École Polytechnique

CSC_52064 – Compilation

Jean-Christophe Filliâtre

object-oriented languages
functional languages

today we focus on the compilation of

1. object-oriented languages
   - object layout
   - dynamic dispatch

2. functional languages
   - first-class functions
   - tail call optimization

compiling OO languages

let us explain

- how an object is represented
- how a method call is implemented

let us use Java as an example (for the moment)

```
class Vehicle {
  static int start = 10;
  int position;
  Vehicle() { position = start; }
  void move(int d) { position += d; } }
```

```
class Car extends Vehicle {
  int passengers;
  void await(Vehicle v) {
    if (v.position < position)
      v.move(position - v.position);
    else
      move(10); } }
```

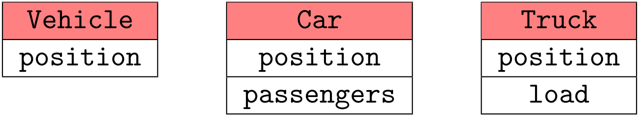
```
class Truck extends Vehicle {
  int load;
  void move(int d) {
    if (d <= 55) position += d; else position += 55; } }
```

an object is a heap-allocated block, containing

- its class (and a few other items of information)
- the values of its fields

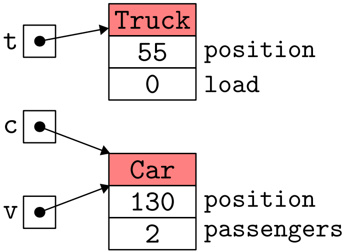
the value of an object is a pointer to the block

key idea: simple inheritance allows us to store the value of some field x at some fixed position in the block: own fields are placed after inherited fields



note the absence of field `start`, which is static and thus allocated elsewhere (for instance in the data segment)

```
Truck t = new Truck();
Car c = new Car();
c.passengers = 2;
c.move(60);
Vehicle v = c;
v.move(70);
c.await(t);
```



for each field, the compiler knows its position, that is the offset to add to the object pointer

if for instance field `position` is at offset +16, then expression `e.position` is compiled to

```
...                   # compile e in %rcx
movl 16(%rcx), %eax   # field position at +16
```

this is sound, even if the compiler **only knows the static type** of `e`, which may differ from the dynamic type (the class of the object)

it could even be a sub-class of `Vehicule` that is not yet defined!

overriding is the ability to redefine a method in a subclass
(so that objects in that subclass behave differently)

example: in class `Truck`

```
class Truck extends Vehicle {
  ...
  void move(int d) { ... }
}
```

the method `move`, inherited from class `Vehicle`, is **overridden** the essence of OO languages lies in **dynamic method call** $e.m(e_1, \dots, e_n)$ (aka dynamic dispatch / message passing)

to do this, we build **class descriptors** containing addresses to method codes (aka **dispatch table**, **vtable**, etc.)

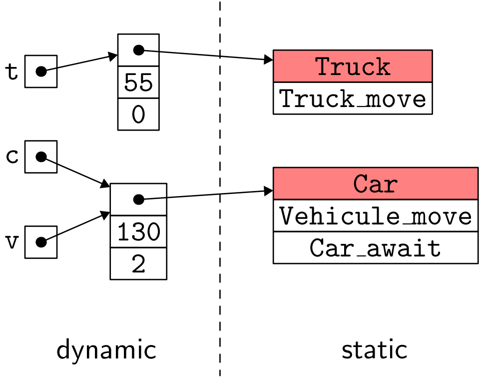
as for class fields, simple inheritance allows us to store the address of (the code of) method m at a fixed offset in this descriptor

class descriptors can be allocated in the data segment; each object points to its class descriptor

```
class Vehicule                     { void move(int d) {...} }
class Car    extends Vehicule { void await(Vehicule v) {...}}
class Truck extends Vehicule { void move(int d) {...} }
```

descr. Vehicule	descr. Car	descr. Truck
Vehicule_move	Vehicule_move	Truck_move
	Car_await	

```
Truck t = new Truck();
Car c = new Car();
c.passengers = 2;
c.move(60);
Vehicle v = c;
v.move(70);
c.await(t);
```



to compile a call such as `e.move(10)`

1. we compile `e`; its value is a pointer to an object
2. this object contains a pointer to its class descriptor
3. inside, the code for method `move` is located at some offset known from the compiler (for instance +8)

```
...                   # compile e into %rdi
movq $10, %rsi        # parameter
movq (%rdi), %rcx     # get the class descriptor
call *8(%rcx)         # call method move
```

as for field access, the compiler has no need to know the actual class of the object (the dynamic type) if we write

```
Truck v = new Truck();
((Vehicule)v).move();
```

this is the method `move` from class `Truck` that is called
since the call is always compiled the same way

the cast only has an influence on the static type
(existence of the method + overloading resolution; see lecture 4)

in practice, the class descriptor for C also points to the class that C inherits from, called the **super class** of C

this can be a pointer to the descriptor of the super class
(for instance stored in the very first slot of the descriptor)

this allows subtyping tests at runtime (*downcast* or `instanceof`)

a few words on C++

let us reuse the vehicles example

```
class Vehicle {
  static const int start = 10;
public:
  int position;
  Vehicle() { position = start; }
  virtual void move(int d) { position += d; }
};
```

`virtual` means that method `move` can be overridden

```
class Car : public Vehicle {
public:
  int passengers;
  Car() {}
  void await(Vehicle &v) { // call by reference
    if (v.position < position)
      v.move(position - v.position);
    else
      move(10);
  }
};
```

```
class Truck : public Vehicle {
public:
  int load;
  Truck() {}
  void move(int d) {
    if (d <= 55) position += d; else position += 55;
  }
};
```

```
#include <iostream>
using namespace std;

int main() {
  Truck t; // object is stack-allocated
  Car c;
  c.passengers = 2;
  c.move(60);
  Vehicle *v = &c; // alias
  v->move(70);
  c.await(t);
}
```

on this example, the object layout is not different from Java's

descr. `Vehicle`
`position`

descr. `Car`
`position`
`passengers`

descr. `Truck`
`position`
`load`

but in C++, we also have **multiple inheritance**

consequence: we cannot use anymore the principle that

- the object layout for the super class is a prefix of the object layout of the subclass
- the descriptor for the super class is a prefix of the descriptor for the subclass

```
class Rocket {
public:
  float thrust;
  Rocket() { }
  virtual void display() {}
};

class RocketCar : public Car, public Rocket {
public:
  char *name;
  void move(int d) { position += 2*d; }
};
```

descr. RocketCar
position
passengers
descr. Rocket
thrust
name

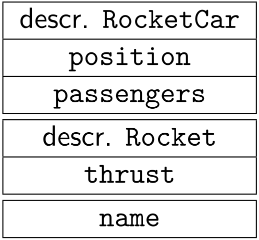
representations of Car and Rocket are appended in particular, a cast such as

```
RocketCar rc;
... (Rocket)rc ...
```

is compiled using pointer arithmetic

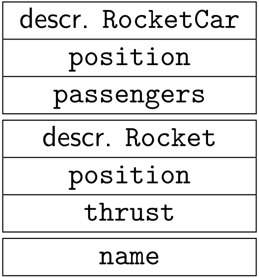
```
... rc + 16 ...
```

this is not a no-op anymore



let us now assume that `Rocket` also inherits from `Vehicle`

```
class Rocket : public Vehicle {
public:
  float thrust;
  Rocket() { }
  virtual void display() {}
};

class RocketCar : public Car, public Rocket {
public:
  char *name;
  ...
};
```



we now have **two** fields `position`

and thus a possible ambiguity

```
class RocketCar : public Car, public Rocket {
public:
  char *name;
  void move(int d) { position += 2*d; }
};
```

```
vehicles.cc: In member function ‘virtual void RocketCar::move(int)’
vehicles.cc:51:22: error: reference to ‘position’ is ambiguous
```

we have to say which one we refer to

```
class RocketCar : public Car, public Rocket {
public:
  char *name;
  void move(int d) { Rocket::position += 2*d; }
};
```

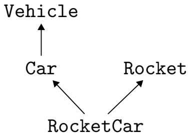
to have a single instance of `Vehicle` inside `RocketCar`, we need to modify the way `Car` and `Rocket` inherit from `Vehicle`; this is **virtual inheritance**

```
class Vehicle { ... };

class Car : public virtual Vehicle { ... };

class Rocket : public virtual Vehicle { ... };

class RocketCar : public Car, public Rocket {
```

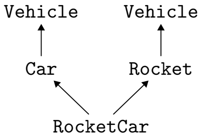
there is no ambiguity anymore:

```
public:
  char *name;
  void move(int d) { position += 2*d; }
};
```

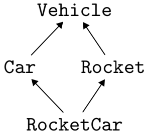
```
class Vehicle { ... };
class Car : Vehicle { ... };
class Rocket { ... };
class RocketCar : Car, Rocket { ... };
```




```
class Vehicle { ... };
class Car : Vehicle { ... };
class Rocket : Vehicle { ... };
class RocketCar : Car, Rocket { ... };
```




```
class Vehicle { ... };
class Car : virtual Vehicle { ... };
class Rocket : virtual Vehicle { ... };
class RocketCar : Car, Rocket { ... };
```



(the diamond)

g++'s command line option `-fdump-lang-class` outputs a text file containing objects and tables layout

Java interfaces

though Java only features simple inheritance, interfaces make method call more complex, in a way analogous to multiple inheritance

```
interface I {
  void m();
}

class C {
  void foo(I x) { x.m(); }
}
```

when compiling `x.m()`, we have no idea what the class of object `x` will be instead of dispatching according to the type of the object, we can use the types of **all** the actual parameters; this is called **multiple dispatch**

an example: Julia, a mathematically-oriented language

```
function +(x::Int64  , y::Int64  ) ... end
function +(x::Float64, y::Float64) ... end
function +(x::Date   , y::Time   ) ... end
```

another example: CLOS (Common Lisp Object System)

pattern matching, as we find in OCaml for instance, e.g.,

```
let rec eval = function
| Const n -> ...
| Call ("print", [e]) -> ...
| Call (f, el) -> ...
```

is a form of dynamic dispatch: the branch is selected according to some runtime information

the polycopié (section 7.3) describes how the compiler turns pattern matching into elementary operations

see also the comparison functional/object in lecture 2

compiling functional languages

first-class functions

on key aspect of functional programming is **first-class functions**, which means that a function is a value like any other

in particular, we can

- receive a function as a parameter
- return a function as a result
- store a function in a data structure
- build new functions dynamically

the ability to pass functions as parameters already exists in languages such as Algol, Pascal, Ada, etc.

similarly, the notion of function pointers already exists (Fortran, C, C++, etc.)

but the notion of first-class functions is strictly more powerful

let us illustrate it with OCaml

let us consider this fragment of OCaml

$$
\begin{array}{rcl}
e & ::= & c \\
  & \mid & x \\
  & \mid & \texttt{fun}\ x \rightarrow e \\
  & \mid & e\ e \\
  & \mid & \texttt{let}\ [\texttt{rec}]\ x = e\ \texttt{in}\ e \\
  & \mid & \texttt{if}\ e\ \texttt{then}\ e\ \texttt{else}\ e \\
 & & \\
d & ::= & \texttt{let}\ [\texttt{rec}]\ x = e \\
 & & \\
p & ::= & d\ \dots\ d
\end{array}
$$

functions can be nested

```
let sum n =
  let f x = x * x in
  let rec loop i =
    if i = n then 0 else f i + loop (i+1)
  in
  loop 0
```

scoping is usual

(`let f x = x * x` is sugar for `let f = fun x -> x * x`) we can pass functions as parameters

```
let square f x =
  f (f x)
```

and return functions

```
let f x =
  if x < 0 then fun y -> y - x else fun y -> y + x
```

here, the function returned by `f` uses `x` but the stack frame for `f` just disappeared!

so we cannot compile functions in the usual way the solution is to use a **closure** (en français, une **fermeture**)

this is a heap-allocated data structure (to survive function calls) containing

- a **pointer to the code** (of the function body)
- the values of the variables that may be needed by this code; this is called the **environment**

P. J. Landin, *The Mechanical Evaluation of Expressions*,
The Computer Journal, 1964

what are the variables to be stored in the environment of the closure representing $\texttt{fun}\ x \to e$?

these are the **free variables** of $\texttt{fun}\ x \to e$

the set $fv(e)$ of the free variables of the expression e is computed as follows:

$$
\begin{array}{rcl}
fv(c) & = & \emptyset \\
fv(x) & = & \{x\} \\
fv(\texttt{fun}\ x \to e) & = & fv(e) \setminus \{x\} \\
fv(e_1\ e_2) & = & fv(e_1) \cup fv(e_2) \\
fv(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & fv(e_1) \cup (fv(e_2) \setminus \{x\}) \\
fv(\texttt{let rec}\ x = e_1\ \texttt{in}\ e_2) & = & (fv(e_1) \cup fv(e_2)) \setminus \{x\} \\
fv(\texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3) & = & fv(e_1) \cup fv(e_2) \cup fv(e_3)
\end{array}
$$

let us consider the following program approximating $\int_0^1 x^n dx$

```
let rec pow i x =
  if i = 0 then 1. else x *. pow (i-1) x

let integrate_xn n =
  let f = pow n in
  let eps = 0.001 in
  let rec sum x =
    if x >= 1. then 0. else f x +. sum (x +. eps) in
  sum 0. *. eps
```

let us make constructions `fun` explicit and let us consider the closures

```
let rec pow =
  fun i ->
    fun x -> if i = 0 then 1. else x *. pow (i-1) x
```

- in the first closure, `fun i ->`, the environment is $\{\texttt{pow}\}$
- in the second closure, `fun x ->`, it is $\{\texttt{i}, \texttt{pow}\}$

```
let integrate_xn = fun n ->
  let f = pow n in
  let eps = 0.001 in
  let rec sum =
    fun x -> if x >= 1. then 0. else f x +. sum (x+.eps) in
  sum 0. *. eps
```

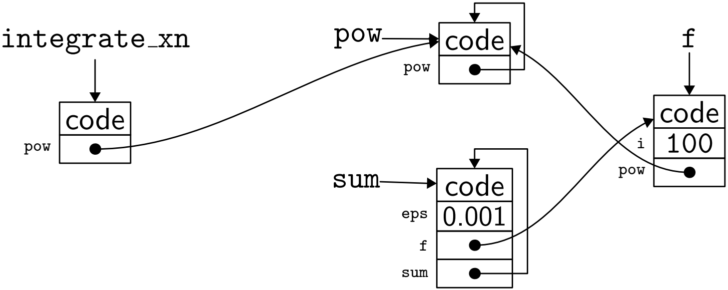
- for `fun n ->`, the environment is $\{\mathtt{pow}\}$
- for `fun x ->`, the environment is $\{\mathtt{eps}, \mathtt{f}, \mathtt{sum}\}$

the closure is a single heap-allocated block, whose

- first field contains the code pointer
- next fields contains the values of the free variables (the environment)

```
let rec pow i x = if i = 0 then 1. else x *. pow (i-1) x
let integrate_xn n =
  let f = pow n in
  let eps = 0.001 in
  let rec sum x = if x >= 1. then 0. else f x +. sum (x+.eps) in
  sum 0. *. eps
```

during the execution of `integrate_xn 100`, we have four closures:



a good way to compile closures is to proceed in two steps

1. first, we replace all expressions `fun` $x \to e$ by explicit closure constructions

$$\texttt{clos}\ f\ [y_1, \ldots, y_n]$$

   where the y_i are the free variables of `fun` $x \to e$ and f is the name of a global function

$$\texttt{letfun}\ f\ [y_1, \ldots, y_n]\ x = e'$$

   where e' is derived from e by replacing constructions `fun` recursively (this is called **closure conversion**)

2. we compile the obtained code, which only contains `letfun` function declarations

on the example, we get

```
letfun fun2 [i,pow] x =
  if i = 0 then 1. else x *. pow (i-1) x
letfun fun1 [pow] i =
  clos fun2 [i,pow]
let rec pow =
  clos fun1 [pow]
letfun fun3 [eps,f,sum] x =
  if x >= 1. then 0. else f x +. sum (x +. eps)
letfun fun4 [pow] n =
  let f = pow n in
  let eps = 0.001 in
  let rec sum = clos fun3 [eps,f,sum] in
  sum 0. *. eps
let integrate_xn =
  clos fun4 [pow]
```

before

$$
\begin{array}{rcl}
e & ::= & c \\
 & | & x \\
 & | & \texttt{fun}\ x \rightarrow e \\
 & | & e\ e \\
 & | & \texttt{let}\ [\texttt{rec}]\ x = e\ \texttt{in}\ e \\
 & | & \texttt{if}\ e\ \texttt{then}\ e\ \texttt{else}\ e \\
\\
d & ::= & \texttt{let}\ [\texttt{rec}]\ x = e \\
\\
p & ::= & d\ \dots\ d
\end{array}
$$

after

$$
\begin{array}{rcl}
e & ::= & c \\
 & | & x \\
 & | & \texttt{clos}\ f\ [x, \dots, x] \\
 & | & e\ e \\
 & | & \texttt{let}\ [\texttt{rec}]\ x = e\ \texttt{in}\ e \\
 & | & \texttt{if}\ e\ \texttt{then}\ e\ \texttt{else}\ e \\
\\
d & ::= & \texttt{let}\ [\texttt{rec}]\ x = e \\
 & | & \texttt{letfun}\ f\ [x, \dots, x]\ x = e \\
\\
p & ::= & d\ \dots\ d
\end{array}
$$

in the new syntax trees, an identifier x can be

- a **global variable** introduced by `let`
  (allocated in the data segment)

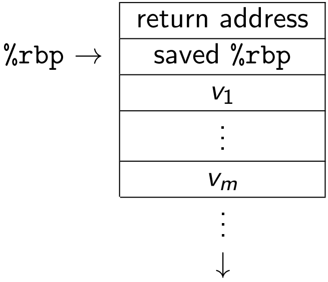
- a **local variable** introduced by `let in`
  (allocated in the stack frame / a register)

- a **variable contained in a closure**

- the **argument** of a function (the `x` of `fun x -> e`) each function has a single argument, passed in register `%rdi`

the closure is passed in register `%rsi`

the stack frame is as follows,
where $v_1, \ldots, v_m$ are the local variables



let us detail how to compile

- the construction of a closure `clos` $f\ [y_1, \dots, y_n]$
- a function call $e_1\ e_2$
- the access to a variable x
- a function declaration `letfun` $f\ [y_1, \dots, y_n]\ x = e$

to compile

$$\texttt{clos}\ f\ [y_1, \dots, y_n]$$

we proceed as follows

1. we allocate a block of size $n + 1$ on the heap (with a GC)
2. we store the address of f in field 0
   (f is a label in the assembly code and we get its address with $\$f$)
3. we store the values of the variables $y_1, \dots, y_n$ in fields 1 to n
4. we return a pointer to the block

note: we delegate the deallocation of the block to the GC (see lecture 9) to compile a function call

$$e_1\ e_2$$

we proceed as follows

1. we compile e_1 into register `%rsi`
   (its value is a p_1 to a closure)
2. we compile e_2 into register `%rdi`
3. we call the function whose address is contained in the first field of the closure, with `call *(%rsi)`

   this is a jump to **dynamic address**
   (similar to what we did earlier to compile OO languages)

to compile the access to the variable x, we distinguish four cases

global variable
: the value is stored at the address given by label x

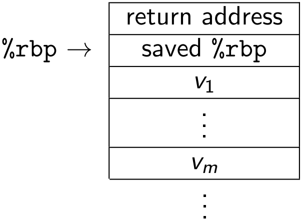
local variable
: the value is at n(`%rbp`) / in a register

variable contained in a closure
: the value is at n(`%rsi`)

function argument
: the value is in register `%rdi`

last, to compile the declaration

$$\texttt{letfun}\ f\ [y_1,\ldots,y_n]\ x = e$$



we proceed as for a usual function declaration

1. save and set `%rbp`
2. allocate the frame (for the local variables of e)
3. evaluate e in register `%rax`
4. delete the stack frame and restore `%rbp`
5. execute `ret`

today we find closures in

- Java (since 2014 and Java 8)
- C++ (since 2011 and C++11)

in these languages, anonymous functions are called **lambdas** a function is a regular object, with a method `apply`

```
LinkedList<B> map(LinkedList<A> l, Function<A, B> f) {
  ... f.apply(x) ...
}
```

an anonymous function is introduced with `->`

```
map(l, x -> { System.out.print(x); return x+y; })
```

the compiler builds a closure object (here capturing the value of `y`) with a method `apply` an anonymous function is introduced with `[]`

```
for_each(v.begin(), v.end(), [y](int &x){ x += y; });
```

we specify the variables captured in the closure (here `y`)

the default behavior is to capture by value

we may specify a capture by reference instead (here of `s`)

```
for_each(v.begin(), v.end(), [y,&s](int x){ s += y*x; });
```

the compiler builds a closure (whose type is not accessible ⇒ use `auto`)

tail call optimization

Definition

We say that a function **call** $f(e_1, \ldots, e_n)$ *that appears in the body of a function* g *is a* **tail call** *if this is the last thing that* g *computes before it returns.*

by extension, we can say that a function is a **tail recursive function** if it is a recursive function whose recursive calls are all tail calls a tail call is not necessarily a recursive call

```
int g(int x) {
  int y = x * x;
  return f(y);
}
```

in a recursive function, we may have recursive calls that are tail calls and others that are not

```
int f91(int n) {
  if (n > 100) return n - 10;
  return f91(f91(n + 11));
}
```

what is the point with tail calls?

we can delete the stack frame of the function performing the tail call **before** we make the call, since it is not needed afterwards

better, we can **reuse** it to make the tail call (in particular, the return address is the right one)

said otherwise, we can make a `jump` rather than a `call`

```c
int fact(int acc, int n) {
  if (n <= 1) return acc;
  return fact(acc * n, n - 1);
}
```

traditional compilation

```
fact: cmpq  $1, %rsi
      jle   L0
      imulq %rsi, %rdi
      decq  %rsi
      call  fact
      ret
L0:   movq  %rdi, %rax
      ret
```

optimization

```
fact: cmpq  $1, %rsi
      jle   L0
      imulq %rsi, %rdi
      decq  %rsi
      jmp   fact    # <--

L0:   movq  %rdi, %rax
      ret
```

the result is a **loop**

the code is indeed identical to the compilation of

```
int fact(int acc, int n) {
  while (n > 1) {
    acc *= n;
    n--;
  }
  return acc;
}
```

the compiler `gcc` optimizes tail calls when we pass option `-foptimize-sibling-calls` (included in option `-O2`)

have a look at the code produced by `gcc -O2` on programs such as `fact` or those of slide 63 in particular, we notice that

```
int f91(int n) {
  if (n > 100) return n - 10;
  return f91(f91(n + 11));
}
```

is compiled **exactly** as if we were compiling

```
int f91(int n) {
  while (n <= 100)
    n = f91(n + 11);
  return n - 10;
}
```

the OCaml compiler optimizes tail calls by default

the compilation of

```
let rec fact acc n =
  if n <= 1 then acc else fact (acc * n) (n - 1)
```

is a loop, as with the C program

even if we started with a functional program (variables `acc` and `n` are immutable) with tail call optimization, we get a more efficient code since we have reduced memory access (we do not use `call` and `ret` anymore, which manipulate the stack) on the `fact` example, **the stack space becomes constant**

in particular, we avoid any stack overflow due to a too large number of nested calls

```
Stack overflow during evaluation (looping recursion?).
```

```
Fatal error: exception Stack_overflow
```

```
Exception in thread "main" java.lang.StackOverflowError
```

```
Segmentation fault
```

etc.

if we implement quicksort as follows

```
void quicksort(int a[], int l, int r) {
  if (r - l <= 1) return;
  // partition a[l..r[ in three
  //     l         lo        hi        r
  //    +---------+---------+---------+
  //   a|...<p...|...=p...|...>p...|
  //    +---------+---------+---------+
  ...
  quicksort(a, l, lo);
  quicksort(a, hi, r);
}
```

we can overflow the stack

but if we make the first recursive call on the smallest half

```
void quicksort(int a[], int l, int r) {
  ...
  if (lo - l < r - hi) {
    quicksort(a, l, lo);
    quicksort(a, hi, r);
  } else {
    quicksort(a, hi, r);
    quicksort(a, l, lo);
  }
}
```

the second call is a tail call and a logarithmic stack space is now guaranteed what if my compiler does not optimize tail calls (e.g. Java)?

no problem, do it yourself!

```
void quicksort(int a[], int l, int r) {
  while (r - l > 1) {
    ...
    if (lo - l < r - hi) {
      quicksort(a, l, lo);
      l = hi;
    } else {
      quicksort(a, hi, r);
      r = lo;
    }
  }
}
```

it is important to point out that the notion of tail call

- could be optimized in any language
  (but Java and Python do not, for instance)

- is not related to recursion
  (even if it is likely that a stack overflow is due to a recursive function)

it is not always easy to turn calls into tail calls

example: given a type for immutable binary trees, such as

```
type 'a tree = Empty | Node of 'a tree * 'a * 'a tree
```

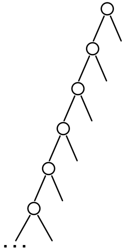
implement a function to compute the height of a tree

```
val height: 'a tree -> int
```

the natural code

```
let rec height = function
| Empty          -> 0
| Node (l, _, r) -> 1 + max (height l) (height r)
```

causes a stack overflow on a tree with a large height



instead of computing the height h of the tree, let us compute $k(h)$ for some arbitrary function k, called a **continuation**

```
val height: 'a tree -> (int -> 'b) -> 'b
```

we call this **continuation-passing style** (or CPS)

the height of a tree is then obtained with the identity continuation

```
height t (fun h -> h)
```

the code looks like

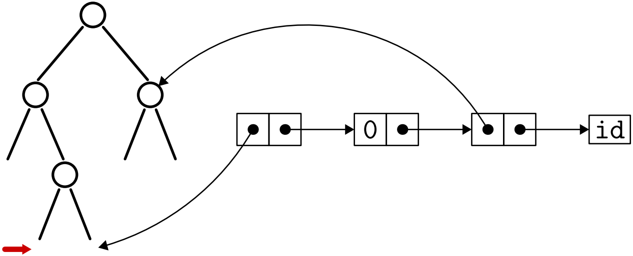
```
let rec height t k = match t with
  | Empty ->
      k 0
  | Node (l, _, r) ->
      height l (fun hl ->
      height r (fun hr ->
      k (1 + max hl hr)))
```

we note that **all** calls to `height` and `k` are **tail calls**

thus `height` runs in constant stack space we have traded stack space for **heap space**

it holds closures

the first closure captures `r` and `k`, the second one captures `hl` and `k`



of course, there are other, ad hoc, solutions to compute the height of a tree without overflowing the stack (e.g. a breadth-first traversal)

similarly, there are solutions for mutable trees, trees with parent pointers, etc.

but the CPS-based solution is **systematic** and what if the compiler optimizes tail calls but the language does not feature anonymous functions (e.g. C)?

we simply have to build closures by ourselves, manually
(a structure with a function pointer and an environment)

we can even introduce some ad hoc data type for closures

```
enum kind { Kid, Kleft, Kright };

struct Kont {
  enum kind kind;
  union { struct Node *r; int hl; };
  struct Kont *kont;
};
```

together with a function to apply it

```
int apply(struct Kont *k, int v) { ... }
```

this is called **defunctionalization** (Reynolds 1972)

- lab 6
  - Mini Java compiler continued
- next lecture
  - optimizing compiler 1/2