Programs as Data 7
Imperative languages, environment and store, micro-C

Peter Sestoft

Monday 2010-10-11

Today

- Course overview
- A naïve imperative language
- C concepts
  - Pointers and pointer arithmetics, arrays
  - Lvalue and rvalue
  - Parameter passing by value and by reference
  - Expression statements
- Micro-C, a subset of C
  - abstract syntax
  - lexing and parsing
  - interpretation

The overall course plan

- F# and functional programming
- Interpreting an expression language
- Lexing and parsing tools
- Interpreting a functional language, micro-ML
  - Higher-order functions
- Type checking and type inference
- Interpreting an imperative language, micro-C
- Compiling micro-C to stack machine code
- Real-world abstract machines: JVM and .NET
  - Garbage collection techniques
- Continuations, exceptions and backtracking
- (Programs that generate programs, Scheme)
- Or maybe Scala, a functional/OO language on JVM

A naive-store imperative language

- **Naive** store model:
  - a variable name maps to an integer value
  - so store is just a runtime environment

```
sum = 0;
for i = 0 to 100 do
   sum = sum + i;
```

i	100
sum	5050

```
i = 1;
sum = 0;
while sum < 10000 do begin
   sum = sum + i;
   i = 1 + i;
end;
```

i	142
sum	10011

Naïve-store statement execution, 1

- Executing a statement gives a new store
- Assignment **x=e** updates the store
- Expressions do not affect the store

```
let rec exec stmt (store : naivestore) : naivestore =
    match stmt with
      | Asgn(x, e) ->
        setSto store (x, eval e store)
      | If(e1, stmt1, stmt2) ->
        if eval e1 store <> 0 then exec stmt1 store
                              else exec stmt2 store
      | ...
```

Update store at x with value of e

Naïve-store statement execution, 2

- A block `{`s_1`; …; `s_n`}` executes s_1 then s_2 …
- Example:

exec (Block [s_1**;** s_2**]) store**

= loop [s_1**;** s_2**] store**

= exec s2 (exec s1 store)

```
let rec exec stmt (store : naivestore) : naivestore =
    match stmt with
      | Block stmts ->
        let rec loop ss sto =
              match ss with
                | []      -> sto
                | s1::sr -> loop sr (exec s1 sto)
        in loop stmts store
      | ...
```

Naïve-store statement execution, 3

- **`for`** and **`while`** update the store sequentially

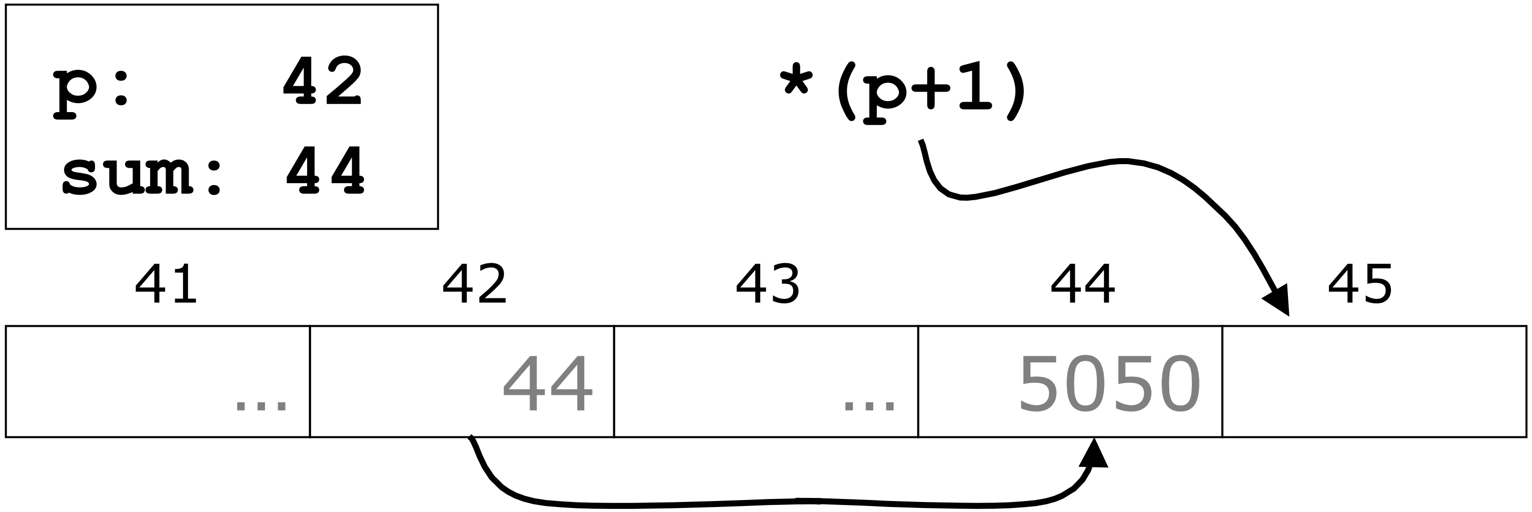
```
let rec exec stmt (store : naivestore) : naivestore =
    match stmt with
    | ...
    | For(x, estart, estop, stmt) -> ...
    | While(e, stmt) ->
      let rec loop sto =
              if eval e sto = 0 then sto
                                else loop (exec stmt sto)
      in loop store
```

Environment and store, micro-C

- The naive model cannot describe *pointers* and *variable aliasing*
- A more realistic store model:
  - *Environment* maps a variable name to an address
  - *Store* maps address to value

The essence of C: Pointers

- Main innovations of C (1972) over Algol 60:
  - Structs, as in COBOL and Pascal
  - Pointers, pointer arithmetics, pointer types, array indexing as pointer indexing
  - Syntax: { } for blocks, as in C++, Java, C#



- Very different from Java and C#, which have no pointer arithmetics, but garbage collection

Desirable language features

	C	C++	F#/ML	Smtalk	Haskell	Java	C#
Garbage collection							
Exceptions							
Bounds checks							
Static types							
Generic types (para. polym.)							
Pattern matching							
Reflection							
Refl. on type parameters							
Anonymous functions (λ)							
Streams							
Lazy eval.							

C pointer basics

- A pointer `p` refers to a storage location
- The dereference expression `*p`
  - *the content of the location* (rvalue) as in
    `*p + 4`
  - *the storage location itself* (lvalue), as in
    `*p = x+4`
- The pointer that points to `x` is `&x`
- Pointer arithmetics:
  `*(p+1)` is the location just after `*p`
- Expression `p[i]` is short for `*(p+i)`
- Strange fact: `p[2]` can be written `2[p]` too
- If `p` equals `&a[0]`, then `p[i]` equals `a[i]`, so an array is a pointer

Using pointers for return values

- Example ex5.c, computing square(x):

```
void main(int n) {
   ...
   int r;
   square(n, &r);
   print r;
}

void square(int i, int *rp) {
   *rp = i * i;
}
```

for input

for return value: a pointer to where to put the result

Recursion and return values

- Computing factorial with MicroC/ex9.c

```
void main(int i) {
  int r;
  fac(i, &r);
  print r;
}

void fac(int n, int *res) {
  if (n == 0)
    *res = 1;
  else {
    int tmp;
    fac(n-1, &tmp);
    *res = tmp * n;
  }
}
```

- **`n`** is input parameter
- **`res`** is output parameter: a pointer to where to put the result
- **`tmp`** holds the result of the recursive call
- **`&tmp`** gets a pointer to **`tmp`**

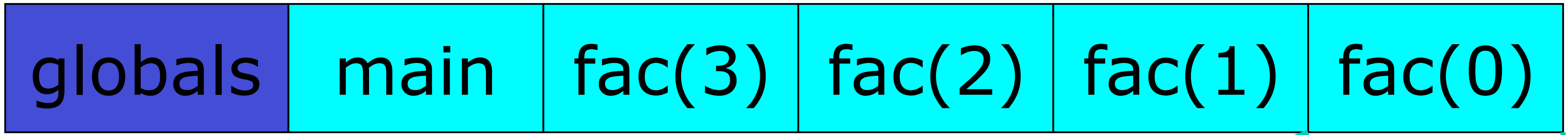
Possible evaluation of main(3)

```
main(3):
  fac(3, 117):                                  &r is 117
      fac(2, 118):                              &tmp is 118
          fac(1, 119):                          &tmp is 119
              fac(0, 120):                      &tmp is 120
                  *120 = 1
              *119 = 1 * 1                      n is 1
          *118 = 1 * 2                          n is 2
      *117 = 2 * 3                              n is 3
  print 6
```

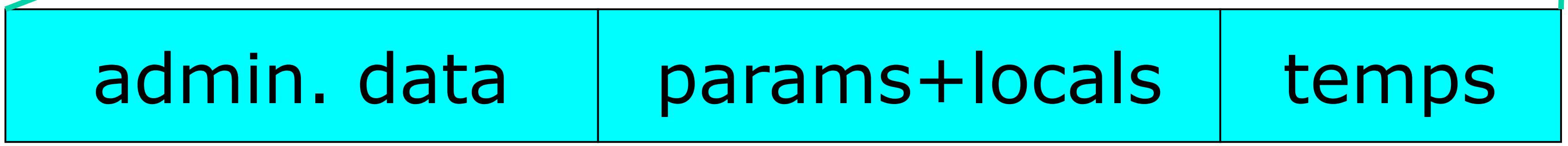
...	117	118	119	120	121
...	6	2	1	1	...

Storage model for micro-C

- The store is an indexable stack
  - Bottom: global variables at fixed addresses
  - Plus, a stack of activation records



- An *activation record* is an executing function
  - return address and other administrative data
  - parameters and local variables
  - temporary results



Lvalue and rvalue of an expression

- Rvalue is “normal” value, right-hand side of assignment: **`17`**, **`true`**
- Lvalue is “location”, left-hand side of assignment: **`x`**, **`a[2]`**
- In assignment **`e1=e2`**, expression **`e1`** must have lvalue

	Has lvalue	**Has rvalue**
`x`	yes	yes
`a[2]`	yes	yes
`*p`	yes	yes
`x+2`	no	yes
`&x`	no	yes

- Where else must an expression have lvalue in C#? In C?

Call-by-value and call-by-reference, C#

```
int a = 11;
int b = 22;
swapV(a, b);
swapR(ref a, ref b);
```

a: 41
b: 42

addresses

by value

```
static void swapV(int x, int y) {
  int tmp = x; x = y; y = tmp;
}
```

x: 43
y: 44
tmp: 45

by reference

```
static void swapR(ref int x, ref int y) {
  int tmp = x; x = y; y = tmp;
}
```

x: 41
y: 42

store

41	42	43	44	45
11	22	22	11	11

C variable declarations

Declaration	Meaning
int n	n is an integer
int *p	p is a pointer to integer
int ia[3]	ia is array of 3 integers
int *ipa[4]	ipa is array of 4 pointers to integers
int (*iap)[3]	iap is pointer to array of 3 integers
int *(*ipap)[4]	ipap is pointer to array of 4 pointers to ints

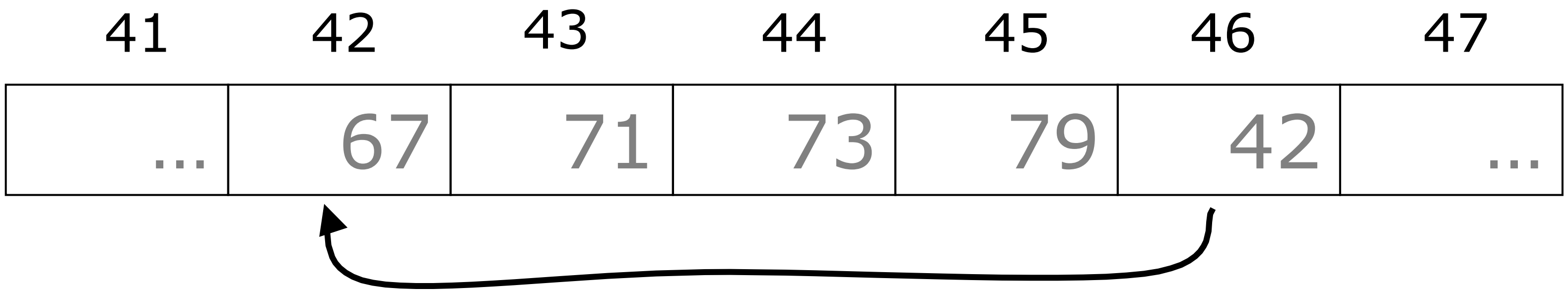
Unix program **`cdecl`** or www.cdecl.org may help:

```
cdecl> explain int *(*ipap)[4]
declare ipap as pointer to array 4 of pointer to int
cdecl> declare n as array 7 of pointer to pointer to int
int **n[7]
```

Micro-C array layout

- An array `int arr[4]` consists of
  - its 4 int elements
  - a pointer to arr[0]

`arr: 46`



- This is the uniform array representation of B
- C treats array parameters and local arrays differently
- Strachey's CPL -> Richards's BCPL -> B -> C

Micro-C syntactic concepts

- Types

`int`	`TypI`
`int *x`	`TypP(TypI)`
`int x[4]`	`TypA(TypI, Some 4)`

- Expressions

```
(*p + 1) * 12
```

- Statements

```
if (x!=0) y = 1/x;
```

- Declarations
  - of global or local variables

    ```
    int x;
    ```

  - of global functions

    ```
    void swap(int *x, int *y) { ... }
    ```

Micro-C abstract syntax

```
type typ =
  | TypI                                   (* Type int                       *)
  | TypC                                   (* Type char                      *)
  | TypA of typ * int option               (* Array type                     *)
  | TypP of typ                            (* Pointer type                   *)
and expr =
  | Access of access                       (* x    or  *p    or  a[e]       *)
  | Assign of access * expr                (* x=e  or  *p=e  or  a[e]=e     *)
  | Addr of access                         (* &x   or  &*p   or  &a[e]      *)
  | CstI of int                            (* Constant                       *)
  | Prim1 of string * expr                 (* Unary primitive operator       *)
  | Prim2 of string * expr * expr          (* Binary primitive operator      *)
  | Andalso of expr * expr                 (* Sequential and                 *)
  | Orelse of expr * expr                  (* Sequential or                  *)
  | Call of string * expr list             (* Function call f(...)           *)
and access =
  | AccVar of string                       (* Variable access        x       *)
  | AccDeref of expr                       (* Pointer dereferencing  *p      *)
  | AccIndex of access * expr              (* Array indexing         a[e]    *)
and stmt =
  | If of expr * stmt * stmt               (* Conditional                    *)
  | While of expr * stmt                   (* While loop                     *)
  | Expr of expr                           (* Expression statement   e;      *)
  | Return of expr option                  (* Return from method             *)
  | Block of stmtordec list                (* Block: grouping and scope      *)
and stmtordec =
  | Dec of typ * string                    (* Local variable declaration     *)
  | Stmt of stmt                           (* A statement                    *)
and topdec =
  | Fundec of typ option * string * (typ * string) list * stmt
  | Vardec of typ * string
and program =
  | Prog of topdec list
```

Types

Expressions

rvalue

lvalue

Statements

Declarations

Lexer specification for micro-C

- New: endline comments `// blah blah`
  and delimited comments `if (x /* y? */)`

```
rule Token = parse
  | ...
  | "//"            { EndLineComment lexbuf; Token lexbuf }
  | "/*"            { Comment lexbuf; Token lexbuf }
```

```
and EndLineComment = parse
    | ['\n' '\r']      { () }
    | (eof | '\026')   { () }
    | _                { EndLineComment lexbuf }
```

```
and Comment = parse
    | "/*"             { Comment lexbuf; Comment lexbuf }
    | "*/"             { () }
    | ['\n' '\r']      { Comment lexbuf }
    | (eof | '\026')   { lexerError lexbuf "Unterminated" }
    | _                { Comment lexbuf }
```

Parsing C variable declarations

- Hard, declarations are *mixfix*: **`int *x[4]`**
- Parser trick: Parse a variable declaration as a type followed by a variable description:

`int` **`*x[4]`**

`TypI`

`(fun t -> TypA(TypP(t),Some 4), "x")`

- Parse var description to get pair **`(f, x)`** of type function **`f`**, and variable name **`x`**
- Apply **`f`** to the declared type to get type of **`x`**

`Vardec(TypA(TypP(TypI),Some 4), "x")`

Interpreting micro-C

- Interpreter data:
  - locEnv, *environment* mapping local variable names to store addresses
  - gloEnv, *environment* mapping global variable names to store addresses, and global function names to (parameter list, body statement)
  - *store*, mapping addresses to (integer) values
- Main interpreter functions:

  exec: stmt -> locEnv -> gloEnv -> store -> store

  eval: expr -> locEnv -> gloEnv -> store -> int * store

  access: access -> locEnv -> gloEnv -> store -> address * store

Micro-C statement execution

- As for the naïve language, but more env.s:

```
let rec exec stmt locEnv gloEnv store : store =
    match stmt with
    | If(e, stmt1, stmt2) ->
      let (v, store1) = eval e locEnv gloEnv store
      in if v<>0 then exec stmt1 locEnv gloEnv store1
                 else exec stmt2 locEnv gloEnv store1
    | While(e, body) ->
      let rec loop store1 =
          let (v, store2) = eval e locEnv gloEnv store1
          in if v<>0 then loop (exec body locEnv gloEnv store2)
                     else store2
      in loop store
    | ...
```

Expression statements in C, C++, Java and C#

- The "assignment statement"

  `x = 2+y;`

  is really an expression

  `x = 2+y`

  followed by a semicolon

Value: none
Effect: change x

Value: 2+y
Effect: change x

- The semicolon means: ignore value

```
let rec exec stmt locEnv gloEnv store : store =
    match stmt with
      | ...
      | Expr e ->
        let (_, store1) = eval e locEnv gloEnv store
        in store1
```

Evaluate expression then ignore its value

Micro-C expression evaluation, 1

- Evaluation of an expression
  - takes local and global env and a store
  - gives a resulting *rvalue* and a *new store*

```
and eval e locEnv gloEnv store : int * store =
    match e with
      | ...
      | CstI i          -> (i, store)
      | Prim2(ope, e1, e2) ->
        let (i1, store1) = eval e1 locEnv gloEnv store
        let (i2, store2) = eval e2 locEnv gloEnv store1
        let res =
            match ope with
              | "*"  -> i1 * i2
              | "+"  -> i1 + i2
              | ...
        in (res, store2)
```

Micro-C expression evaluation, 2

- To evaluate access expression **`x`**, **`*p`**, **`arr[i]`**
  - find its lvalue, as an address **`loc`**
  - look up the rvalue in the store, as **`store1[loc]`**
- To evaluate **`&e`**
  - just evaluate **`e`** as lvalue
  - return the lvalue

```
and eval e locEnv gloEnv store : int * store =
    match e with
      | Access acc ->
        let (loc, store1) = access acc locEnv gloEnv store
        in (getSto store1 loc, store1)
      | Addr acc -> access acc locEnv gloEnv store
      | ...
```

Micro-C access evaluation, to *lvalue*

- A variable **`x`** is looked up in environment
- A dereferencing **`*e`** just evaluates **`e`** to an address
- An array indexing **`arr[idx]`**
  - evaluates arr to address a, then gets aval=store[a]
  - evaluates e to rvalue index i
  - returns address (aval+i)

```
and access acc locEnv gloEnv store =
    match acc with
    | AccVar x           -> (lookup (fst locEnv) x, store)
    | AccDeref e         -> eval e locEnv gloEnv store
    | AccIndex(acc, idx) ->
      let (a, store1) = access acc locEnv gloEnv store
      let aval = getSto store1 a
      let (i, store2) = eval idx locEnv gloEnv store1
      in (aval + i, store2)
```

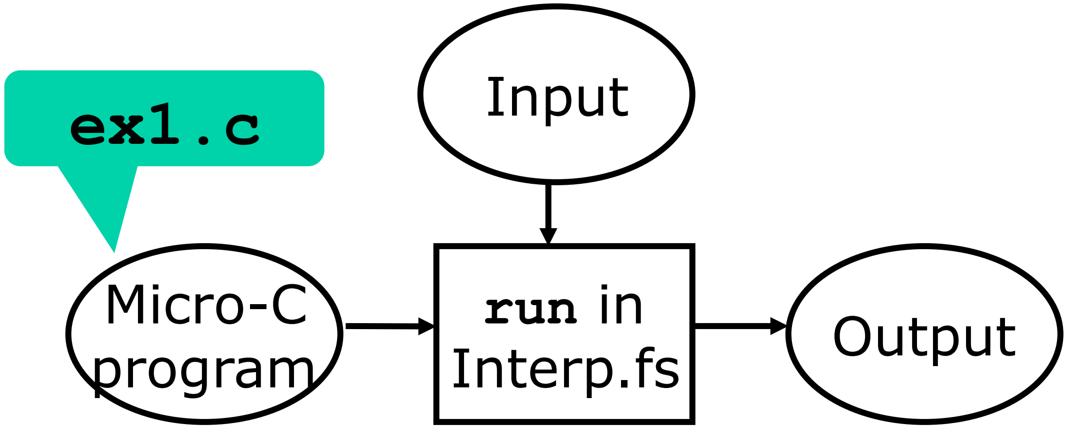
Operators &x and *p are inverses

- The address-of operator `&e`
  - evaluates `e` to its lvalue
  - returns the lvalue (address) as if it were an rvalue
- The dereferencing operator `*e`
  - evaluates `e` to its rvalue
  - returns the rvalue as if it were an lvalue

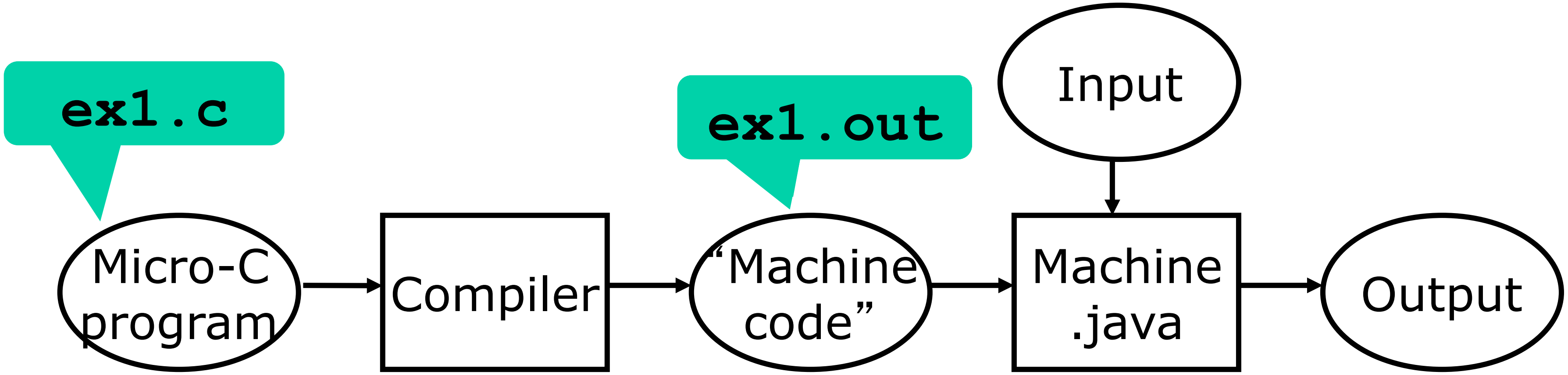
- It follows
  - that `&(*e)` equals `e`
  - that `*(&e)` equals `e`, provided `e` has lvalue

Micro-C, interpreter and compiler

- This lecture: Interpretation of micro-C



- Next lecture: Compilation of micro-C



Reading and homework

- This week's lecture:
  - PLCSD chapter 7
  - Strachey: Fundamental Concepts …
  - Kernighan & Ritchie: The C programming language, chapter 5.1-5.5

- Next lecture, October 10
  - PLCSD chapter 8