Advanced Models and Programs:

MicroC, pointer programming, type system, compilation

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Agenda

- Concepts: Pointers, lvalue, rvalue
- MicroC parsing challenges
- MicroC abstract syntax
- MicroC compilation schemes

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
  - Using { } for blocks, as in C++, Java, C#
- Java and safe C# lack pointers and are completely different from C/C++
- Except for the core language, which is Algol with **`{ }`** instead of **`begin end`**.

Pointer basics

- A pointer **`p`** refers to a storage location
- The dereference expression **`*p`**
  - may mean the content of the location as in **`*p+4`**
  - may mean the storage location itself, as in **`*p = x+4`**
- The pointer that points to **`x`** is **`&x`**
- Pointer arithmetics: **`*(p+1)`** is the storage location after **`*p`**
- If **`p`** equals **`&a[0]`**
  then **`*(p+i)`** equals **`p[i]`** equals **`a[i]`**, so arrays are pointers

Using pointers for return values

- Example test12.c, computing square(x):

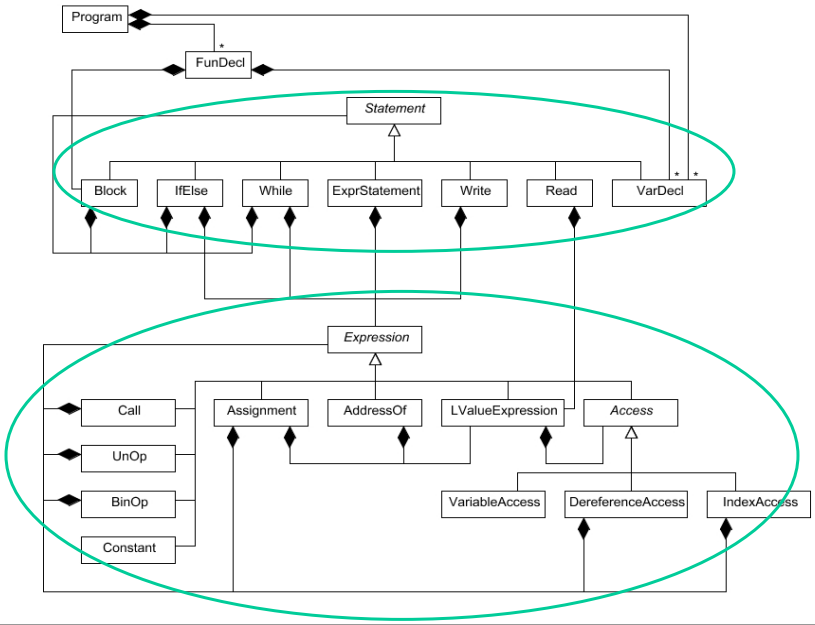
```
void main() {
  int res;
  square(5, &res);
  write res;
  square(res, &res);
  square(res, &res);
  write res;
}

void square(int x, int *p) {
  *p = x*x;
}
```

for input

for output: a pointer to where to put the result

MicroC abstract syntax



Concepts

- Expression statements
- Storage model
- Activation records (frames)
  - Base pointer bp
  - Return address
  - Array layout (B rather than C)
- Lvalue and Rvalue

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

- The "assignment statement"

  x = 2+y;

  Value: none
  Effect: change x

  is really an expression

  x = 2+y

  Value: 2+y
  Effect: change x

  followed by a semicolon

  ;

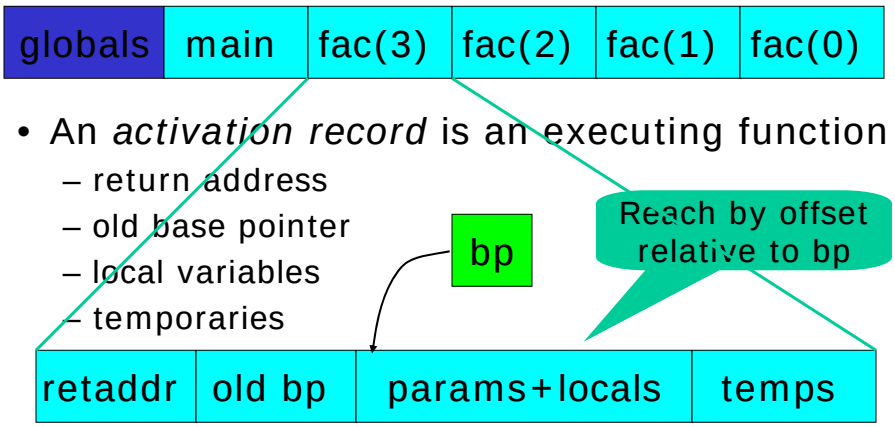
- The semicolon means: ignore value

```
public class ExprStatement : Statement {
  private readonly Expression e;
  public override void Compile(CEnv env, Generator gen) {
    e.Compile(env, gen);
    gen.Emit(new INCSP(-1));
  }
}
```

Eval. expr. then pop its value

Storage model

- 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
  - old base pointer
  - local variables
  - temporaries

Array layout

- An array **`int arr[5]`** consists of
  - its 5 int elements
  - a pointer to arr[0]

- This is the array representation of B, the predecessor to C

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 **e1=e2**, expression **e1** must have lvalue
- Where else must an expression have lvalue in C#? In C?

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

MicroC parsing

- Variable declaration syntax
- Lvalue and rvalue expressions
- Right-associative operators

C variable type 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

The Unix program **cdecl** helps understand C types:

```
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]
```


Parsing C variable declarations

- Cumbersome because declarations are mixfix, eg:
  int *x[4]
- Parser trick: Use C# delegate type **T2V** that transforms **Type** to **VarDecl**:
  public delegate VarDecl T2V(Type t);
- Return a T2V and apply it to the type:

```
VarDec<out VarDecl varDecl>     (. Type ty; T2V t2v; .)
= Typ<out ty>
  VarDesc<out t2v>              (. varDecl = t2v(ty); .)
.
VarDesc<out T2V t2v>            (. String name; .)
= (Ident<out name>
   (. t2v = delegate(Type ty) { return new VarDecl(name, ty); };
   .)
 | "*" VarDesc<out t2v>
   (. t2v = delegate(Type ty) { return t2v(new PointerType(ty));
  ...
```

Parsing Lvalue and Rvalue expressions

- LR parsing can distinguish expressions having lvalues from those that don't
- LL parsing cannot, and must parse assignment as **`Expr "=" Expr`**
- But **`x+2=78;`** should be illegal.
- Solution: Make grammar too general
  `Expr<out lhs> "=" Expr<out rhs>`
  and then check that lhs has lvalue:

```
e = new Assignment(lhs.MakeLvalue(), rhs);
```

Throw exception if no lvalue

Only accesses (x, a[2], *p) have lvalue

```
public abstract class Expression {
  public virtual LvalueExpression MakeLvalue() {
    throw new Exception("Illegal lvalue expression");
  }
}
public class LvalueExpression : Expression {
  private readonly Access access;
  public override LvalueExpression MakeLvalue() {
    return this;
  }
}
public abstract class Access : Expression {
  public override LvalueExpression MakeLvalue() {
    return new LvalueExpression(this);
  }
}
public class VariableAccess : Access {
  public readonly String name;
}
```

Parsing assignment x=y=e, which is right associative

- Expr. **x=y=z=v** should parse as **x=(y=(z=v))**
- Parse as **Expr AssignExpr** where **AssignExpr** is **['=' Expr]**

Throws if no lvalue

```
Expr<out Expression e> (. Expression rhs; .)
= LogOrExp<out e>
  [
    '=' Expr<out rhs>
                  (. e = new Assignment(e.MakeLvalue(),
                                        rhs);
                  .)
  ]
.
```

MicroC checking

- Check that variables and functions are declared when used
- Check that types match
  - in arithmetic and logical expressions
  - in pointer and array indexing
  - in pointer dereferencing and address-of
  - in function parameter passing
  - in assignment expressions

Ten-minute exercise

- Assume **p** is pointer to **int**
- What kinds of pointer arithmetics are allowed by MicroC.cs?
  - Addition of integer: **p+2**
  - Multiplication by integer: **p*2**
  - Subtraction of integer: **p-2**
- What should be changed to make pointer difference **p-q** have type **int**?

Compiling arithmetic expressions and assignment

- Compile **e1 + e2**:
  <e1> as rvalue
  <e2> as rvalue
  ADD

- Compile **e1 = e2**:
  <e1> as lvalue
  <e2> as rvalue
  STI

- **<e1>** means: the result of compiling **e1**

Compiling lvalues and rvalues

- Compile **e** as rvalue:
  <e> as lvalue
  LDI
- Compile **&e** as rvalue:
  <e> as lvalue
- Compile **x** as lvalue:
  GETBP
  CSTI <xoffset>
  ADD
- Compile ***e** as lvalue:
  <e> as rvalue
- Compile **e1[e2]** as lvalue:
  <e1> as rvalue
  <e2> as rvalue
  ADD

Compiling blocks and declarations

- To compile a block **{ s1 s2 … sn }**
  - Enter new scope
  - **<s1> <s2> … <sn>**
  - Leave scope
- To compile declaration **int x:**
  - Generate code to push 0; this takes a stack place
- To compile declaration **int a[5]:**
  - Generate code to allocate 5 stack locations, that is, increment SP by 5
  - Generate code to compute address of the first of those locations

Statement compilation schemes

- Compile
  if (e) s1 else s2:

```
<e> as rvalue
IFZERO L1
<s1>
GOTO L2
L1: <s2>
L2:
```

- Compile
  while (e) s:

```
L1: <e> as rvalue
IFZERO L2
<s>
GOTO L1
L2:
```


Ten-minute exercise

- What code should be generated for a do-while block:
  do s while (e) ;
- What code should be generated for a **for** statement:
  for (e1; e2; e3) s

The Micro-C stack machine

- Compiling and running Micro-C

```
Coco -namespace MicroC MicroC.ATG
csc MicroC.cs Scanner.cs Parser.cs

csc Machine.cs

unzip test-c.zip
MicroC test5.c check
MicroC test5.c compile


Machine a.out

Machine /trace a.out
```

Build compiler

Build stack machine

Compile example

Run it

with trace

The stack of frames

- Example test5.c, computing factorial:

```
void main() {
  int res;
  fac(3, &res);
  write res;
}

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

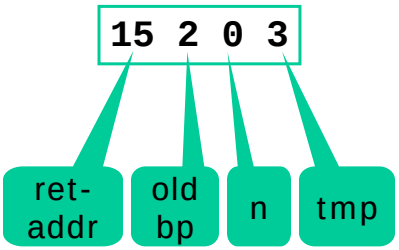
- **n** is input parameter
- **res** is output parameter, a pointer to where to put the result
- **tmp** holds the result of the recursive call to **fac**
- **&tmp** gets the pointer to **tmp**

The code for test5.c

```
 0 CALL 0 L1
 3 STOP
 4 L1:
 4 INCSP 1
 6 CSTI 3
 8 GETBP
 9 CSTI 0
11 ADD
12 CALL 2 L2
15 INCSP -1
17 GETBP
18 CSTI 0
20 ADD
21 LDI
22 PRINTI
23 INCSP -1
25 INCSP -1
27 RET -1
29 L2:
29 GETBP
30 CSTI 0
32 ADD
33 LDI
34 CSTI 0
36 EQ
37 IFZERO L3
39 GETBP
40 CSTI 1
42 ADD
43 LDI
44 CSTI 1
46 STI
47 INCSP -1
49 GOTO L4
51 L3:
51 INCSP 1
53 GETBP
54 CSTI 0
56 ADD
57 LDI
58 CSTI 1
60 SUB
61 GETBP
62 CSTI 2
64 ADD
65 CALL 2 L2
68 INCSP -1
70 GETBP
71 CSTI 1
73 ADD
74 LDI
75 GETBP
76 CSTI 0
78 ADD
79 LDI
80 GETBP
81 CSTI 2
83 ADD
84 LDI
85 MUL
86 STI
87 INCSP -1
89 INCSP -1
91 L4:
91 INCSP 0
93 RET 1
```

The stack of frames

- Example test5.c: computing fac(0)
- Stack frame for fac(0):



- What stack frame?

3 -999 0

```
[ ]{0: CALL 0 4}
[ 3 -999 ]{4: INCSP 1}
[ 3 -999 0 ]{6: CST 0}
[ 3 -999 0 0 ]{8: GETBP}
[ 3 -999 0 0 2 ]{9: CST 0}
[ 3 -999 0 0 2 0 ]{11: ADD}
[ 3 -999 0 0 2 ]{12: CALL 2 29}
[ 3 -999 0 15 2 0 2 ]{29: GETBP}
[ 3 -999 0 15 2 0 2 5 ]{30: CST 0}
[ 3 -999 0 15 2 0 2 5 0 ]{32: ADD}
[ 3 -999 0 15 2 0 2 5 ]{33: LDI}
[ 3 -999 0 15 2 0 2 0 ]{34: CST 0}
[ 3 -999 0 15 2 0 2 0 0 ]{36: EQ}
[ 3 -999 0 15 2 0 2 1 ]{37: IFZERO 51}
[ 3 -999 0 15 2 0 2 ]{39: GETBP}
[ 3 -999 0 15 2 0 2 5 ]{40: CST 1}
[ 3 -999 0 15 2 0 2 5 1 ]{42: ADD}
[ 3 -999 0 15 2 0 2 6 ]{43: LDI}
[ 3 -999 0 15 2 0 2 2 ]{44: CST 1}
[ 3 -999 0 15 2 0 2 2 1 ]{46: STI}
[ 3 -999 1 15 2 0 2 1 ]{47: INCSP -1}
[ 3 -999 1 15 2 0 2 ]{49: GOTO 91}
[ 3 -999 1 15 2 0 2 ]{91: INCSP 0}
[ 3 -999 1 15 2 0 2 ]{93: RET 1}
[ 3 -999 1 2 ]{15: INCSP -1}
[ 3 -999 1 ]{17: GETBP}
[ 3 -999 1 2 ]{18: CST 0}
[ 3 -999 1 2 0 ]{20: ADD}
[ 3 -999 1 2 ]{21: LDI}
[ 3 -999 1 1 ]{22: PRINTI}
1 [ 3 -999 1 1 ]{23: INCSP -1}
[ 3 -999 1 ]{25: INCSP -1}
[ 3 -999 ]{27: RET -1}
[ -999 ]{3: STOP}
```

Computing fac(3) with test5.c

- On the whiteboard…

Exercises Wednesday / Week 4

- Write Micro-C programs
  - to sum elements of an array
  - to make histogram of the elements of array
- Change Micro-C parser and compiler to
  - Allow (==) and (!=) to compare pointers and ints
  - Add a C/C++/Java/C#-style for-loop
  - Add prefix increment (++) operator
  - Add conditional operator (?:)
- Investigate the (Java or .NET) bytecode of selection sort