CS:3820
Programming Language Concepts

Imperative languages, environment and store, micro-C

Overview

- A Naive imperative language
- C concepts
  - Pointers and pointer arithmetic, 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

Imperative Programming

- Based on *stateful* computation
- A *state* is a mapping from variables to values
- (Terminating) programs start with an initial state and end with a final state
- Programs are sequences of *statements*
- Each statement modifies the current state
- Statements may contain *expressions*, which are evaluated to *values*
- Some expressions have also the *side effect* of modifying the store

A naive-store imperative language

- **Naive** store model:
  - a variable name maps to an integer value
  - a 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

Naive-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

Naive-store statement execution, 2

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

```
exec (Block [s₁; s₂]) store // F# interpreter
= loop [s₁; s₂] 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)
        loop stmts store
      | ...
```

Naive-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)
      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

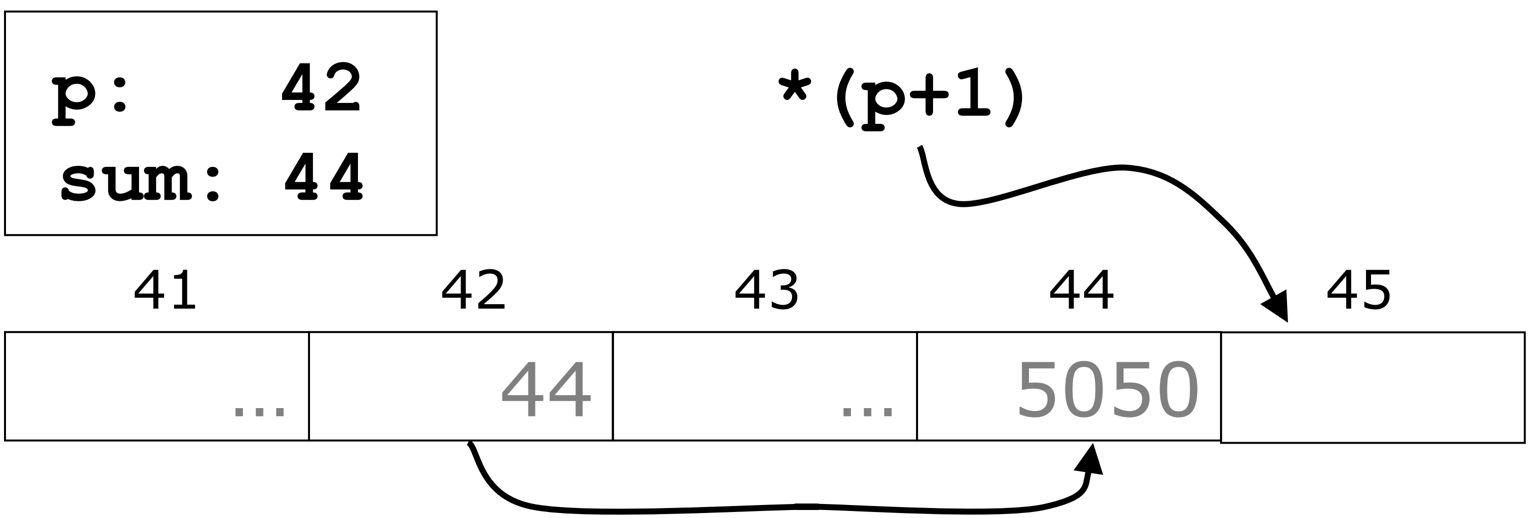
- Main innovations of C (1972) over Algol 60:
  - Structs, as in COBOL and Pascal
  - Pointers, pointer arithmetic, pointer types, array indexing as pointer indexing
  - Syntax: { } for blocks, as in C++, Java, C#
- Very different from Java and C#, which have no pointer arithmetic, but garbage collection

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 variable basics

- A variable **`x`** refers to an address (storage location)
- Addresses are mapped to values in the store
- *Pointers* are variables whose values is an address



C variable basics

- What a variable **`x`** refers to depends on its position in a statement

- It can be:
  - *the content of* **`x`** *'s storage location* (rvalue), as in
    `x + 4`
  - *the storage location itself* (lvalue), as in
    `x = y + 4`

C pointer basics

- The value of a pointer **`p`** is a storage location (address)

- Depending on context, the dereference expression **`*p`** means:
  - *the content of the location* (rvalue), as in **`*p + 4`**
  - *the storage location itself* (lvalue), as in **`*p = x + 4`**

C pointer basics

- The pointer that points to **`x`** is **`&x`**
- Pointer arithmetic:
  `*(p+1)` is the content of the loc just after **`p`**
- If **`p`** equals **`&a[0]`**
  then **`*(p+i)`** equals **`p[i]`** equals **`a[i]`**,
  so an array is a pointer
- **`a[0]`** equals **`*a`**

Lvalue and rvalue of an expression

- Rvalue is *usual* value, on right-hand side of assignment: **`17`**, **`true`**
- Lvalue is *location*, on 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

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 **p	p is a pointer to a pointer to an integer

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]
```

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 micro-C/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

globals	main	fac(3)	fac(2)	fac(1)	fac(0)

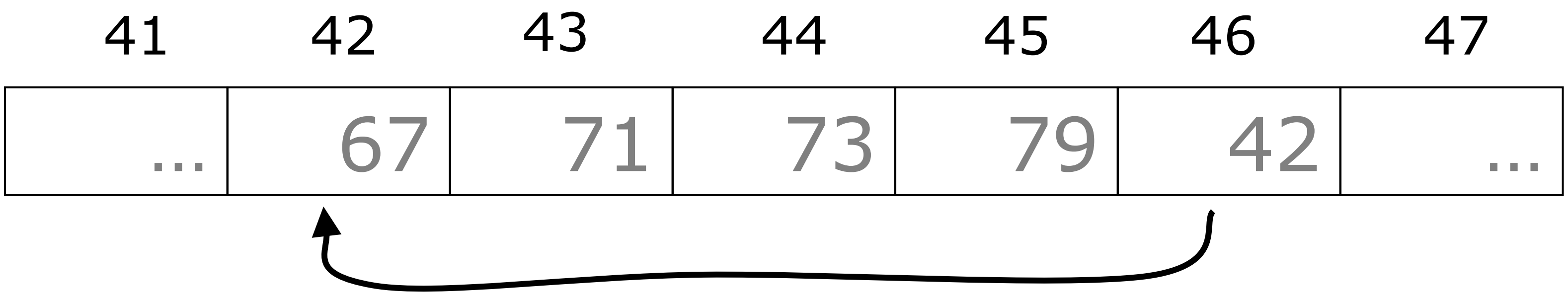
- An *activation record* is an executing function
  - return address and other administrative data
  - parameters and local variables
  - temporary results

admin. data	params+locals	temps

Micro-C array layout

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

`a: 46`



Operators &x and *p are inverses

x:	41
y:	45
p:	42

41	42	43	44	45
1	45	7	8	6

- The address-of operator **`&`** in **`&e`**
  - evaluates **`e`** to its lvalue (address) and returns it as an rvalue

  Ex: **`&x == 41`**, **`&p == 42`**
- The dereferencing operator **`*`** in **`*e`**
  - evaluates **`e`** to its rvalue and returns as an lvalue

  Ex: **`*p`** *is effectively the same as* **`y`**
- It follows that
  1. **`&(*e)`** equals **`e`** Ex: **`&(*p) == &y == 45 == p`**
  2. **`*(&e)`** equals **`e`**, provided **`e`** has lvalue Ex: **`*(&y) == *45 == 6 == y`**

Modifying input parameters

```
int a = 11;
int b = 22;
swap1(a, b);
swap2(&a, &b);
```

```
a:  41
b:  42
```

addresses

incorrect

```
static void swap1(int x, int y) {
  int tmp = x; x = y; y = tmp;
}
```

```
x:    43
y:    44
tmp:  45
```

correct

```
static void swap2(int *p, int *q) {
  int tmp = *p; *p = *q; *q = tmp;
}
```

```
x:    41
y:    42
tmp:  43
```

store

41	42	43	44	45
11	22	22	11	11

Micro-C syntactic concepts

Types	Abstract Syntax
`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

Interpreting Micro-C in F#

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`**, *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
```

Interpreter's functions

```
run: program -> int list -> store
(run p [a1; …; an])
```

Execute program **`p`** by initializing global vars and then calling **`p`**'s **`main`** function with args **`a1; …; an`**, returning final store

```
exec: stmt -> locEnv -> gloEnv -> store -> store
(exec sta lenv genv sto)
```

Execute statement **`sta`** in local env **`lenv`** and global env **`genv`** and store **`sto`**, returning updated store

```
stmtordec: stmtordec -> locEnv -> gloEnv -> store ->
           locEnv * store
(stmtordec sd lenv genv sto)
```

Execute statement or declaration **`sd`** in local env **`lenv`** and global env **`genv`** and store **`sto`**, returning updated local env and store

Interpreter's functions

```
eval: expr -> locEnv -> gloEnv -> store -> int * store
(eval e lenv genv st)
```

Evaluate expression **e** in local env **lenv** and global env **genv** and store **sto**, returning **e**'s result and updated store

```
access: access -> locEnv -> gloEnv -> store ->
        address * store
(access a lenv genv st)
```

Evaluate access expression **a** in local env **lenv** and global env **genv** and store **sto**, returning an address and updated store

```
allocate: typ * string -> locEnv -> store ->
          locEnv * store
(allocate t x lenv sto)
```

Bind var **x** in local env **lenv** and allocate space for **x** in store **sto**, returning updated env and store

Micro-C statement execution

As with the naive language, but two envs:

```
let rec exec stmt locEnv gloEnv store : store =
    match stmt with

    | If(e, stmt1, stmt2) ->
      let (v, store1) = eval e locEnv gloEnv store
      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
          if v<>0 then loop (exec body locEnv gloEnv store2)
                  else store2
      loop store

    | ...
```

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

- The "assignment statement"

  `x = 2+4;`

  is really an expression

  `x = 2+4`

  followed by a semicolon

Value: none
Effect: change x

Value: 6
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
        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(op, e1, e2) ->
      let (i1, store1) = eval e1 locEnv gloEnv store in
      let (i2, store2) = eval e2 locEnv gloEnv store1 in
      let res =
          match op 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 a location **`loc`**
  - look up the rvalue in the store, as **`store1[loc]`**
- To evaluate **`&e`**
  - just evaluate **`e`** as lvalue
  - return the lvalue

rvalue

```
eval e locEnv gloEnv store : int * store =
  match e with
    | Access acc ->
      let (loc, store1) = access acc locEnv gloEnv store
      (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 **`a[e]`**
  - evaluates **`a`** to address **`k`**, then gets **`v = store[k]`**
  - evaluates **`e`** to rvalue index **`i`**
  - returns address **`v+i`**

lvalue

```
access acc locEnv gloEnv store : int * store =
  match acc with
  | AccVar x            -> (lookup (fst locEnv) x, store)

  | AccDeref e          -> eval e locEnv gloEnv store

  | AccIndex(a, e) ->
    let (k, store1) = access a locEnv gloEnv store
    let v = getSto store1 k
    let (i, store2) = eval e locEnv gloEnv store1
     (v + i, store2)
```

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 *a[4]`**
- Parser trick: Parse a variable declaration as a type followed by a variable description:

type info

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

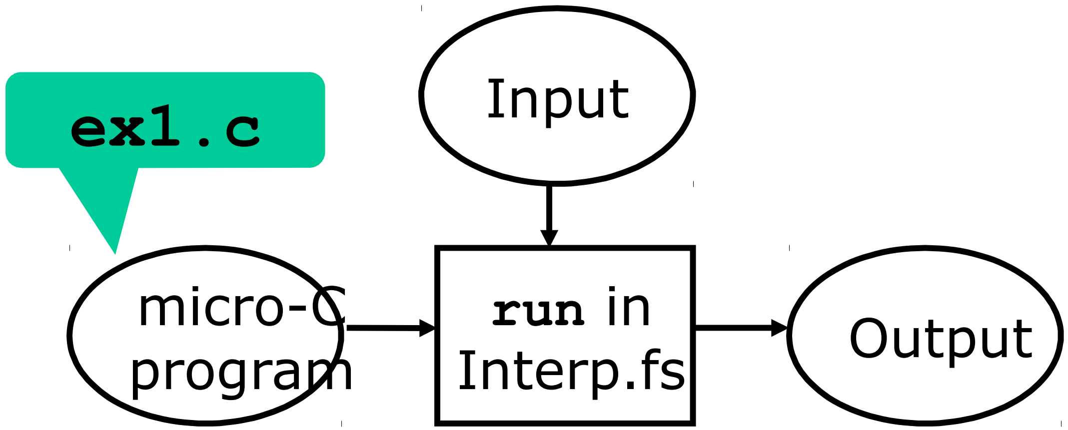
`TypI` **`((fun t -> TypA (TypP t, Some 4)), “a”)`**

- 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), “a”)`

Micro-C, interpreter and compiler

- So far: Interpretation of micro-C



- Next: Compilation of micro-C