Memory Locations For Variables

A Binding Question

- Variables are bound (dynamically) to values
- Those values must be stored somewhere
- Therefore, variables must somehow be bound to memory locations
- How?

Functional Meets Imperative

- Imperative languages expose the concept of memory locations: **`a := 0`**
  - Store a zero in **`a`**'s memory location
- Functional languages hide it: **`val a = 0`**
  - Bind **`a`** to the value zero
- But both need to connect variables to values represented in memory
- So both face the same binding question

Outline

- Activation records
- Static allocation of activation records
- Stacks of activation records
- Handling nested function definitions
- Functions as parameters
- Long-lived activation records

Function Activations

- The lifetime of one execution of a function, from call to corresponding return, is called an *activation* of the function
- When each activation has its own binding of a variable to a memory locations, it is an *activation-specific* variable
- (Also called *dynamic* or *automatic*)

Activation-Specific Variables

- In most modern languages, activation-specific variables are the most common kind:

```
fun days2ms days =
  let
    val hours = days * 24.0
    val minutes = hours * 60.0
    val seconds = minutes * 60.0
  in
    seconds * 1000.0
  end;
```

Block Activations

- For block constructs that contain code, we can speak of an activation of the *block*
- The lifetime of one execution of the block
- A variable might be specific to an activation of a particular block within a function:

```
fun fact n =
  if (n=0) then 1
  else let val b = fact (n-1) in n*b
end;
```

Other Lifetimes For Variables

- Most imperative languages have a way to declare a variable that is bound to a single memory location for the entire runtime
- Obvious binding solution: static allocation (classically, the loader allocates these)

```
int count = 0;
int nextcount() {
  count = count + 1;
  return count;
}
```

Scope And Lifetime Differ

- In most modern languages, variables with local *scope* have activation-specific *lifetimes*, at least by default
- However, these two aspects can be separated, as in C:

```
int nextcount() {
  static int count = 0;
  count = count + 1;
  return count;
}
```

Other Lifetimes For Variables

- Object-oriented languages use variables whose lifetimes are associated with object lifetimes
- Some languages have variables whose values are persistent: they last across multiple executions of the program
- Today, we will focus on activation-specific variables

Activation Records

- Language implementations usually allocate all the activation-specific variables of a function together as an *activation record*
- The activation record also contains other activation-specific data, such as
  - Return address: where to go in the program when this activation returns
  - Link to caller's activation record: more about this in a moment

Block Activation Records

- When a block is entered, space must be found for the local variables of that block
- Various possibilities:
  - Preallocate in the containing function's activation record
  - Extend the function's activation record when the block is entered (and revert when exited)
  - Allocate separate block activation records
- Our illustrations will show the first option

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Static Allocation

- The simplest approach: allocate one activation record for every function, statically
- Older dialects of Fortran and Cobol used this system
- Simple and fast

Example

```
      FUNCTION AVG (ARR, N)
      DIMENSION ARR(N)
      SUM = 0.0
      DO 100 I = 1, N
        SUM = SUM + ARR(I)
100   CONTINUE
      AVG = SUM / FLOAT(N)
      RETURN
      END
```

N address
ARR address
return address
I
SUM
AVG

Drawback

- Each function has one activation record
- There can be only one activation alive at a time
- Modern languages (including modern dialects of Cobol and Fortran) do not obey this restriction:
  - Recursion
  - Multithreading

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Stacks Of Activation Records

- To support recursion, we need to allocate a new activation record for each activation
- Dynamic allocation: activation record allocated when function is called
- For many languages, like C, it can be deallocated when the function returns
- A stack of activation records: *stack frames* pushed on call, popped on return

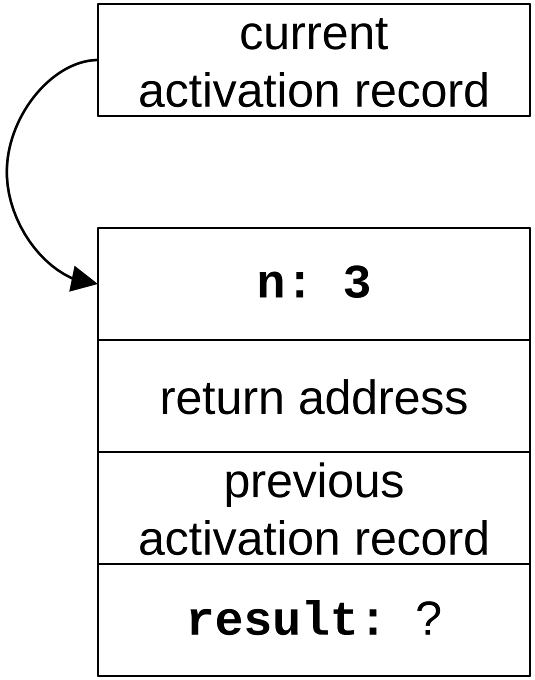
Current Activation Record

- Before, static: location of activation record was determined before runtime
- Now, dynamic: location of the *current* activation record is not known until runtime
- A function must know how to find the address of its current activation record
- Often, a machine register is reserved to hold this

C Example

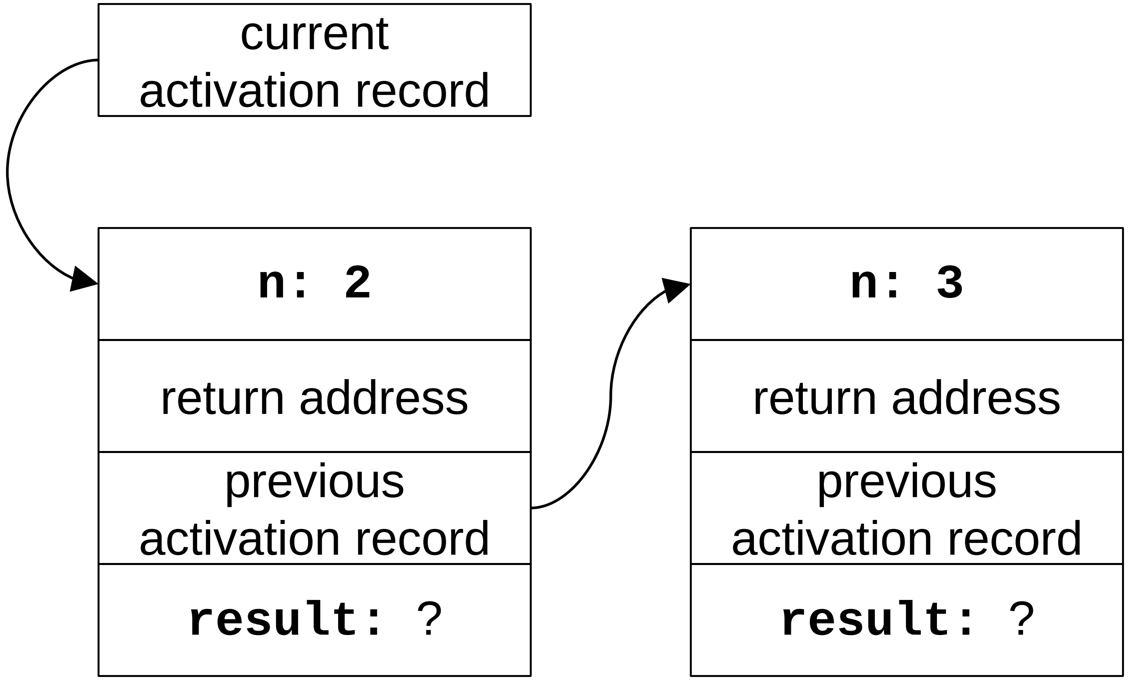
```
int fact(int n) {
  int result;
  if (n<2) result = 1;
  else result = n * fact(n-1);
  return result;
}
```

We are evaluating **`fact(3)`**. *This shows the contents of memory just before the recursive call that creates a second activation.*



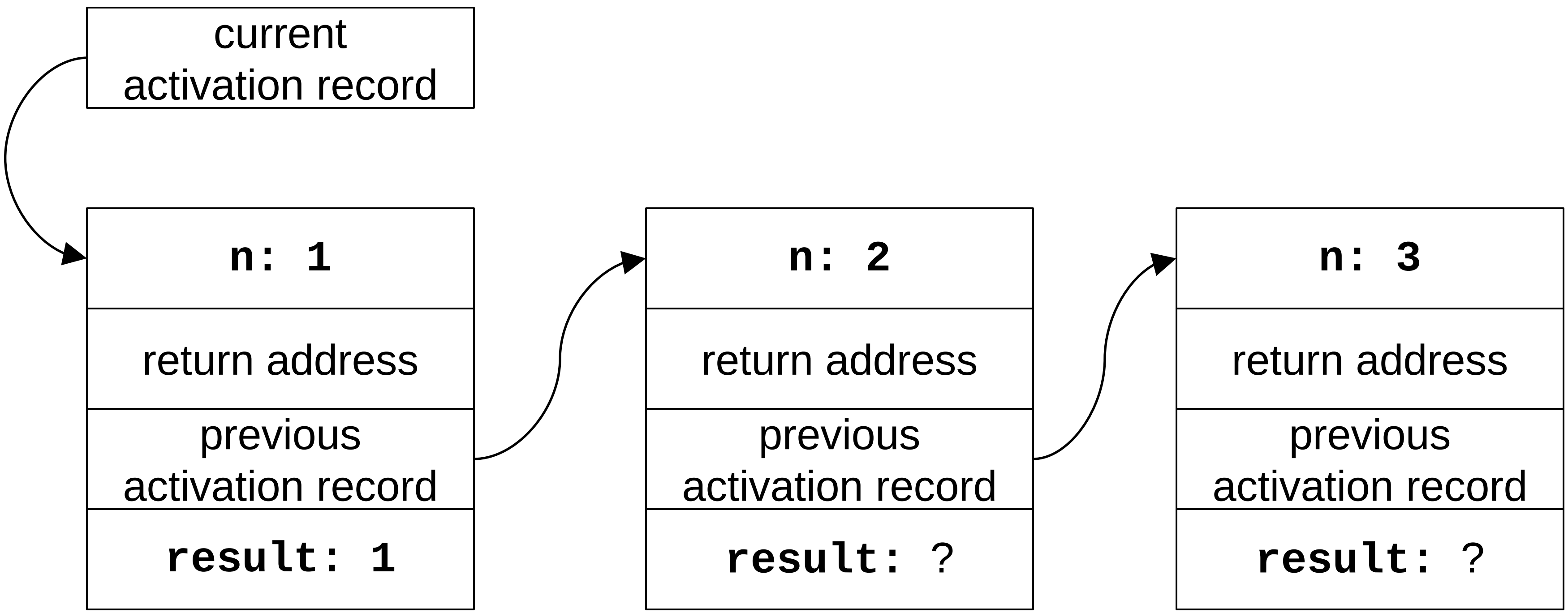
This shows the contents of memory just before the third activation.

```
int fact(int n) {
  int result;
  if (n<2) result = 1;
  else result = n * fact(n-1);
  return result;
}
```



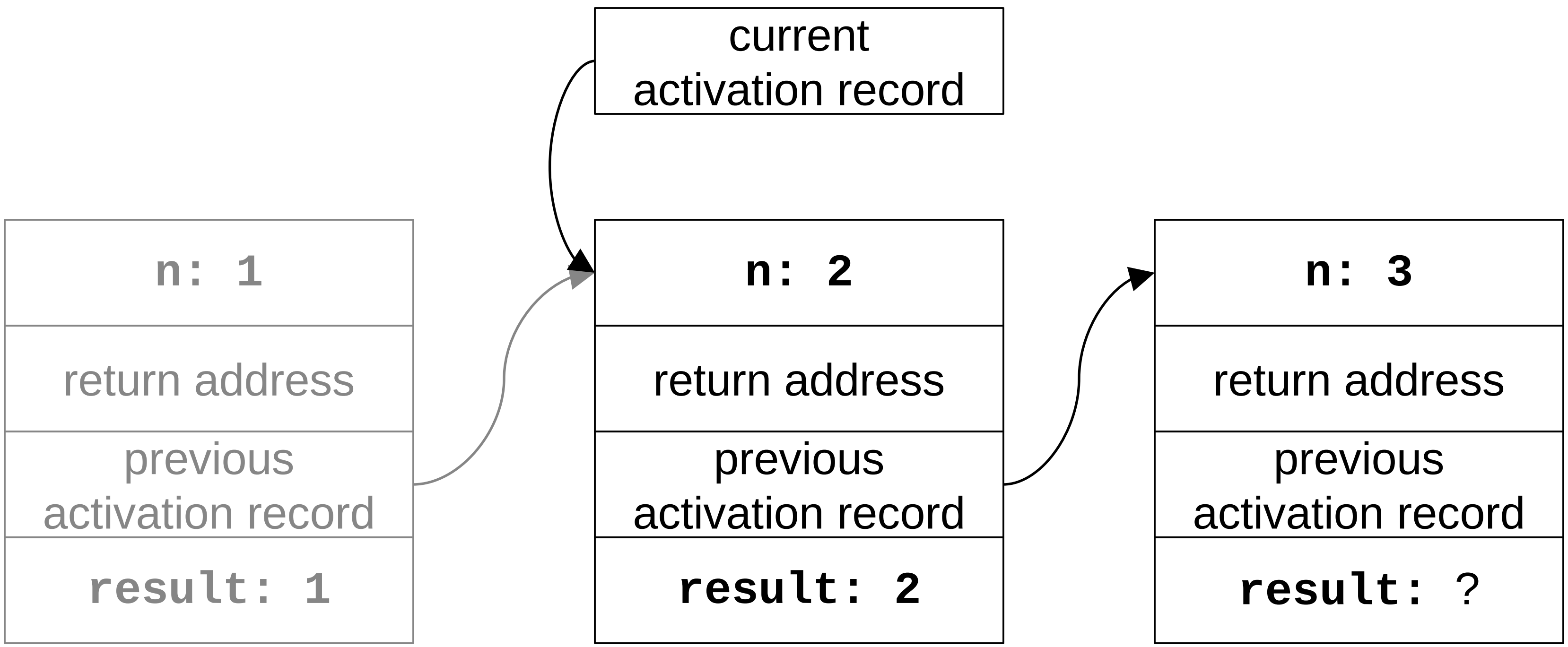
This shows the contents of memory just before the third activation returns.

```
int fact(int n) {
  int result;
  if (n<2) result = 1;
  else result = n * fact(n-1);
  return result;
}
```



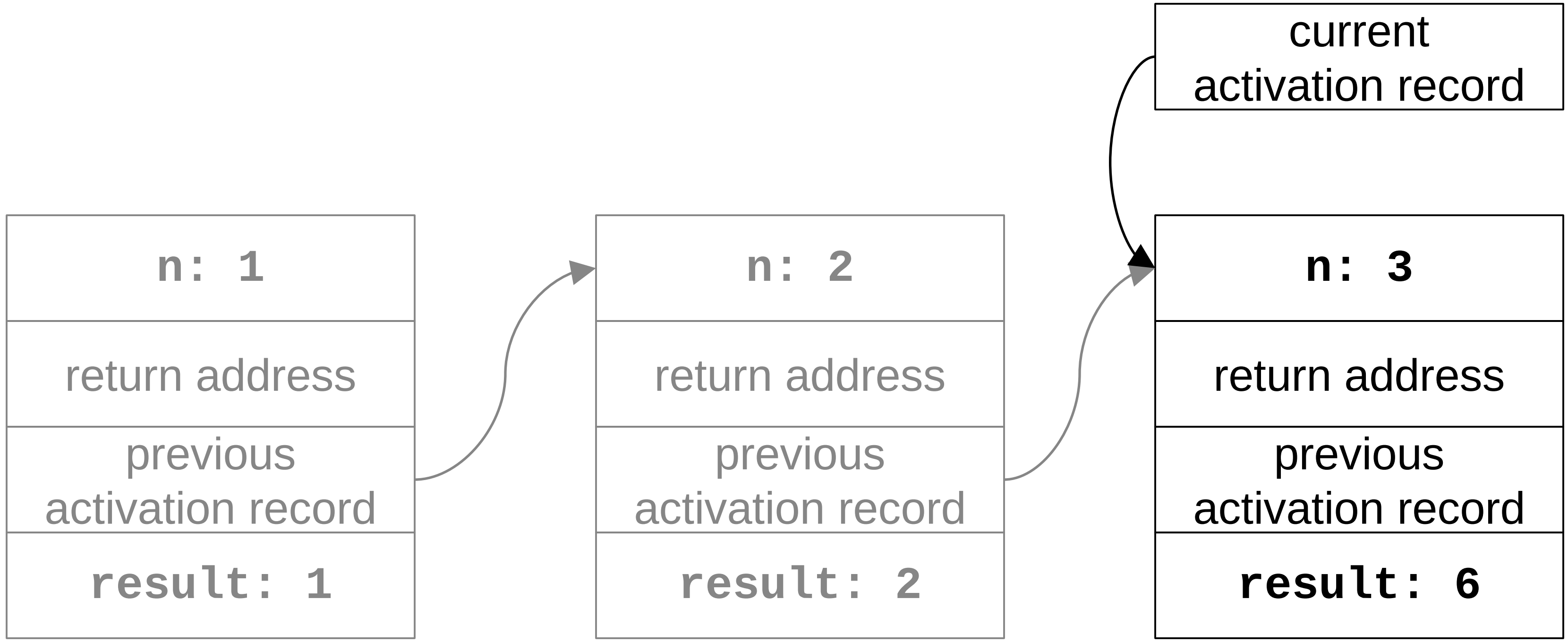
The second activation is about to return.

```
int fact(int n) {
  int result;
  if (n<2) result = 1;
  else result = n * fact(n-1);
  return result;
}
```



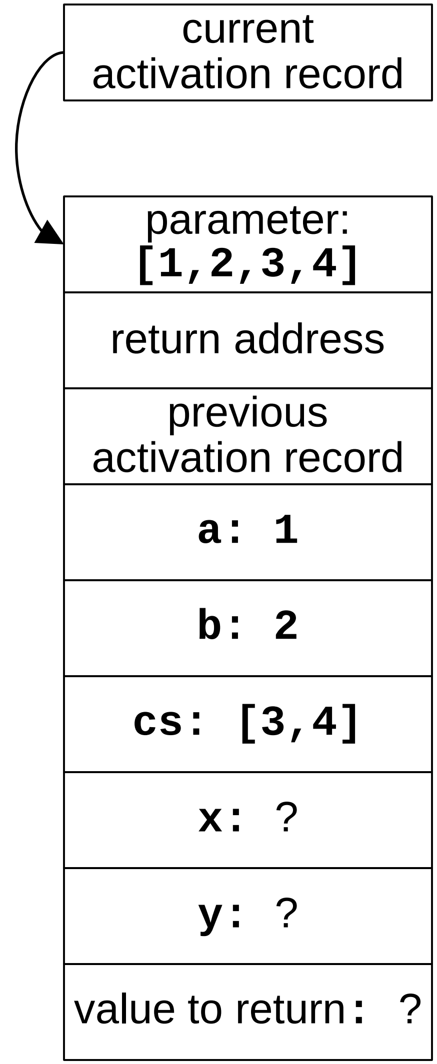
The first activation is about to return with the result **`fact(3) = 6`**.

```
int fact(int n) {
  int result;
  if (n<2) result = 1;
  else result = n * fact(n-1);
  return result;
}
```



ML Example

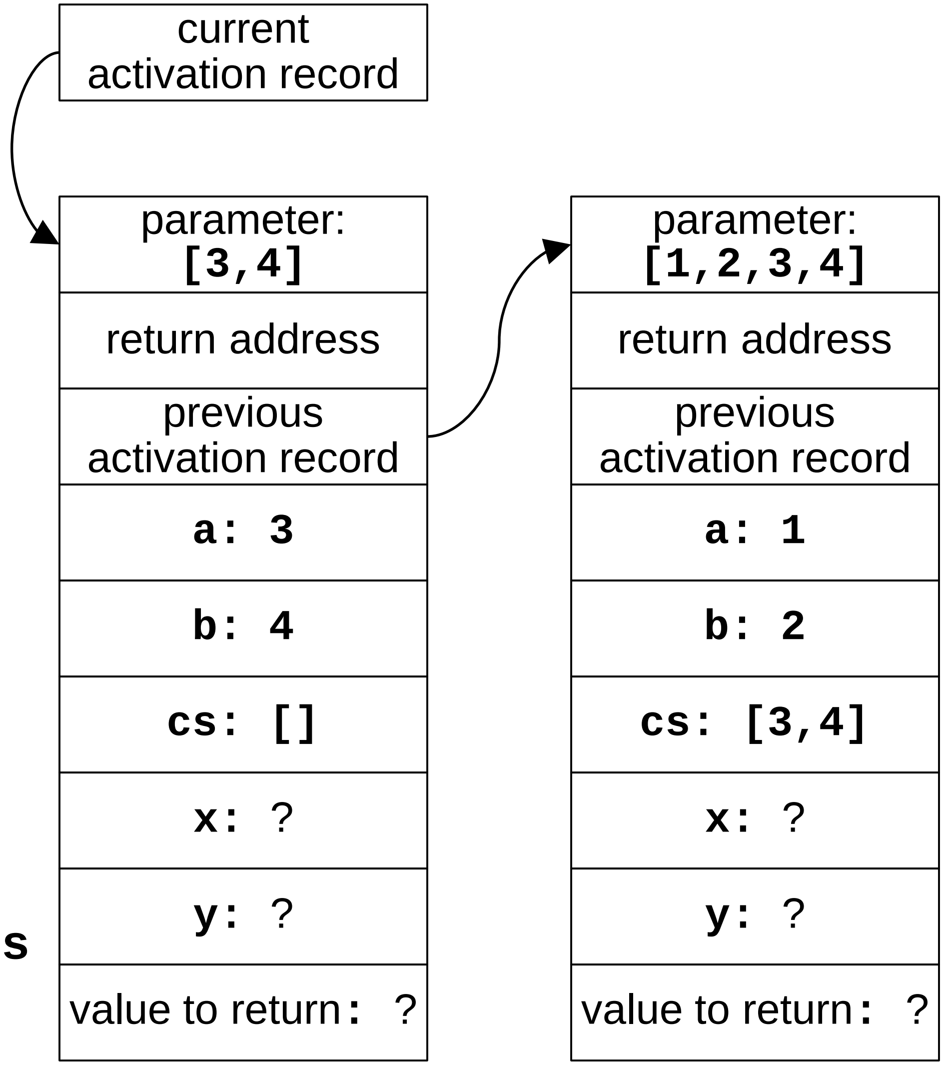
We are evaluating **`halve [1,2,3,4]`**. *This shows the contents of memory just before the recursive call that creates a second activation.*



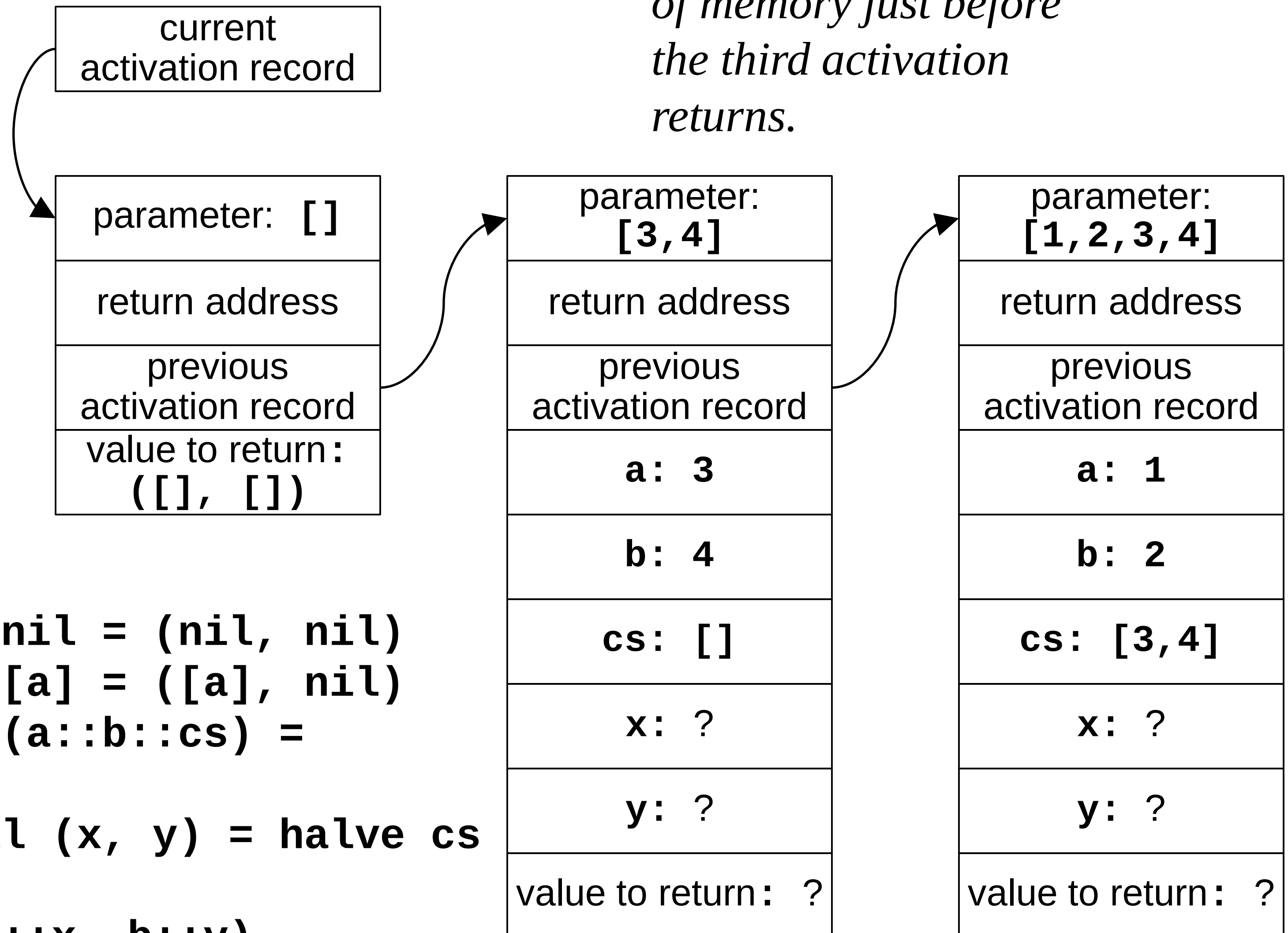

```
fun halve nil = (nil, nil)
|   halve [a] = ([a], nil)
|   halve (a::b::cs) =
      let
        val (x, y) = halve cs
      in
        (a::x, b::y)
      end;
```

This shows the contents of memory just before the third activation.

```
fun halve nil = (nil, nil)
|   halve [a] = ([a], nil)
|   halve (a::b::cs) =
      let
        val (x, y) = halve cs
      in
        (a::x, b::y)
      end;
```

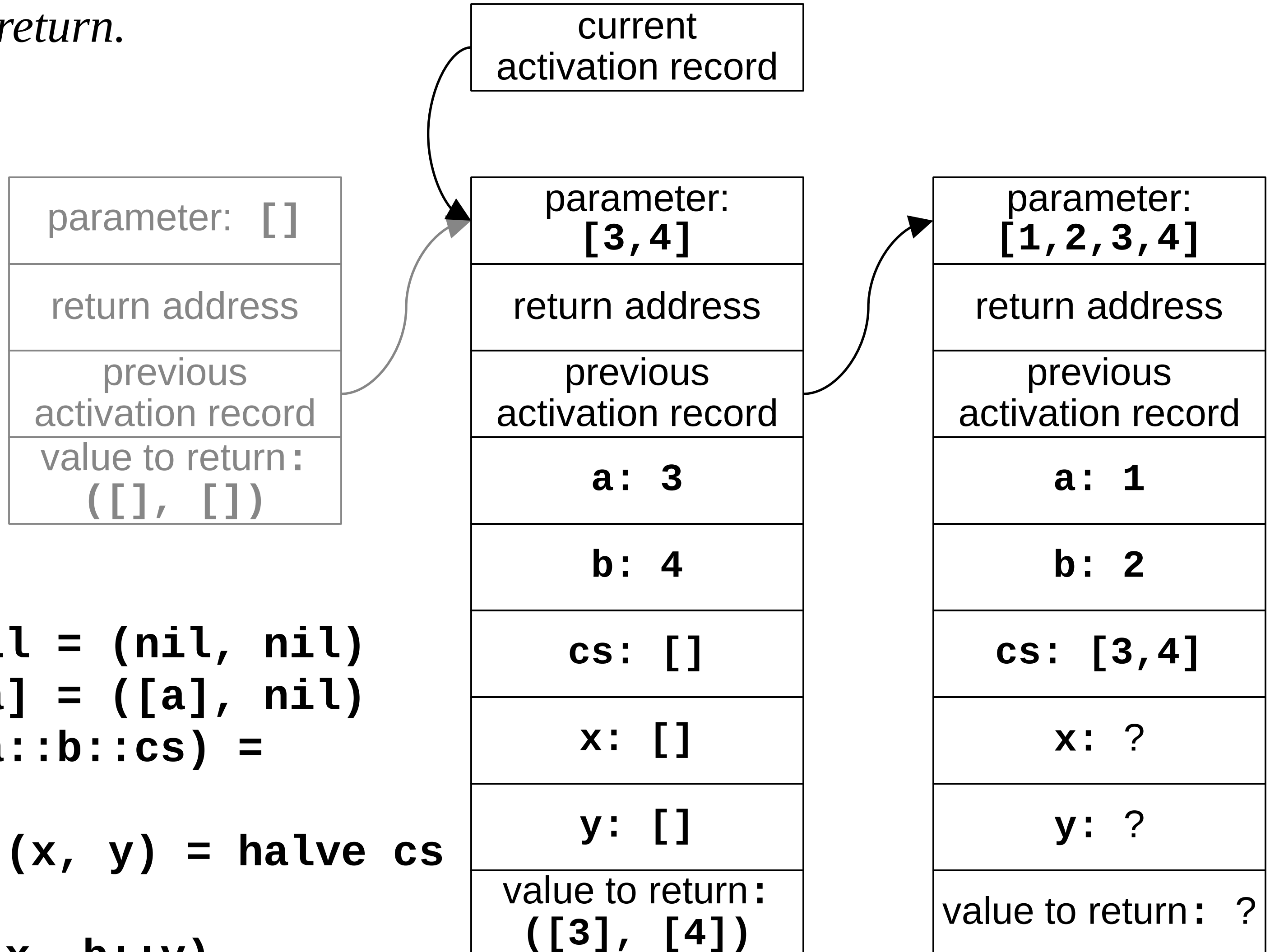


This shows the contents of memory just before the third activation returns.



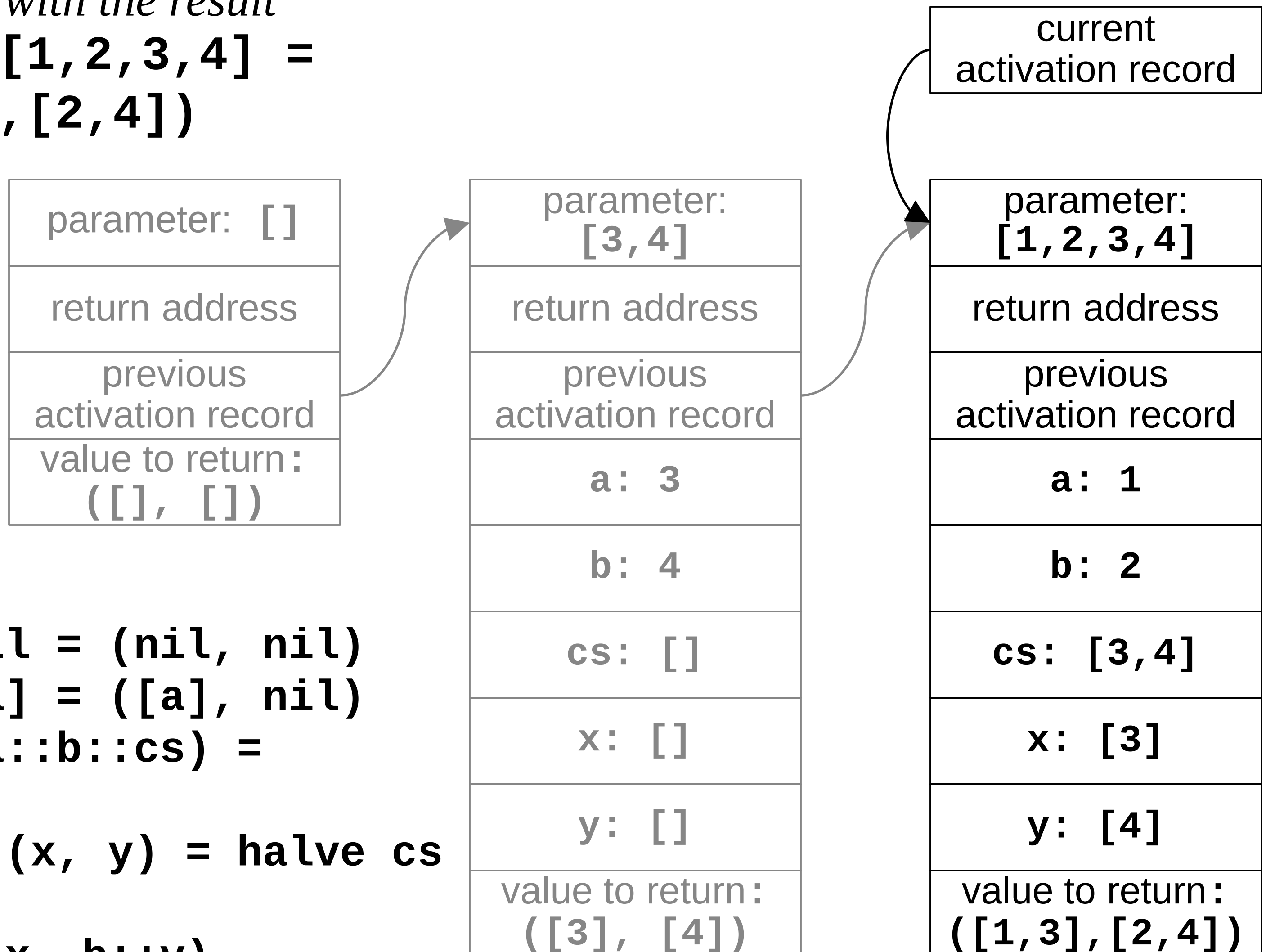

```
fun halve nil = (nil, nil)
|   halve [a] = ([a], nil)
|   halve (a::b::cs) =
      let
        val (x, y) = halve cs
      in
        (a::x, b::y)
      end;
```

The second activation is about to return.




```
fun halve nil = (nil, nil)
|   halve [a] = ([a], nil)
|   halve (a::b::cs) =
      let
        val (x, y) = halve cs
      in
        (a::x, b::y)
      end;
```

The first activation is about to return with the result
halve [1,2,3,4] = ([1,3],[2,4])




```
fun halve nil = (nil, nil)
|   halve [a] = ([a], nil)
|   halve (a::b::cs) =
      let
        val (x, y) = halve cs
      in
        (a::x, b::y)
      end;
```

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Nesting Functions

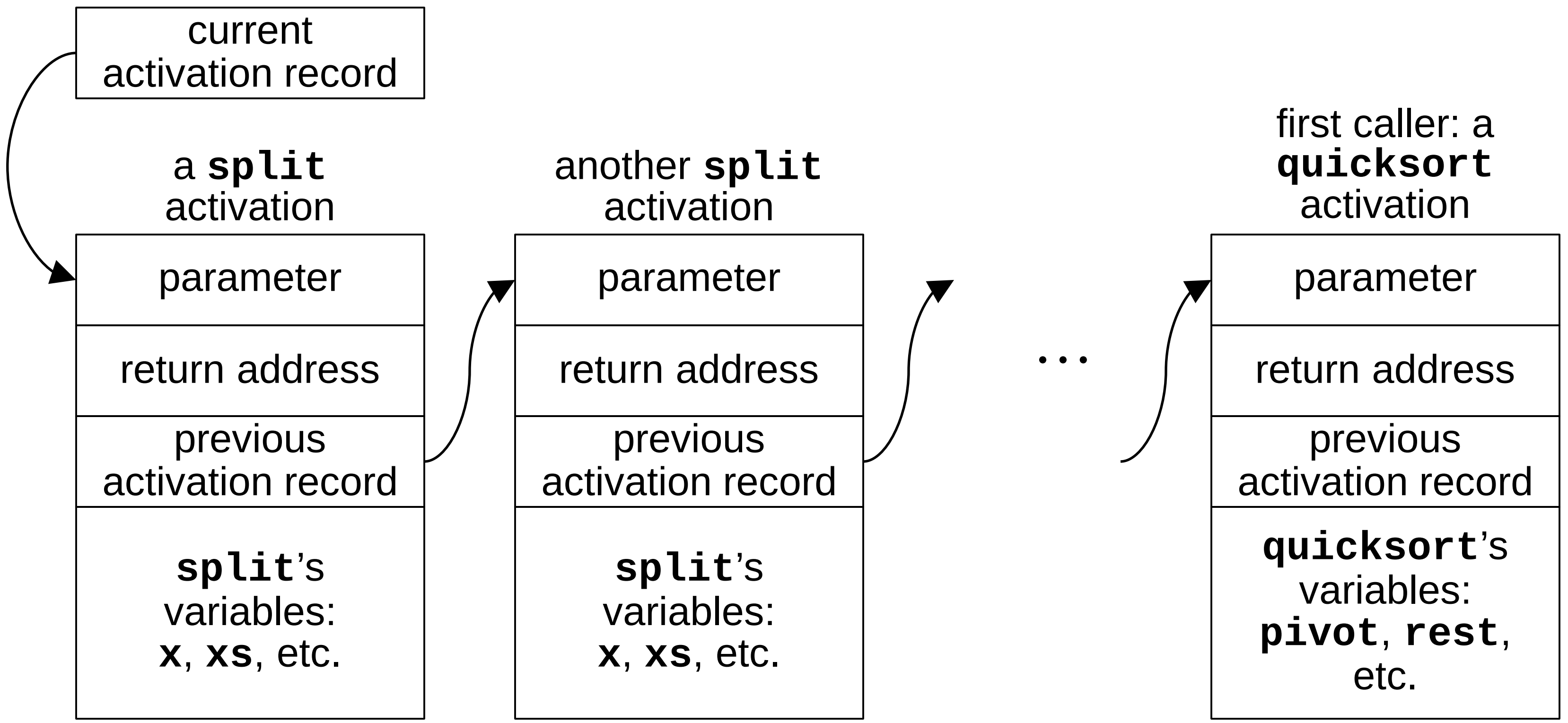
- What we just saw is adequate for many languages, including C
- But not for languages that allow this trick:
  - Function definitions can be nested inside other function definitions
  - Inner functions can refer to local variables of the outer functions (under the usual block scoping rule)
- Like ML, Ada, Pascal, etc.

Example

```
fun quicksort nil = nil
|   quicksort (pivot::rest) =
      let
        fun split(nil) = (nil,nil)
        |   split(x::xs) =
              let
                val (below, above) = split(xs)
              in
                if x<pivot then (x::below, above)
                else (below, x::above)
              end;
        val (below, above) = split(rest)
      in
        quicksort below @ [pivot] @ quicksort above
      end;
```

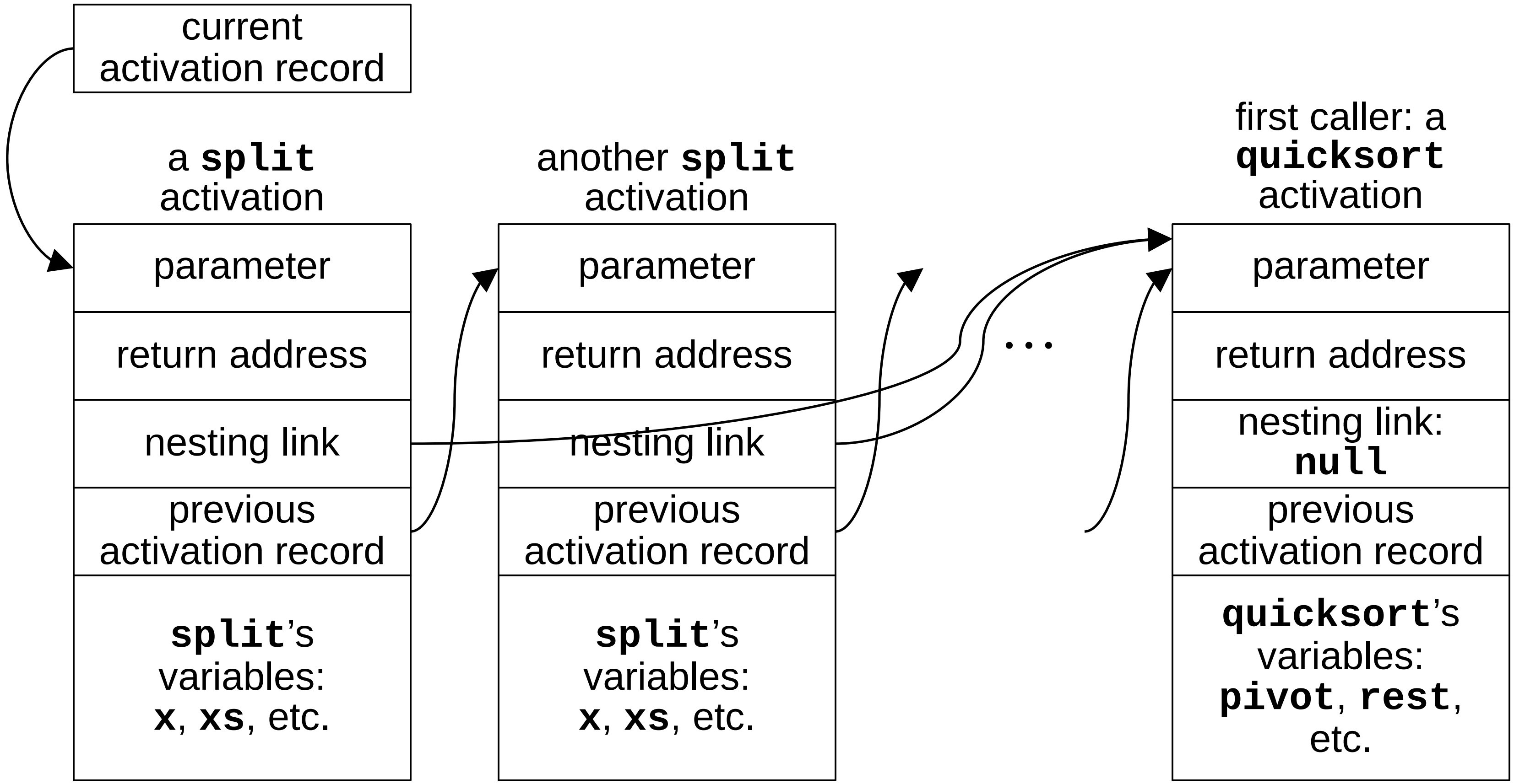
The Problem

- How can an activation of the inner function (**`split`**) find the activation record of the outer function (**`quicksort`**)?
- It isn't necessarily the previous activation record, since the caller of the inner function may be another inner function
- Or it may call itself recursively, as **`split`** does…


current
activation record
a split
activation
another split
activation
first caller: a
quicksort
activation
parameter
return address
previous
activation record
split's
variables:
x, xs, etc.
parameter
return address
previous
activation record
split's
variables:
x, xs, etc.
. . .
parameter
return address
previous
activation record
quicksort's
variables:
pivot, rest,
etc.

Nesting Link

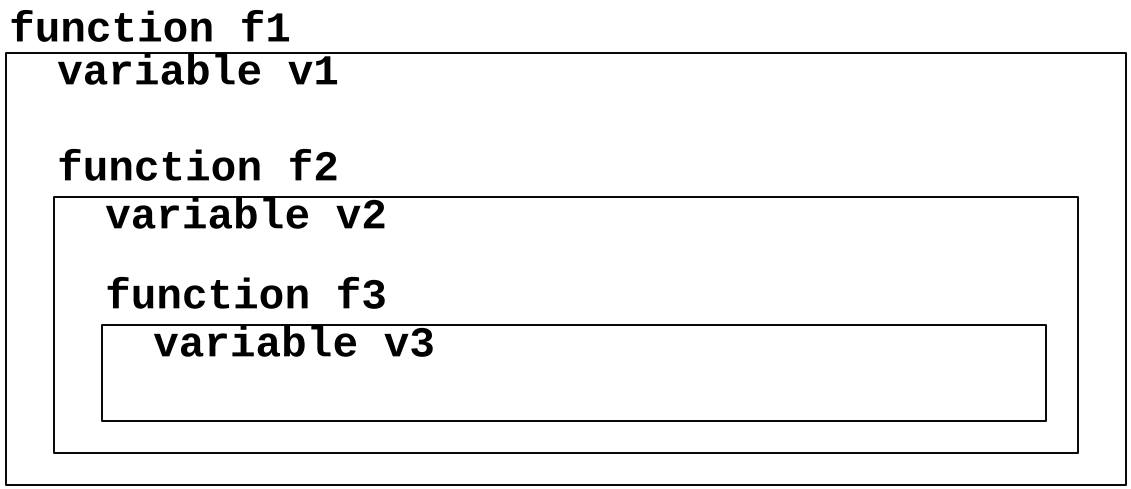
- An inner function needs to be able to find the address of the most recent activation for the outer function
- We can keep this *nesting link* in the activation record…


current activation record
a split activation
another split activation
first caller: a quicksort activation
parameter
return address
nesting link
previous activation record
split's variables: x, xs, etc.
parameter
return address
nesting link
previous activation record
split's variables: x, xs, etc.
. . .
parameter
return address
nesting link: null
previous activation record
quicksort's variables: pivot, rest, etc.

Setting The Nesting Link

- Easy if there is only one level of nesting:
  - Calling outer function: set to null
  - Calling from outer to inner: set nesting link same as caller's activation record
  - Calling from inner to inner: set nesting link same as caller's nesting link
- More complicated if there are multiple levels of nesting…

Multiple Levels Of Nesting



- References at the same level (**`f1`** to **`v1`**, **`f2`** to **`v2`**, **`f3`** to **`v3`**) use current activation record
- References *n* nesting levels away chain back through *n* nesting links

Other Solutions

- The problem: references from inner functions to variables in outer ones
  - Nesting links in activation records: as shown
  - Displays: nesting links not in the activation records, but collected in a single static array
  - Lambda lifting: problem references replaced by references to new, hidden parameters

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Functions As Parameters

- When you pass a function as a parameter, what really gets passed?
- Code must be part of it: source code, compiled code, pointer to code, or implementation in some other form
- For some languages, something more is required…

Example

```
fun addXToAll (x,theList) =
  let
    fun addX y =
      y + x;
  in
    map addX theList
  end;
```

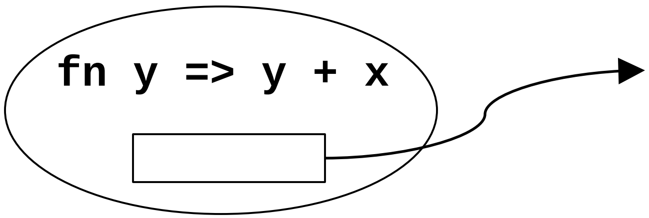
- This function adds **`x`** to each element of **`theList`**
- Notice: **`addXToAll`** calls **`map`**, **`map`** calls **`addX`**, and **`addX`** refers to a variable **`x`** in **`addXToAll`**'s activation record

Nesting Links Again

- When `map` calls `addX`, what nesting link will `addX` be given?
  - Not `map`'s activation record: `addX` is not nested inside `map`
  - Not `map`'s nesting link: `map` is not nested inside anything
- To make this work, the parameter `addX` passed to `map` must include the nesting link to use when `addX` is called

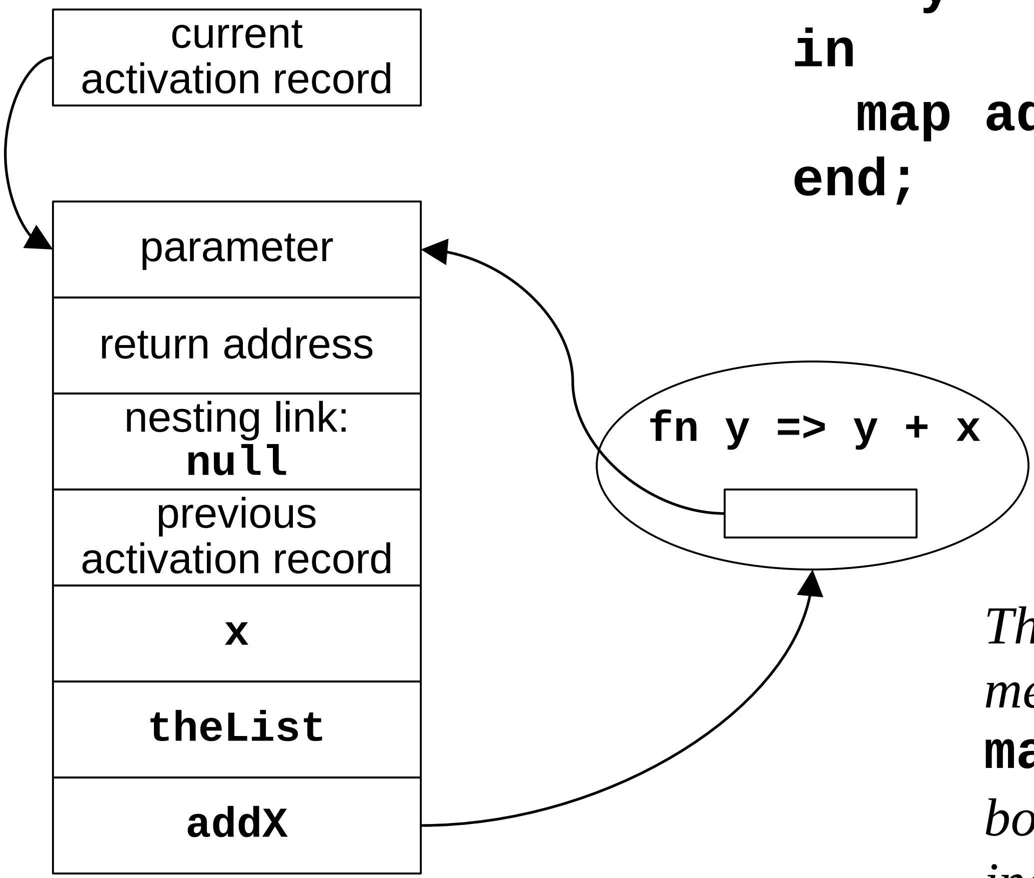
Not Just For Parameters

- Many languages allow functions to be passed as parameters
- Functional languages allow many more kinds of operations on function-values:
  - passed as parameters, returned from functions, constructed by expressions, etc.
- Function-values include both parts: code to call, and nesting link to use when calling it



Example

```
fun addXToAll (x,theList) =
  let
    fun addX y =
      y + x;
  in
    map addX theList
  end;
```



This shows the contents of memory just before the call to **`map`**. *The variable* **`addX`** *is bound to a function-value including code and nesting link.*

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One More Complication

- What happens if a function value is used after the function that created it has returned?

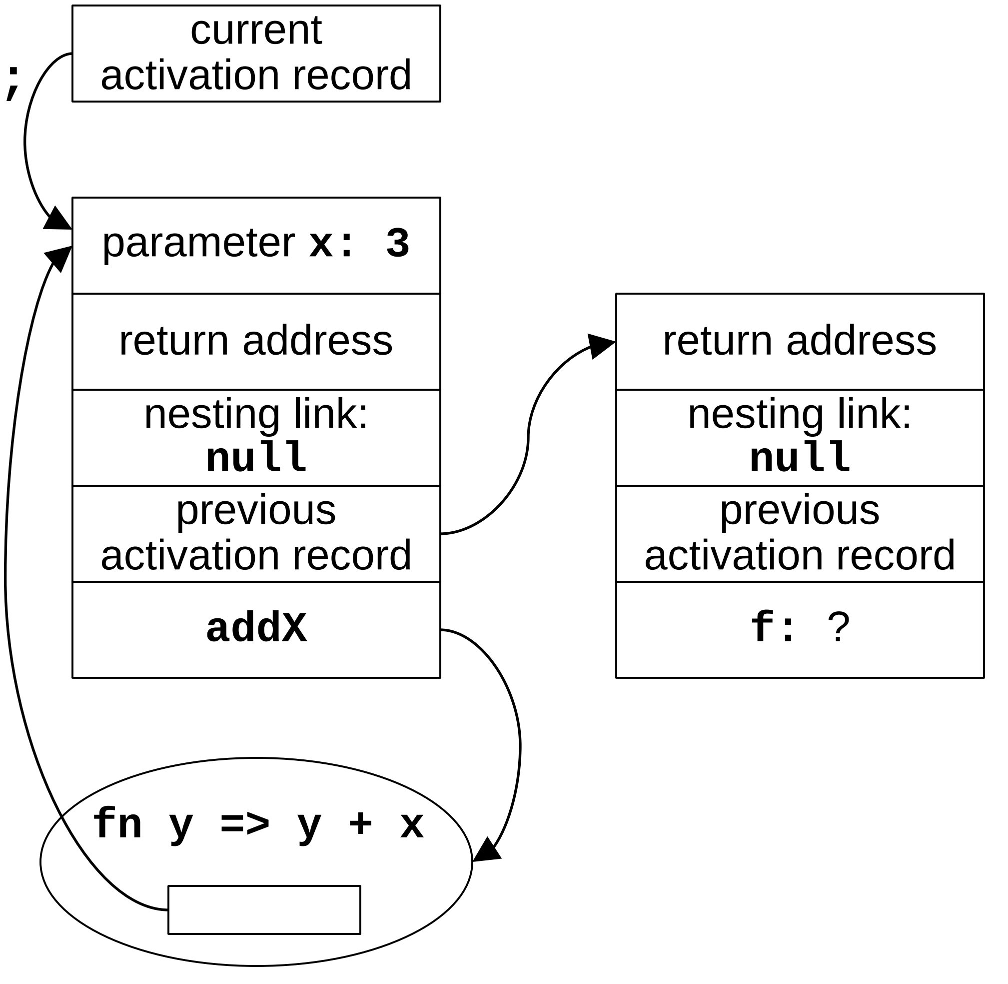
```
fun test () =
  let
    val f = funToAddX 3;
  in
    f 5
  end;
```

```
fun funToAddX x =
  let
    fun addX y =
      y + x;
  in
    addX
  end;
```

Note: **`test`***'s parameter here is the special value* **`()`**. *That's the one and only value of type* **`unit`** *in ML. It often serves as a dummy parameter—a sort of placeholder for functions that don't have significant parameters.*

```
fun test () =
  let
    val f = funToAddX 3;
  in
    f 5
  end;

fun funToAddX x =
  let
    fun addX y =
      y + x;
  in
    addX
  end;
```

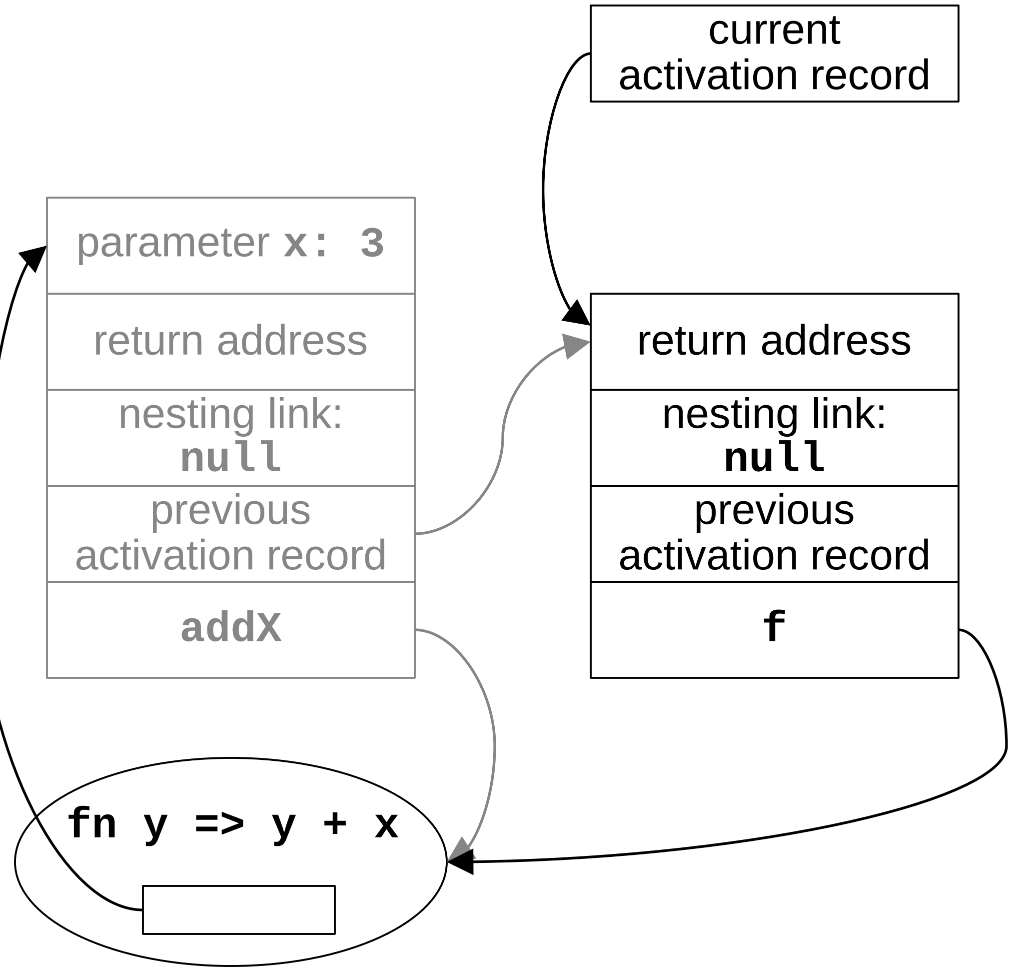


This shows the contents of memory just before **funToAddX** *returns.*

```
fun test () =
  let
    val f = funToAddX 3;
  in
    f 5
  end;

fun funToAddX x =
  let
    fun addX y =
      y + x;
  in
    addX
  end;
```

After **funToAddX** *returns,* **f** *is the bound to the new function-value.*



The Problem

- When **`test`** calls **`f`**, the function will use its nesting link to access **`x`**
- That is a link to an activation record for an activation that is finished
- This will fail if the language system deallocated that activation record when the function returned

The Solution

- For ML, and other languages that have this problem, activation records cannot always be allocated and deallocated in stack order
- Even when a function returns, there may be links to its activation record that will be used; it can't be deallocated it is unreachable
- *Garbage collection*: chapter 14, coming soon!

Conclusion

- The more sophisticated the language, the harder it is to bind activation-specific variables to memory locations
  - Static allocation: works for languages that permit only one activation at a time (like early dialects of Fortran and Cobol)
  - Simple stack allocation: works for languages that do not allow nested functions (like C)

Conclusion, Continued

- Nesting links (or some such trick): required for languages that allow nested functions (like ML, Ada and Pascal); function values must include both code and nesting link
- Some languages (like ML) permit references to activation records for activations that are finished; so activation records cannot be deallocated on return