# Programs as Data 8
## A stack machine for micro-C; compiling micro-C to stack machine code

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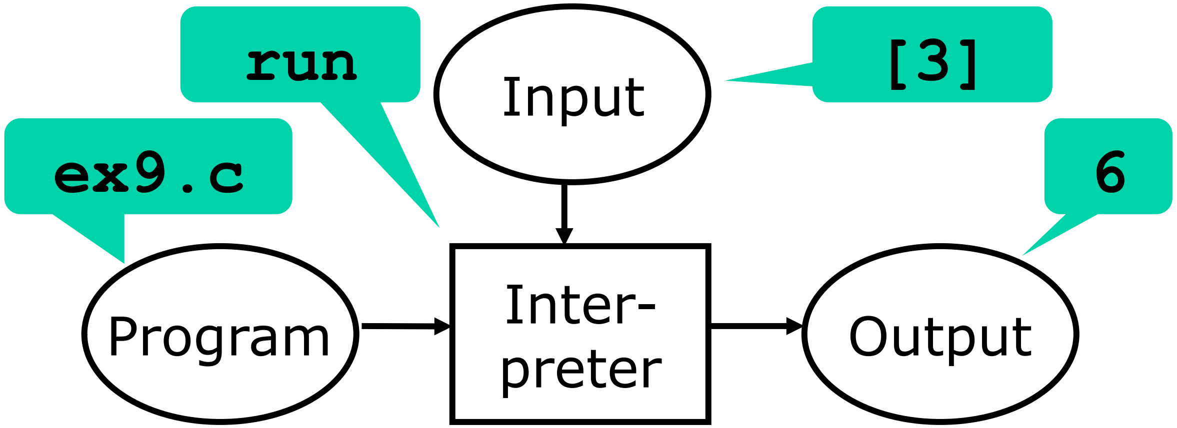
# Today

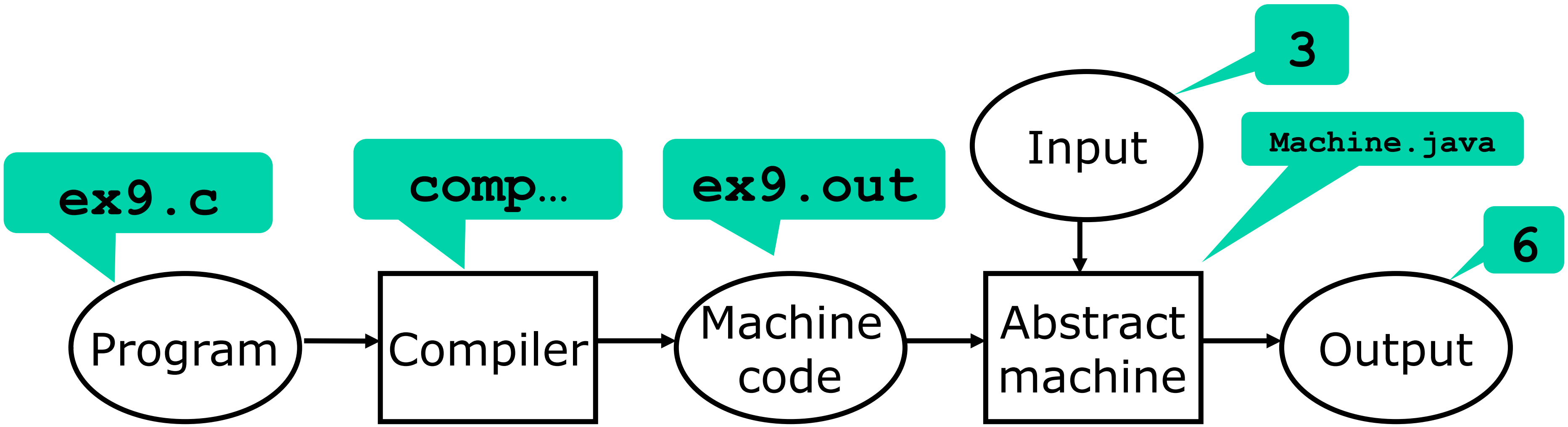
- Stack machine, target for micro-C compiler
  - Stack machine state
  - Instruction set
  - Implementations in Java and C
- Compiling micro-C to stack machine code

# Interpretation and compilation

- Interpretation = one-stage execution/evaluation:




- Compilation = two-stage execution/evaluation:



# Stack machine state transitions

| Instruction | Stack before | | Stack after | Effect |
|---|---|---|---|---|
| 0 CSTI $i$ | $s$ | $\Rightarrow$ | $s, i$ | Push constant $i$ |
| 1 ADD | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 + i_2)$ | Add |
| 2 SUB | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 - i_2)$ | Subtract |
| 3 MUL | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 * i_2)$ | Multiply |
| 4 DIV | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 / i_2)$ | Divide |
| 5 MOD | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 \% i_2)$ | Modulo |
| 6 EQ | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 = i_2)$ | Equality (0 or 1) |
| 7 LT | $s, i_1, i_2$ | $\Rightarrow$ | $s, (i_1 < i_2)$ | Less-than (0 or 1) |
| 8 NOT | $s, v$ | $\Rightarrow$ | $s, !v$ | Negation (0 or 1) |
| 9 DUP | $s, v$ | $\Rightarrow$ | $s, v, v$ | Duplicate |
| 10 SWAP | $s, v_1, v_2$ | $\Rightarrow$ | $s, v_2, v_1$ | Swap |
| 11 LDI | $s, i$ | $\Rightarrow$ | $s, s[i]$ | Load indirect |
| 12 STI | $s, i, v$ | $\Rightarrow$ | $s, v$ | Store indirect $s[i] = v$ |
| 13 GETBP | $s$ | $\Rightarrow$ | $s, bp$ | Load base ptr $bp$ |
| 14 GETSP | $s$ | $\Rightarrow$ | $s, sp$ | Load stack ptr $sp$ |
| 15 INCSP $m$ | $s$ | $\Rightarrow$ | $s, v_1, .., v_m$ | Grow stack ($m \geq 0$) |
| 15 INCSP $m$ | $s, v_1, .., v_{-m}$ | $\Rightarrow$ | $s$ | Shrink stack ($m < 0$) |
| 16 GOTO $a$ | $s$ | $\Rightarrow$ | $s$ | Jump to $a$ |
| 17 IFZERO $a$ | $s, v$ | $\Rightarrow$ | $s$ | Jump to $a$ if $v = 0$ |
| 18 IFNZRO $a$ | $s, v$ | $\Rightarrow$ | $s$ | Jump to $a$ if $v \neq 0$ |
| 19 CALL $m$ $a$ | $s, v_1, .., v_m$ | $\Rightarrow$ | $s, r, bp, v_1, .., v_m$ | Call function at $a$ |
| 20 TCALL $m$ $n$ $a$ | $s, r, b, u_1, .., u_n, v_1, .., v_m$ | $\Rightarrow$ | $s, r, b, v_1, .., v_m$ | Tailcall function at $a$ |
| 21 RET $m$ | $s, r, b, v_1, .., v_m, v$ | $\Rightarrow$ | $s, v$ | Return $bp = b$, $pc = r$ |
| 22 PRINTI | $s, v$ | $\Rightarrow$ | $s, v$ | Print integer $v$ |
| 23 PRINTC | $s, v$ | $\Rightarrow$ | $s, v$ | Print character $v$ |
| 24 LDARGS | $s$ | $\Rightarrow$ | $s, i_1, .., i_n$ | Command line args |
| 25 STOP | $s$ | $\Rightarrow$ | $\_$ | Halt the machine |

# Example stack machine program

- A simple program, file prog1:

```
0 20000000 16 7 0 1 2 9 18 4 25
```

Numeric code

```
0 20000000
16 7
0 1
2
9
18 4
25
```

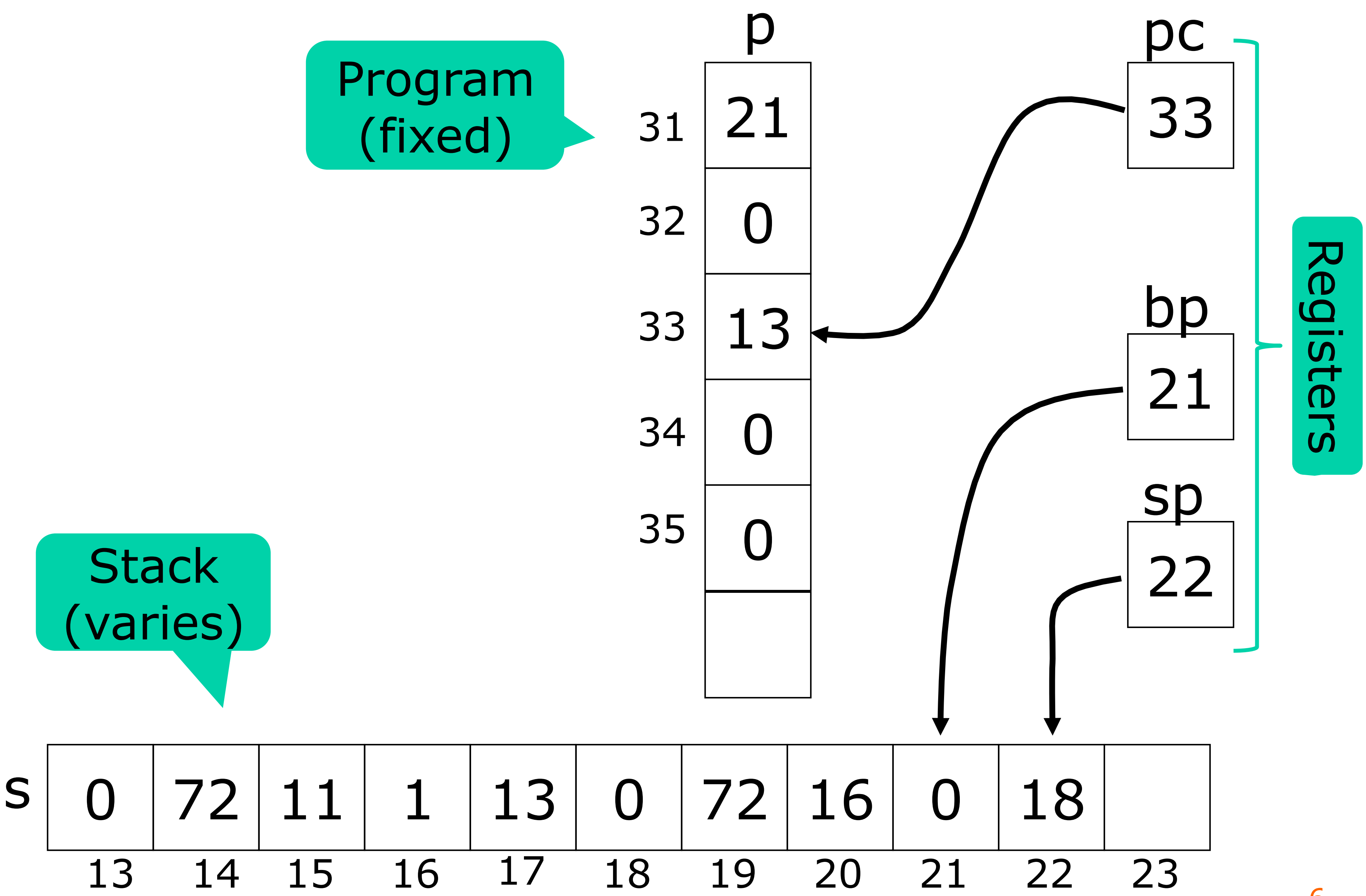
```
 0: CSTI 20000000
 2: GOTO 7
 4: CSTI 1
 6: SUB
 7: DUP
 8: IFNZRO 4
10: STOP
```

Symbolic code

- Running the code in file prog1:

```
C:>java Machine prog1
Ran 0.641 seconds
```

# Machine state: p, pc, s, sp, bp



# Stack machine for micro-C

- Runtime state:
  - Program **p**, holds the instructions
  - Program counter **pc**, points to next instruction
  - Stack **s**, holds variables and intermediate results
  - Stack pointer **sp**, points to top of stack
  - Base pointer **bp**, points to first local variable in top stack frame
- Structure of the stack
  - Bottom: Global variables
  - One stack frame for each active method

# Implementations of the micro-C abstract machine

- File Machine.java: An implementation of the abstract machine as a Java program
- File machine.c: An implementation of the abstract machine as a C program

- File Machine.fs: A definition of the instruction set for use in the compiler Comp.fs
- The instruction numbers in Machine.fs agree with Machine.java and machine.c

# Stack machine instruction execution

Java or C or C#

```
for (;;) {
  switch (p[pc++]) {
  case CSTI:
    s[sp+1] = p[pc++]; sp++; break;
  case ADD:
    s[sp-1] = s[sp-1] + s[sp]; sp--; break;
  case EQ:
    s[sp-1] = (s[sp-1] == s[sp] ? 1 : 0); sp--; break;
  case DUP:
    s[sp+1] = s[sp]; sp++; break;
  case LDI:
    s[sp] = s[s[sp]]; break;
  case GOTO:
    pc = p[pc]; break;
  case IFZERO:
    pc = (s[sp--] == 0 ? p[pc] : pc+1); break;
  case ...
  case STOP:
    return sp;
  ...
} }
```

# Structure of the micro-C stack

- Computing factorial with MicroC/ex9.c

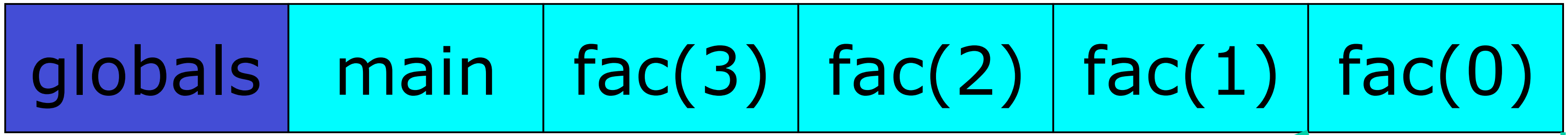
```
void main(int i) {
  int r;
  fac(i, &r);
  print r;
}

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

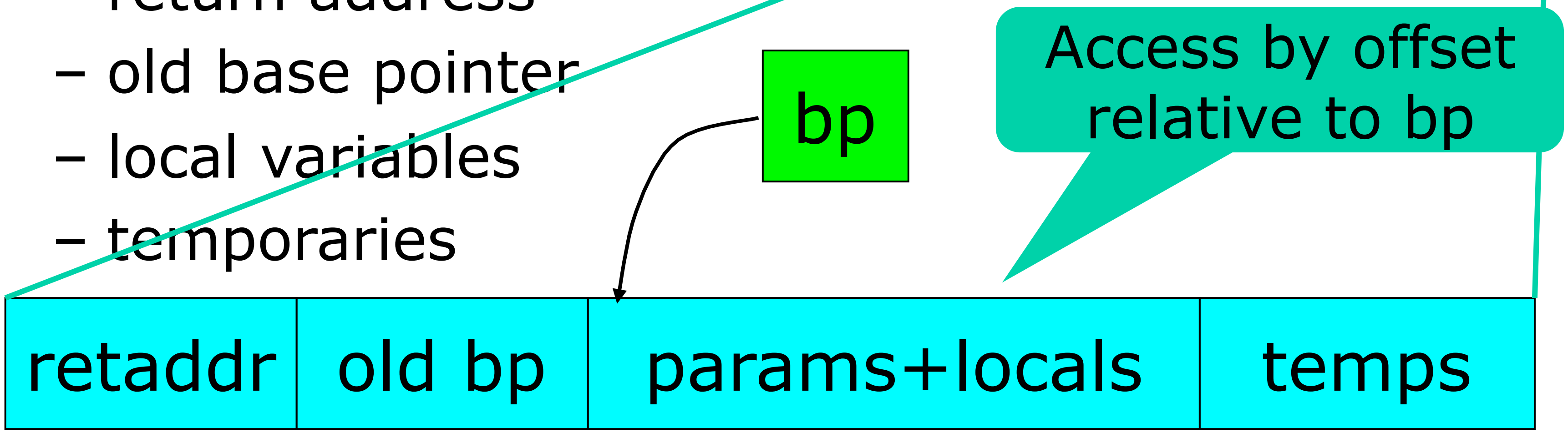
- **n** is input parameter
- **res** is output parameter, a pointer to where to put the result
- **tmp** holds the result of the recursive call
- **&tmp** gets the pointer to **tmp**

# Runtime storage: the stack

- The store is an indexable stack
  - bottom: global variables at fixed addresses
  - followed by activation records




- An *activation record* is an executing function
  - return address
  - old base pointer
  - local variables
  - temporaries



# Compiling micro-C

- Overall structure of a micro-C program
  - Global variable declarations **`int x; int y;`**
  - Global function declarations **`void main(…) {…}`**

- Overall structure of the generated code:
  - Code to allocate all global variables
  - Code to load arguments, call **`main`**, and stop
  - Code for each function, including **`main`**
- Structure of code for a function:
  - Code for the function's body statement
  - Code (RET) to return from the function

# Observations

- At runtime, a local variable's place within a stack frame is always the same
- This *offset* can be computed at compile-time
- The compiletime environment in the micro-C compiler maps a local variable to an offset
- The runtime environment is the stack of activation records in the abstract machine
- At runtime, the base pointer BP points at the bottom of the current activation record
- So a local variable's address is BP+offset

# Compile-time environments

- varEnv = variable environment
  - maps global variable to global address in stack
  - maps local variable to offset in activation record
- funEnv = function environment
  - maps function name to (label, returntype, parametertypes)

# Main micro-C compiler functions

- **`cStmt stmt varEnv funEnv : instr list`**
  - Compile **`stmt`** to code that performs the statement's actions
- **`cExpr expr varEnv funEnv : instr list`**
  - Compile **`expr`** to code that leaves the expr's rvalue on the stack top
- **`cAccess expr varEnv funEnv : instr list`**
  - Compile **`expr`** to code that leaves the expr's lvalue on the stack top
- **`cProgram topdecs : instr list`**
  - Build global varEnv and global funEnv
  - Generate code for global variables
  - Generate code to call function **`main`**
  - Generate code for all functions, including **`main`**

# Compiling arithmetic expressions and assignment

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

<u>Compile **17** as rvalue:</u>

```
CSTI 17
```

<u>Compile **e1 + e2** as rvalue:</u>

```
<e1> as rvalue
<e2> as rvalue
ADD
```

<u>Compile **e1 = e2** as rvalue:</u>

```
<e1> as lvalue
<e2> as rvalue
STI
```

**cExpr**

# Micro-C compiler fragment

```
and cExpr e varEnv funEnv : instr list =
    match e with
    | Access acc      -> cAccess acc varEnv funEnv
                         @ [LDI]
    | Assign(acc, e) -> cAccess acc varEnv funEnv
                         @ cExpr e varEnv funEnv
                         @ [STI]
    | CstI i          -> [CSTI i]
    | Addr acc        -> cAccess acc varEnv funEnv
    | Prim2(ope, e1, e2) ->
      cExpr e1 varEnv funEnv
      @ cExpr e2 varEnv funEnv
      @ (match ope with
           | "*"   -> [MUL]
           | "+"   -> [ADD]
           | "<"   -> [LT]
           | ...)
     | ...
```

# Compiling comparisons

Compile **e1 < e2** as rvalue:

```
<e1> as rvalue
<e2> as rvalue
LT
```

**cExpr**

- Q: How compile >=, >, <= when we have only LT?
- A: Use NOT and SWAP – but how?

# Compiling lvalues and rvalues

Compile **x** as lvalue:

```
GETBP
CSTI <xoffset>
ADD
```

Compile **e1[e2]** as lvalue:

```
<e1> as rvalue
<e2> as rvalue
ADD
```

Compile ***e** as lvalue:

```
<e> as rvalue
```

**cAccess**

Compile **e** as rvalue:

```
<e> as lvalue
LDI
```

Compile **&e** as rvalue:

```
<e> as lvalue
```

**cExpr**

# Compiling blocks and declarations

- To compile a block **`{ s1 s2 … sn }`**
  - Make new scope in varEnv
  - Compile **`<s1> <s2> … <sn>`**
  - Drop new scope from varEnv
  - Generate code (INCSP (–m)) to forget m locals
- To compile int declaration **`int x`**
  - Generate code to increment stack pointer by 1
- To compile array declaration **`int a[5]`**
  - Generate code to allocate 5 stack places, that is, increment stack pointer by 5
  - Generate code to compute address of the first of those locations, and put it on the stack

# Statement compilation schemes

Compile `if (e) s1 else s2`:

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

Compile `while (e) s`:

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

Compile `e;` :

```
<e> as rvalue
INCSP -1
```

`cStmt`

# Micro-C compiler fragment

```
let rec cStmt stmt varEnv funEnv : instr list =
    match stmt with
    | If(e, stmt1, stmt2) ->
      let labelse = newLabel()
      let labend  = newLabel()
      in cExpr e varEnv funEnv @ [IFZERO labelse]
         @ cStmt stmt1 varEnv funEnv @ [GOTO labend]
         @ [Label labelse] @ cStmt stmt2 varEnv funEnv
         @ [Label labend]
    | While(e, body) ->
      let labbegin = newLabel()
      let labtest  = newLabel()
      in [GOTO labtest; Label labbegin]
         @ cStmt body varEnv funEnv
         @ [Label labtest] @ cExpr e varEnv funEnv
         @ [IFNZRO labbegin]
    | Expr e -> cExpr e varEnv funEnv @ [INCSP -1]
    | ...
```

# Ten-minute exercise

- What code should be generated for a **`do-while`** block:

```
do
  stmt
while (e) ;
```

- What code should be generated for a **`for`** statement:

```
for (e1; e2; e3)
  stmt
```

# Compiling and running Micro-C programs

```
fslex --unicode CLex.fsl
fsyacc --module CPar CPar.fsy
fsi -r FSharp.PowerPack.dll Absyn.fs CPar.fs \
  CLex.fs Parse.fs Machine.fs Comp.fs ParseAndComp.fs

open ParseAndComp;;
compileToFile (fromFile "ex9.c") "ex9.out";;
#q;;

javac Machine.java

java Machine ex9.out 8

java Machinetrace ex9.out 8
```

Build compiler

Compile fac ex.

Compile stack machine

Run it

... with tracing

# The code generated for ex9.c

init

```
 0 LDARGS
 1 CALL 1 L1
 4 STOP
 5 L1:
```

main

```
 5 CSTI 0
 7 GETBP
 8 CSTI 0
10 ADD
11 LDI
12 GETBP
13 CSTI 1
15 ADD
16 CALL 2 L2
19 INCSP -1
21 GETBP
22 CSTI 1
24 ADD
25 LDI
26 PRINTI
27 INCSP -1
29 INCSP -1
21 RET 0
33 L2:
```

fac

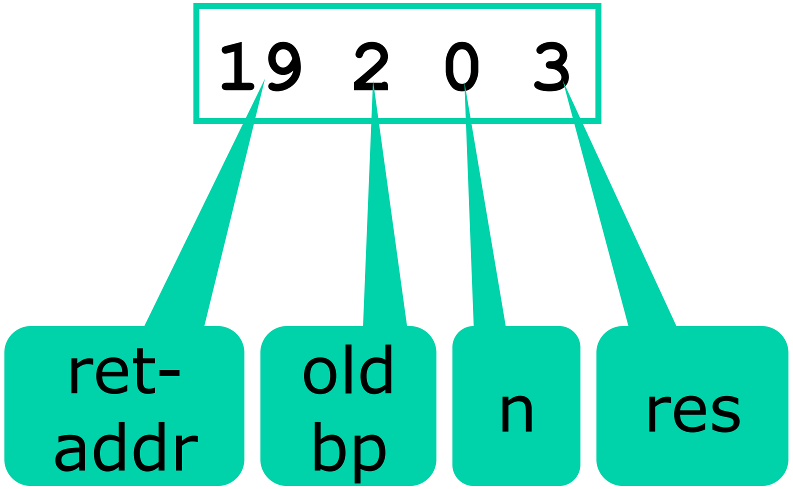
```
33 GETBP
34 CSTI 0
36 ADD
37 LDI
38 CSTI 0
40 EQ
41 IFZERO L3
43 GETBP
44 CSTI 1
46 ADD
47 LDI
48 CSTI 1
50 STI
51 INCSP -1
53 GOTO L4
55 L3:
55 CSTI 0
57 GETBP
58 CSTI 0
60 ADD
61 LDI
62 CSTI 1
64 SUB
65 GETBP
66 CSTI 2
68 ADD
69 CALL 2 L2
72 INCSP -1
74 GETBP
75 CSTI 1
77 ADD
78 LDI
79 GETBP
80 CSTI 2
82 ADD
83 LDI
84 GETBP
85 CSTI 0
87 ADD
88 LDI
89 MUL
90 STI
91 INCSP -1
93 INCSP -1
95 L4:
95 INCSP 0
97 RET 1
```

# The code generated for ex9.c

```
 0 LDARGS
 1 CALL 1 L1
 4 STOP
 5 L1:
 5 CSTI 0
 7 GETBP
 8 CSTI 0
10 ADD
11 LDI
12 GETBP
13 CSTI 1
15 ADD
16 CALL 2 L2
19 INCSP -1
21 GETBP
22 CSTI 1
24 ADD
25 LDI
26 PRINTI
27 INCSP -1
29 INCSP -1
21 RET 0
33 L2:
33 GETBP
34 CSTI 0
36 ADD
37 LDI
38 CSTI 0
40 EQ
41 IFZERO L3
43 GETBP
44 CSTI 1
46 ADD
47 LDI
48 CSTI 1
50 STI
51 INCSP -1
53 GOTO L4
55 L3:
55 CSTI 0
57 GETBP
58 CSTI 0
60 ADD
61 LDI
62 CSTI 1
64 SUB
65 GETBP
66 CSTI 2
68 ADD
69 CALL 2 L2
72 INCSP -1
74 GETBP
75 CSTI 1
77 ADD
78 LDI
79 GETBP
80 CSTI 2
82 ADD
83 LDI
84 GETBP
85 CSTI 0
87 ADD
88 LDI
89 MUL
90 STI
91 INCSP -1
93 INCSP -1
95 L4:
95 INCSP 0
97 RET 1
```

# Running ex9.c on 0: The stack of frames

- Example ex9.c: computing fac(0)
- Stack frame for fac(0):




- What stack frame?

```
4 -999 0 0
```

```
[ ]{0: LDARGS}
[ 0 ]{1: CALL 1 5}
[ 4 -999 0 ]{5: CSTI 0}
[ 4 -999 0 0 ]{7: GETBP}
[ 4 -999 0 0 2 ]{8: CSTI 0}
[ 4 -999 0 0 2 0 ]{10: ADD}
[ 4 -999 0 0 2 ]{11: LDI}
[ 4 -999 0 0 0 ]{12: GETBP}
[ 4 -999 0 0 0 2 ]{13: CSTI 1}
[ 4 -999 0 0 0 2 1 ]{15: ADD}
[ 4 -999 0 0 0 3 ]{16: CALL 2 33}
[ 4 -999 0 0 19 2 0 3 ]{33: GETBP}
[ 4 -999 0 0 19 2 0 3 6 ]{34: CSTI 0}
[ 4 -999 0 0 19 2 0 3 6 0 ]{36: ADD}
[ 4 -999 0 0 19 2 0 3 6 ]{37: LDI}
[ 4 -999 0 0 19 2 0 3 0 ]{38: CSTI 0}
[ 4 -999 0 0 19 2 0 3 0 0 ]{40: EQ}
[ 4 -999 0 0 19 2 0 3 1 ]{41: IFZERO 55}
[ 4 -999 0 0 19 2 0 3 ]{43: GETBP}
[ 4 -999 0 0 19 2 0 3 6 ]{44: CSTI 1}
[ 4 -999 0 0 19 2 0 3 6 1 ]{46: ADD}
[ 4 -999 0 0 19 2 0 3 7 ]{47: LDI}
[ 4 -999 0 0 19 2 0 3 3 ]{48: CSTI 1}
[ 4 -999 0 0 19 2 0 3 3 1 ]{50: STI}
[ 4 -999 0 1 19 2 0 3 1 ]{51: INCSP -1}
[ 4 -999 0 1 19 2 0 3 ]{53: GOTO 95}
[ 4 -999 0 1 19 2 0 3 ]{95: INCSP 0}
[ 4 -999 0 1 19 2 0 3 ]{97: RET 1}
[ 4 -999 0 1 3 ]{19: INCSP -1}
[ 4 -999 0 1 ]{21: GETBP}
[ 4 -999 0 1 2 ]{22: CSTI 1}
[ 4 -999 0 1 2 1 ]{24: ADD}
[ 4 -999 0 1 3 ]{25: LDI}
[ 4 -999 0 1 1 ]{26: PRINTI}
1 [ 4 -999 0 1 1 ]{27: INCSP -1}
[ 4 -999 0 1 ]{29: INCSP -1}
[ 4 -999 0 ]{31: RET 0}
[ 0 ]{4: STOP}
```

# Highlights from computing fac(3)

```
[ ]{0: LDARGS}
[ 3 ]{1: CALL 1 5}
[ 4 -999 3 ]{5: CSTI 0}
[ 4 -999 3 0 ]{7: GETBP}
...
[ 4 -999 3 0 3 3 ]{16: CALL 2 33}
[ 4 -999 3 0 19 2 3 3 ]{33: GETBP}
...
[ 4 -999 3 0 19 2 3 3 0 2 8 ]{69: CALL 2 33}
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 ]{33: GETBP}
...
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 0 1 13 ]{69: CALL 2 33}
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 0 72 11 1 13 ]{33: GETBP}
...
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 0 72 11 1 13 0 0 18 ]{69: CALL 2 33}
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 0 72 11 1 13 0 72 16 0 18 ]{33: GETBP}
...
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 0 72 11 1 13 1 72 16 0 18 ]{97: RET 1}
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 0 72 11 1 13 1 18 ]{72: INCSP -1}
...
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 1 72 11 1 13 ]{97: RET 1}
[ 4 -999 3 0 19 2 3 3 0 72 6 2 8 1 13 ]{72: INCSP -1}
...
[ 4 -999 3 0 19 2 3 3 2 72 6 2 8 ]{97: RET 1}
[ 4 -999 3 0 19 2 3 3 2 8 ]{72: INCSP -1}
...
[ 4 -999 3 6 19 2 3 3 ]{97: RET 1}
...
[ 4 -999 3 6 3 ]{25: LDI}
[ 4 -999 3 6 6 ]{26: PRINTI}
6 [ 4 -999 3 6 6 ]{27: INCSP -1}
[ 4 -999 3 6 ]{29: INCSP -1}
[ 4 -999 3 ]{31: RET 0}
[ 3 ]{4: STOP}
```

ret-addr

old bp

n

res

# Shortcomings of the compiler

- The compiler often generates inefficient code

```
GETBP
CSTI 0
ADD
LDI
```

could be

```
GETBP
LDI
```

```
INCSP -1
INCSP -1
```

could be

```
INCSP -2
```

- The compiler itself is inefficient, using (@) a lot:

```
| If(e, stmt1, stmt2) ->
  let labelse = newLabel()
  let labend  = newLabel()
  in cExpr e varEnv funEnv @ [IFZERO labelse]
     @ cStmt stmt1 varEnv funEnv @ [GOTO labend]
     @ [Label labelse] @ cStmt stmt2 varEnv funEnv
     @ [Label labend]
```

- Tail calls are not executed in constant space
- We fix these problems in course week 10

# Adding a switch-statement to micro-C

- Exercise this week, add switch-statement:
  - each case has an int constant and a block
  - no fall-through, no **break**, no **default**

```
switch (month) {
  case 2:
    { days = 28; if (y%4==0) days = 29; }
  case 3:
    { days = 31; }
  case 1:
    { days = 31; }
}
```

- May be compiled as a sequence of tests
- The abstract syntax may be as simple as this:

```
Switch of expr * (int * stmt) list
```

# Reading and homework

- This week's lecture:
  - PLCSD chapter 8
  - Exercises 8.1, 8.3, 8.4, 8.5, 8.6

- Next week's lecture
  - The Java and C#/.NET virtual machines
  - Garbage collection techniques
  - PLCSD chapter 9 and 10
  - David Bacon: Realtime garbage collection