Compilation and Program Analysis (#8) : Functions: syntax, semantics, code generation

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Big picture

So far :

- All variables were global.
- No function call.

Inspiration : Y. Lakhnesh, UGA (first part), N. Louvet, Lyon1 (archi part), C. Alias (code gen part).

Concrete syntax 1/2

- we add variable declaration (with the `var` keyword) :

```
vardecl
  : VAR ID ASSIGN expr
  ;
```

- blocks are like before :

```
block
  : stat*   #statList
  ;
stat_block
  : OBRACE block CBRACE
  | stat
;
```

- procedures declaration :

```
declproc:
  : PROC ID IS stat
;
```

Concrete syntax 2/2

And now there will two new kinds of statements :

```
stat
  : assignment
  | if_stat
  | while_stat
  | log
  | CALL ID
  | BEGIN declvar* declproc* block_stat END
  ;
```

- We can declare local procedures inside local procedures.

On board : add new concrete syntax for **functions**.

Abstract syntax

WLOG, we will only consider programs with procedures :

$$
\begin{array}{lcl}
S & \in & \textbf{Stm} \\
S & ::= & x := a \mid \text{skip} \mid S_1 ; S_2 \mid \\
 & & \text{if } b \text{ then } S_1 \text{ else } S_2 \\
 & & \text{while } b \text{ do } S \text{ od } \mid \text{begin } D_V\ D_P ; S \text{ end} \mid \text{call } p \\
D_V & ::= & \text{var } x := a ;\ D_V \mid \epsilon \\
D_P & ::= & \text{proc } p \text{ is } S ;\ D_P \mid \epsilon
\end{array}
$$

Operational semantics for local variables

Variable declaration : we invent $\rightarrow_D$ a semantic for declarations, and the following definitions :

- $DV(D_V)$ is the set of variables declared in D_V
- $\sigma'[X \mapsto \sigma] = \lambda x.$ if $x \in X$ then $\sigma(x)$ else $\sigma'(x)$.

Rules :

$$\frac{(D_V, \sigma[x \mapsto \mathcal{A}[a]\sigma]) \rightarrow_D \sigma'}{(\text{var } x := a; D_V, \sigma) \rightarrow_D \sigma'}$$

$$(\varepsilon, \sigma) \rightarrow_D \sigma$$

Rules for blocs + Example

Be careful to restore everything after the local bloc :

$$\frac{(D_V,\sigma) \rightarrow_D \sigma' \qquad (S,\sigma') \rightarrow \sigma"}{(\text{begin } D_V; S \text{ end}, \sigma) \rightarrow_D \sigma"[DV(D_V) \mapsto \sigma]}$$

Seq is unchanged :

$$\frac{(S_1,\sigma) \rightarrow \sigma' \ (S_2,\sigma') \rightarrow \sigma''}{\big((S_1;S_2),\sigma\big) \rightarrow \sigma''}$$

Execute the semantics :

```
begin var y := 1;
      (x := 1;
      begin var x := 2; y := x+1 end;
      x := y+x)
end
```

Dynamic versus Static binding, an example

What will be the behavior of call q ?

begin var $x := 0;$
proc p is $x := x * 2;$
proc q is call p;
begin var $x := 5;$
proc p is $x := x + 1;$
call $q; y := x;$
end;
end

It depends !

Dynamic versus Static binding, ex 3/4

Dynamic binding for variables and static for procedures :

begin var $x := 0;$	begin var $x := 0;$
proc p is $x := x * 2;$	proc p is $x := x * 2;$
proc q is call $p;$	proc q is call $p;$
begin var $x := 5;$	begin var $x := 5;$
proc p is $x := x + 1;$	proc p is $x := x + 1;$
call $p; y := x;$	$x := x + 1; y := x;$
end;	end;
end	end

Dynamic versus Static binding, ex 4/4

Static for variables and procedures :

begin var $x := 0;$
proc p is $x := x * 2;$
proc q is call $p;$
begin var $x := 5;$
proc p is $x := x + 1;$
call $p; y := x;$
end;
end

begin var $x := 0;$
proc p is $x := x * 2;$
proc q is call $p;$
begin var $x := 5;$
proc p is $x := x + 1;$
$x := x * 2; y := x;$
end;
end

Semantics : dynamic links 1/2

How ?

- States : variable $\rightarrow$ int.
- Environment : procedure name $\rightarrow$ Stm.
- Configuration : $(Env_P \times Stm \times State) \cup State$

The dynamic link for procedures is made by calling the *current* value at the call :

$$\frac{(env, env(p), \sigma) \rightarrow \sigma'}{(env, \text{call } p, \sigma) \rightarrow \sigma'}$$

Semantics : dynamic links 2/2

Thus, environments are kept for the sequence :

$$\frac{(env, S_1, \sigma) \rightarrow \sigma' \qquad (env, S_2, \sigma') \rightarrow \sigma"}{(env, (S_1; S_2), \sigma) \rightarrow \sigma'}$$

but they are updated with a local declaration :

$$\frac{(D_V, \sigma) \rightarrow_D \sigma' \quad (\mathtt{upd}(env, D_P), S, \sigma') \rightarrow \sigma"}{(env, \mathtt{begin}\ \ D_V D_P; S\ \ \mathtt{end}\ \ , \sigma) \rightarrow \sigma"[\mathtt{DV}(D_V) \mapsto \sigma]}$$

with

- $\mathtt{upd}(env, \varepsilon) = env$
- $\mathtt{upd}(env, \mathtt{proc}\ \ p\ \ \mathtt{is}\ \ \mathtt{S}; D_P) = \mathtt{upd}(env[p \mapsto S], D_P)$

▶ Ex : test on the example !

Static links for procedures

We need to store an environnement while defining a procedure :

- Environment : procedure name $\rightarrow Stm \times Env_P$
- Configuration : $(Env_P \times Stm \times State) \cup State$

Now update is modified :

- $\texttt{upd}(env, \varepsilon) = env$
- $\texttt{upd}(env, \texttt{proc}\ \ p\ \ \texttt{is}\ \ \texttt{S}; D_P) = \texttt{upd}(env[p \mapsto (S, env)], D_P)$.

begin var $x := 2$;
proc p is $x := 0$;
proc q is begin $x := 1$; (proc p is call p); call p end;
call q
end

Static links for procedures 2/2

Two possibilities for the call, let $env(p) = (S, env')$ in :

$$\frac{(env', S, \sigma) \rightarrow \sigma'}{(env, \texttt{call}\ \ p, \sigma) \rightarrow \sigma'}$$

or

$$\frac{(env'[p \mapsto [(S, env')], S, \sigma) \rightarrow \sigma'}{(env, \texttt{call}\ \ p, \sigma) \rightarrow \sigma'}$$

Static link for variables and procedures 1/3

Config = (env_V, env_P, S, sto) or (env_V, sto) with :

- env_V : $x \mapsto address$ "symbol table".
- env_P : $p \mapsto (env_V, env_P, S)$ to store values during variable/proc declaration
- sto : $address \mapsto \mathbb{Z}$ (old $\sigma(x) = sto(env_V(x))$).
- $new(sto)$ gives a new address.

Static link for variables and procedures 2/3

Variable declaration :

- $(\varepsilon, env_V, sto) \rightarrow_D (env_V, sto)$
- $$\frac{(D_V, env_V[x \mapsto nc], sto[nc \mapsto v]) \rightarrow_D (env'_V, sto')}{((\texttt{var}\ \ x := a; D_V), env_V, sto) \rightarrow_D (env'_V, sto')}$$

  with $v = \mathcal{A}[a](sto \circ env_V)$, $nc = new(sto)$ such that

  $x \rightarrow nc \rightarrow v$

Static link for variables and procedures 3/3

$$(env_V, env_P, x := a, sto) \rightarrow (env_V, sto[nc \mapsto v])$$

with $v = \mathcal{A}[a](sto \circ env_V)$ and $nc = env_V(x)$

$$\frac{(env'_V, env'_P, S, sto) \rightarrow (env'_V, sto')}{(env_V, env_P, \texttt{call}\ \ p, sto) \rightarrow (env_V, sto')}$$

or

$$\frac{(env'_V, env'_P[p \mapsto (env'_V, env'_P, S)], S, sto) \rightarrow (env'_V, sto')}{(env_V, env_P, \texttt{call}\ \ p, sto) \rightarrow (env_V, sto')}$$

where $env_P(p) = (env'_V, env'_P, S)$.

A bit about Typing

Two important remarks :

- Now that variables are local, the typing environnement should also be updated each time we enter a procedure.
- Type checking for functions : construct the type from definitions, check when a call is performed (see the course on typing ML).

Routines

A procedure/routine in assembly is just a piece of code

- its first instruction's address is known and tagged with a label.
- the JSR instruction jumps to this piece of code (routine call).
- at the end of the routine, a RET instruction is executed for the PC to get the address of the instruction after the routine call.

Slides coming from the architecture course, N. Louvet

Routines in LC-3, how ? JSR

When a routine is called, we have to store the address where to come back :

- syntax : JSR label
- action : R7 <- PC ; PC <- PC + SEXT(PCoffset11)
  - -1024$\leqslant$Sext(Offset11)$\leqslant$1023.
  - if adl is the JSR instruction's address, the branching address is :

$$\text{adM} = \text{adI}+1+\text{Sext(PCOffset11)}, \quad \text{with}$$
$$\text{adI} - 1023 \leqslant \text{adM} \leqslant \text{adI} + 1024.$$

Routines in LC-3, how RET

Inside the routine code, the RET instruction enables to come back :

- syntax : RET
- action : PC <- R7

Writing routines

Call to the `sub` routine :

```
 ...
JSR sub     ; R7 <- next line address
...
```

The last instruction of the routine is RET :

```
; sub routine
sub:  ...
      ...
      RET         ; back to main
```

An example - strlen, without routine

```
        .ORIG x3000
        LEA R0,string    ;
        AND R1,R1,0      ;
loop:   LDR R2,R0,0      ;
        BRz end          ;
        ADD R0,R0,1      ;
        ADD R1,R1,1      ;
        BR loop
end:    ST R1,res
        HALT
; Constant chain
string: .STRINGZ "Hello World"
res:    .BLKW #1
        .END
```

String length routine 1/2

`strlen` call (the result will be stored in R0).

```
       .ORIG x3000
; Main program
        LEA R0,string  ; R0 <- @(string)
        JSR strlen      ; routine call
        ST R0,lg1
        HALT

; Data
string: .STRINGZ "Hello World"
lg1:    .BLKW #1
```

String length routine 2/2

```
strlen: AND R1,R1,0     ;
loop:   LDR R2,R0,0     ;
        BRz end         ;
        ADD R0,R0,1     ;
        ADD R1,R1,1     ;
        BR loop
end:    ADD R0,R1,0     ; R0 <- R1
        RET             ; back to main (JMP R7)

        .END            ; END of complete prog
```

Routines in LC-3 : chaining routines

If a routine needs to **call another one** :

- Some temporary registers may have to be stored somewhere
- Its return address (in R7 !) needs also to be stored.

▶ Store in the stack (R6) before, restore after.

Rules of the game

We still have our LC-3 machine with registers :

- general purpose registers R0 to R5.
- a stack pointer (SP), here R6.
- a frame pointer (FP), here R7

Simplification : **no imbricated** function declaration.

- when `call p`, there is a unique `p` code labeled by p :

Key notion : activation record - Vocabulary 1/2

(picture needed)

- Any execution instance of a function is called an **activation**.
- We can represent all the activations of a given program with an **activation tree**.

Key notion : activation record - Vocabulary 2/2

During execution, we need to keep track of alive activations :

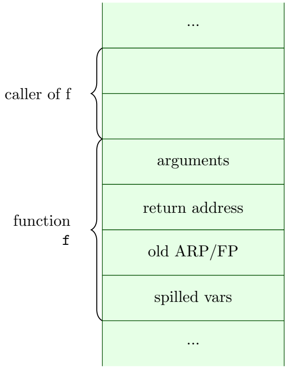
- Control stack
- An activation is pushed when activated
- When its over, it is poped out.

▶ **Notion of activation record** that stores the information of one function call at execution.

▶ **The compiler** is in charge of their management.

Slides inspired by C. Alias

Activation record of a given function



The frame pointer (ARP or FP) points to the current activation record (first spilled variable).

Code generation 1/2

For functions, we have to reserve (local) place before knowing the number of spilled variables !

int f(x1,x2) S ;
return e
	`code.addMacro(PUSH R7)        #store @ret`
	`code.addcopy(R6,R7)           #R7<-R6`
	`code.addCode(SUB R6 R6 xx)    #xx= future nb of spilled vars`
	`code.addCode(LDR tmp1 R7 -2)  #arg1`
	`code.addCode(LDR tmp2 R7 -1)  #arg2 (in rev order)`
	`CodeGenSmt(S)                 #under the context x1->tmp1...`
	`dr<-CodeGen(e)                #same!`
	`code.addcopy(dr,R0)  #convention return val in R0`
	`code.addMacro(RET,2+xx) #desalloc args + spilled vars + retur`

- `CodeGenSmt` must be called with a modified map.

Code generation 2/2

call f(e1,e2)	`Gencodesaveregisters()   #save current values of reg.`
	`dr <- newtmp`
	`dr1=Gencode(e1)`
	`code.addMacro(PUSH dr1)`
	`dr2=Gencode(e2)`
	`code.addMacro(PUSH dr2)`
	`code.add(JSR f)     #return @ in R7`
	`code.addcopy(r0,dr) # dr <- returned value`
	`Gencoderestoreregisters() #restore curr values of reg.`
	`return dr`

A simple example 1/3

Generate code and draw the activation records during the call execution of f :

```
int f(x) {return x+1;}
```

```
main:
z:=f(7);
```

A simple example 2/3

```
main:
PUSH(R0,R1....R5)   #should be replaced by R6 manipulation.
AND tmp1 tmp1 0
ADD tmp1 temp1 7
PUSH(tmp1)
JSR f
AND tmp2 tmp2 0
AND tmp2 R0 0
pop(R5... ,R1,R0) #but not the register associated to temp2
[use of temp2 here]
```

A simple example 3/3

```
f:  PUSH(R7)
    COPY(R6,R7)
    ADD R6 R6 xx        #xx=number of spilled vars
    LDR tmp1 R7 #1      #first argument
    ADD tmp2 tmp1 1
    COPY(tmp2,R0)       #store result in R0
    COPY(R7,R6)         #this is postlude
    ADD R6 R6 xx+1     #1 argument
    POP(R7)
```

Register allocation gives tmp1,tmp2 mapsto R1 (or R0 if we are clever). Thus `xx=0`.

To go further

- How to implement the different calling conventions ? (here, call by value) ?
- How to implement imbricated functions (dynamic link, static link).
- How to store more complex types (arrays, structs, user defined types) ?