Compiler Construction

Lecture 13: exceptions

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Exceptions

Exception-handling constructs

Raising exceptions

`raise e`

Evaluate `e` to value `v`

then raise `v` as an *exceptional value* which can only be handled.

Handling exceptions

`try` e_1 `with x` $\rightarrow$ e_2

If e_1 evaluates to value `v`
then `v` is the result of the entire expression.

Otherwise, an exceptional value `w` is raised in the evaluation of e_1, and `w` is *handled*:

i.e. e_2 is evaluated with `w` bound to `x`
and becomes the result of the entire expression.

Exception types

```
(* extensible type *)
type exn = ...

(* add constructor *)
type exn +=
   E of string
```

Raising

```
raise (E "...")
```

Catching

```
try e with
| E1 x → e1
| E2 x → e2
...
| En x → en
```

desugar

```
try e with
| v → (match v with
       | E1 x → e1
       | E2 x → e2
       ...
       | En x → en
       | _ → raise v)
```

Exception types

```
(* extensible type *)
type exn = ...

(* add constructor *)
type exn +=
   E of string
```

Raising

```
raise (E "...")
```

Catching

```
try e with
| E1 x → e1
| E2 x → e2
...
| En x → en
```

desugar

```
try e with
| v → (match v with
        | E1 x → e1
        | E2 x → e2
        ...
        | En x → en
        | _ → raise v)
```

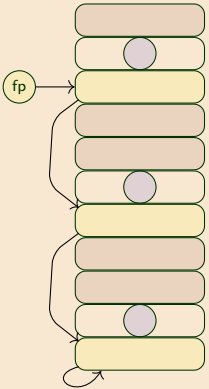
Implementing exceptions

`raise` **transfers control to the most-recent handler**.

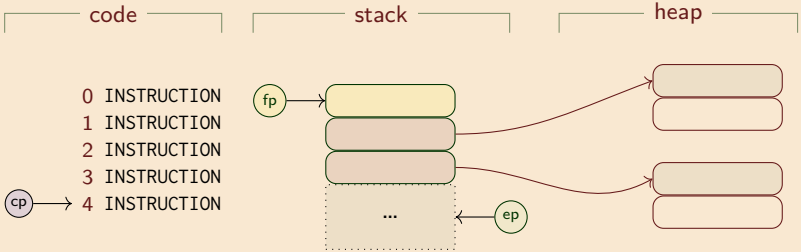
Handlers behave like a stack:
- entering `try` pushes to the stack
- exiting `try` pops from the stack

We *could* use the `fp` chain to search for the handler

Instead: **remember the position of the handler**



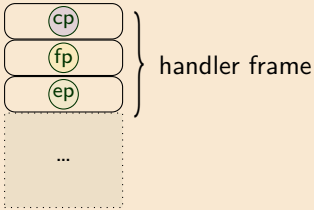
New VM state: exception pointer



- cp — code pointer (to next instruction)
- fp — frame pointer (to current activation frame)
- ep — exception pointer (to current handler frame)

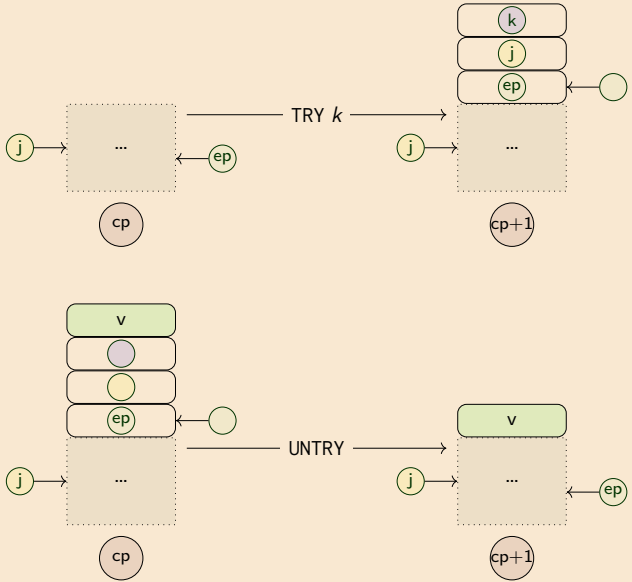
not shown: stack pointer, heap limit

The exception pointer points to a **handler frame** with the information `raise` needs:

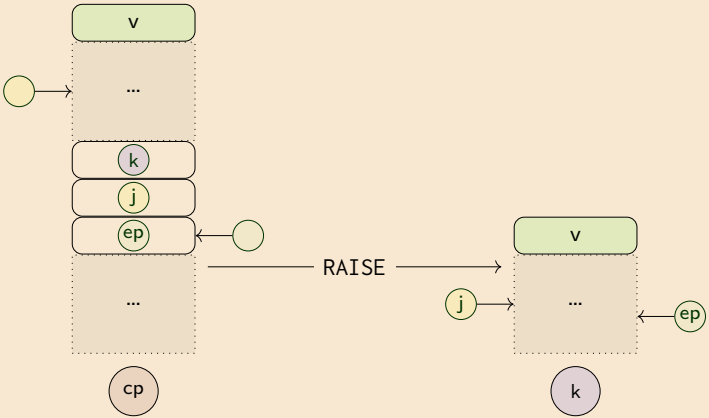


- cp — code address for `raise` to jump to
- fp — saved frame pointer for `raise` to restore
- ep — saved exception pointer for `raise` to restore

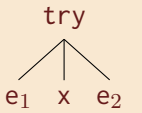
New instructions: TRY/UNTRY



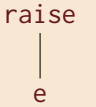
New instructions: RAISE



Compilation scheme




```
        TRY k
        <code for e1>
        UNTRY
        GOTO m
k:      <code for (λx.e2)>
        APPLY
m:
```




```
        <code for e>
        RAISE
```

Exception handling: tracing execution

Tracing execution: try

code

```
cp → 0  PUSH STACK_INT 1
     1  TRY L0 = 7
     2  PUSH STACK_INT 2
     3  PUSH STACK_INT 3
     4  OPER ADD
     5  UNTRY
     6  GOTO L1 = 10
     7  LABEL L0
     8  MK_CLOSURE(L2 = 13, 0)
     9  APPLY
    10  LABEL L1
    11  OPER ADD
    12  HALT
    13  LABEL L2
    14  LOOKUP STACK_LOCATION -2
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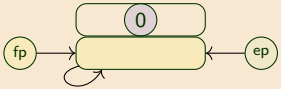
    16  OPER ADD
    17  RETURN
```

```
1 + try 2 + 3
    with e → e + 10
```

stack

heap



Tracing execution: try

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stack

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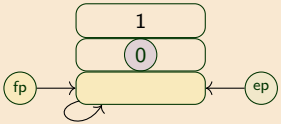

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14 LOOKUP STACK_LOCATION -2
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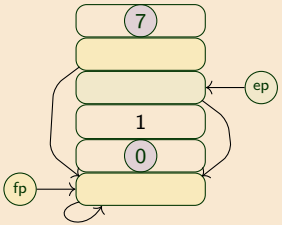
16 OPER ADD
17 RETURN
```

cp → 2

```
1 + try 2 + 3
    with e → e + 10
```

stack heap



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cp

```
1 + try 2 + 3
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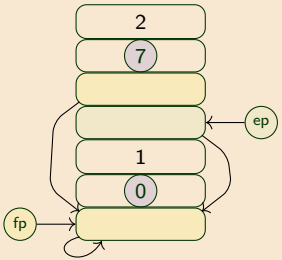
stack heap



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cp

```
1 + try 2 + 3
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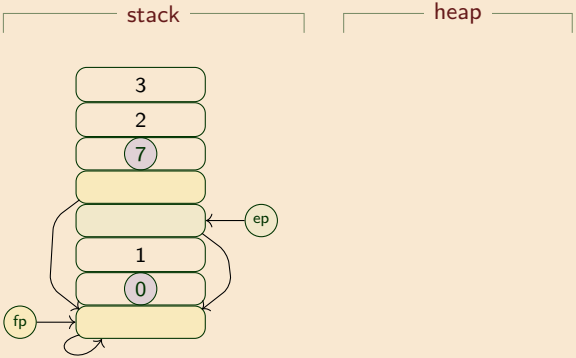

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cp

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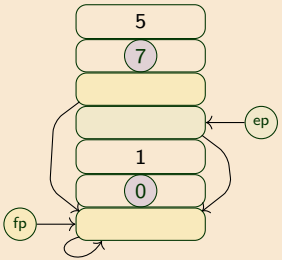
stack

heap



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cp

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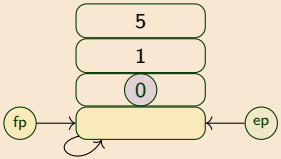
stack

heap



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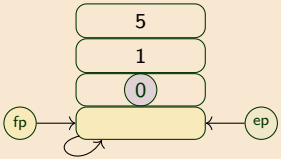
11 OPER ADD
12 HALT
13 LABEL L2
14 LOOKUP STACK_LOCATION -2
15 PUSH STACK_INT 10
16 OPER ADD
17 RETURN
```

cp → 10

```
1 + try 2 + 3
    with e → e + 10
```

stack

heap



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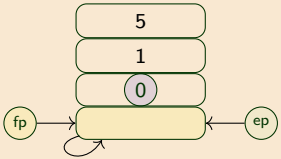
 9 APPLY
10 LABEL L1
11 OPER ADD
12 HALT
13 LABEL L2
14 LOOKUP STACK_LOCATION -2
15 PUSH STACK_INT 10
16 OPER ADD
17 RETURN
```

cp → 11

```
1 + try 2 + 3
    with e → e + 10
```

stack

heap



Tracing execution: try

code

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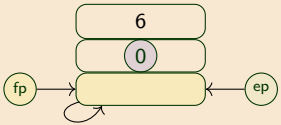
 9 APPLY
10 LABEL L1
11 OPER ADD
12 HALT
13 LABEL L2
14 LOOKUP STACK_LOCATION -2
15 PUSH STACK_INT 10
16 OPER ADD
17 RETURN
```

cp → 12 HALT

```
1 + try 2 + 3
    with e → e + 10
```

stack

heap



Tracing execution: try + raise

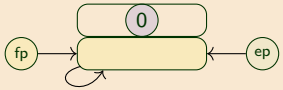
code

```
cp → 0  PUSH STACK_INT 1
     1  TRY L0 = 8
     2  PUSH STACK_INT 2
     3  PUSH STACK_INT 5
     4  RAISE
     5  OPER ADD
     6  UNTRY
     7  GOTO L1 = 11
     8  LABEL L0
     9  MK_CLOSURE(L2 = 14, 0)
    10  APPLY
    11  LABEL L1
    12  OPER ADD
    13  HALT
    14  LABEL L2
    15  LOOKUP STACK_LOCATION -2
    16  PUSH STACK_INT 10
    17  OPER ADD
    18  RETURN
```

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap



Tracing execution: try + raise

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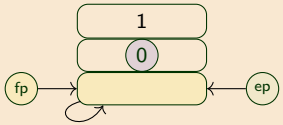
    18  RETURN
```

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap



Tracing execution: try + raise

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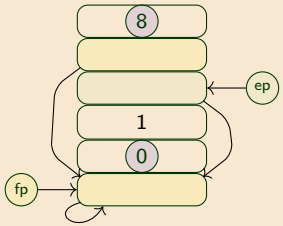
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 2

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap



Tracing execution: try + raise

code

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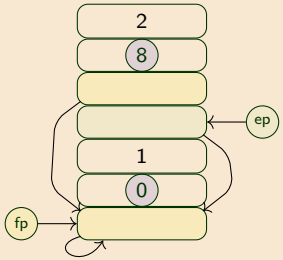
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 3

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap



Tracing execution: try + raise

code

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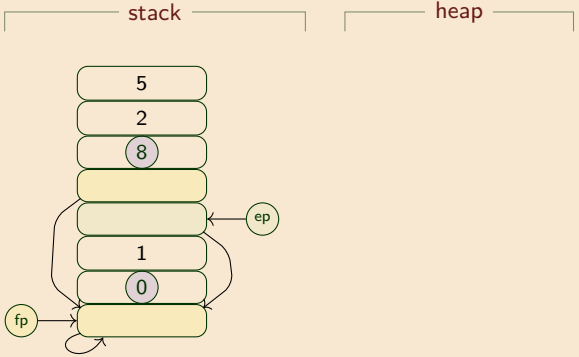
17 OPER ADD
18 RETURN
```

cp

```
1 + try 2 + raise 5
    with e → e + 10
```



Tracing execution: try + raise

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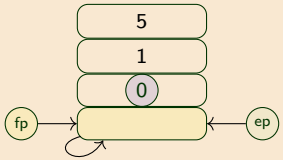
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 8

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap



Tracing execution: try + raise

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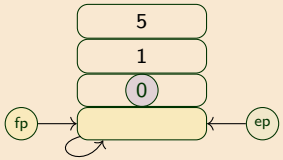
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 9

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap



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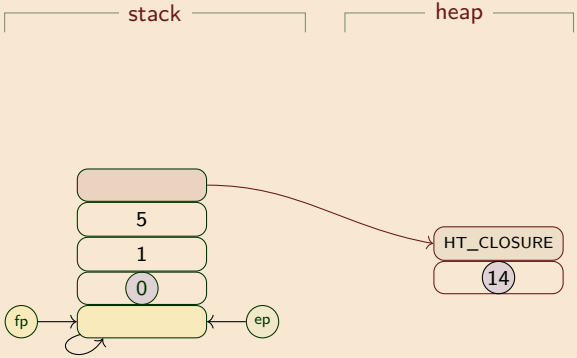
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 10

```
1 + try 2 + raise 5
    with e → e + 10
```



Tracing execution: try + raise

code

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14 LABEL L2
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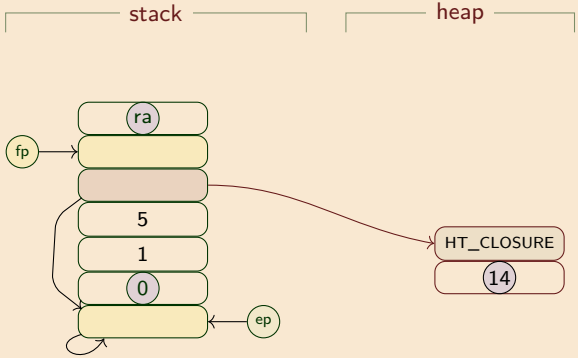
17 OPER ADD
18 RETURN
```

cp → 14

```
1 + try 2 + raise 5
    with e → e + 10
```



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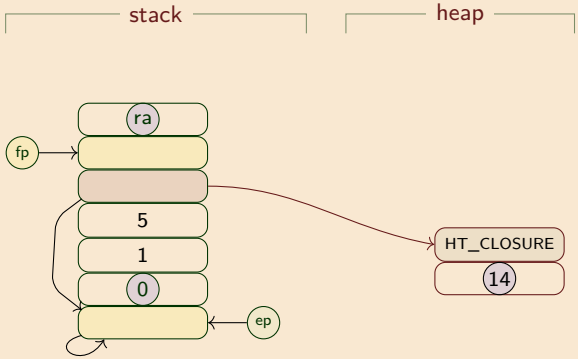
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 15

```
1 + try 2 + raise 5
    with e → e + 10
```



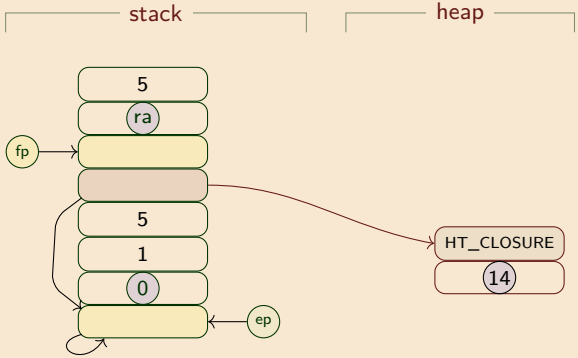
Tracing execution: try + raise

code

```
 0 PUSH STACK_INT 1
 1 TRY L0 = 8
 2 PUSH STACK_INT 2
 3 PUSH STACK_INT 5
 4 RAISE
 5 OPER ADD
 6 UNTRY
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 16

```
1 + try 2 + raise 5
    with e → e + 10
```

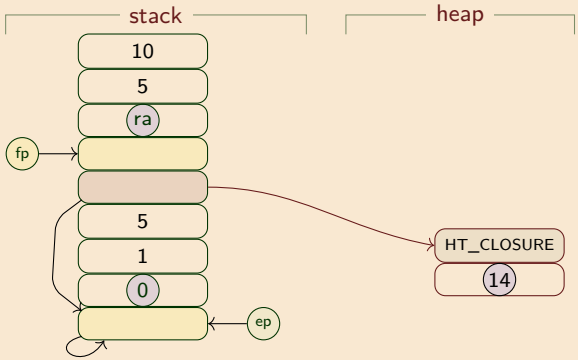


Tracing execution: try + raise

```
code
 0 PUSH STACK_INT 1
 1 TRY L0 = 8
 2 PUSH STACK_INT 2
 3 PUSH STACK_INT 5
 4 RAISE
 5 OPER ADD
 6 UNTRY
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 17

```
1 + try 2 + raise 5
    with e → e + 10
```



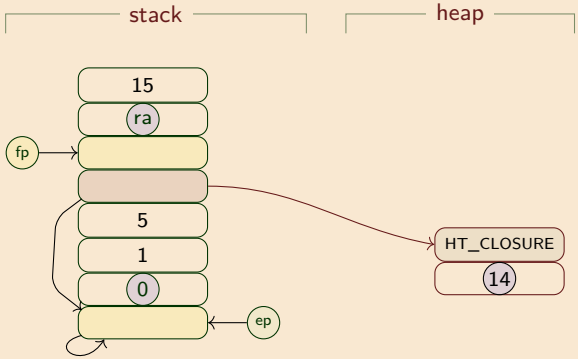
Tracing execution: try + raise

code

```
 0 PUSH STACK_INT 1
 1 TRY L0 = 8
 2 PUSH STACK_INT 2
 3 PUSH STACK_INT 5
 4 RAISE
 5 OPER ADD
 6 UNTRY
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

cp → 18

```
1 + try 2 + raise 5
    with e → e + 10
```



Tracing execution: try + raise

code

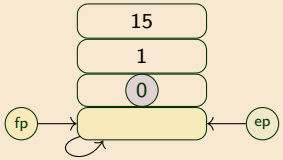
```
 0 PUSH STACK_INT 1
 1 TRY L0 = 8
 2 PUSH STACK_INT 2
 3 PUSH STACK_INT 5
 4 RAISE
 5 OPER ADD
 6 UNTRY
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

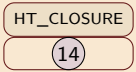
cp → 11

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap





Tracing execution: try + raise

code

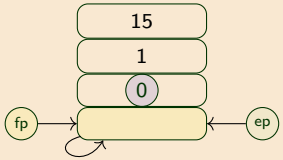
```
 0 PUSH STACK_INT 1
 1 TRY L0 = 8
 2 PUSH STACK_INT 2
 3 PUSH STACK_INT 5
 4 RAISE
 5 OPER ADD
 6 UNTRY
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

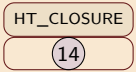
cp → 12

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

heap





Tracing execution: try + raise

code

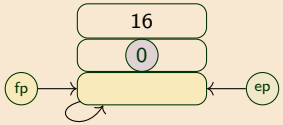
```
 0 PUSH STACK_INT 1
 1 TRY L0 = 8
 2 PUSH STACK_INT 2
 3 PUSH STACK_INT 5
 4 RAISE
 5 OPER ADD
 6 UNTRY
 7 GOTO L1 = 11
 8 LABEL L0
 9 MK_CLOSURE(L2 = 14, 0)
10 APPLY
11 LABEL L1
12 OPER ADD
13 HALT
14 LABEL L2
15 LOOKUP STACK_LOCATION -2
16 PUSH STACK_INT 10
17 OPER ADD
18 RETURN
```

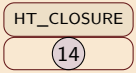
cp → 13

```
1 + try 2 + raise 5
    with e → e + 10
```

stack

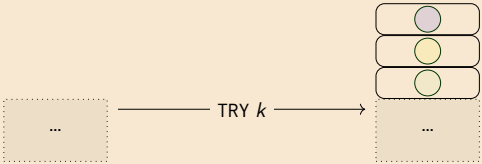
heap





Exception pragmatics

Since handler frames use stack space, a **call inside a handler is not a tail call**



For example, the following function is **not tail recursive**

```
let rec all_except f = function
  | [] → true
  | x :: xs → try f x && all_except f xs with Not_found → false
```

but can be made tail-recursive by moving the recursive call outside the handler:

```
let rec all_except2 f = function
  | [] → true
  | x :: xs → (try f x with Not_found → false) && all_except2 f xs
```

In C++, raising an exception deallocates stack-allocated objects.

Deallocation executes the code of each object's *destructor*

```
struct C { ~C() { cout <<"Goodbye\n"; } /* destructor */ };

void g() { throw runtime_error("No resources\n"); }

void f() { C c; g(); }

int main() {
  try { f(); }
  catch (const runtime_error& e) { cout << e.what(); }
}
```

For example, the example above prints:

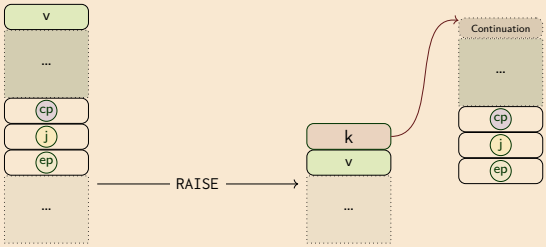
```
Goodbye
No resources
```

Jumping directly to the handler is not valid: throw must **unwind the stack**

Idea: don't discard the stack on `raise`

Option 1: handle the exception before discarding the stack
(the program chooses: discard the stack / continue)

Option 2: make the stack available to the program
(the program chooses: discard stack / continue / save stack & restore later)



Next time: optimisation