Programming Languages and Compiler Design

Generation of Assembly-code

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Outline - Generation of Assembly-code

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Introduction

Machine "M"

Code Generation for Language **While**

Code Generation for Language **Block**

Code Generation for Language **Proc**

Main issues for code generation

- input: (well-typed) source pgm AST (or intermediate code)
- output: machine level code (assembly, relocatable, or absolute code)

Expected properties for the output

- compliance with the target machine
  instruction set, architecture, memory access, OS, ...
- correctness of the generated code
  semantically equivalent to the source pgm
- optimality w.r.t. non-functional criteria
  execution time, memory size, energy comsumption, ...

Main issues for code generation (ctd)

Tasks of the Code Generator

- **Instruction selection**: choosing appropriate target-machine instructions to implement the (IR) statements.
  Complexity depends on:
  - how abstract is the IR,
  - "expressiveness of instruction set" (e.g., support of some types),
  - expected quality of the output code according to some criteria (speed and size).
- **Registers allocation and assignment**: deciding what variables to keep in which registers at every location (when the target machine uses registers).
- **Instruction ordering**: deciding the scheduling order for the execution of instructions.
  - It affects the efficiency of the code and the required registers.
  - It is generally not possible to obtain an optimal (NP-complete) $\Rightarrow$ heuristics

A pragmatic approach

AST

↓

intermediate code generation

↓

Intermediate Representation 1 ⇄ optimization(s)

↓

...

↓

Intermediate Representation n ⇄ optimization(s)

↓

(final) code generation

↓

target machine code

Intermediate Representations

- Abstractions of a real target machine
  - generic code level instruction set
  - simple addressing modes
  - simple memory hierarchy
- Examples
  - a "stack machine"
  - a "register machine"
  - etc.

Remark Other intermediate representations are used in the optimization phases. □

Outline - Generation of Assembly-code

Machine "M"

Machine with Registers

- Unlimited registers, denoted by `Ri`.
- Special registers:
  - program counter `PC`,
  - stack pointer `SP`,
  - frame pointer `FP`,
  - register `R0` (contains always 0).

  (the exact purpose of these registers will become clear later)

Instructions, addresses, and integers take 4 bytes in memory.

Addressing

- Address of variable `x` is `E - offx` where:
  - `E` = address of the environment where `x` is defined
  - `offx` = offset of `x` within this environment
    (staticaly computed, stored in the symbol table)
- Addressing modes:
  `Ri`, `val` (immediate), `Ri +/- Rj`, `Ri +/- offset`

Instruction Set

- Usual arithmetic instructions OPER: ADD, SUB, AND, etc.
- Usual (conditional) branch instructions BRANCH: BA, BEQ ($=$), BGT ($>$), BLT ($<$), BGE ($\geq$), BLE ($\leq$), BNE ($\neq$).

instruction	informal semantics
`OPER Ri, Rj, Rk`	Ri $\leftarrow$ Rj oper Rk
`OPER Ri, Rk, val`	Ri $\leftarrow$ Rj oper val
`CMP Ri, Rj`	Ri - Rj (set cond flags)
`LD Ri, [adr]`	Ri $\leftarrow$ Mem[adr]
`ST Ri, [adr]`	Mem[adr] $\leftarrow$ Ri
`BRANCH label`	if cond then PC $\leftarrow$ `label`
	else PC $\leftarrow$ PC $+$ 4
`CALL label`	branch to the procedure
	labelled with `label`
	`PUSH(PC)` $\|\|$ PC$\leftarrow$ `label`
`CALL R`	branch to the address
	contained in register `R`
	`PUSH(PC)` $\|\|$ PC$\leftarrow$ `R`
`RET`	end of procedure

Language **While**

Reminder

$$
\begin{array}{lll}
p & ::= & d \,;\, s \\
d & ::= & \mathsf{var}\ x \mid d \,;\, d \\
s & ::= & x := a \mid s \,;\, s \mid \mathsf{if}\ b\ \mathsf{then}\ s\ \mathsf{else}\ s \mid \mathsf{while}\ b\ \mathsf{do}\ s\ \mathsf{od} \\
a & ::= & n \mid x \mid a + a \mid a * a \mid \ldots \\
b & ::= & a = a \mid b\ \mathsf{and}\ b \mid \mathsf{not}\ b \mid \ldots
\end{array}
$$

Remark Terms are well-typed.
$\rightarrow$ distinction between boolean and arithmetic expr. $\square$

Language `While`

Reminder

Informal code generation

Give the "Machine M" code for the following statements:

1. `y := x+42 * (3+y)`
2. ```
   if (not x=1) then x := x+1
                else x := x-1 ; y := x ;
   ```
   ```

Outline - Generation of Assembly-code

Functions for code generation

Notation

- Code^*: instruction sequences for machine "M"
- $\|$: concatenation operator for code and sequences of code

$\texttt{GCStm} : \text{Stm} \to \text{Code}^*$

`GCStm(s)` *computes the code* `C` *corresponding to statement* `s`.

$\texttt{GCAExp} : \text{Exp} \to \text{Code}^* \times \texttt{Reg}$

`GCAExp(e)` returns a pair (`C`, `i`) where `C` is the code allowing to

1. computes the value of `e`,
2. stores it in `Ri`.

$\texttt{GCBExp} : \text{BExp} \times \mathcal{L}\text{abel} \times \mathcal{L}\text{abel} \to \text{Code}^*$

`GCBExp(b, ltrue, lfalse)` produces the code `C` that computes the value of `b` and branches to label `ltrue` when this value is "true" and to `lfalse` otherwise.

Auxiliary functions

$$
\begin{array}{rcl}
\texttt{AllocRegister} & : & \rightarrow \texttt{Reg} \\
 & & \text{allocates a new register } \texttt{Ri} \\
 & & \\
\texttt{newLabel} & : & \rightarrow \texttt{Labels} \\
 & & \text{produces a new } \texttt{label} \\
 & & \\
\texttt{GetOffset} & : & \text{Var} \rightarrow \mathbb{Z} \\
 & & \text{returns the offset corresponding to the specified name} \\
 & & \text{which depends on the position} \\
 & & \text{at which the variable is declared} \\
 & & \text{(shall be defined precisely for blocks and procedures)}
\end{array}
$$

Function GCStm

Assignments, sequential and iterative compositions

GCStm (x := e)	=	Let	(C,i)=GCAExp(e),
			k=GetOffset(x)
		in	C‖ ST Ri, [FP + k]
GCStm (s_1 ; s_2)	=	Let	C_1 = GCStm(s_1),
			C_2 = GCStm(s_2)
		in	C_1 ‖ C_2
GCStm (while e do s od)	=	Let	lb=newLabel(),
			ltrue=newLabel(),
			lfalse=newLabel()
		in	lb:‖
			GCBExp(e,ltrue,lfalse)‖
			ltrue:‖
			GCStm(s)‖
			BA lb‖
			lfalse:

Function GCStm (ctd)

Conditional statement

$$
\begin{array}{lcll}
\texttt{GCStm}\,(\texttt{if e then s}_1\ \texttt{else s}_2) & = & \texttt{Let} & \text{lnext}=\texttt{newLabel()}, \\
 & & & \text{ltrue}=\texttt{newLabel()}, \\
 & & & \text{lfalse}=\texttt{newLabel()} \\
 & & \texttt{in} & \texttt{GCBExp}(\text{e},\text{ltrue},\text{lfalse})\| \\
 & & & \text{ltrue:} \\
 & & & \texttt{GCStm}(\text{s}_1)\| \\
 & & & \texttt{BA}\ \text{lnext}\ \| \\
 & & & \text{lfalse:}\| \\
 & & & \texttt{GCStm}(\text{s}_2)\| \\
 & & & \text{lnext:}
\end{array}
$$

Function GCAexp

Arithmetic expressions

GCAExp(x)	=	Let	i=AllocRegister()
			k=GetOffset(x)
		in	((LD Ri, [FP + k]),i)
GCAExp(n)	=	Let	i=AllocRegister()
		in	((ADD R_i, R_0, n),i)
GCAExp(e_1 + e_2)	=	Let	(C_1,i_1)=GCAExp(e_1),
			(C_2,i_2)=GCAExp(e_2),
			k=AllocRegister()
		in	((C_1 ‖ C_2 ‖ ADD Rk, Ri_1, Ri_2),k)

Function GCBexp

Boolean expressions

GCBExp (e_1 = e_2,ltrue,lfalse)	$=$	Let	(C_1, i_1)=GCAExp(e_1),
			(C_2, i_2)=GCAExp(e_2),
		in	$C_1 \| C_2 \|$
			CMP Ri_1, Ri_2
			BEQ ltrue
			BA lfalse
GCBExp (e_1 and e_2,ltrue,lfalse)	$=$	Let	l=newLabel()
		in	GCBExp(e_1,l,lfalse)$\|$
			l:$\|$
			GCBExp(e_2,ltrue,lfalse)
GCBExp(NOT e,ltrue,lfalse)	$=$		GCBExp(e,lfalse,ltrue)

Exercise

Informal code generation

Give the "Machine M" code for the following statements:

1. `x := 10;` while $x > 10$ do $x := x - 1$ od
2.

Adding new statements to **While**

Extend the code generation function

- to consider statements of the form repeat S until b,
- to consider Boolean expressions of the form `b1 xor b2`,
- to consider arithmetical expressions of the form `b ? e1 : e2`.

Outline - Generation of Assembly-code

Blocks

Syntax

$$\begin{array}{rcl} S & ::= & \cdots \mid \textbf{begin}\ D_V\ ;\ S\ \textbf{end} \\ D_V & ::= & \textbf{var}\ x \mid D_V\ ;\ D_V \end{array}$$

Remark Variables are not initialized and assumed to be of type **Int**. □

Problems raised for code generation

→ to preserve scoping rules:

- local variables should be *visible* inside the block,
- their *lifetime* should be limited to block execution.

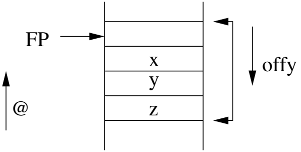
Possible locations to store local variables

→ registers vs memory

Storing local variables in memory - Example 1

Access to local variables within a block

```
begin
   var x ; var y ; var z ;
   ...
end
```



- A *memory environment* is associated to each declaration in D_V.
- Register `FP` contains the address of the current environment.
- (Static) offsets are associated to each local variables.

Definition (Offset of a local variable)

The offset of a local variable is $-4 \times i$, where i is the position of the variable in the sequence of local declarations.

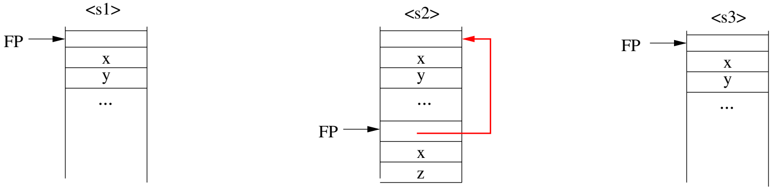
Example (Offset of a local variable)

For `var x ; var y ; var z ;`: `GetOffset(x)` = -4, `GetOffset(y)` = -8, `GetOffset(z)` = -12.

Storing local variables in memory - Example 2

Access to local variables in case of nested blocks

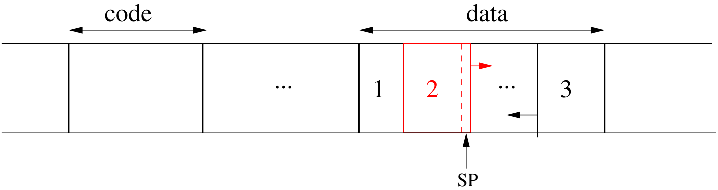
```
begin
   var x ; var y ; <s1>
   begin
      var x ; var z ; <s2>
   end ;
   <s3>
end
```



- entering/leaving a block → allocate/de-allocate a mem. env.
- nested block env. have to be linked together: "Ariane link"

⇒ a stack of memory environments . . . (∼ operational semantics)

Structure of the memory



1: global variables

2: execution stack, `SP` = last occupied address

3: heap (for dynamic allocation)

Code generation for variable declarations

$\texttt{SizeDecl} : D_V \to \mathbb{N}$

`SizeDecl(d)` *computes the size of declarations* `d`

$\texttt{SizeDecl}\ (\texttt{var x})$	$=$	$4 \quad (\texttt{x}\ \text{of type}\ \texttt{Int})$	
$\texttt{SizeDecl}\ (\texttt{d}_1\ ;\ \texttt{d}_2)$	$=$	$\texttt{Let}$	$\texttt{v}_1 = \texttt{SizeDecl}(\texttt{d}_1)$,
			$\texttt{v}_2 = \texttt{SizeDecl}(\texttt{d}_2)$
		$\texttt{in}$	$\texttt{v}_1 + \texttt{v}_2$

Code generation for blocks

$$
\begin{array}{lcll}
\texttt{GCStm (begin d ; s ; end)} & = & \texttt{Let} & \text{size} = \texttt{SizeDecl(d)}, \\
 & & & \text{C} = \texttt{GCStm(s)} \\
 & & \texttt{in} & \texttt{ADD}\text{, SP, SP, -4} \parallel \\
 & & & \texttt{ST}\text{ FP, [SP]} \parallel \\
 & & & \texttt{ADD}\text{ FP, SP, 0} \parallel \\
 & & & \texttt{ADD}\text{ SP, SP, -size} \parallel \\
 & & & \text{C} \parallel \\
 & & & \texttt{ADD}\text{ SP, FP, 0} \parallel \\
 & & & \texttt{LD}\text{ FP, [SP]} \parallel \\
 & & & \texttt{ADD}\text{ SP, SP, 4} \parallel
\end{array}
$$

With the help of some auxiliary functions . . .

prologue(size)	epilogue	push register (Ri)

ADD SP, SP, -4
ST FP, [SP]
ADD FP, SP, 0
ADD SP, SP, -size
	ADD SP, FP, 0
	LD FP, [SP]
	ADD SP, SP, +4
		ADD SP, SP, -4
		ST Ri, [SP]

GCStm (begin d ; s ; end)	=	Let	size =SizeDecl(d), C=GCStm(s)
		in	Prologue(size) $\|$ C $\|$ Epilogue

Access to variables from a block ?

```
...
begin
   var ...
   x := ...
end
```

What is the memory address of x ?

- if x is a local variable (w.r.t the current block)
  $\Rightarrow$ adr(x) $=$ FP $+$ GetOffset(x)
- if x is a non local variable
  $\Rightarrow$ it is defined in a "nesting" memory env. E
  $\Rightarrow$ adr(x) $=$ adr(E) $+$ GetOffset(x)
  adr(E) can be accessed through the "Ariane link" ...

Access to *non local* variables

The number n of indirections to perform on the "Ariane link" depends on the "distance" between:

- the nesting level of the current block : p
- the nesting level of the target environment : r

More precisely:

- $r \leq p$
- $n = p - r$

$\Rightarrow$ n can be statically computed ...

Example

```
begin
   var x ; /* env. E1, nesting level = 1 */
   begin
     var y ; /* env. E2, nesting level = 2 */
     begin
        var z ; /* env. E3, nesting level = 3 */
        x := y + z /* s, nesting level = 3 */
     end
   end
end
```

From statement s:

- no indirection to access to z
- 1 indirection to access to y
- 2 indirections to access to x

Code generation for variable access

1. the nesting level r of each identifier `x` is computed during type-checking;
2. it is associated to each occurrence of `x` in the AST (via the symbol table)
3. function GCStm keeps track of the current nesting level p (incremented/decremented at each block entry/exit)

adr(`x`) is obtained by executing the following code:

- if $r = p$:

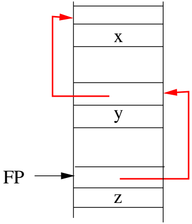
$$\mathtt{FP} + \mathrm{GetOffset}(\mathtt{x})$$

- if $r < p$:

```
LD Ri, [FP]
LD Ri, [Ri]}   (p - r - 1) times
Ri + GetOffset(x)
```

Example (ctn'd)

```
begin
   var x ; /* env. E1, nesting level = 1 */
   begin
     var y ; /* env. E2, nesting level = 2 */
     begin
        var z ; /* env. E3, nesting level = 3 */
        x := y + z /* s, nesting level = 3 */
     end
   end
end
```




```
LD  R1, [FP]         ! R1 = adr(E2)
LD R2,  [R1 + offy]      ! R2 = y
LD R3,  [FP + offz]      ! R3 = z
ADD R4, R2, R3       ! R4 = y+z
LD  R5, [FP]
LD  R5, [R5]         ! R5 = adr(E1)
ST R4,  [R5 + offx]      ! x = y + z
```

Code generated for statement s

Outline - Generation of Assembly-code

Syntax of Language **Proc**

Reminder

Procedure declarations:

$$\begin{array}{rcl} D_P & ::= & \textbf{proc}\ p\ (FP_L)\ \textbf{is}\ S\ ;\ D_P \mid \epsilon \\ FP_L & ::= & \mathbf{x},\ FP_L \mid \epsilon \end{array}$$

Statements:

$$\begin{array}{rcl} S & ::= & \cdots \mid \textbf{begin}\ D_V\ ; D_P\ ;\ S\ \textbf{end} \mid \textbf{call}\ p(EP_L) \\ EP_L & ::= & AExp,\ EP_L \mid \epsilon \end{array}$$

FP_L: list of formal parameters; EP_L: list of effective parameters

Remark We assume value-passing of integer parameters. □

Example

```
var z ;

proc p1 () is
    begin
      proc p2(x, y) is z := x + y ;
      z := 0 ;
      call p2(z+1, 3) ;
    end

proc p3 (x) is
    begin
       var z ;
       call p1() ; z := z+x ;
    end

call p3(42) ;
```

Main issues for code generation with procedures

Procedure `P` is calling procedure `Q` ...

Before the call:

- set up the memory environment of `Q`
- evaluate and "transmit" the effective parameters
- switch to the memory environment of `Q`
- branch to first intruction of `Q`

During the call:

- access to local/non local procedures and variables
- access to parameter values

After the call:

- switch back to the memory environment of `P`
- resume execution to the instruction of `P` following the call

Access to non-local variables

```
proc main is
begin                /* definition env. of p */
   var x ;
   proc p() is x:=3 ;
   proc q() is
     begin
         var x ;
         proc r() is call p() ;
         call r() ;
     end ;
   call q() ;
end
```

Static binding $\Rightarrow$ when p is executed:

- access to the memory env. of `main` =
  definition environment of the callee, static link
- access to the memory env. of `r`
  memory environment of the caller, dynamic link

Information exchanged between *callers* and *callees*?

- parameter values
- return address
- address of the caller memory environment (dynamic link)
- address of the callee environment definition (static link)

This information should be stored in a memory zone:

- dynamically allocated
  (exact number of procedure calls cannot be foreseen at compile time)
- accessible from both parties
  (those addresses should be computable by the caller and the callee)

$\Rightarrow$

inside the execution stack, at well defined offsets w.r.t `FP`

A possible "protocol" between the two parties

Before the call, the caller:

- evaluates the effective parameters
- pushes their values
- pushes the static link of the callee
- pushes the return address, and branch to the callee's 1st instruction

When it begins, the callee:

- pushes `FP` (dynamic link)
- assigns `SP` to `FP` (memory env. address)
- allocates its local variables on the stack

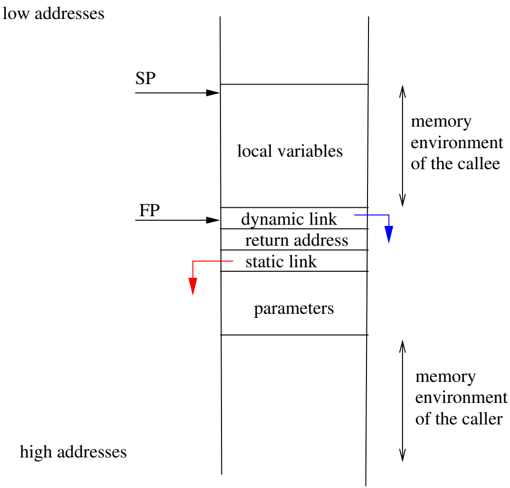
When it ends, the callee:

- de-allocates its local variables
- restores `FP` to caller's memory env. (dynamic link)
- branch to the return address, and pops it from the stack

After the call, the caller

- de-allocates the static link and parameters

Organization of the execution stack



Addresses, from the callee:

loc. variables: FP+d, d<0

dynamic link: FP

return address: FP+4

static link: FP+8

parameters: FP+d, d>=12

Memory environment of the callee

...	0
Loc. var_n	←SP, FP- 4*n
...	
Loc. var_1	←FP-4
Dynamic link	←FP
Return address	←FP+4
Static link	←FP+8
$Param_n$	←FP+12
...	
$Param_1$	←FP+8+4*n

Definition (Offset of a variable or a parameter)

- For local variable $\texttt{var}_i$, as before, $\texttt{GetOffset}(\texttt{var}_i)$ is $-4 \times i$.
- For parameter $\texttt{param}_\texttt{i}$, $\texttt{GetOffset}(\texttt{param}_i)$ is $8 + 4 \times (n + 1 - i)$.

Code generation for a procedure declaration

GCProc : $D_P \rightarrow$ Code*

`GCStm(dp)` *computes the code* `C` *corresponding to procedure declaration* `dp`.

```
GCProc (proc p (FP_L) is s end ) = Let
                                       C=GCStm(s)
                                   in  Prologue(0) ||
                                       C ||
                                       Epilogue
```

```
GCProc (proc p (FP_L) is begin dv ; dp ; s end )
=
 Let  size =SizeDecl(dv),
      C=GCStm(s)
 in   Prologue(size) ||
      C ||
      Epilogue
```

Remark `GCProc` is applied to each procedure declaration.

Code generation for a procedure declaration (ctd)

Prologue & Epilogue

Prologue (size):

```
push (FP)              ! dynamic link
ADD FP, SP, 0          ! FP := SP
ADD SP, SP, -size      ! loc. variables allocation
```

Epilogue:

```
ADD SP, FP, 0          ! SP := FP, loc. var. de-allocation
LD FP, [SP]            ! restore FP
ADD SP, SP, +4         ! erase previous backup of FP
RET                    ! return to caller
```

RET:

```
LD PC, [SP]  //  ADD SP, SP, +4
```

Code generation for a procedure call

Four steps:

1. evaluate and push each effective parameter
2. push the static link of the callee
3. push the return address and branch to the callee
4. de-allocate the parameter zone

`GCStm` (**call** p (ep))	=	`Let`	(C, size) = `GCParam`(ep)
		`in`	
			C ‖
			Push (StaticLink(p)) ‖
			`CALL p` ‖
			`ADD SP, SP,` size+4

`CALL p`:

`ADD R1, PC, +4` // Push (`R1`) // `BA p`

Parameters evaluation

$\texttt{GCParam} : EP_L \rightarrow \text{Code}^* \times \mathbb{N}$

`GCStm(ep)=(c,n)` *where* `c` *is the code to evaluate and "push" each effective parameter of* `ep` *and* `n` *is the size of pushed data.*

$\texttt{GCParam}\ (\varepsilon)$	$=$	$(\varepsilon,\ 0)$	
$\texttt{GCParam}\ (\texttt{a ; ep})$	$=$	$\texttt{Let}$	
			$(\text{Ca, i}) = \texttt{GCAexp}\ (\text{a}),$
			$(\text{C, size}) = \texttt{GCParam}\ (\text{ep})$
		$\texttt{in}$	
			$(\text{Ca} \parallel \text{Push}\ (R_i) \parallel \text{C},\ 4 + \text{size})$

Static link and non-local variable access?

Principle

- A global (unique) name is given to each identifier:

```
proc Main is
   proc P1 (...) is
     ...
         proc Pn (...) is
          begin
             var x ...
          end
```

$\rightarrow$ x is named $Main.P_1.\cdots.P_n.x$

- This notation induces a partial order:

$$(Main{\cdot}P_1\cdots P_n \leq Main{\cdot}P'_1\cdots P'_{n'}) \Leftrightarrow (n \leq n' \text{ and } \forall k \leq n{\cdot}P_k = P'_k)$$

- For an identifier $x = Main \cdot P_1 \cdots P_n \cdot x$,
  $x^\bullet = Main.P_1 \cdots P_n$ is the definition environment of x
- For any identifier x (variable or procedure), procedure P can access x iff $x^\bullet \leq P$.

Static link and non-local variable access?

Examples

- A variable x declared in P can be accessed from P since $x^\bullet = P$ (hence $x^\bullet \leq P$).
- If g and x are declared in f, then x can be accessed from g since $x^\bullet = f$ and $f \leq g$.
- If x and f_1 are declared in $Main$, f_2 is declared in f_1, then x can be accessed from f_2 since $x^\bullet = Main$, $f_2 = Main.f_1.f_2$ ($x^\bullet \leq f_2$)
- If p_1 and p_2 are both declared in $Main$, x is declared in p_1, then x cannot be accessed from p_2, since $x^\bullet = Main.p_1$ and $Main.p_1 \not\leq Main.p_2$

Code Generation for accessing (non-) local identifiers

Let us consider:

- d_x: offset of x (variables or parameters) in its definition environment ($x^\bullet$);
- P: current procedure.

Condition	x = variable or parameter	x = procedure
$x^\bullet = P$	adr(x) = FP+d_x	SL(x) = FP
$x^\bullet < P$ $x = M.P_1 \cdots P_k$ $P = M.P_1 \cdots P_k \cdots P_n$	n-k-1 indirections `LD R,[FP+8]` `LD R,[R+8]` $\} \times (n-k-1)$ adr(x) = R+d_x	n-k-1 indirections `LD R,[FP+8]` `LD R,[R+8]` $\} \times (n-k-1)$ SL(x)=R

Back to the first example

```
var z ;
proc p1 () is
    begin
      proc p2(x, y) is z := x + y ;
      z := 0 ;
      call p2(z+1, 3) ;
    end
proc p3 (x) is
    begin
       var z ;
       call p1() ; z := z+x ;
    end
call p3(42) ;
```

Exercise

- Give the execution stack when `p2` is executed.
- Give the code for procedures `p1` and `p2`.