École Polytechnique

CSC_52064 – Compilation

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evaluation strategies
parameter passing

1. evaluations strategies, parameter passing
   - Java
   - OCaml
   - Python
   - C
   - C++

2. compiling call by value and call by reference
   - illustrated with C++

evaluation strategies, parameter passing

when **declaring** a function

```
function f(x1, ..., xn) =
  ...
```

variables `x1,...,xn` are called the **formal parameters** of `f`

and when **calling** this function

```
f(e1, ..., en)
```

expressions `e1,...,en` are called the **actual parameters** of `f` in a language with in-place modifications, an assignment

```
e1 := e2
```

modifies a memory location designated by `e1`

the expression `e1` is limited to certain constructs,
and assignments such as

```
42 := 17
true := false
```

do not make sense

an expression that is legal on the left-hand side of an assignment is called a **left value** the evaluation strategy of a language defines the order in which computations are performed

this can be defined using a formal semantics (see lecture 2)

the compiler must obey the evaluation strategy in particular, the evaluation strategy **may** specify

- **when** actual parameters are evaluated
- the evaluation **order** of operands and actual parameters

some aspects of evaluation may be **left unspecified**

this allows the compiler to perform more aggressive optimizations
(such as reordering computations)

we distinguish

- **eager evaluation**: operands / actual parameters are evaluated before the operation / the call

  examples: C, C++, Java, OCaml, Python

- **lazy evaluation**: operands / actual parameters are evaluated only when needed

  examples: Haskell, Clojure
  but also Boolean operators `&&` and `||` in most languages

an imperative language has to adopt an eager evaluation, to ensure that side effects are performed consistently with the source code

for instance, the Java code

```
int r = 0;
int id(int x) { r += x; return x; }
int f(int x, int y) { return r; }

{ System.out.println(f(id(40), id(2))); }
```

prints 42 since both arguments of `f` are evaluated an exception is made for Boolean operations && and || in most languages, which is really useful

```
void insertionSort(int[] a) {
  for (int i = 1; i < a.length; i++) {
    int v = a[i], j = i;
    for (; 0 < j && v < a[j-1]; j--)
      a[j] = a[j-1];
    a[j] = v;
  }
}
```

non-termination is also a side effect

for instance, the Java code

```
int loop() { while (true); return 0; }
int f(int x, int y) { return x+1; }

{ System.out.println(f(41, loop())); }
```

does not terminate, even if argument y is not used a **purely functional** language (= without imperative features) may adopt any evaluation strategy, since an expression will always evaluate to the same value (this is called **referential transparency**)

in particular, it may adopt a lazy evaluation the Haskell program

```
loop () = loop ()
f x y = x
main = putChar (f 'a' (loop ()))
```

terminates (and prints a)

the semantics also defines the way parameters are passed in a function call

several approaches:

- **call by value**
- **call by reference**
- **call by name**
- **call by need**

(we also say **passing by value**, etc.)

new variables receive the **values** of actual parameters

```
function f(x) =
  x := x + 1

main() =
  int v := 41
  f(v)
  print(v)    // prints 41
```

formal parameters denote the **same left values** as actual parameters

```
function f(x) =
  x := x + 1

main() =
  int v := 41
  f(v)
  print(v)    // prints 42
```

actual parameters are **substituted** to formal parameters, textually, and thus are evaluated only if necessary

```
function f(x, y, z) =
  return x*x + y*y

main() =
  print(f(1+2, 2+2, 1/0)) // prints 25
  // 1+2 is evaluated twice
  // 2+2 is evaluated twice
  // 1/0 is never evaluated
```

call by need

actual parameters are evaluated only if necessary,
and **at most once**

```
function f(x, y, z) =
  return x*x + y*y

main() =
  print(f(1+2, 2+2, 1/0)) // prints 25
  // 1+2 is evaluated once
  // 2+2 is evaluated once
  // 1/0 is never evaluated
```

a few words on Java

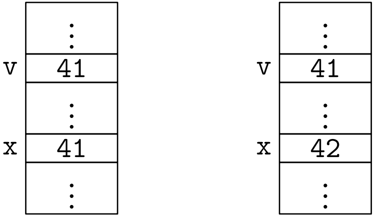
Java uses an eager evaluation, with **call by value**

evaluation order is left-to-right

a value is

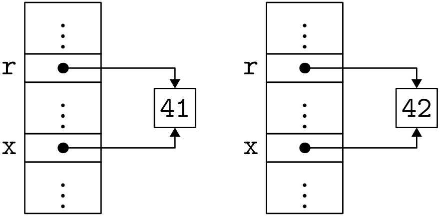
- either of a primitive type (Boolean, character, machine integer, etc.)
- or a pointer to a heap-allocated object

```
void f(int x) {
  x = x + 1;
}

int main() {
  int v = 41;
  f(v);
  // v is still 41
}
```



an object is allocated on the heap

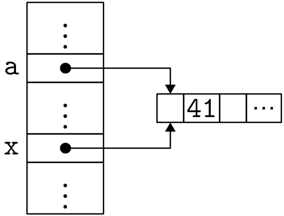
```
class C { int f; }

void incr(C x) {
  x.f += 1;
}
void main () {
  C r = new C();
  r.f = 41;
  incr(r);
  // r.f now is 42
}
```

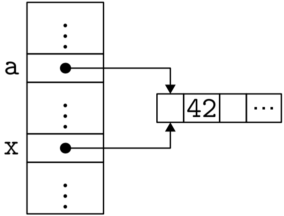


this is still **call by value**,
with a value that is an (implicit) pointer to an object

an array is an object

```
void incr(int[] x) {
  x[1] += 1;
}
void main () {
  int[] a = new int[17];
  a[1] = 41;
  incr(a);
  // a[1] now is 42
}
```





we can **emulate call by name** in Java, by replacing parameters with functions; for instance, the function

```
int f(int x, int y) {
  if (x == 0) return 42; else return y + y;
}
```

can be turned into

```
int f(Supplier<Integer> x, Supplier<Integer> y) {
  if (x.get() == 0)
    return 42;
  else
    return y.get() + y.get();
}
```

and called like this

```
int v = f(() -> 0, () -> { throw new Error(); });
```

more efficiently, we can **simulate call by need** in Java

```
class Lazy<T> implements Supplier<T> {
  private T cache = null;
  private Supplier<T> f;

  Lazy(Supplier<T> f) { this.f = f; }

  public T get() {
    if (this.cache == null) {
      this.cache = this.f.get();
      this.f = null; // allows the GC to reclaim f
    }
    return this.cache;
  }
}
```

(this is memoization)

and we use it like this

```
int w = f(new Lazy<Integer>(() -> 1),
          new Lazy<Integer>(() -> { ...takes time... }));
```

a few words on OCaml

OCaml has an eager evaluation, with **call by value**

evaluation order is left unspecified

a value is

- either of a primitive type (Boolean, character, machine integer, etc.)
- or a pointer to a heap-allocated block (array, record, non constant constructor, etc.)

left values are array elements

```
a.(2) <- true
```

and mutable record fields

```
x.age <- 42
```

OCaml's "mutable variables" (aka references) are records

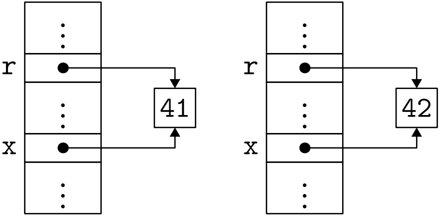
```
type 'a ref = { mutable contents: 'a }
```

and operations `:=` and `!` are defined as

```
let (!)  r   = r.contents
let (:=) r v = r.contents <- v
```

a reference is allocated on the heap

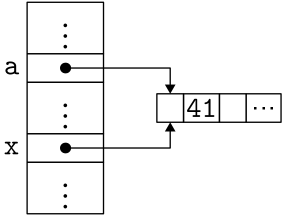
```
let incr x =
  x := !x + 1

let main () =
  let r = ref 41 in
  incr r
  (* !r now is 42 *)
```

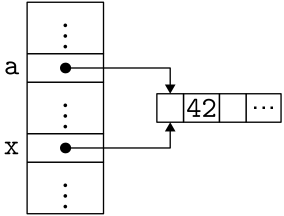


this is still **call by value**,
with a value that is an (implicit) pointer to a mutable data

an array is allocated on the heap

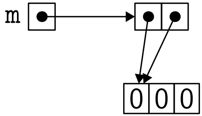
```
let incr x =
  x.(1) <- x.(1) + 1

let main () =
  let a = Array.make 17 0 in
  a.(1) <- 41;
  incr a
  (* a.(1) now is 42 *)
```





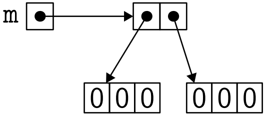
to build a matrix, do not write

```
let m = Array.make 2 (Array.make 3 0)
```



but

```
let m = Array.make_matrix 2 3 0
```



we can **simulate call by name** in OCaml, by replacing parameters with functions

for instance, the function

```
let f x y =
  if x = 0 then 42 else y + y
```

can be turned into

```
let f x y =
  if x () = 0 then 42 else y () + y ()
```

and called like this

```
let v = f (fun () -> 0) (fun () -> failwith "oups")
```

we can also **simulate call by need** in OCaml

we first introduce a type to represent lazy computations

```
type 'a value = Value  of 'a
              | Frozen of (unit -> 'a)

type 'a by_need = 'a value ref
```

and a function to evaluate a computation when it is not yet done

```
let force l = match !l with
  | Value  v -> v
  | Frozen f -> let v = f () in l := Value v; v
```

(this is memoization)

then we define function `f` as follows

```
let f x y =
  if force x = 0 then 42 else force y + force y
```

and we call it with

```
let v = f (ref (Frozen (fun () -> 1)))
          (ref (Frozen (fun () -> ...takes time...)))
```

note: OCaml has a `lazy` construct that does something similar
(but in a more subtle and more efficient way)

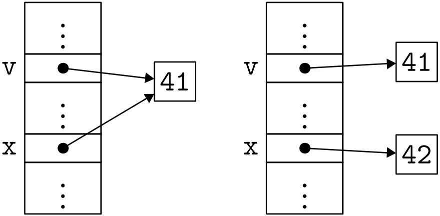
a few words on Python

Python has an eager evaluation, with **call by value**

evaluation order is left-to-right
(but right-to-left for an assignment)

a value is a pointer to a heap-allocated object an integer is an **immutable** object

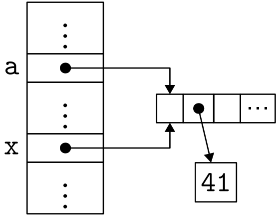
```
def f(x):
    x += 1

v = 41
f(v)
print(v) # prints 41
```

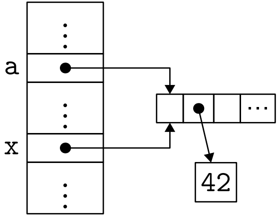


this is still **call by value**,
with a value that is an (implicit) pointer to an object

an array is a mutable object

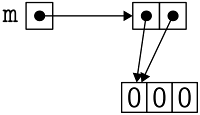
```
def incr(x):
    x[1] += 1

a = [0] * 17
a[1] = 41
incr(a)
# a[1] now is 42
```





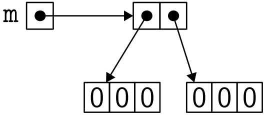
to build a matrix, do not write

```
m = [[0] * 3] * 2
```



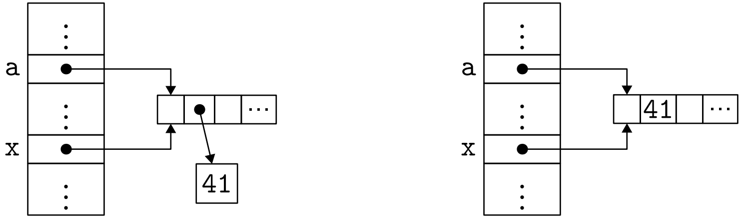
but

```
m = [[0] * 3 for _ in range(2)]
```



the integers being **immutable objects**, we can forget they are heap-allocated objects

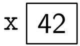
for instance, we can identify the following two representations



remark

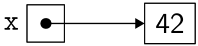
the execution models of Java, OCaml, and Python are **very close**:
call by value only, and atomic (64 bits) values

even if their surface languages (syntax and static typing) are way different



OCaml: immutable variable

Java: mutable variable



OCaml: immutable variable
+ mutable contents

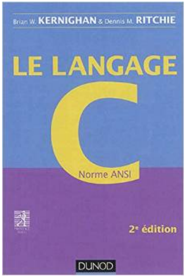
Python: mutable variable +
immutable contents

a few words on C

C is an imperative language that is considered low-level, notably because pointers and pointer arithmetic are explicit

conversely, C can be considered as a high-level assembly language

a book that is still relevant:
The C Programming Language
by Brian Kernighan and Dennis Ritchie



the C language has an eager evaluation, with **call by value**

evaluation order is left unspecified

- we have primitive types such as `char`, `int`, `float`, etc.

- a type $\tau *$ for pointers to values of type τ

  if p is a pointer of $\tau *$, then $*p$ stands for the value pointed to by p, of type τ

  if e is a left value of type τ, then $\&e$ is a pointer to its memory location, with type $\tau *$

- we have records, called *structures*, such as

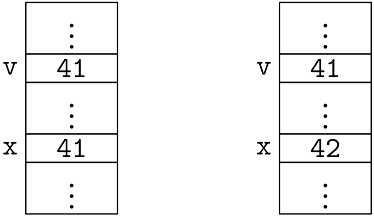
```
struct L { int head; struct L *next; };
```

if `e` has type `struct L`, we write `e.head` for a field access in C, a left value is either

- `x`, a variable
- `*e`, the dereferencing of a pointer
- `e.x`, a structure field access
  if `e` is itself a left value

- `t[e]`, that is sugar for `*(t+e)`
- `e->x`, that is sugar for `(*e).x`

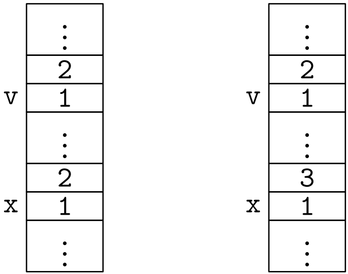
```
void f(int x) {
  x = x + 1;
}

int main() {
  int v = 41;
  f(v);
  // v is still 41
}
```



call by value means that **structures are copied** when passed to functions or returned

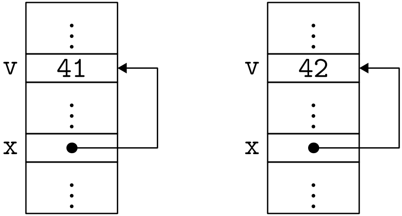
structures are also copied when variables of structure types are assigned, *i.e.* assignments such as `x = y`, where `x` and `y` have type `struct S`

```
struct S { int a; int b; };

void f(struct S x) {
  x.b = x.b + 1;
}

int main() {
  struct S v = { 1, 2 };
  f(v);
  // v.b is still 2
}
```



we can **simulate** a call by reference by passing an explicit pointer

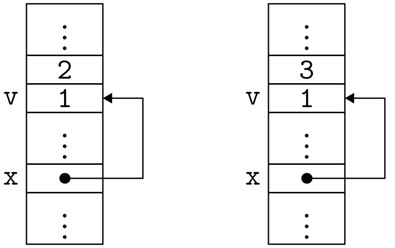
```
void incr(int *x) {
  *x = *x + 1;
}

int main() {
  int v = 41;
  incr(&v);
  // v now is 42
}
```



but this is still **call by value**

to avoid copies, we often use pointers to structures

```
struct S { int a; int b; };

void f(struct S *x) {
  x->b = x->b + 1;
}

int main() {
  struct S v = { 1, 2 };
  f(&v);
  // v.b now is 3
}
```



explicit pointer manipulation can be dangerous

```
int* p() {
  int x;
  ...
  return &x;
}
```

this function returns a pointer to a memory location on the stack (the stack frame of p) that is not meaningful anymore, and that is going to be reused for another stack frame

we call this a **dangling reference**

notation `t[i]` is syntactic sugar for `*(t+i)` where

- `t` is a pointer to a memory location containing consecutive integers
- `+` stands for **pointer arithmetic** (adding `4i` to `t` for an array of 32 bit integers)

the first element of the array is thus `t[0]`, that is `*t` an array may be allocated on the stack, as follows

```
void f() {
  int t[10];
```

and it will be deallocated when the function exits

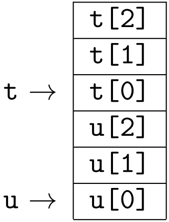
or allocated on the heap, as follows

```
int *t = malloc(10 * sizeof(int));
```

and it has to be deallocated with `free` (see lecture 9) we cannot assign arrays, only pointers

so we can't write

```
void p() {
  int t[3];
  int u[3];
  t = u;     // <- error
}
```



since `t` and `u` are (stack-allocated) arrays and arrays assignment is not possible when passing an array, we only pass a pointer (by value, as always)

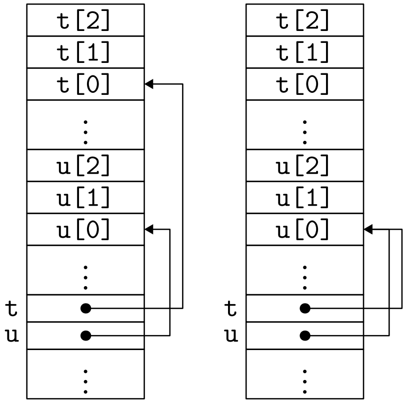
we can write

```
void q(int t[3], int u[3]) {
  t = u;
}
```

and this is exactly the same as

```
void q(int *t, int *u) {
  t = u;
}
```

and pointer assignment is possible



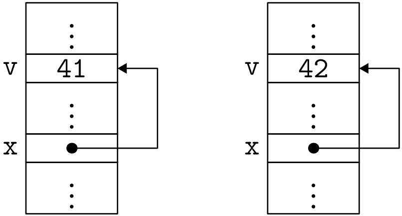
a few words on C++

in C++, we have (among other things) all the types and constructs of C with an eager evaluation

passing is **call by value** by default

but we also have **call by reference**
indicated with symbol & at the formal parameter site

```
void f(int &x) {
  x = x + 1;
}

int main() {
  int v = 41;
  f(v);
  // v now is 42
}
```



this is the compiler that

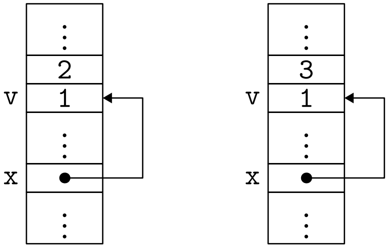
- passed a pointer to `v` at the call site
- dereferenced the pointer `x` in function `f`

the actual parameter has to be a left value

```
void f(int &x) {
  x = x + 1;
}

int main() {
  f(41); // <- error (not a left value)
}
```

we can pass structures by reference

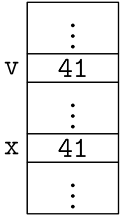
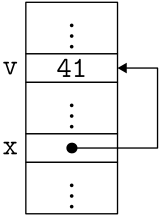
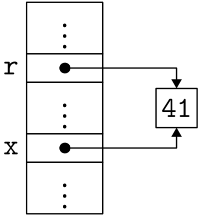
```
struct S { int a; int b; };

void f(struct S &x) {
  x.b = x.b + 1;
}

int main() {
  struct S v = { 1, 2 };
  f(v);
  // v.b now is 3
}
```



we can pass pointers by reference

for instance to insert an element into a mutable tree

```
struct Node { int elt; Node *left, *right; };

void add(Node* &t, int x) {
  if      (t == NULL ) t = create(NULL, x, NULL);
  else if (x < t->elt) add(t->left,  x);
  else if (x > t->elt) add(t->right, x);
}
```

			
Java	integer by value	—	pointer by value (object)
OCaml	integer by value	—	pointer by value (`ref`, array, etc.)
Python	—	—	pointer by value (object)
C	integer by value	pointer by value	pointer by value
C++	integer by value	pointer by value integer by reference	pointer by value or by reference

compiling call by value and call by reference

let us consider a tiny fragment of C++ with

- integers
- functions (without return value)
- call by value and call by reference

$$
\begin{array}{rcl}
E & \rightarrow & n \\
  & | & x \\
  & | & E \;\texttt{+}\; E \mid E \;\texttt{-}\; E \\
  & | & E \;\texttt{*}\; E \mid E \;\texttt{/}\; E \\
  & | & \texttt{-}\; E
\end{array}
\qquad
\begin{array}{rcl}
C & \rightarrow & E \;\texttt{==}\; E \mid E \;\texttt{!=}\; E \\
  & | & E \;\texttt{<}\; E \mid E \;\texttt{<=}\; E \mid E \;\texttt{>}\; E \mid E \;\texttt{>=}\; E \\
  & | & C \;\texttt{\&\&}\; C \\
  & | & C \;\texttt{||}\; C \\
  & | & \texttt{!}\; C
\end{array}
$$

$$
\begin{array}{rcl}
S & \rightarrow & x \;\texttt{=}\; E\texttt{;} \\
  & | & \texttt{if (}\; C \;\texttt{)}\; S \\
  & | & \texttt{if (}\; C \;\texttt{)}\; S \;\texttt{else}\; S \\
  & | & \texttt{while (}\; C \;\texttt{)}\; S \\
  & | & f\texttt{(}E,\ldots,E\texttt{);} \\
  & | & \texttt{printf("\%d\textbackslash n",}\; E\texttt{);} \\
  & | & \texttt{int}\; x\texttt{,}\ldots\texttt{,}x\texttt{;} \\
  & | & B
\end{array}
\qquad
\begin{array}{rcl}
B & \rightarrow & \texttt{\{}\; S \ldots S \;\texttt{\}} \\
  & & \\
F & \rightarrow & \texttt{void}\; f(X\texttt{,}\ldots\texttt{,}X)\; B \\
  & & \\
X & \rightarrow & \texttt{int}\; x \\
  & | & \texttt{int \&}x \\
  & & \\
P & \rightarrow & F \ldots F \\
  & & \texttt{int main()}\; B
\end{array}
$$

```
void fib(int n, int &r) {
  if (n <= 1)
    r = n;
  else {
    int tmp;
    fib(n - 2, tmp);
    fib(n - 1, r);
    r = r + tmp;
  }
}

int main() {
  int f;
  fib(10, f);
  printf("%d\n", f);
}
```

scoping defines the places in the code where a variable is visible

here, if the body of function f mentions a variable x, then

- either x is a parameter of f
- or x is declared upper in a block (including the current block)

beside, a variable can **shadow** another variable with the same name

```c
void f(int n) {
  printf("%d\n", n);   // prints 34
  if (n > 0) {
    int n; n = 89;
    printf("%d\n", n); // prints 89
  }
  if (n > 21) {
    printf("%d\n", n); // prints 34
    int n; n = 55;
    printf("%d\n", n); // prints 55
  }
  printf("%d\n", n);   // prints 34
}

int main() {
  f(34);
}
```

here, scoping only depends on the program source (this is called **lexical scoping**) and it can be solving during type checking

the abstract syntax keeps track of this analysis,
by identifying each variable in a unique way

before

abstract syntax out of the parser

```
abstract class Expr {...}
class UseVar extends Expr
  { String name; ... }
...
abstract class Stmt {...}
class DeclVar extends Stmt
  { String name; ... }
...
```

variables are strings (names)

after

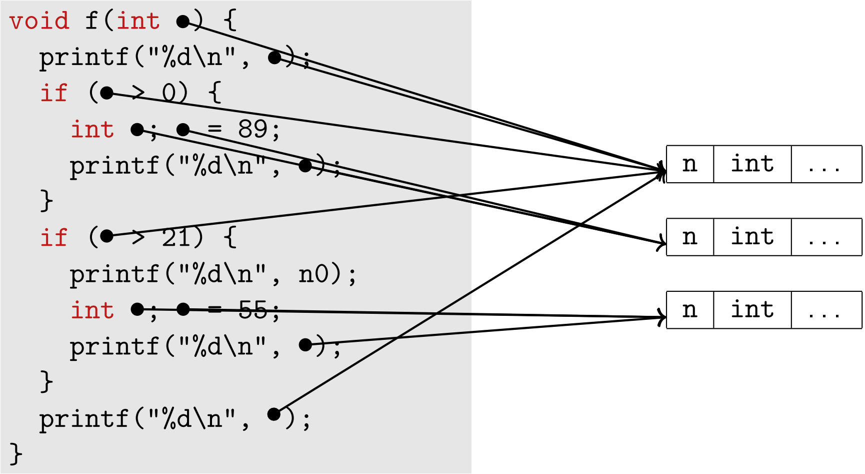
abstract syntax after type checking

```
abstract class TExpr {...}
class TUseVar extends TExpr
  { Var x; ... }
...

abstract class TStmt {...}
class TDeclVar extends TStmt
  { Var x; ... }
```

now `Var` is a unique **identifier** object the abstract syntax tree now corresponds to something like this:

```
void f(int n0) {
  printf("%d\n", n0);
  if (n0 > 0) {
    int n1; n1 = 89;
    printf("%d\n", n1);
  }
  if (n0 > 21) {
    printf("%d\n", n0);
    int n2; n2 = 55;
    printf("%d\n", n2);
  }
  printf("%d\n", n0);
}
```

or more precisely like this:



there are languages where scoping is **dynamic** i.e. depends on the execution of the program

example: `bash`

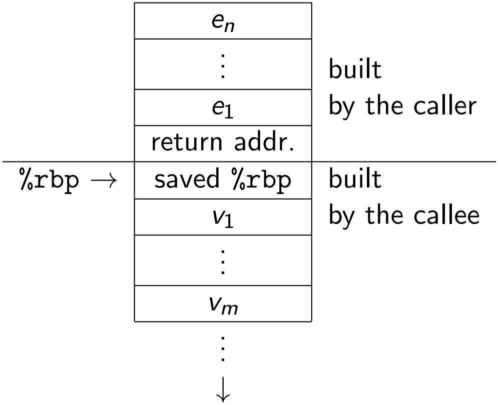
we need to allocate variables in memory and to be able to access them at runtime

here we allocate all the variables on the stack

each on-going function call is implemented with a portion of the stack, called a **stack frame**, that contains

- actual parameters
- the return address
- local variables

the stack frame of a call $f(e_1, \ldots, e_n)$ of a function f with n parameters



```c
void g(int a, int b) {
  if (...) {
    int c;
    ...
  }
  if (...) {
    int d;
    ...
    int e;
    ...
  }
}

int main() {
  g(100, 10);
}
```

b	10
a	100
	return addr.
%rbp →	saved %rbp
c, d	...
e	...

purpose of %rbp

setting %rbp this way allows us to easily retrieve the location of a variable, with a constant offset (e.g. $\texttt{\%rbp} + 16$ or $\texttt{\%rbp} - 8$)

indeed, the top of the stack may change when

- we store temporary values
- we prepare a function call

for each variable, the compiler chooses a position in the stack frame

```
class Var {
  String name;
  int ofs; // position wrt %rbp
```

```
type var = {
  name: string;
  ofs: int;
   (* position wrt %rbp *)
```

assuming 64-bit integers (to make things simpler),

- for parameters, these are $+16$, $+24$, etc.
- for local variables, these are -8, -16, etc.,
  with several options, some of which more economical

let us show now how to compile micro C++ to x86-64

let us focus on **call by value** only for the moment we adopt a simple compilation scheme, where the results of intermediate computations are stored on the stack (we'll talk about register allocation in lectures 7&8)

we note $C(e)$ the assembly code produced by the compiler for an expression e

principles: after the execution of $C(e)$,

- the value of expression e is in register `%rdi` (arbitrary choice)
- the top of the stack is unchanged
- caller-saved registers can be clobbered

constants

$$C(n) \stackrel{\text{def}}{=} \texttt{movq}\ \ n\ \ \texttt{\%rdi}$$

operations

$$C(e_1 + e_2) \stackrel{\text{def}}{=} \quad C(e_1)$$

```
pushq %rdi
```
$C(e_2)$
```
popq %rsi
addq %rsi, %rdi
```

of course, this is extremely inefficient; for 1+2, we get

```
        movq  $1, %rdi
        pushq %rdi
        movq  $2, %rdi
        popq  %rsi
        addq  %rsi, %rdi
```

even though we have 16 registers!

for a **variable**, we use indirect addressing, since the position wrt `%rbp` is a constant that the compiler knows

$$C(x) \stackrel{\text{def}}{=} \texttt{movq}\ \mathit{ofs}\texttt{(\%rbp), \%rdi}$$

(reminder: we only consider call by value for the moment)

Boolean expressions are compiled in a similar way

$C(e_1 = e_2) \stackrel{\text{def}}{=}$ $C(e_1)$
```
pushq %rdi
```
$C(e_2)$
```
popq %rsi
cmpq %rdi, %rsi
sete %dil
movzbq %dil, %rdi
```

caveat: more complex for operators `&&` and `||`, that must be evaluated lazily *i.e.* e_2 is not evaluated in e_1 `&&` e_2 (resp. e_1 `||` e_2) if e_1 is false (resp. true) a statement s is compiled into a piece of assembly code $C(s)$

principles: after the execution of $C(s)$,

- the top of the stack is unchanged
- caller-saved registers can be clobbered

e.g. $C(\texttt{print}(e)) \stackrel{\text{def}}{=} C(e)$
`call print_int`

```
print_int:
        pushq %rbp
        movq  %rsp, %rbp
        andq  $-16, %rsp  # 16-byte stack alignment
        movq  %rdi, %rsi
        movq  $.Sprint_int, %rdi
        movq  $0, %rax
        call  printf
        movq  %rbp, %rsp
        popq  %rbp
        ret
.data
.Sprint_int:
        .string "%d\n"
```

for a call to function `f`, we need to

1. push actual parameters
2. call the code at label `f`
3. pop the parameters

$C(f(e_1, \dots, e_n)) \stackrel{\text{def}}{=}$

```
C(e_n)
pushq %rdi
⋮
C(e_1)
pushq %rdi
call f
addq $8n, %rsp
```

in an assignment `x = e;`, the left value is limited to a variable `x` and we know where this variable is located on the stack

$$C(x = e) \stackrel{\text{def}}{=} \quad C(e)$$
$$\texttt{movq \%rdi, } \mathit{ofs}\texttt{(\%rbp)}$$

up to now, parameters were passed **by value**

i.e. the formal parameter is a **new variable** that receives the value of the actual parameter

in C++, the qualifier & indicates a call **by reference**

in this case, the formal parameter stands for the **same variable** as the actual parameter, which must be a variable (a left value, in the general case)

```
void fib(int n, int &r) {
  if (n <= 1)
    r = n;
  else {
    int tmp;
    fib(n - 2, tmp);
    fib(n - 1, r);
    r = r + tmp;
  }
}

int main() {
  int f;
  fib(10, f);        // updates the value of f
  printf("%d\n", f); // prints 55
}
```

to account for call by reference, we extend the type of variables to indicate whether it is passed by reference

```
class Var {
  String name;
  int ofs; // position wrt %rbp
  boolean byref;
```

```
type var = {
  name: string;
  ofs: int;
   (* position wrt %rbp *)
  byref: bool;
```

(is `false` for a local variable)

in a call `f(e)` the actual parameter `e` is not typed nor compiled the same way anymore when passed by reference

indeed, the type checker

1. checks that this is a left value
2. recalls it is passed by reference

a nice way to proceed is to add a new construct "compute a left value" in the abstract syntax of expressions

```
...
class Addr extends TExpr {
  Var x;
```

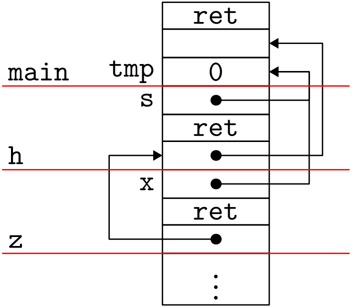
then we replace `f(e)` with `f(Addr(e))` when `e` is passed by reference

note: this is exactly the C operator `&`, even if it is not part of our fragment we have to extend the compilation of expressions:

$$C(\&x) \stackrel{\text{def}}{=} \texttt{leaq } \mathit{ofs}\texttt{(\%rbp), \%rdi}$$
$$\texttt{movq (\%rdi), \%rdi} \qquad \texttt{if } x\texttt{.byref}$$

note: the case x.byref=true accounts for a variable x that is itself passed by reference

```
void z(int &x) { x = 0; }
void h(int &s) { z(s); while (s < 100) s = 2*s+1; }
int main() { int tmp; h(tmp); printf("%d\n", tmp); }
```



we also need to update the case of a variable access:

$$C(x) \stackrel{\text{def}}{=} \begin{array}{ll} \texttt{movq } \mathit{ofs}\texttt{(\%rbp), \%rdi} & \\ \texttt{movq (\%rdi), \%rdi} & \quad \texttt{if } x\texttt{.byref} \end{array}$$

as well as that of an assignment:

$C(x = e) \stackrel{\text{def}}{=}$

```
C(e)
movq ofs(%rbp), %rsi      if x.byref
leaq ofs(%rbp), %rsi      otherwise
movq %rdi, (%rsi)
```

on the contrary, we do not have to update the compilation of a function call, thanks to the new operator &

we are left with the compilation of functions

```
void f(x1, ..., xn) {
  // local variables y1,...,ym
  body
}
```

compute

$$fs = \max_{y_i} |y_i.\mathtt{ofs}|$$

then

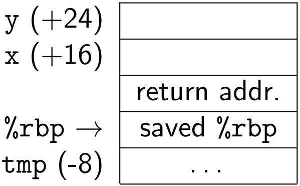
```
f:      pushq %rbp            # save %rbp
        movq  %rsp, %rbp      # and set it
        subq  $fs, %rsp       # allocate the frame
```

$C(\text{body})$

```
        movq  %rbp, %rsp      # deallocate the frame
        popq  %rbp            # restore %rbp
        ret                   # return to caller
```

example

```
void swap(int &x, int &y) {
  int tmp;
  tmp = x;
  x = y;
  y = tmp;
}
```




```
swap:   pushq %rbp
        movq %rsp, %rbp
        subq $8, %rsp
        movq 16(%rbp), %rdi
        movq 0(%rdi), %rdi
        leaq -8(%rbp), %rsi
        movq %rdi, 0(%rsi)
        movq 24(%rbp), %rdi
        movq 0(%rdi), %rdi
        movq 16(%rbp), %rsi
        movq %rdi, 0(%rsi)
        movq -8(%rbp), %rdi
        movq 24(%rbp), %rsi
        movq %rdi, 0(%rsi)
        movq %rbp, %rsp
        popq %rbp
        ret
```

- lab 5
  - static typing of Mini Java continued

- next lecture
  - OO and functional languages