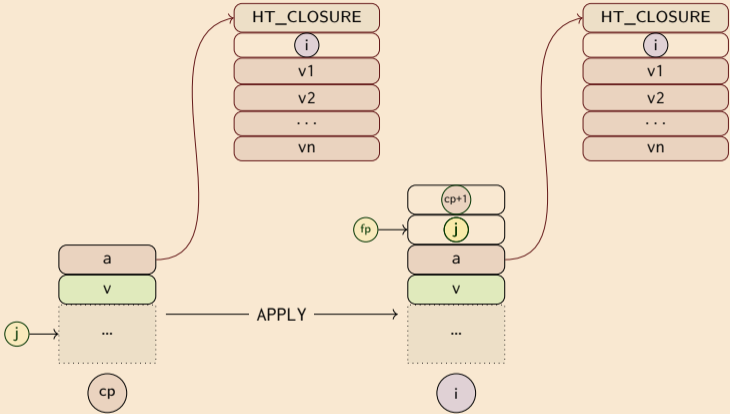
Functions



Variables

Example

The Gap



- Push stack frame
- Save return address (code pointer)
- Save and update frame pointer

Jargon VM

Instructions

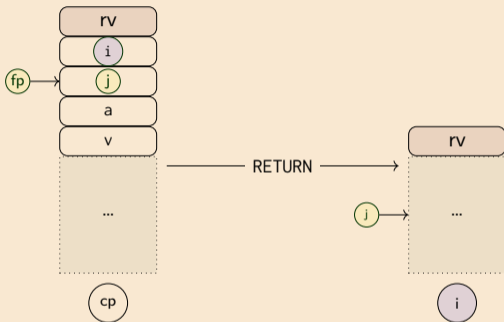
Functions



Variables

Example

The Gap



Discard stack frame

Update code pointer to return address

Restore frame pointer

Variables

Finding a variable's value at runtime

Jargon VM

Instructions

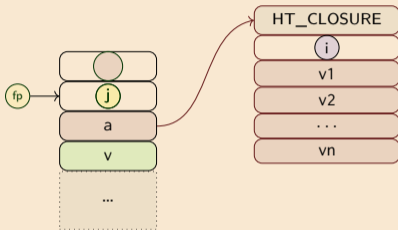
Functions

Variables



Example

The Gap



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)

Jargon VM

Instructions

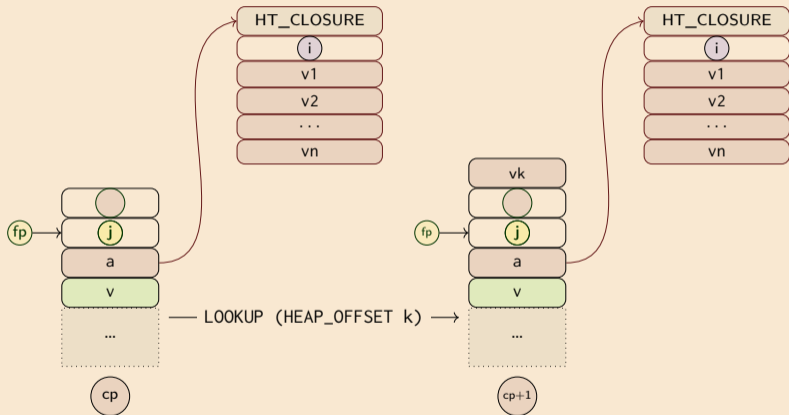
Functions

Variables



Example

The Gap



LOOKUP (STACK_OFFSET -2)

Jargon VM

Instructions

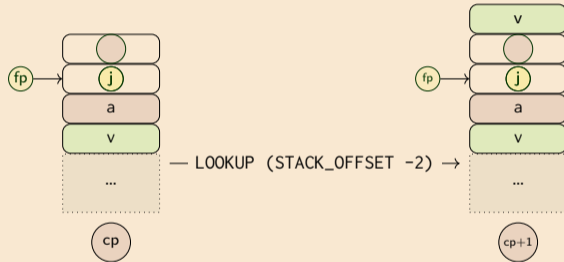
Functions

Variables



Example

The Gap



Example

Example: compiling rev_pair.slang (front end)

Jargon VM

Instructions

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Example



The Gap

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

slang
front end

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

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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")))))
```

jargon
compiler

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

Jargon VM

Instructions

Functions

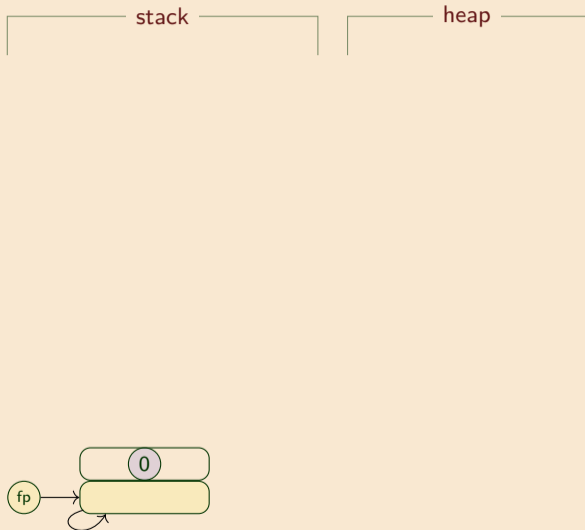
Variables

Example



The Gap

```
code
cp → 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

Jargon VM

Instructions

Functions

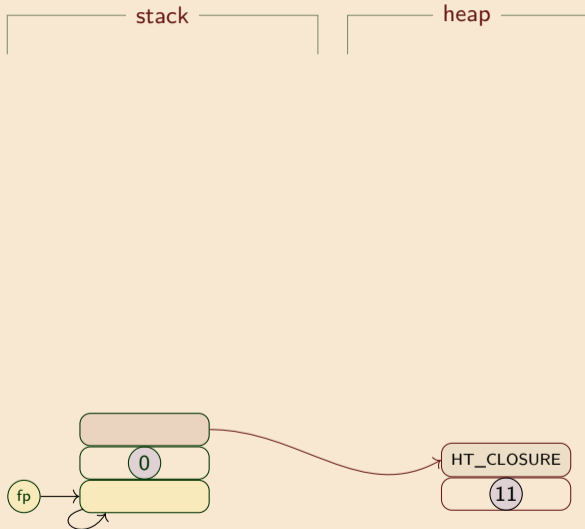
Variables

Example



The Gap

```
code
0 MK_CLOSURE(L1 = 11, 0)
cp → 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

Jargon VM

Instructions

Functions

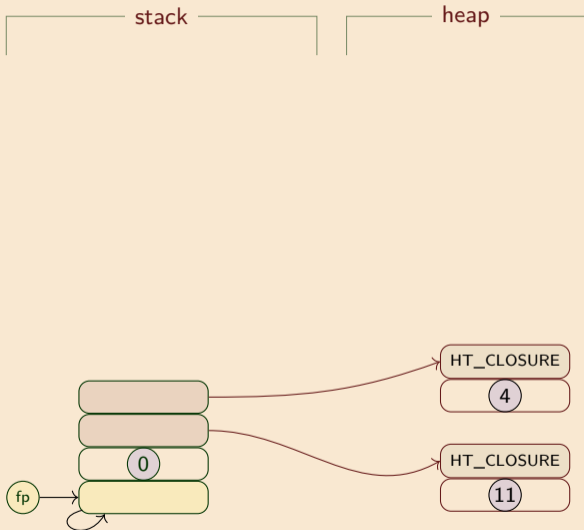
Variables

Example



The Gap

```
code
0 MK_CLOSURE(L1 = 11, 0)
1 MK_CLOSURE(L0 = 4, 0)
cp → 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
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Example: executing rev_pair.slang

Jargon VM

Instructions

Functions

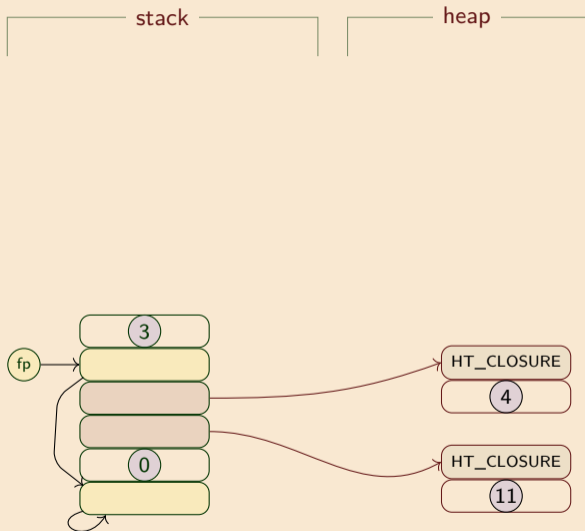
Variables

Example



The Gap

```
code
0 MK_CLOSURE(L1 = 11, 0)
1 MK_CLOSURE(L0 = 4, 0)
2 APPLY
3 HALT
cp → 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

Jargon VM

Instructions

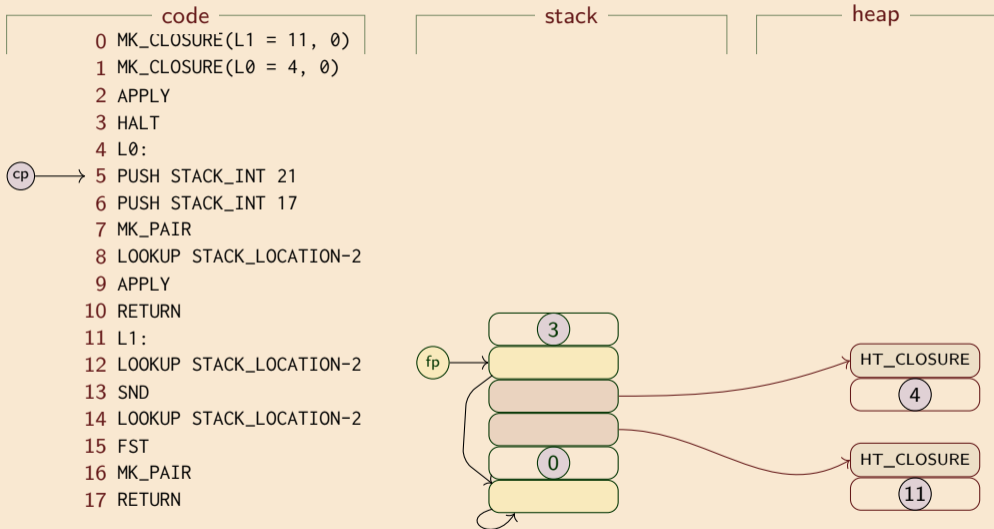
Functions

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The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

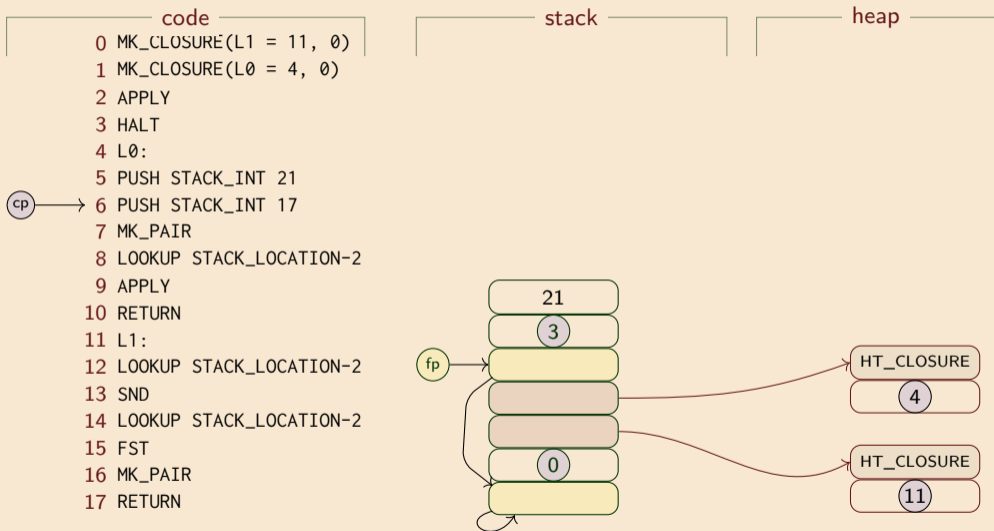
Functions

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Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

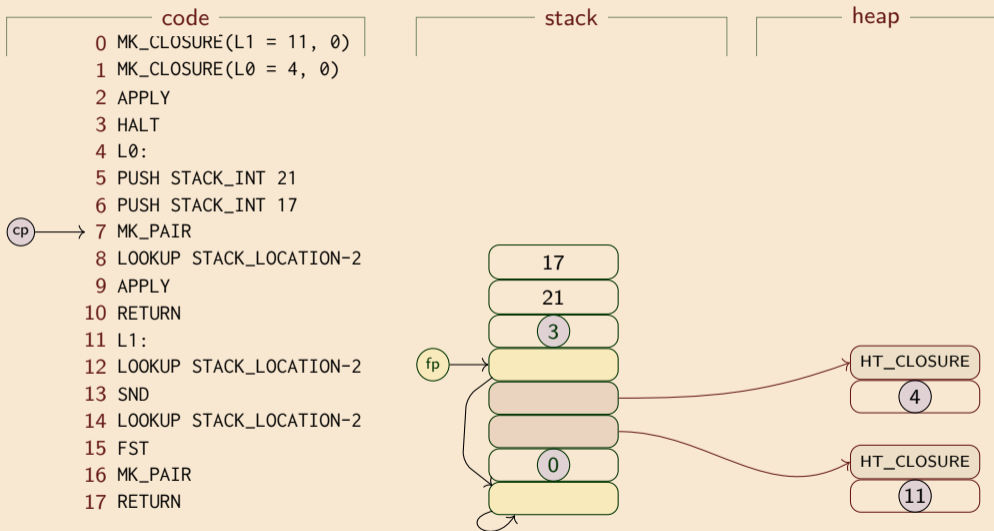
Functions

Variables

Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

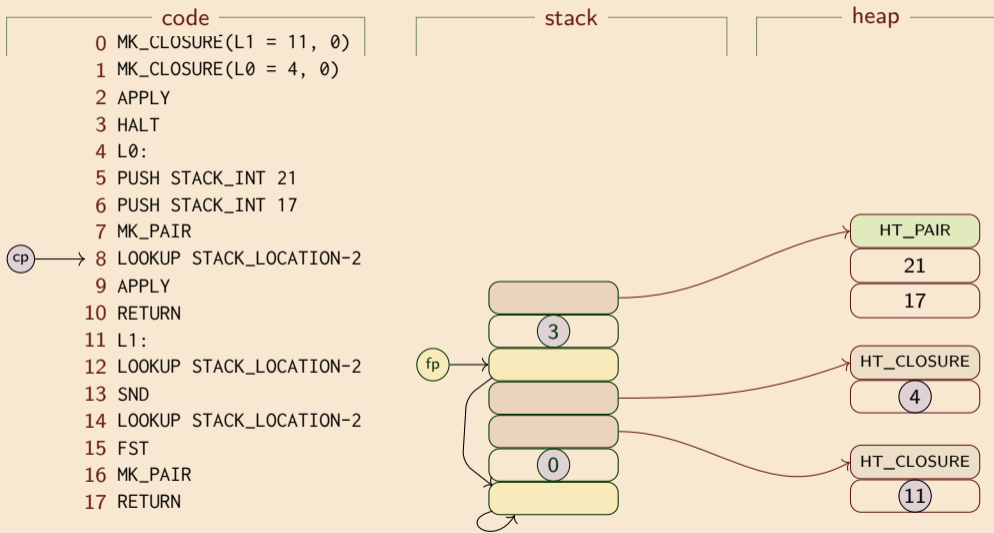
Functions

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Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

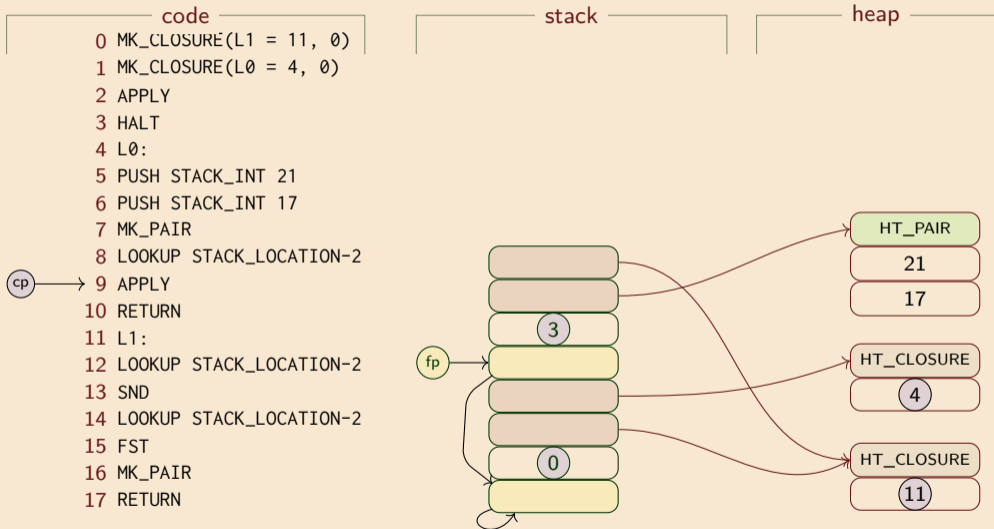
Functions

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Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

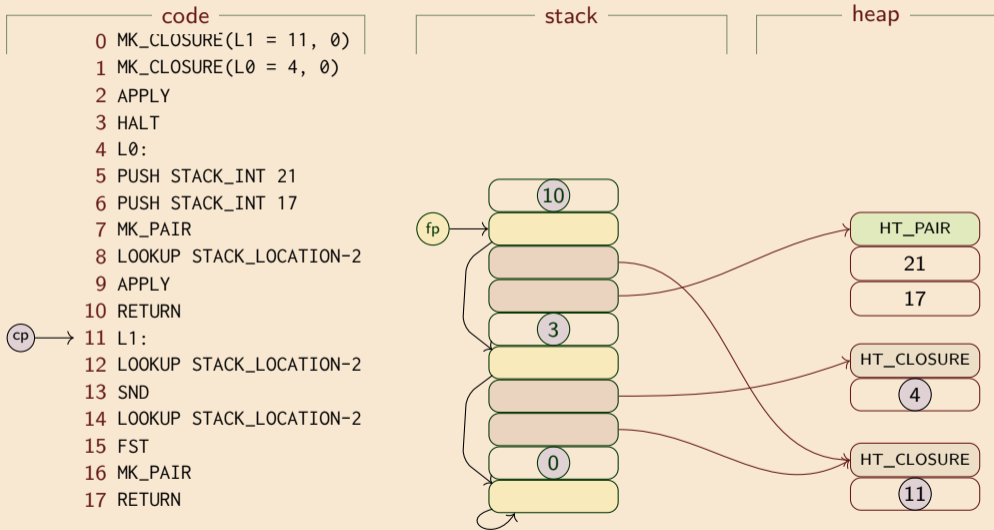
Functions

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Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

Functions

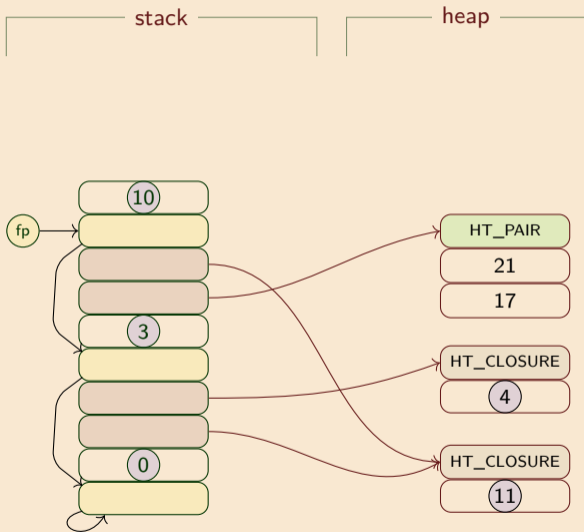
Variables

Example



The Gap

```
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:
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

Jargon VM

Instructions

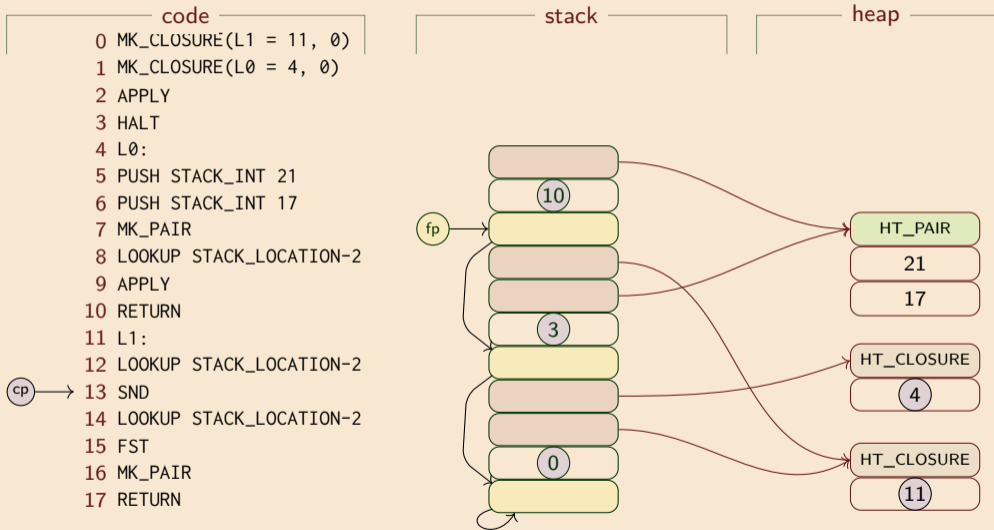
Functions

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The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

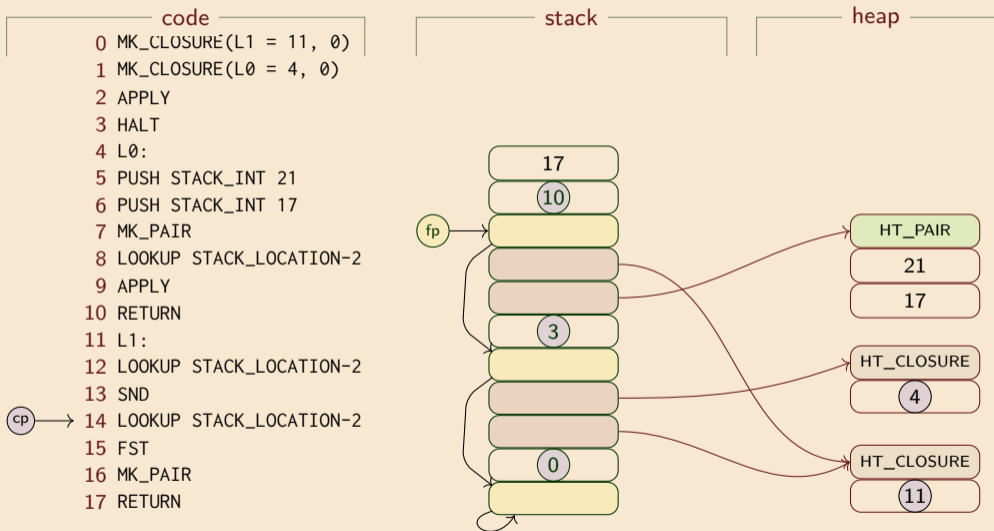
Functions

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The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

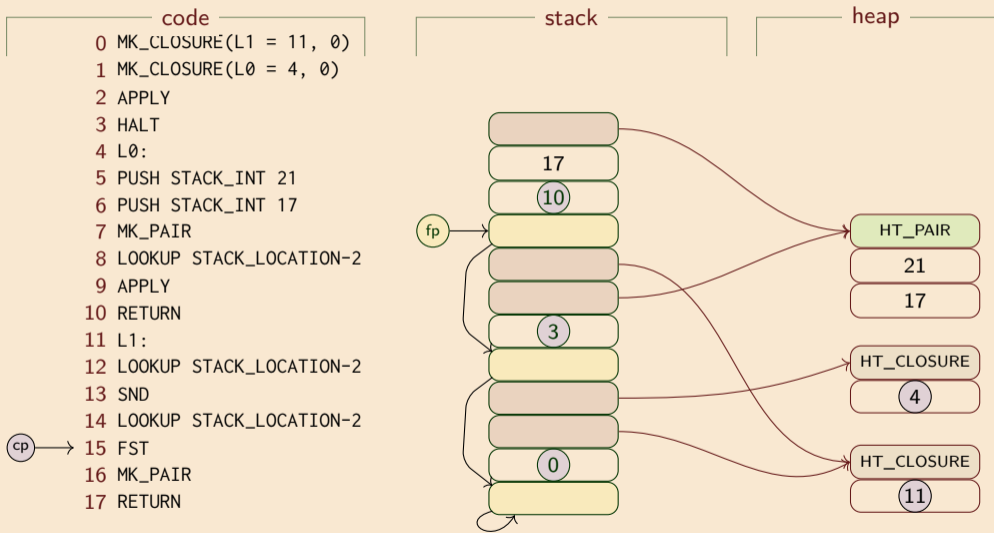
Functions

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The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

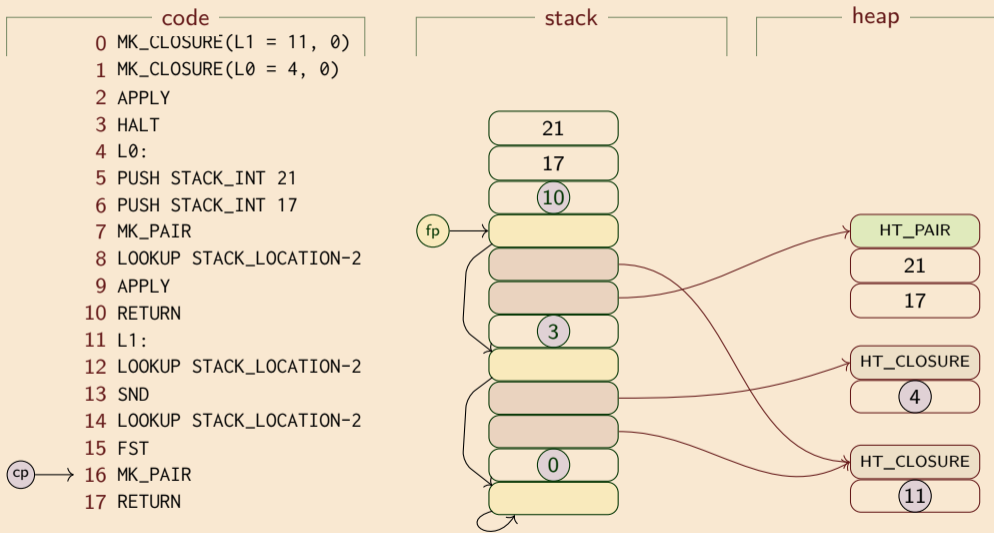
Functions

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Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

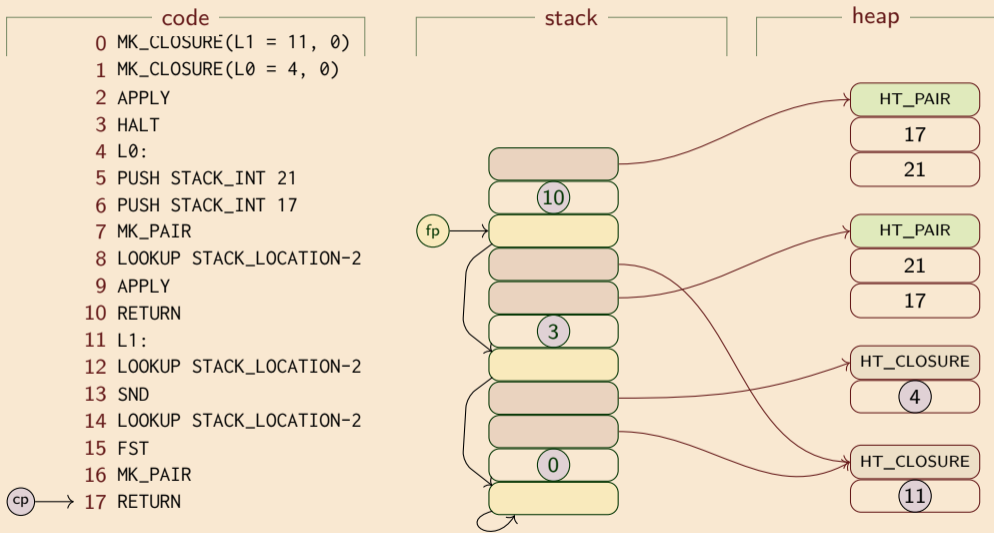
Functions

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The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

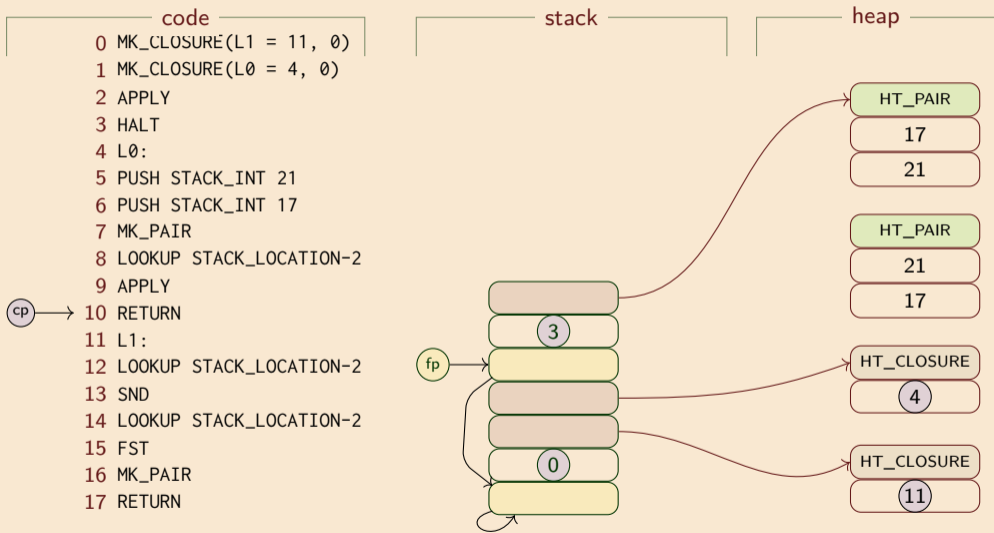
Functions

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Example



The Gap



Example: executing rev_pair.slang

Jargon VM

Instructions

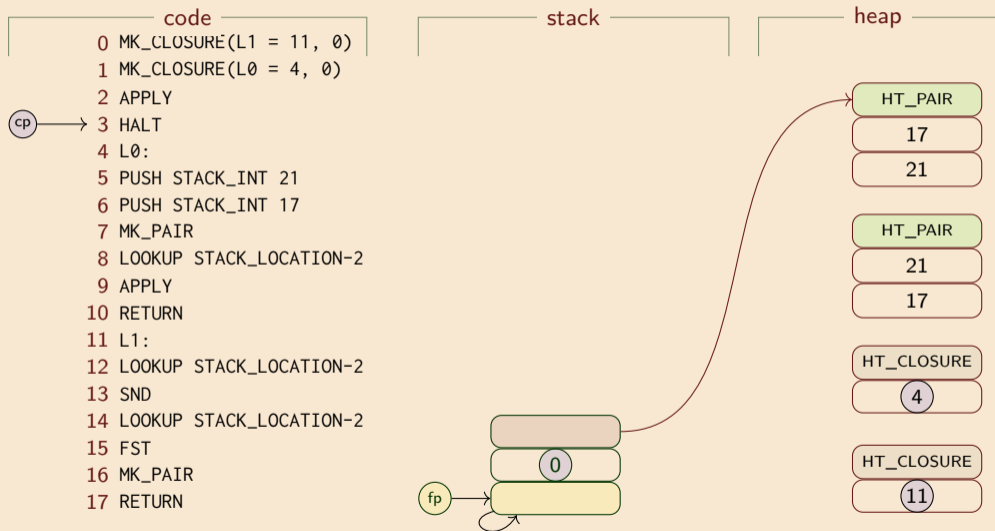
Functions

Variables

Example



The Gap



The Gap, revisited

The Gap: Slang to Jargon VM

Jargon VM

Instructions

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

Functions

Transform the evaluator:

CPS + defunctionalize, make stack explicit (Lecture 8)

split stacks (Lecture 9)

refactor: compiler + low-level interpreter

linearise + cp + LABEL/GOTO (Lecture 10)

compile away conditionals and loops

make stack addressable + add fp (Lecture 11)

optimize closure representation

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 Gap



Jargon VM

Instructions

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

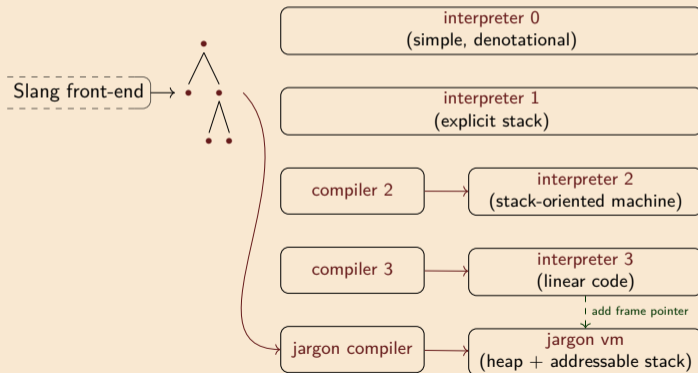
The correctness of each step is easy to check.

Functions

Variables

Example

The Gap



Jargon VM

Instructions

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

Functions

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

Variables

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](#)).

Example

The Gap



New possibility: Jargon bytecode interpreter in C

Jargon VM

Instructions

```
...
...
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; }
        ...
    }
} ...
```

Functions

Variables

Example

- 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

The Gap



Backend could target multiple platforms

Jargon VM

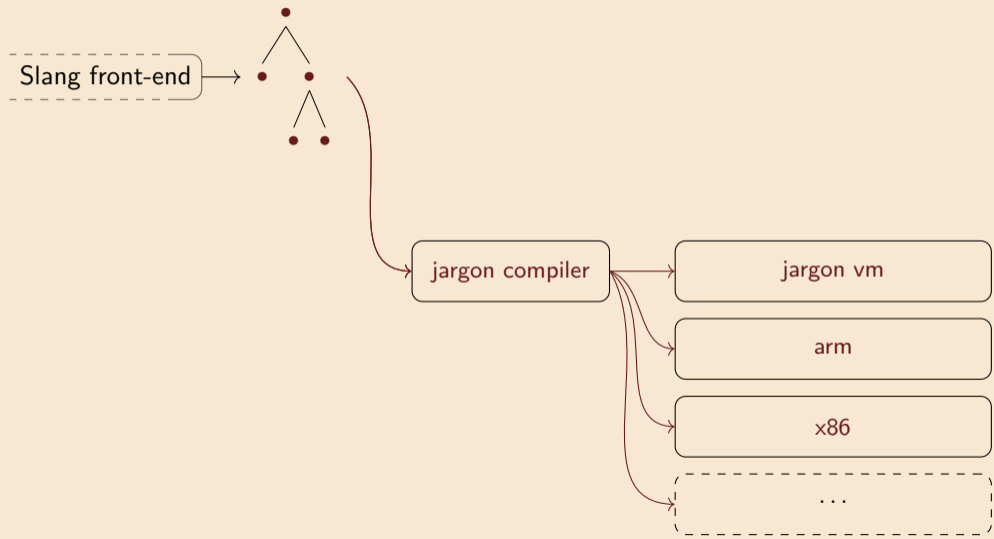
Instructions

Functions

Variables

Example

The Gap



Next time: *miscellany*