Course Script

INF 5110: Compiler construction

INF5110, spring 2018

Martin Steffen

Contents

Chapter
Run-time environments

What is it about?

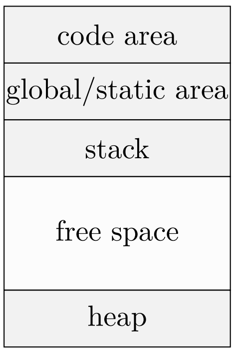
Learning Targets of this Chapter

1. memory management
2. run-time environment
3. run-time stack
4. stack frames and their layout
5. heap

Contents

8.1 Intro

Static & dynamic memory layout at runtime

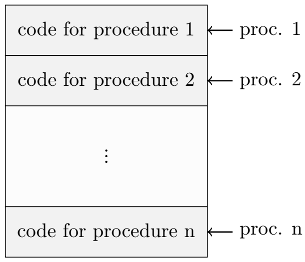


Memory

typical memory layout: for languages (as nowadays basically all) with

- static memory
- dynamic memory:
  - stack
  - heap

Translated program code

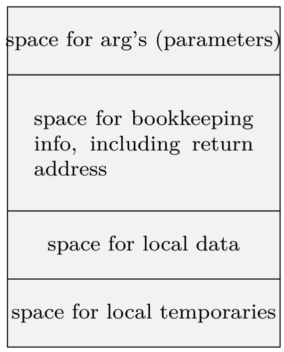


Code memory

- *code* segment: almost always considered as **statically** allocated

⇒ neither moved nor changed at runtime
- compiler aware of all addresses of "chunks" of code: *entry points* of the procedures
- but:
  - generated code often *relocatable*
  - final, absolute adresses given by *linker* / *loader*

Activation record

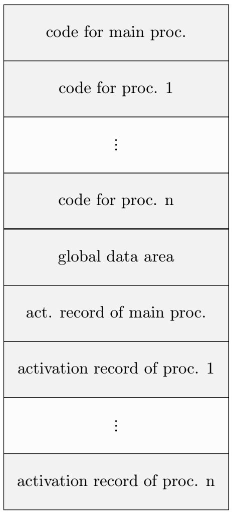


Schematic activation record

- *schematic* organization of activation records/activation block/stack frame ...
- goal: realize
  - parameter passing
  - scoping rules /local variables treatment
  - prepare for call/return behavior
- *calling conventions* on a platform

8.2 Static layout

Full static layout



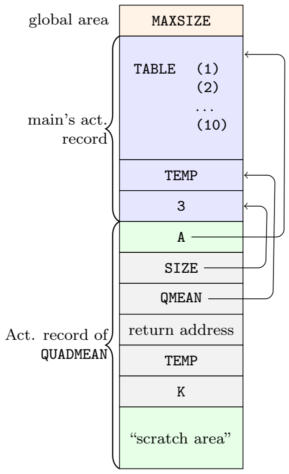
- static addresses of all of memory known to the compiler
  - executable code
  - variables
  - all forms of auxiliary data (for instance big constants in the program, e.g., string literals)
- for instance: (old) Fortran
- nowadays rather seldom (or special applications like safety critical embedded systems)

Fortran example

```
      PROGRAM TEST
      COMMON MAXSIZE
      INTEGER MAXSIZE
      REAL TABLE(10),TEMP
      MAXSIZE = 10
      READ *, TABLE(1),TABLE(2),TABLE(3)
      CALL QUADMEAN(TABLE,3,TEMP)
      PRINT *,TEMP
      END

      SUBROUTINE QUADMEAN(A,SIZE,QMEAN)
      COMMON MAXSIZE
      INTEGERMAXSIZE,SIZE
      REAL A(SIZE),QMEAN, TEMP
      INTEGER K
      TEMP = 0.0
      IF ((SIZE.GT.MAXSIZE).OR.(SIZE.LT.1)) GOTO 99
      DO 10 K = 1, SIZE
         TEMP = TEMP + A(K)*A(K)
10    CONTINUE
99    QMEAN = SQRT(TEMP/SIZE)
```

```
RETURN
END
```

Static memory layout example/runtime environment



Static memory layout example/runtime environment

in Fortan (here Fortran77)

- **parameter passing** as *pointers* to the actual parameters
- activation record for QUADMEAN contains place for intermediate results, compiler calculates, how much is needed.
- note: one possible memory layout for FORTRAN 77, details vary, other implementations exists as do more modern versions of Fortran

8.3 Stack-based runtime environments

Stack-based runtime environments

- so far: no(!) *recursion*
- everything static, incl. placement of activation records

⇒ also return addresses statically known

- *ancient* and *restrictive* arrangement of the run-time envs
- calls and returns (also without recursion) follow at runtime a LIFO (= **stack-like**) discipline

Stack of activation records

- procedures as abstractions with own *local data*

⇒ run-time memory arrangement where procedure-local data together with other info (arrange proper returns, parameter passing) is organized as stack.

- AKA: *call stack*, *runtime stack*
- AR: exact format depends on language and platform

Situation in languages without local procedures

- recursion, but all procedures are *global*
- C-like languages

Activation record info (besides local data, see later)

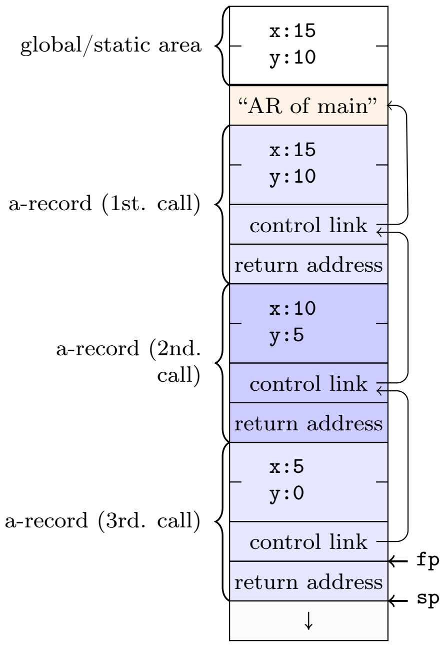
- *frame pointer*
- *control link* (or *dynamic link*)[1]
- (optional): *stack pointer*
- *return address*

Euclid's recursive gcd algo

```
#include <stdio.h>

int x,y;

int gcd (int u, int v)
{ if (v==0) return u;
    else return gcd(v,u % v);
}

int main ()
{ scanf("%d%d",&x,&y);
  printf("%d\n",gcd(x,y));
  return 0;
}
```

[1] Later, we'll encounter also *static links* (aka *access* links).

Stack gcd



- **control link**
  - aka: dynamic link
  - refers to caller's FP
- **frame pointer** FP
  - points to a fixed location in the current a-record
- **stack pointer** (SP)
  - border of current stack and unused memory
- **return address**: program-address of call-site

Local and global variables and scoping

Code

```
int x  = 2;  /* global var */
void g(int); /* prototype  */

void f(int n)
  { static int x = 1;
    g(n);
    x--;
  }

void g(int m)
  { int y = m-1;
    if (y > 0)
      { f(y);
        x--;
       g(y);
      }
  }

int  main ()
```

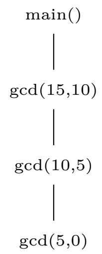
```
{ g(x);
  return 0;
}
```

- global variable x
- but: (different) x *local* to f
- remember C:
  - call by value
  - static lexical scoping

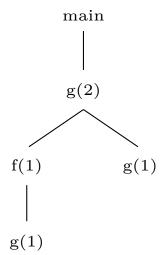
Activation records and activation trees

- *activation* of a function: corresponds to: *call* of a function
- **activation record**
  - data structure for run-time system
  - holds all relevant data for a function call and control-info in "standardized" form
  - control-behavior of functions: LIFO
  - if data *cannot* outlive activation of a function
  - ⇒ activation records can be arranged in as **stack** (like here)
  - in this case: activation record AKA *stack frame*

GCD

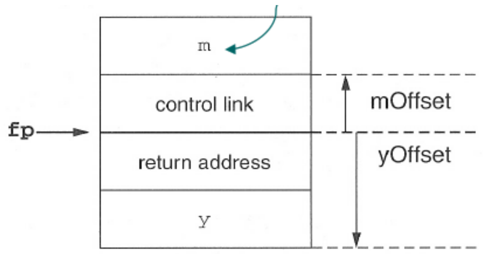


f and g example



Variable access and design of ARs

Layout g



- fp: frame pointer
- m (in this example): parameter of g

Possible arrangement of g's AR

- AR's: structurally *uniform* per language (or at least compiler) / platform
- different function defs, different size of AR

⇒ *frames* on the stack differently sized

- note: FP points
  - not to the "top" of the frame/stack, but
  - to a well-chosen, well-defined position in the frame
  - other local data (local vars) accessible *relative* to that
- conventions
  - higher addresses "higher up"
  - stack "grows" towards lower addresses
  - in the picture: "pointers" to the "bottom" of the meant slot (e.g.: fp points to the control link: offset 0)

Layout for arrays of statically known size

Code

```
void f(int x, char c)
{ int a[10];
  double y;
  ..
}
```

name	offset
x	+5
c	+4
a	-24
y	-32

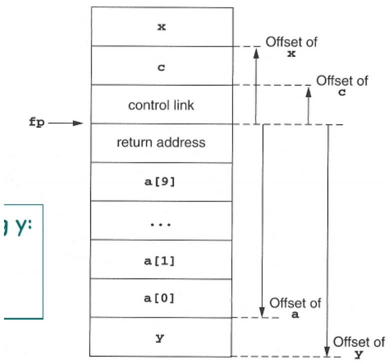
1. access of c and y

```
c: 4(fp)
y: -32(fp)
```

2. access for A[i]

```
(-24+2*i)(fp)
```

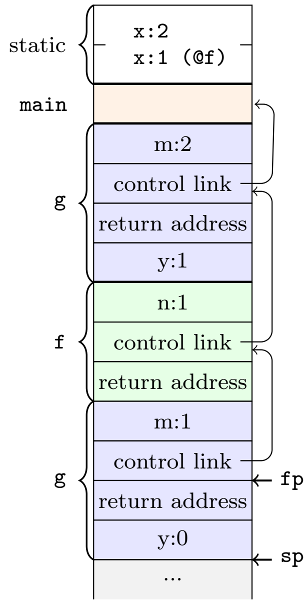
Layout

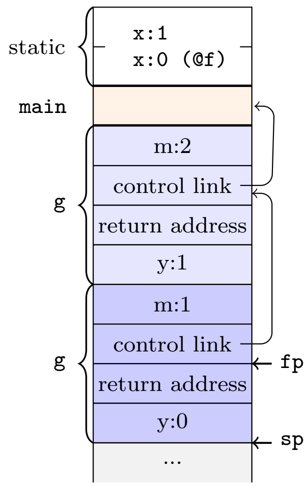


Back to the C code again (global and local variables)

```
int x  = 2;  /* global var */
void g(int); /* prototype  */

void f(int n)
  { static int x = 1;
    g(n);
    x--;
  }

void g(int m)
  { int y = m-1;
    if (y > 0)
      { f(y);
        x--;
       g(y);
      }
  }

int  main ()
  { g(x);
    return 0;
  }
```

2 snapshots of the call stack





- note: call by value, x in f *static*

How to do the "push and pop"

- **calling sequences**: AKA as *linking conventions* or *calling conventions*
- for RT environments: uniform design not just of
  - data structures (=ARs), but also of
  - uniform *actions* being taken when calling/returning from a procedure
- how to *do* details of "push and pop" on the call-stack

E.g: Parameter passing

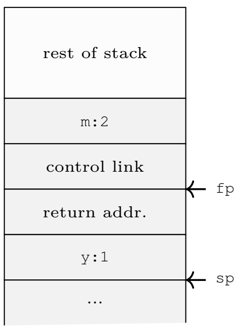
- not just *where* (in the ARs) to find value for the actual parameter needs to be defined, but well-defined **steps** (ultimately **code**) that copies it there (and potentially reads it from there)
- "jointly" done by compiler + OS + HW
- distribution of *responsibilities* between caller and callee:
  - who copies the parameter to the right place
  - who saves registers and restores them
  - ...

Steps when calling

- For procedure call (entry)
  1. compute arguments, store them in the correct positions in the *new* activation record of the procedure (pushing them in order onto the runtime stack will achieve this)
  2. store (push) the `fp` as the *control link* in the new activation record
  3. change the `fp`, so that it points to the beginning of the new activation record. If there is an `sp`, copying the `sp` into the `fp` at this point will achieve this.
  4. store the return address in the new activation record, if necessary
  5. perform a *jump* to the code of the called procedure.
  6. Allocate space on the stack for local var's by appropriate adjustement of the `sp`
- procedure exit
  1. copy the `fp` to the `sp` (inverting 3. of the entry)
  2. load the control link to the `fp`
  3. perform a jump to the return address
  4. change the `sp` to pop the arg's

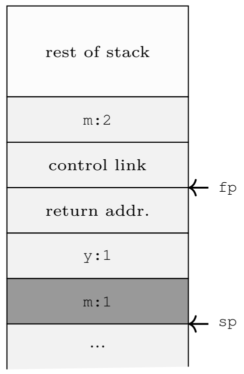
Steps when calling g

Before call



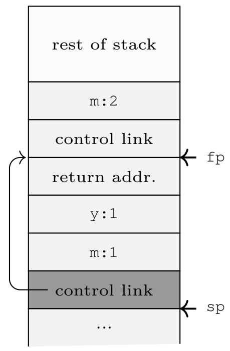
before call to g

Pushed m



pushed param.

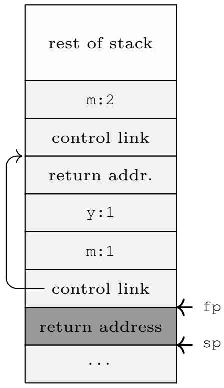
Pushed fp



pushed fp

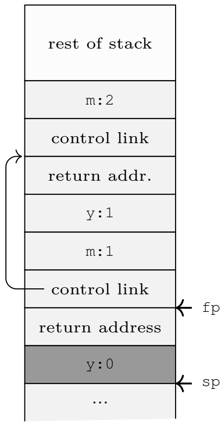
Steps when calling g (cont'd)

Return pushed



fp := sp,push return addr.

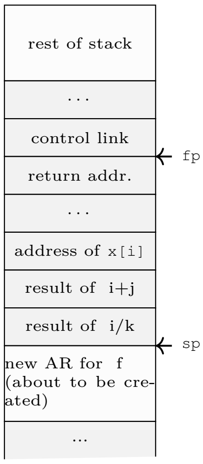
local var's pushed



alloc. local var y

Treatment of auxiliary results: "temporaries"

Layout picture



- calculations need *memory* for intermediate results.
- called **temporaries** in ARs.

```
x[i] = (i + j) * (i/k + f(j));
```

- note: `x[i]` represents an *address* or reference, `i`, `j`, `k` represent *values*[2]
- assume a strict left-to-right evaluation (call `f(j)` may change values.)
- *stack* of temporaries.
- [NB: compilers typically use **registers** as much as possible, what does not fit there goes into the AR.]

Variable-length data

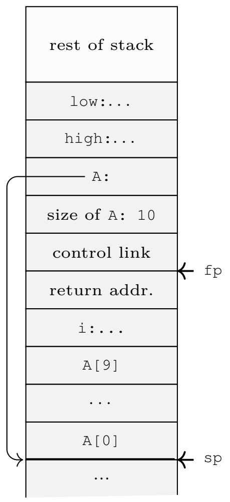
Ada code

```
type Int_Vector is
array(INTEGER range <>) of INTEGER;

procedure Sum(low, high: INTEGER;
 A: Int_Vector) return INTEGER
is
  i: integer
begin
     ...
  end Sum;
```

- Ada example
- assume: array passed *by value* ("copying")
- `A[i]`: calculated as `@6(fp) + 2*i`
- in Java and other languages: arrays passed *by reference*
- note: space for `A` (as ref) and size of `A` is fixed-size (as well as `low` and `high`)

[2]integers are good for array-offsets, so they act as "references" as well.

Layout picture



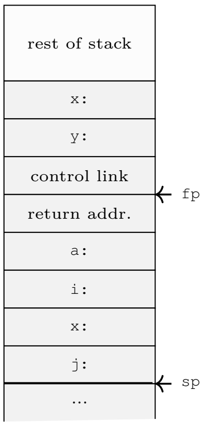
AR of call to SUM

Nested declarations ("compound statements")

C Code

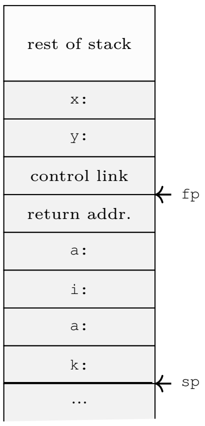
```
void p(int x, double y)
{ char a;
  int i;
  ...;
 A:{ double x;
    int j;
    ...;
  }
  ...;
 B: { char * a;
    int k;
    ...;
  };
  ...;
}
```

Nested blocks layout (1)



area for block A allocated

Nested blocks layout (2)



area for block B allocated

8.4 Stack-based RTE with nested procedures

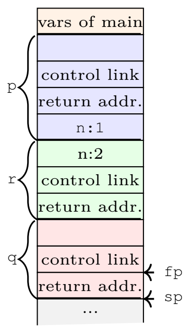
Nested procedures in Pascal

```
program nonLocalRef;
procedure p;
var n : integer;
   procedure q;
   begin
      (* a ref to n is now
       non-local, non-global *)
   end; (* q *)

   procedure r(n : integer);
   begin
      q;
   end; (* r *)

begin (* p *)
   n := 1;
   r(2);
end; (* p *)

begin (* main *)
   p;
end.
```

- proc. `p` contains `q` and `r` nested
- also "nested" (i.e., local) in `p`: integer `n`
  - in scope for `q` and `r` but
  - neither *global* nor *local* to `q` and `r`

Accessing non-local var's

Stack layout



calls m → p → r → q

- `n` in `q`: under *lexical* scoping: `n` declared in `procedure p` is meant
- this is not reflected in the stack (of course) as this stack represents the *run-time* call stack.
- remember: static links (or access links) in connection with *symbol tables*

Symbol tables

- "name-addressable" mapping
- access at compile time

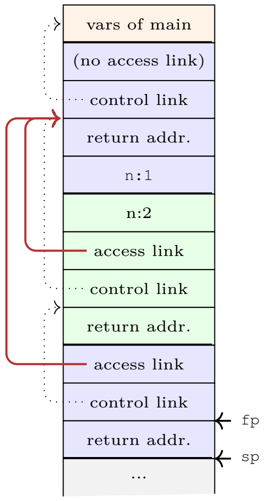
- cf. scope tree

Dynamic memory

- "adresss-adressable" mapping
- access at run time
- stack-organized, reflecting paths in call graph
- cf. activation tree

Access link as part of the AR

Stack layout



calls m → p → r → q

- **access link** (or **static link**): part of AR (at fixed position)
- points to stack-frame representing the current AR of the statically enclosed "procedural" scope

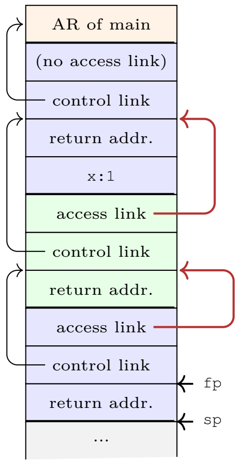
Example with multiple levels

```
program chain;

procedure p;
var x : integer;

   procedure q;
      procedure r;
      begin
         x:=2;
         ...;
         if ... then p;
      end; (*r *)
   begin
      r;
   end; (* q *)

begin
   q;
```

```
end; (* p *)

begin (* main *)
   p;
end.
```

Access chaining

Layout



calls m → p → q → r

- program `chain`
- access (conceptual): `fp.al.al.x`
- access link slot: fixed "offset" inside AR (but: AR's differently sized)
- "distance" from current AR to place of `x`
  - not fixed, i.e.
  - *statically* unknown!
- However: **number of access link dereferences statically known**
- lexical **nesting level**

Implementing access chaining

As example:

```
fp.al.al.al. ... al.x
```

- access need to be fast => use registers
- assume, at `fp` in dedicated register

```
4(fp) -> reg   // 1
4(fp) -> reg   // 2
...
4(fp) -> reg   // n = difference in nesting levels
6(reg)         // access content of x
```

- often: not so many block-levels/access chains nessessary

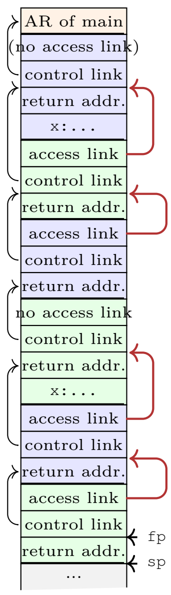
Calling sequence

- For procedure call (entry)
  1. compute arguments, store them in the correct positions in the *new* activation record of the procedure (pushing them in order onto the runtume stack will achieve this)
  2. – **push access link**, value calculated via link chaining (“ `fp.al.al....` ”)
     – store (push) the `fp` as the *control link* in the new AR
  3. change `fp`, to point to the “beginning”

  of the new AR. If there is an `sp`, copying `sp` into `fp` at this point will achieve this.
  1. store the return address in the new AR, if necessary
  2. perform a jump to the code of the called procedure.
  3. Allocate space on the stack for local var’s by appropriate adjustement of the `sp`
- procedure exit
  1. copy the `fp` to the `sp`
  2. load the control link to the `fp`
  3. perform a jump to the return address
  4. change the `sp` to pop the arg’s **and the access link**

Calling sequence: with access links

Layout



after 2nd call to r

- `main` → `p` → `q` → `r` → `p` → `q` → `r`
- calling sequence: actions to do the “push & pop”
- distribution of responsibilities between caller and callee
- generate an appropriate access chain, chain-length statically determined
- actual computation (of course) done at run-time

8.5 Functions as parameters

Nested procedures in Pascal

Access link (again)

Procedures as parameter

```
program closureex(output);

procedure p(procedure a);
begin
   a;
end;

procedure q;
var x : integer;
   procedure r;
   begin
      writeln(x);   // ``non-local''
   end;

begin
   x := 2;
   p (r);
end; (* q *)

begin (* main *)
   q;
end.
```

Procedures as parameters, same example in Go

```
package main
import ("fmt")

var p = func (a (func () ())) {  // (unit -> unit) -> unit
        a()
}

var q = func () {
        var x = 0
        var r = func () {
        fmt.Printf(" x = %v", x)
        }
        x = 2
        p(r)    // r as argument
}


func main() {
        q();
}
```

Procedures as parameters, same example in ocaml

```
let p (a :unit -> unit) : unit =  a();;

let q() =
  let x: int ref  =  ref 1
  in let r = function () ->  (print_int !x) (* deref *)
  in
  x := 2;    (* assignment to ref-typed var *)
  p(r);;

q();;  (* ``body of main'' *)
```

Closures in [2]

- [2] rather "implementation centric"
- closure there:
  - **restricted** setting
  - specific way to achieve closures
  - specific semantics of non-local vars ("by reference")
- higher-order functions:
  - functions as arguments *and* return values
  - nested function declaration
- similar problems with: "function variables"
- Example shown: **only** procedures as *parameters*, not *returned*

Closures, schematically

- independent from concrete design of the RTE/ARs:
- what do we need to execute the body of a procedure?

Closure (abstractly)

A closure is a function body[3] *together* with the values for all its variables, including the non-local ones.[3]

- individual AR not enough for all variables used (non-local vars)
- in *stack*-organized RTE's:
  - fortunately ARs are *stack*-allocated
  - → with clever use of "links" (access/static links): possible to access variables that are "nested further out"/ deeper in the *stack* (following links)

Organize access with procedure parameters

- when calling `p`: allocate a stack frame
- executing `p` calls `a` => another stack frame
- number of parameters etc: knowable from the type of `a`
- *but* 2 problems

"control-flow" problem

currently only RTE, but: how can (the compiler arrange that) `p` calls `a` (and allocate a frame for `a`) if `a` is not know yet?

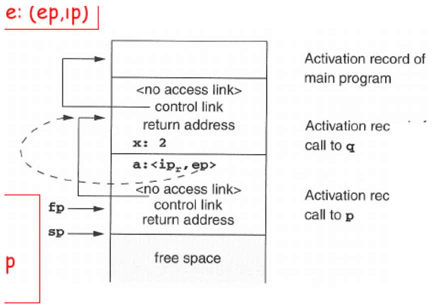
data problem

How can one statically arrange that `a` will be able to access non-local variables if statically it's not known what `a` will be?

- solution: for a procedure variable (like `a`): *store* in AR
  - **reference** to the code of argument (as representation of the function body)
  - **reference** to the frame, i.e., the relevant *frame pointer* (here: to the frame of `q` where `r` is defined)
- this pair = **closure**!

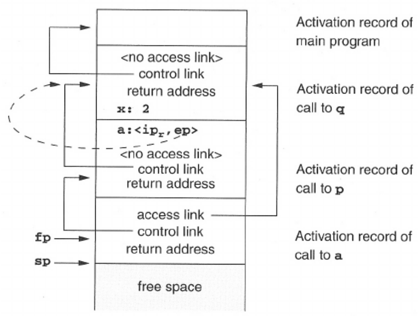
[3]Resp.: at least the possibility to locate them.

Closure for formal parameter a of the example



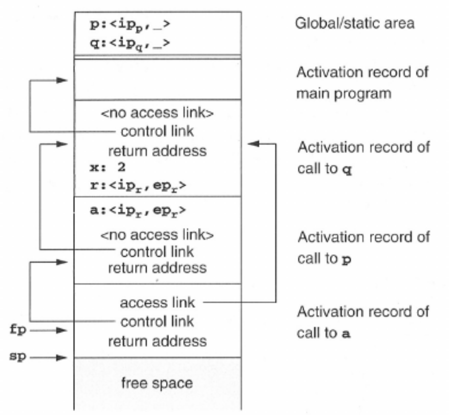
- stack after the call to p
- closure $\langle ip, ep \rangle$
- *ep*: refers to q's frame pointer
- note: distinction in calling sequence for
  - calling "ordinary" proc's and
  - calling procs in proc parameters (i.e., via closures)
- that may be unified ("closures" only)

After calling a (= r)



- note: *static* link of the new frame: used from the closure!

Making it uniform



- note: calling conventions *differ*
  - calling procedures as formal parameters
  - "standard" procedures (statically known)
- treatment can be made uniform

Limitations of stack-based RTEs

- procedures: **central** (!) control-flow abstraction in languages
- stack-based allocation: intuitive, common, and efficient (supported by HW)
- used in many languages
- procedure calls and returns: LIFO (= stack) behavior
- AR: local data for procedure body

Underlying assumption for stack-based RTEs

The data (=AR) for a procedure cannot **outlive** the activation where they are declared.

- assumption can break for many reasons
  - returning *references* of local variables
  - higher-order functions (or function variables)
  - "undisciplined" control flow (rather deprecated, goto's can break any scoping rules, or procedure abstraction)
  - explicit memory allocation (and deallocation), pointer arithmetic etc.

Dangling ref's due to returning references

```
int * dangle (void) {
  int x;       // local var
  return &x;   // address of x
}
```

- similar: returning references to objects created via `new`
- variable's lifetime may be over, but the reference lives on ...

Function variables

```
program Funcvar;
var pv : Procedure (x: integer);   (* procedur var     *)

   Procedure Q();
   var
      a : integer;
      Procedure P(i : integer);
      begin
         a:= a+i;     (* a def'ed outside            *)
      end;
   begin
      pv := @P;       (* ``return'' P (as side effect) *)
   end;               (* "@" dependent on dialect     *)
begin                 (* here: free Pascal            *)
   Q();
   pv(1);
end.
```

```
funcvar
Runtime error 216 at $0000000000400233
  $0000000000400233
  $0000000000400268
  $00000000004001E0
```

Functions as return values

```
package main
import ("fmt")

var f = func () (func (int) int)  { // unit -> (int -> int)
        var x = 40                  // local variable
        var g = func (y int) int { // nested function
                return x + 1
        }
        x = x+1                     // update x
        return g                    // function as return value
}

func main() {
        var x = 0
        var h = f()
        fmt.Println(x)
        var r = h (1)
        fmt.Printf(" r = %v", r)
}
```

- function `g`
  - defined local to `f`
  - uses `x`, non-local to `g`, local to `f`
  - is being returned from `f`

Fully-dynamic RTEs

- full higher-order functions = functions are "data" same as everything else
  - function being locally defined
  - function as arguments to other functions
  - functions returned by functions
- → ARs cannot be stack-allocated
- closures needed, but *heap*-allocated (≠ Louden)
- objects (and references): *heap*-allocated
- less "disciplined" memory handling than stack-allocation
- **garbage** collection
- often: stack based allocation + fully-dynamic (= heap-based) allocation

The stack discipline can be seen as a particularly simple (and efficient) form of garbage collection: returning from a function makes it clear that the local data can be thrashed.

8.6 Parameter passing

Communicating values between procedures

- procedure *abstraction*, **modularity**
- parameter passing = communication of values between procedures
- from caller to callee (and back)
- binding actual parameters
- with the help of the RTE
- **formal** parameters vs. **actual** parameters
- two modern versions
  1. call by value
  2. call by reference

CBV and CBR, roughly

Core distinction/question

on the level of caller/callee *activation records* (on the stack frame): how does the AR of the callee get hold of the value the caller wants to hand over?

1. callee's AR with a *copy* of the value for the formal parameter
2. the callee AR with a *pointer* to the memory slot of the actual parameter

- if one has to choose only one: it's call-by-value
- remember: non-local variables (in lexical scope), nested procedures, and even closures:
  - those variables are "smuggled in" *by reference*
  - [NB: there are also *by value* closures]

CBV is in a way the prototypical, most dignified way of parameter passsing, supporting the procedure abstraction. If one has references (explicit or implicit, of data on the *heap*, typically), then one has call-by-value-of-references, which, in some way "feels" for the programmer as call-by-reference. Some people even call that call-by-reference, even if it's technically not.

Parameter passing "by-value"

- in C: CBV only parameter passing method
- in some lang's: formal parameters "immutable"
- straightforward: *copy* actual parameters → formal parameters (in the ARs).

C examples

```
void inc2 (int x)
{ ++x, ++x; }
```

```
void inc2 (int* x)
{ ++(*x), ++(*x); }
/* call: inc(&y) */
```

```
void init(int x[], int size) {
  int i;
  for (i=0;i<size,++i) x[i]= 0
}
```

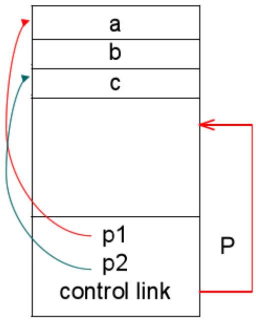
arrays: "by-reference" data

Call-by-reference

- hand over pointer/reference/address of the actual parameter
- useful especially for large data structures
- typically (for cbr): actual parameters must be *variables*
- Fortran actually allows things like `P(5,b)` and `P(a+b,c)`.

```
void inc2 (int* x)
{ ++(*x), ++(*x); }
/* call: inc(&y) */
```

```
void P(p1,p2) {
  ..
  p1 = 3
}
var a,b,c;
P(a,c)
```



Call-by-value-result

- *call-by-value-result* can give *different* results from cbr
- allocated as a *local* variable (as cbv)
- however: copied "two-way"
  - when calling: actual → formal parameters
  - when returning: actual ← formal parameters
- aka: "copy-in-copy-out" (or "copy-restore")
- Ada's `in` and `out` paremeters
- *when* are the value of actual variables determined when doing "actual ← formal parameters"
  - when calling
  - when returning
- not the cleanest parameter passing mechanism around...

Call-by-value-result example

```
void p(int x, int y)
{
  ++x;
  ++y;
}

main ()
{  int a = 1;
  p(a,a);    // :-O
```

```
  return 0;
}
```

- C-syntax (C has cbv, not cbvr)
- note: *aliasing* (via the arguments, here obvious)
- cbvr: same as cbr, unless *aliasing* "messes it up"[4]

Call-by-name (C-syntax)

- most complex (or is it „,?)
- hand over: textual representation ("name") of the argument (substitution)
- in that respect: a bit like *macro expansion* (but lexically scoped)
- actual paramater *not* calculated *before* actually used!
- on the other hand: if needed more than once: *recalculated* over and over again
- aka: *delayed evaluation*
- Implementation
  - actual paramter: represented as a small procedure (*thunk*, *suspension*), if actual parameter = expression
  - optimization, if actually parameter = variable (works like call-by-reference then)

Call-by-name examples

- in (imperative) languages without procedure parameters:
  - delayed evaluation most visible when dealing with things like `a[i]`
  - `a[i]` is actually like "apply `a` to index `i`"
  - combine that with side-effects (`i++`) ⇒ pretty confusing

Example 1

```
void p(int x) {...; ++x; }
```

- call as `p(a[i])`
- corresponds to `++(a[i])`
- note:
  - `++ _` has a side effect
  - `i` may change in ...

Example 2

```
int i;
int a[10];
void p(int x) {
  ++i;
  ++x;
}

main () {
  i = 1;
  a[1] = 1;
  a[2] = 2;
  p(a[i]);
  return 0;
}
```

[4]One can ask though, if not call-by-reference would be messed-up in the example already.

Another example: "swapping"

```
int i; int a[i];

swap (int a, b) {
  int i;
  i = a;
  a = b;
  b = i;
}

i = 3;
a[3] = 6;

swap (i,a[i]);
```

- note: local and global variable i

Call-by-name illustrations

Code

```
procedure P(par): name par, int par
begin
  int x,y;
  ...
  par := x + y; (* alternative: x:= par + y *)

end;

P(v);
P(r.v);
P(5);
P(u+v)
```

	v	r.v	5	u+v
par := x+y	ok	ok	error	error
x := par +y	ok	ok	ok	ok

Call by name (Algol)

```
begin comment Simple array example;
  procedure zero (Arr,i,j,u1,u2);
  integer Arr;
  integer i,j,u1,u2;
begin
    for i := 1 step 1 until u1 do
      for j := 1 step 1 until u2 do
        Arr := 0

end;

integer array Work [1:100,1:200];
integer p,q,x,y,z;
x := 100;
y := 200
zero(Work[p,q],p,q,x,y);
end
```

Lazy evaluation

- call-by-name
  - complex & potentially confusing (in the presence of *side effects*)
  - not really used (there)
- declarative/functional languages: **lazy** evaluation
- optimization:

  - avoid recalculation of the argument
  - ⇒ remember (and share) results after first calculation ("memoization")
  - works only in absence of side-effects
- most prominently: Haskell
- useful for operating on *infinite* data structures (for instance: streams)

Lazy evaluation / streams

```
magic :: Int -> Int -> [Int]
magic 0 _ = []
magic m n = m : (magic n (m+n))

getIt :: [Int] -> Int -> Int
getIt []     _ = undefined
getIt (x:xs) 1 = x
getIt (x:xs) n = getIt xs (n-1)
```

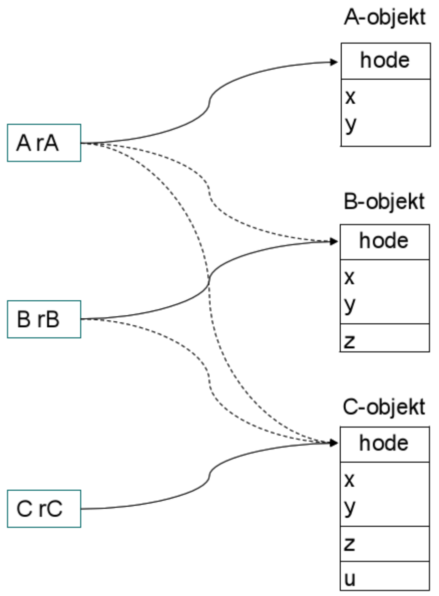
8.7 Virtual methods in OO

Object-orientation

- class-based/inheritance-based OO
- classes and sub-classes
- typed references to objects
- *virtual* and *non-virtual* methods

Virtual and non-virtual methods + fields

```
class A {
  int x,y
    void f(s,t) { ... F_A ... };
  virtual void g(p,q) { ... G_A ... };
};

class B extends A {
  int z
    void f(s,t) { ... F_B ... };
    redef void g(p,q) {... G_B ...};
    virtual void h(r) { ... H_B ...}
};

class C extends B {
  int u;
  redef void h(r) { ... H_C ... };
}
```



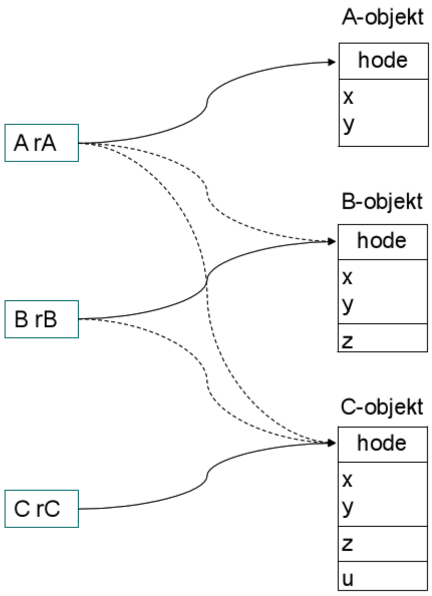
Call to virtual and non-virtual methods

non-virtual method f

call	target
$r_A.f$	F_A
$r_B.f$	F_B
$r_C.f$	F_B

virtual methods g and h

call	target
$r_A.g$	G_A or G_B
$r_B.g$	G_B
$r_C.g$	G_B
$r_A.h$	illegal
$r_B.h$	H_B or H_C
$r_C.h$	H_C



Late binding/dynamic binding

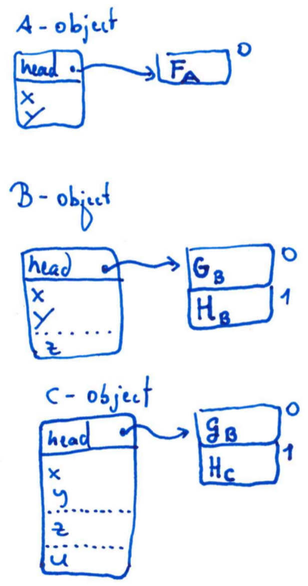
- details very much depend on the language/flavor of OO
  - single vs. multiple inheritance?
  - method update, method extension possible?
  - how much information available (e.g., static type information)?
- simple approach: "embedding" methods (as references)
  - seldomly done (but needed for updateable methods)
- using *inheritance graph*
  - each object keeps a pointer to its class (to locate virtual methods)
- virtual function table
  - in static memory
  - no traversal necessary
  - class structure need be known at compile-time
  - C^{++}

Virtual function table

- static check ("type check") of $r_X.f()$
  - for virtual methods: `f` must be defined in X or one of its superclasses
- non-virtual binding: finalized by the compiler (static binding)
- virtual methods: enumerated (with offset) from the first class with a virtual method, redefinitions get the same "number"
- object "headers": point to the class's **virtual function table**
- $r_A.g()$:

```
call r_A.virttab[g_offset]
```

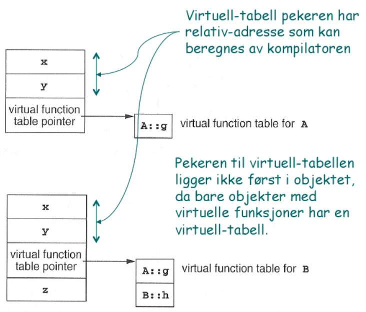
- compiler knows
  - `g_offset = 0`
  - `h_offset = 1`



Virtual method implementation in C++

- according to [2]

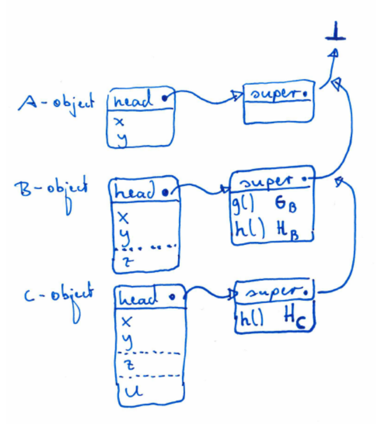
```
class A {
  public:
  double x,y;
  void f();
  virtual void g();
};

class B: public A {
  public:
  double z;
  void f();
  virtual void h();
};
```



Untyped references to objects (e.g. Smalltalk)

- all methods *virtual*
- *problem* of virtual-tables now: virtual tables need to contain all methods of all classes
- additional complication: *method extension*, extension methods
- Thus: implementation of `r.g()` (assume: `f` omitted)
  - go to the object's class

– *search* for g following the superclass hierarchy.



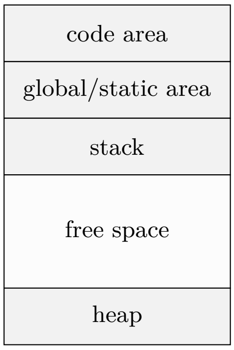
8.8 Garbage collection

Management of dynamic memory: GC & alternatives

- *dynamic* memory: allocation & deallocation at *run-time*
- different alternatives
  1. manual
     – "alloc", "free"
     – error prone
  2. "stack" allocated dynamic memory
     – typically not called GC
  3. automatic *reclaim* of unused dynamic memory
     – requires extra provisions by the compiler/RTE

Heap

- "heap" unrelated to the well-known heap-data structure from A&D
- part of the *dynamic* memory
- contains typically
  – objects, records (which are dynamocally allocated)
  – often: arrays as well
  – for "expressive" languages: heap-allocated activation records
    * coroutines (e.g. Simula)
    * higher-order functions



Memory

Problems with free use of pointers

```c
int * dangle (void) {
  int x;        // local var
  return &x;   // address of x
}
```

```c
typedef int (* proc) (void);

proc g(int x) {
  int f(void) { /* illegal  */
    return x;
  }
  return f;
}

main () {
  proc c;
  c = g(2);
  printf("%d\n", c()); /* 2? */
  return 0;
}
```

- as seen before: references, higher-order functions, coroutines etc ⇒ heap-allocated ARs
- higher-order functions: typical for functional languages,
- heap memory: no LIFO discipline
- *unreasonable* to expect user to “clean up” AR’s (already `alloc` and `free` is error-prone)
- ⇒ garbage collection (already dating back to 1958/Lisp)

Some basic design decisions

- gc *approximative*, but non-negotiable condition: **never** reclaim cells which *may* be used in the future
- one basic decision:
  1. never *move* “objects”
     - may lead to fragmentation
  2. *move* objects which are still needed
     - extra administration/information needed
     - all reference of moved objects need adaptation
     - all free spaces collected adjacently (defragmentation)

- *when* to do gc?
- *how* to get info about definitely unused/potentially used obects?
  - “monitor” the interaction program ↔ heap while it *runs*, to keep “up-to-date” all the time
  - inspect (at approriate points in time) the *state* of the heap

Objects here are meant as heap-allocated entities, which in OO languages includes objects, but here referring also to other data (records, arrays, closures . . .).

Mark (and sweep): marking phase

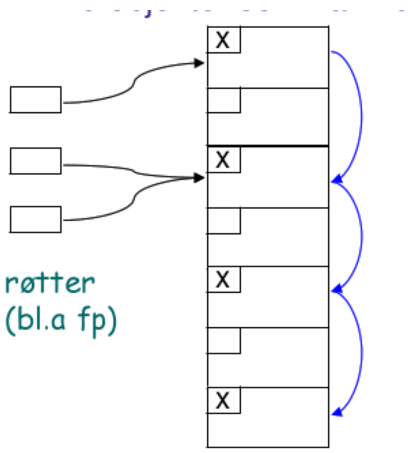
- observation: heap addresses only **reachable**

  directly through variables (with references), kept in the run-time stack (or registers)

  indirectly following fields in reachable objects, which point to further objects ...

- heap: *graph* of objects, entry points aka "roots" or *root set*
- *mark*: starting from the root set:
  - find reachable objects, *mark* them as (potentially) used
  - one boolean (= 1 *bit* info) as mark
  - depth-first search of the graph

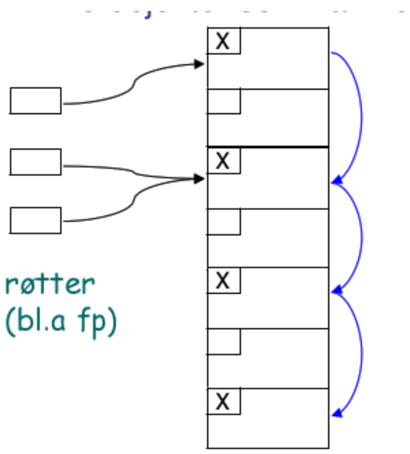
Marking phase: follow the pointers via DFS



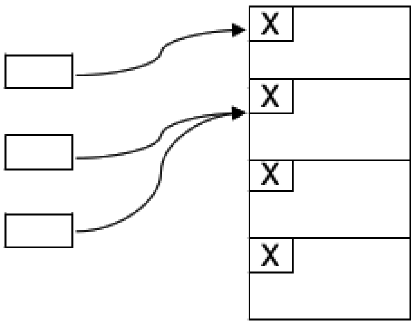
- layout (or "type") of objects need to be known to determine where pointers are
- food for thought: doing DFS requires a *stack*, in the worst case of comparable size as the heap itself ....

Compactation

Marked



Compacted

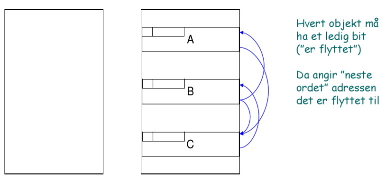


After marking?

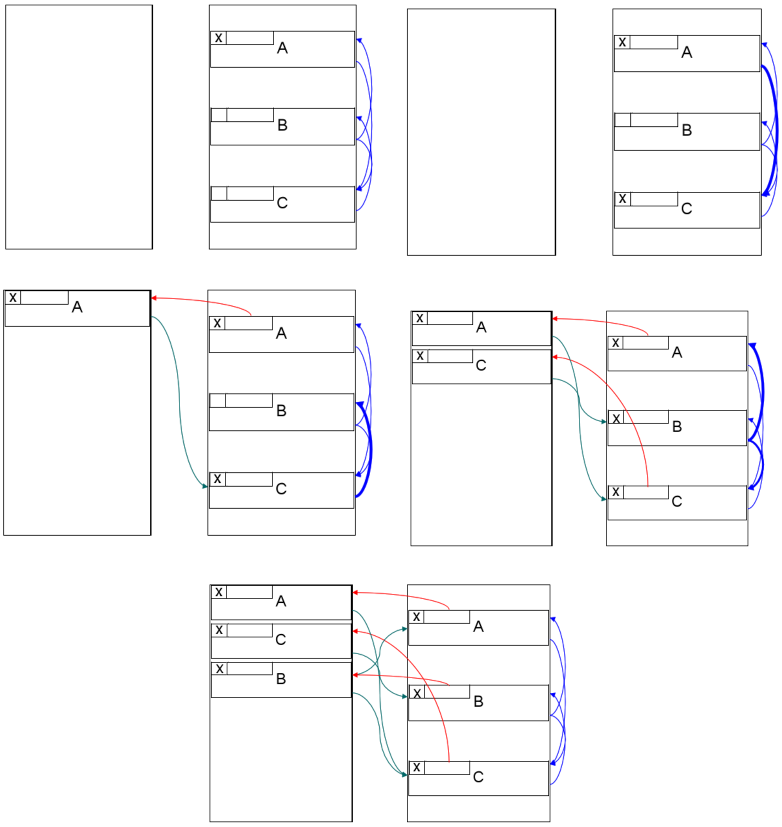
- known *classification* in "garbage" and "non-garbage"
- pool of "unmarked" objects
- however: the "free space" not really ready at hand:
- two options:
  1. *sweep*
     - go again through the heap, this time sequentially (no graph-search)
     - collect all unmarked objects in **free list**
     - objects remain at their place
     - RTE need to allocate new object: grab free slot from free list
  2. *compaction* as well:
     - avoid fragmentation
     - move non-garbage to one place, the rest is big free space
     - when *moving* objects: adjust pointers

Stop-and-copy

- variation of the previous compactation
- mark & compactation can be done in recursive pass
- space for heap-managment
  - split into *two halves*
  - only one half used at any given point in time
  - compactation by copying all non-garbage (marked) to the currently unused half



Step by step



Bibliography

Bibliography

[1] Cooper, K. D. and Torczon, L. (2004). *Engineering a Compiler*. Elsevier.

[2] Louden, K. (1997). *Compiler Construction, Principles and Practice*. PWS Publishing.

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