Accessing Global Variables

- The bindings of global variables of an expression or a function are kept in a vector in the heap (Global Vector).
- They are addressed consecutively starting with 0.
- When an F-object or a C-object are constructed, the Global Vector for the function or the expression is determined and a reference to it is stored in the gp-component of the object.
- During the evaluation of an expression, the (new) register GP (Global Pointer) points to the actual Global Vector.
- In constrast, local variables should be administered on the stack ...

$\Longrightarrow$ General form of the address environment:

$$\rho : Vars \to \{L, G\} \times \mathbb{Z}$$

Accessing Local Variables

Local variables are administered on the stack, in stack frames.

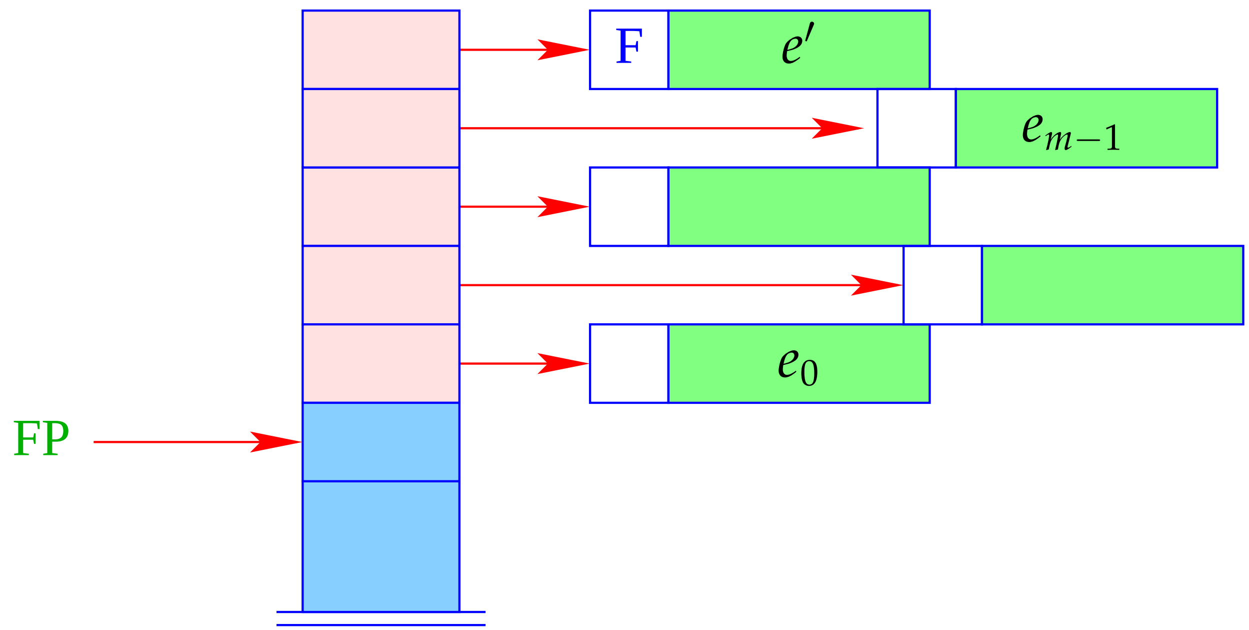
Let $e \equiv e' \; e_0 \; \ldots \; e_{m-1}$ be the application of a function e' to arguments $e_0, \ldots, e_{m-1}$.

Warning:

The arity of e' does not need to be m :-)

- f may therefore receive less than n arguments (under supply);
- f may also receive more than n arguments, if t is a functional type (over supply).

Possible stack organisations:

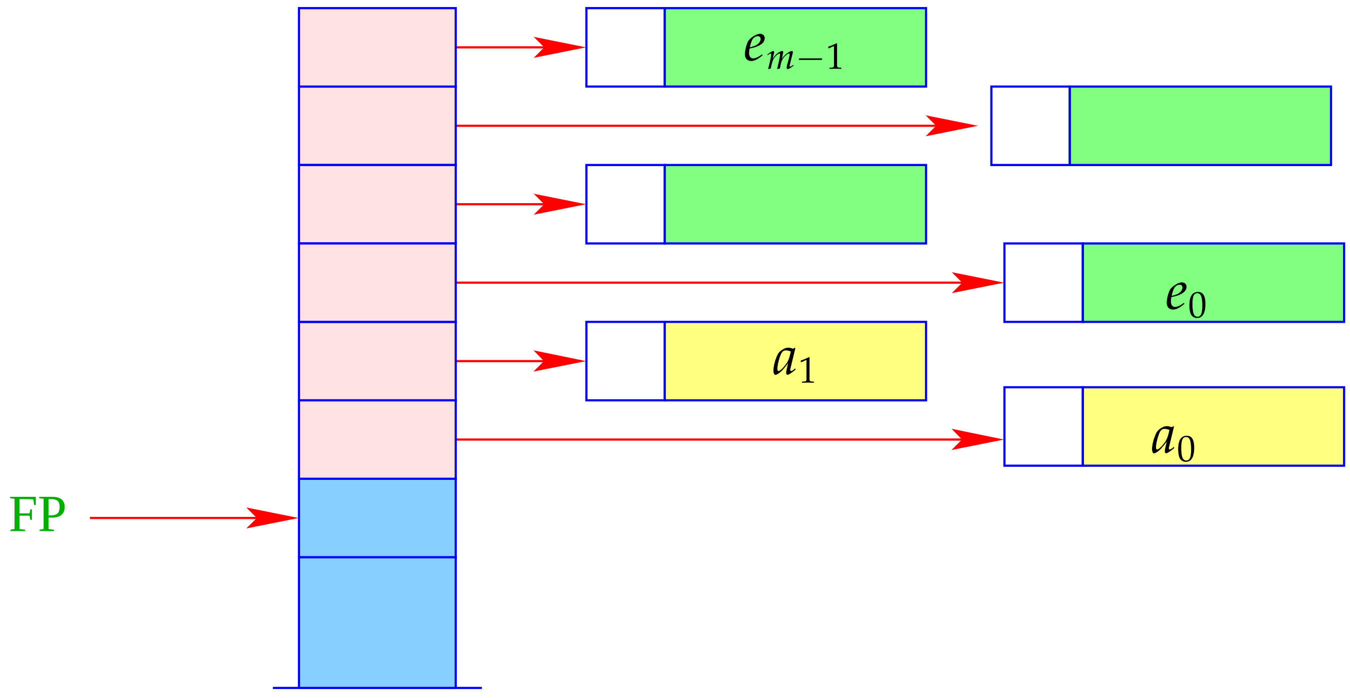


$+$ Addressing of the arguments can be done relative to FP

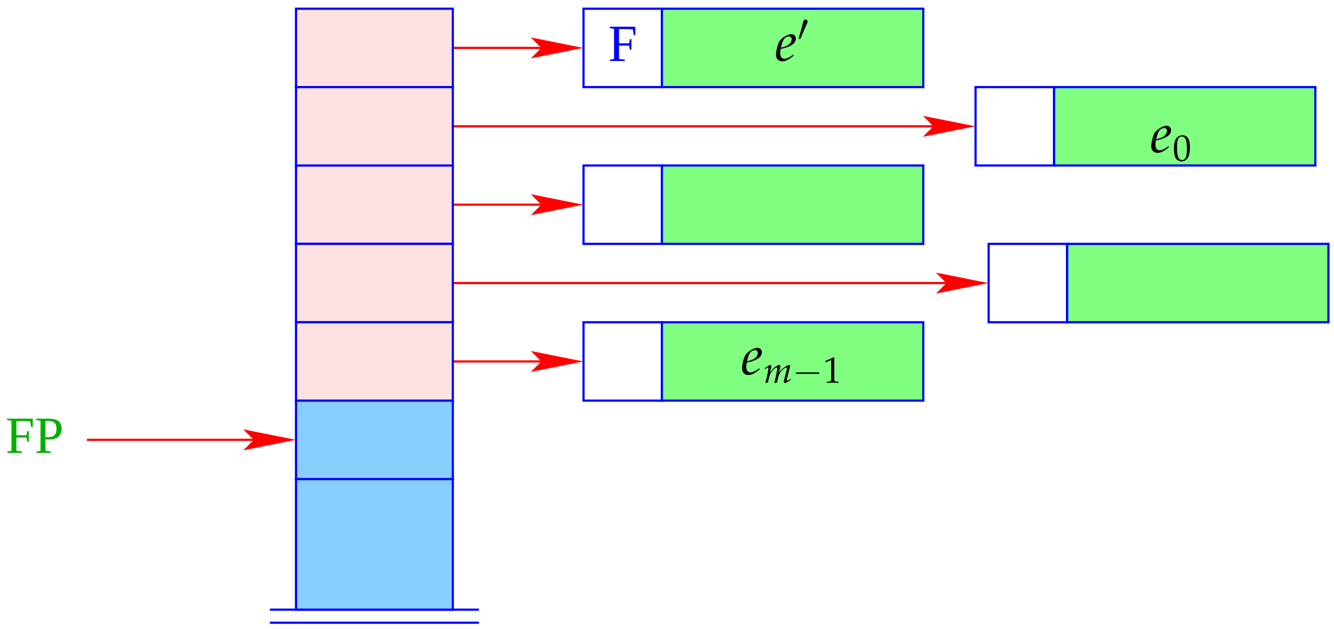
$-$ The local variables of e' cannot be addressed relative to FP.

$-$ If e' is an n-ary function with $n < m$, i.e., we have an over-supplied function application, the remaining $m - n$ arguments will have to be shifted.

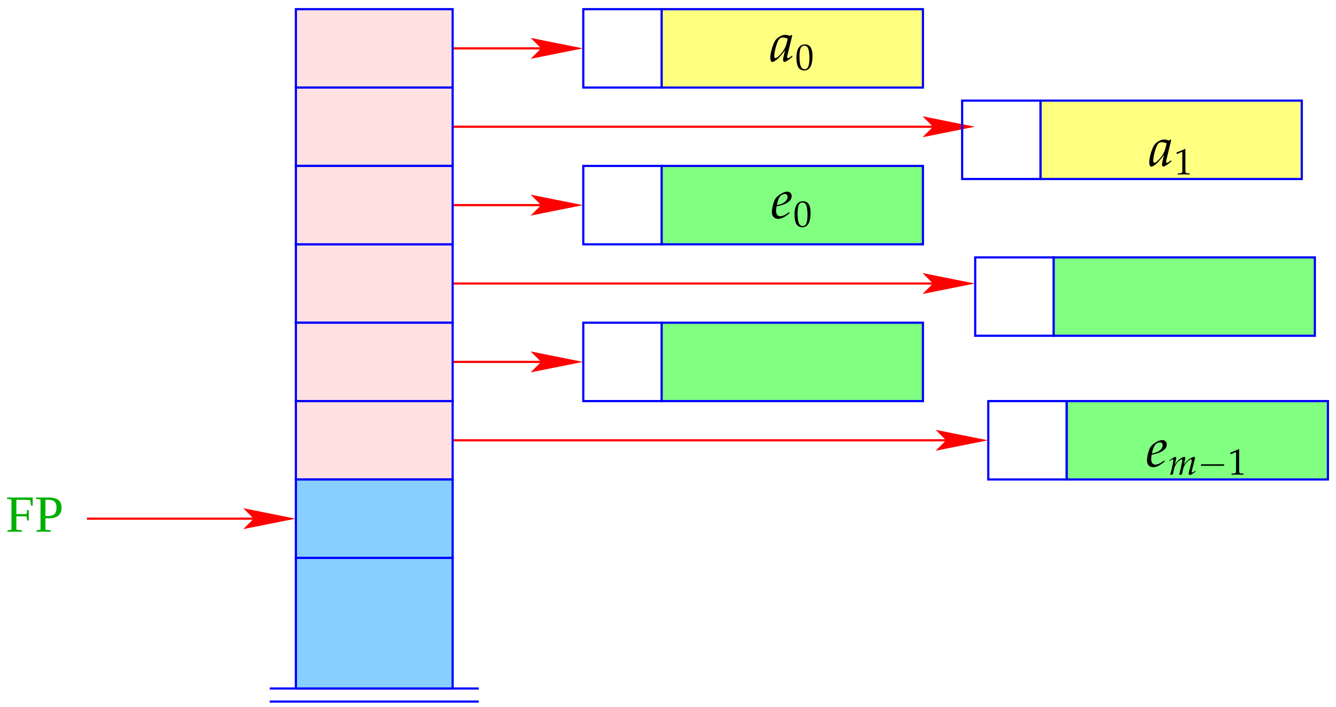
– If e' evaluates to a function, which has already been partially applied to the parameters $a_0, \ldots, a_{k-1}$, these have to be sneaked in underneath e_0:



Alternative:



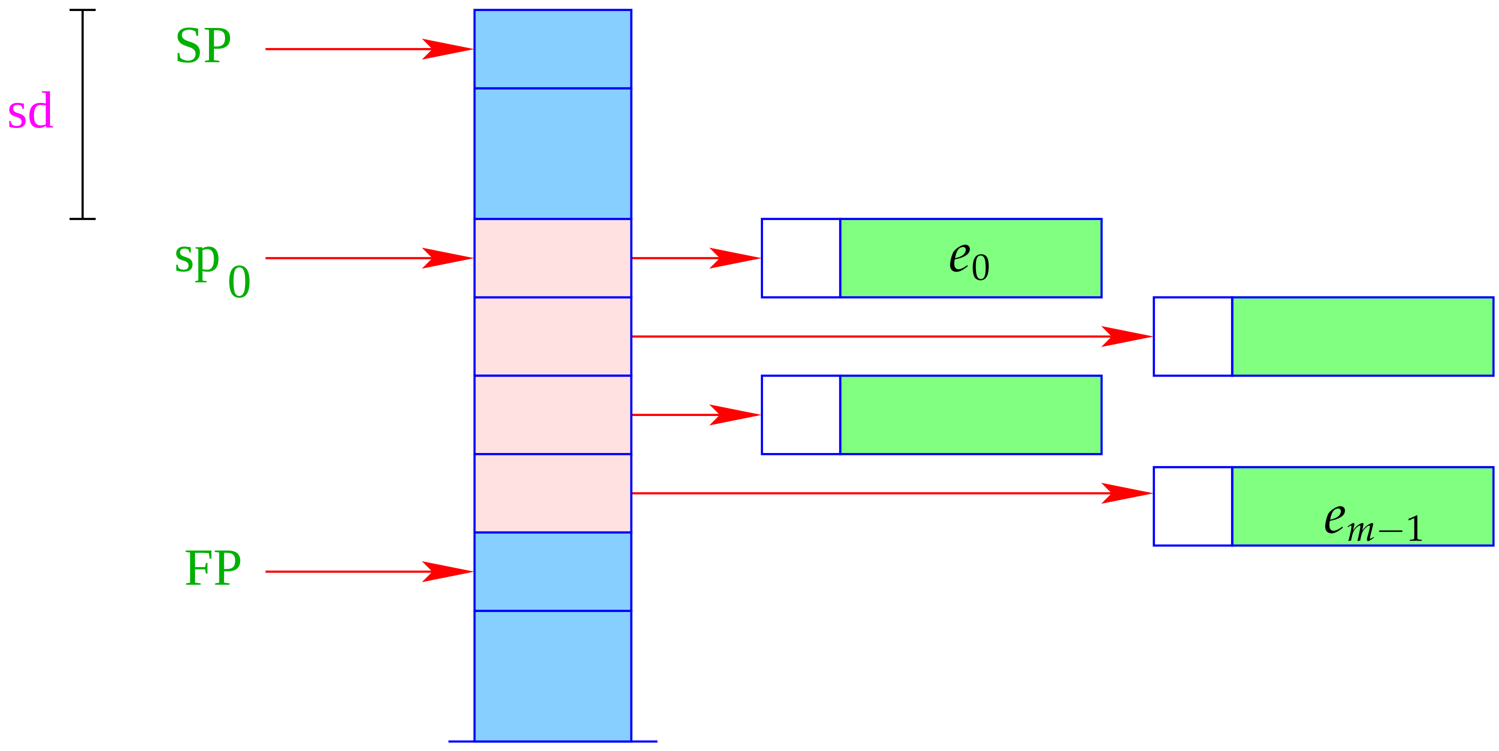
+ The further arguments $a_0, \ldots, a_{k-1}$ and the local variables can be allocated above the arguments.



– Addressing of arguments and local variables relative to FP is no more possible. (Remember: m is unknown when the function definition is translated.)

Way out:

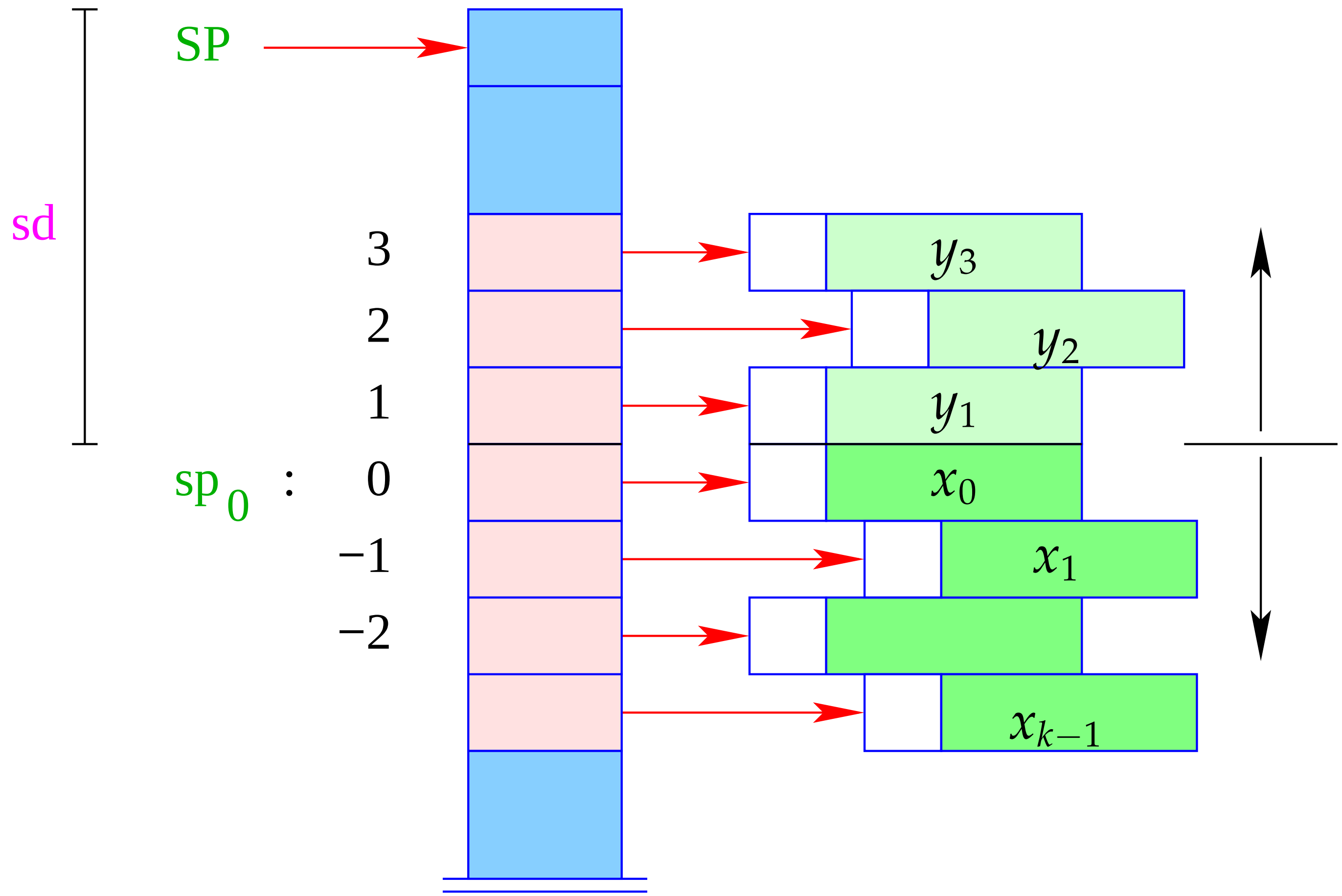
- We address both, arguments and local variables, relative to the stack pointer SP !!!
- However, the stack pointer changes during program execution...



- The differerence between the current value of SP and its value sp_0 at the entry of the function body is called the stack distance, sd.
- Fortunately, this stack distance can be determined at compile time for each program point, by simulating the movement of the SP.
- The formal parameters $x_0, x_1, x_2, \ldots$ successively receive the non-positive relative addresses $0, -1, -2, \ldots$, i.e., $\rho\, x_i = (L, -i)$.
- The absolute address of the i-th formal parameter consequently is

$$sp_0 - i = (SP - sd) - i$$

- The local **let**-variables $y_1, y_2, y_3, \ldots$ will be successively pushed onto the stack:



- The y_i have positive relative addresses $1, 2, 3, \ldots$, that is: $\rho\, y_i = (L, i)$.
- The absolute address of y_i is then $sp_0 + i = (SP - sd) + i$

With CBN, we generate for the access to a variable:

$$\begin{array}{lll} \text{code}_V\ x\ \rho\ \text{sd} & = & \text{getvar}\ x\ \rho\ \text{sd} \\ & & \text{eval} \end{array}$$

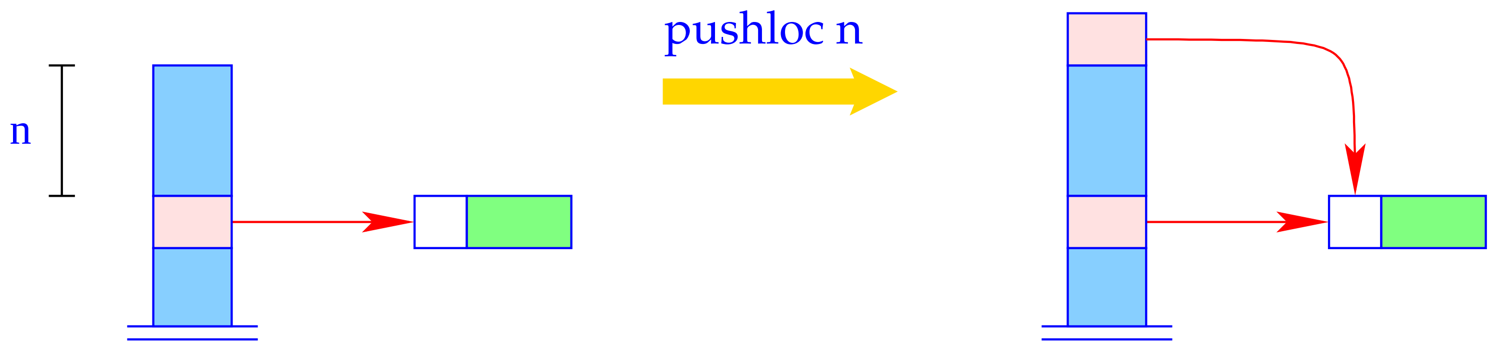
The instruction eval checks, whether the value has already been computed or whether its evaluation has to yet to be done ($\Longrightarrow$ will be treated later :-)

With CBV, we can just delete eval from the above code schema.

The (compile-time) macro getvar is defined by:

$$\begin{array}{lll} \text{getvar}\ x\ \rho\ \text{sd} & = & \textbf{let}\ (t,i) = \rho\ x\ \textbf{in} \\ & & \textbf{match}\ t\ \textbf{with} \\ & & \quad L \to \text{pushloc}\ (\text{sd} - i) \\ & & \ \mid G \to \text{pushglob i} \\ & & \textbf{end} \end{array}$$

The access to local variables:



S[SP+1] =S[SP - n]; SP++;

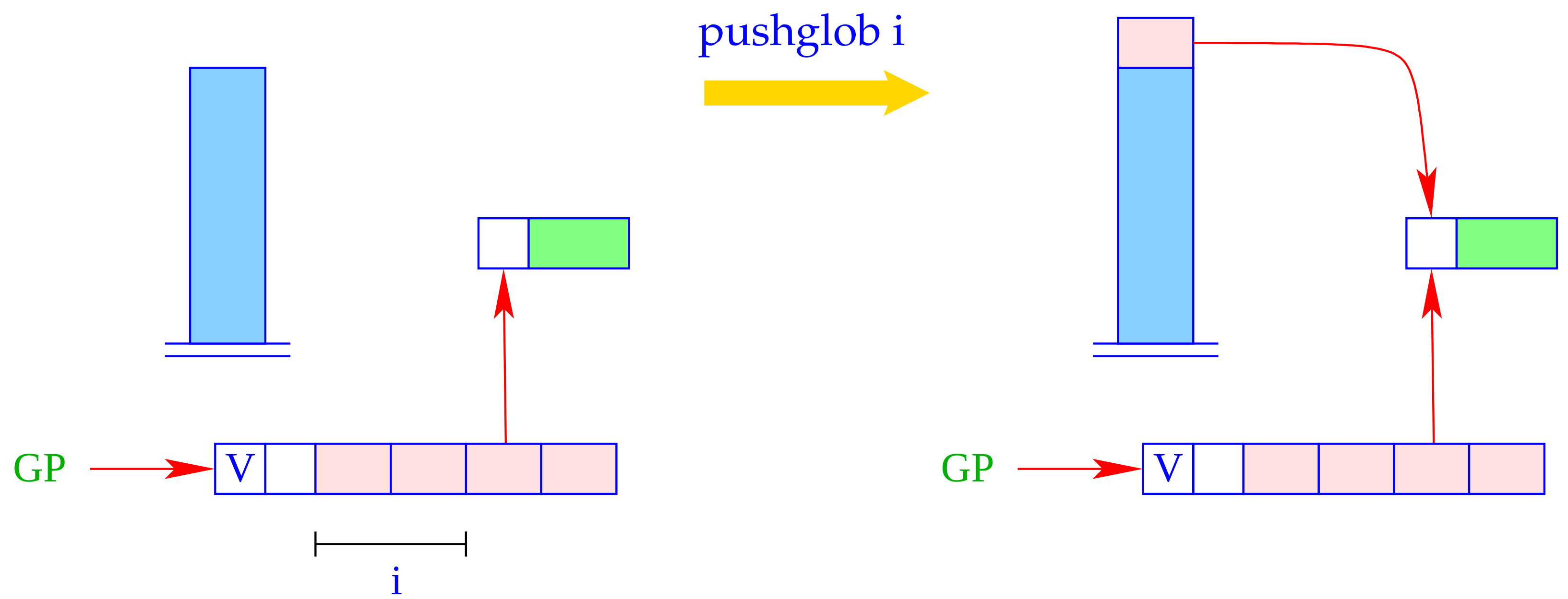
Correctness argument:

Let sp and sd be the values of the stack pointer resp. stack distance before the execution of the instruction. The value of the local variable with address i is loaded from $S[a]$ with

$$a = \text{sp} - (\text{sd} - i) = (\text{sp} - \text{sd}) + i = \text{sp}_0 + i$$

... exactly as it should be :-)

The access to global variables is much simpler:



$SP = SP + 1;$
$S[SP] = GP \to v[i];$

Example:

Regard $e \equiv (b + c)$ for $\rho = \{b \mapsto (L, 1), c \mapsto (G, 0)\}$ and sd $= 1$.

With CBN, we obtain:

$\text{code}_V\ e\ \rho\ 1$	$=$	getvar $b\ \rho\ 1$	$=$	1	pushloc 0
		eval		2	eval
		getbasic		2	getbasic
		getvar $c\ \rho\ 2$		2	pushglob 0
		eval		3	eval
		getbasic		3	getbasic
		add		3	add
		mkbasic		2	mkbasic

15 let-Expressions

As a warm-up let us first consider the treatment of local variables :-)

Let $e \equiv \textbf{let } y_1 = e_1 \textbf{ in} \ldots \textbf{let } e_n \textbf{ in } e_0$ be a nested **let**-expression.

The translation of e must deliver an instruction sequence that

- allocates local variables $y_1, \ldots, y_n$;
- in the case of
  CBV: evaluates $e_1, \ldots, e_n$ and binds the y_i to their values;
  CBN: constructs closures for the $e_1, \ldots, e_n$ and binds the y_i to them;
- evaluates the expression e_0 and returns its value.

Here, we consider the non-recursive case only, i.e. where y_j only depends on $y_1, \ldots, y_{j-1}$. We obtain for CBN:

$$
\begin{array}{rcl}
\mathrm{code}_V\; e\; \rho\; \mathrm{sd} & = & \mathrm{code}_C\; e_1\; \rho\; \mathrm{sd} \\
& & \mathrm{code}_C\; e_2\; \rho_1\; (\mathrm{sd}+1) \\
& & \ldots \\
& & \mathrm{code}_C\; e_n\; \rho_{n-1}\; (\mathrm{sd}+n-1) \\
& & \mathrm{code}_V\; e_0\; \rho_n\; (\mathrm{sd}+n) \\
& & \mathrm{slide}\; \mathrm{n} \qquad\qquad // \text{ deallocates local variables}
\end{array}
$$

where $\rho_j = \rho \oplus \{y_i \mapsto (L, \mathrm{sd}+i) \mid i = 1, \ldots, j\}$.

In the case of CBV, we use code_V for the expressions $e_1, \ldots, e_n$.

Warning!

All the e_i must be associated with the same binding for the global variables!

Example:

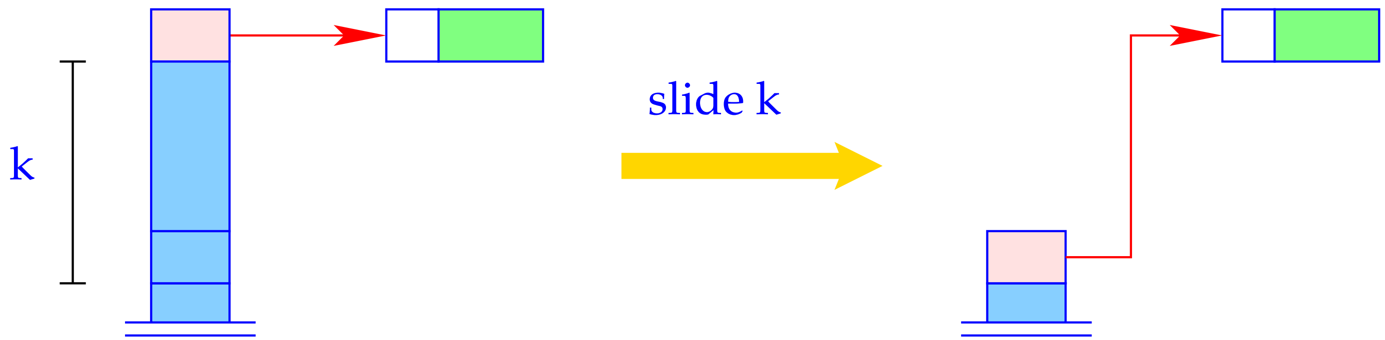
Consider the expression

$$e \equiv \textbf{let } a = 19 \textbf{ in let } b = a * a \textbf{ in } a + b$$

for $\rho = \emptyset$ and sd $= 0$. We obtain (for CBV):

0	loadc 19	3	getbasic	3	pushloc 1
1	mkbasic	3	mul	4	getbasic
1	pushloc 0	2	mkbasic	4	add
2	getbasic	2	pushloc 1	3	mkbasic
2	pushloc 1	3	getbasic	3	slide 2

The instruction slide k deallocates again the space for the locals:



S[SP-k] = S[SP];
SP = SP - k;

16 Function Definitions

The definition of a function f requires code that allocates a functional value for f in the heap. This happens in the following steps:

- Creation of a Global Vector with the binding of the free variables;
- Creation of an (initially empty) argument vector;
- Creation of an F-Object, containing references to theses vectors and the start address of the code for the body;

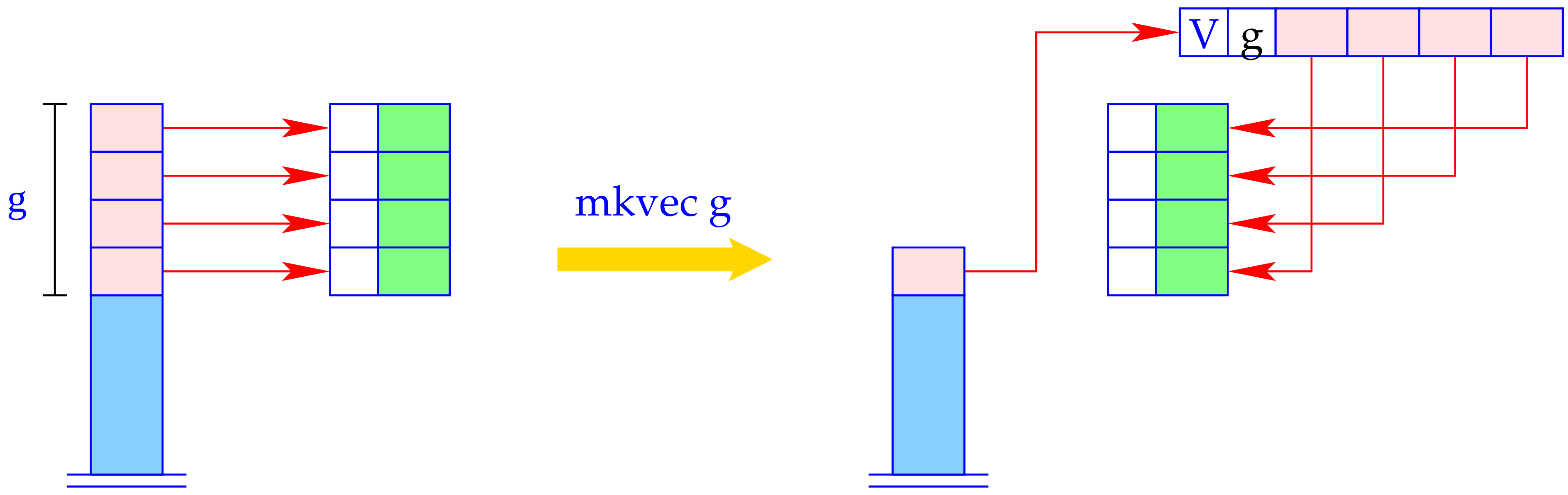
Separately, code for the body has to be generated.

Thus:

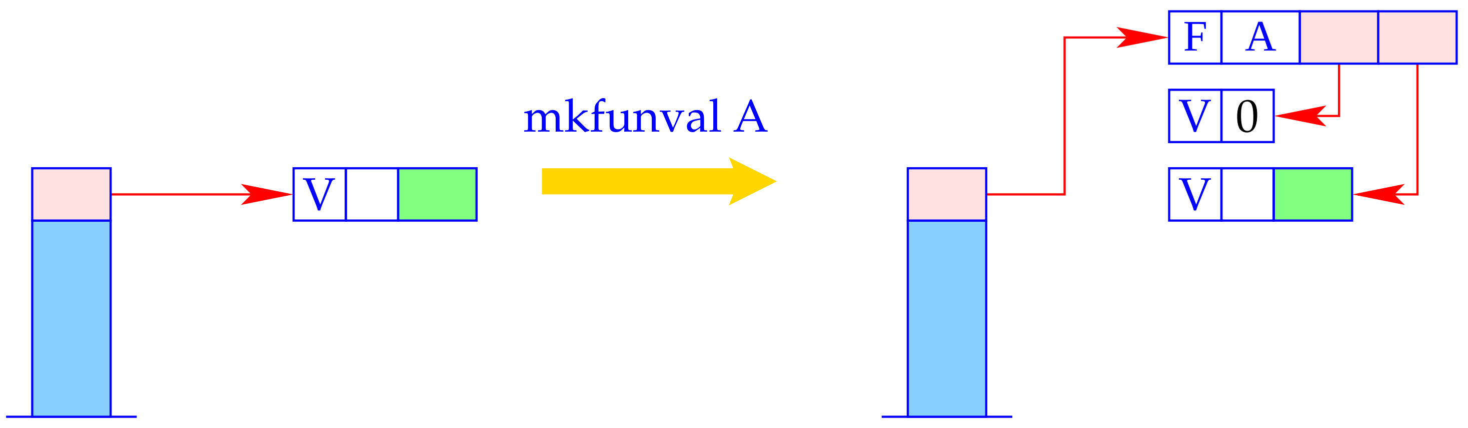
$$
\begin{array}{rcll}
\mathrm{code}_V\ (\textbf{fun}\ x_0 \ldots x_{k-1} \to e)\ \rho\ \mathrm{sd} & = & & \mathrm{getvar}\ z_0\ \rho\ \mathrm{sd} \\
 & & & \mathrm{getvar}\ z_1\ \rho\ (\mathrm{sd}+1) \\
 & & & \ldots \\
 & & & \mathrm{getvar}\ z_{g-1}\ \rho\ (\mathrm{sd}+g-1) \\
 & & & \mathrm{mkvec}\ \mathrm{g} \\
 & & & \mathrm{mkfunval}\ \mathrm{A} \\
 & & & \mathrm{jump}\ \mathrm{B} \\
 & & \mathrm{A}: & \mathrm{targ}\ \mathrm{k} \\
 & & & \mathrm{code}_V\ e\ \rho'\ 0 \\
 & & & \mathrm{return}\ \mathrm{k} \\
 & & \mathrm{B}: & \ldots
\end{array}
$$

where $\{z_0, \ldots, z_{g-1}\} = \mathit{free}(\textbf{fun}\ x_0 \ldots x_{k-1} \to e)$

and $\rho' = \{x_i \mapsto (L, -i) \mid i = 0, \ldots, k-1\} \cup \{z_j \mapsto (G, j) \mid j = 0, \ldots, g-1\}$




```
h = new (V, n);
SP = SP - g + 1;
for (i=0; i<g; i++)
    h→v[i] = S[SP + i];
S[SP] = h;
```



a = new (V,0);
S[SP] = new (F, A, a, S[SP]);

Example:

Regard $f \equiv \textbf{fun } b \to a + b$ for $\rho = \{a \mapsto (L, 1)\}$ and sd $= 1$.

$\text{code}_V\ f\ \rho\ 1$ produces:

1		pushloc 0	0	pushglob 0	2		getbasic
2		mkvec 1	1	eval	2		add
2		mkfunval A	1	getbasic	1		mkbasic
2		jump B	1	pushloc 1	1		return 1
0	A :	targ 1	2	eval	2	B :	...

The secrets around targ k and return k will be revealed later :-)

17 Function Application

Function applications correspond to function calls in C.
The necessary actions for the evaluation of $e' \; e_0 \; \ldots \; e_{m-1}$ are:

- Allocation of a stack frame;
- Transfer of the actual parameters , i.e. with:
  CBV: Evaluation of the actual parameters;
  CBN: Allocation of closures for the actual parameters;
- Evaluation of the expression e' to an F-object;
- Application of the function.

Thus for CBN:

$$
\begin{array}{rcll}
\text{code}_V\ (e'\ e_0\ \ldots\ e_{m-1})\ \rho\ \text{sd} & = & \text{mark A} & \text{// Allocation of the frame} \\
 & & \text{code}_C\ e_{m-1}\ \rho\ (\text{sd}+3) & \\
 & & \text{code}_C\ e_{m-2}\ \rho\ (\text{sd}+4) & \\
 & & \ldots & \\
 & & \text{code}_C\ e_0\ \rho\ (\text{sd}+m+2) & \\
 & & \text{code}_V\ e'\ \rho\ (\text{sd}+m+3) & \text{// Evaluation of } e' \\
 & & \text{apply} & \text{// corresponds to call} \\
 & A: & \ldots &
\end{array}
$$

To implement CBV, we use code_V instead of code_C for the arguments e_i.

Example: For $(f\ 42)$, $\rho = \{f \mapsto (L, 2)\}$ and $\text{sd} = 2$, we obtain with CBV:

2	mark A	6	mkbasic	7		apply
5	loadc 42	6	pushloc 4	3	A :	...

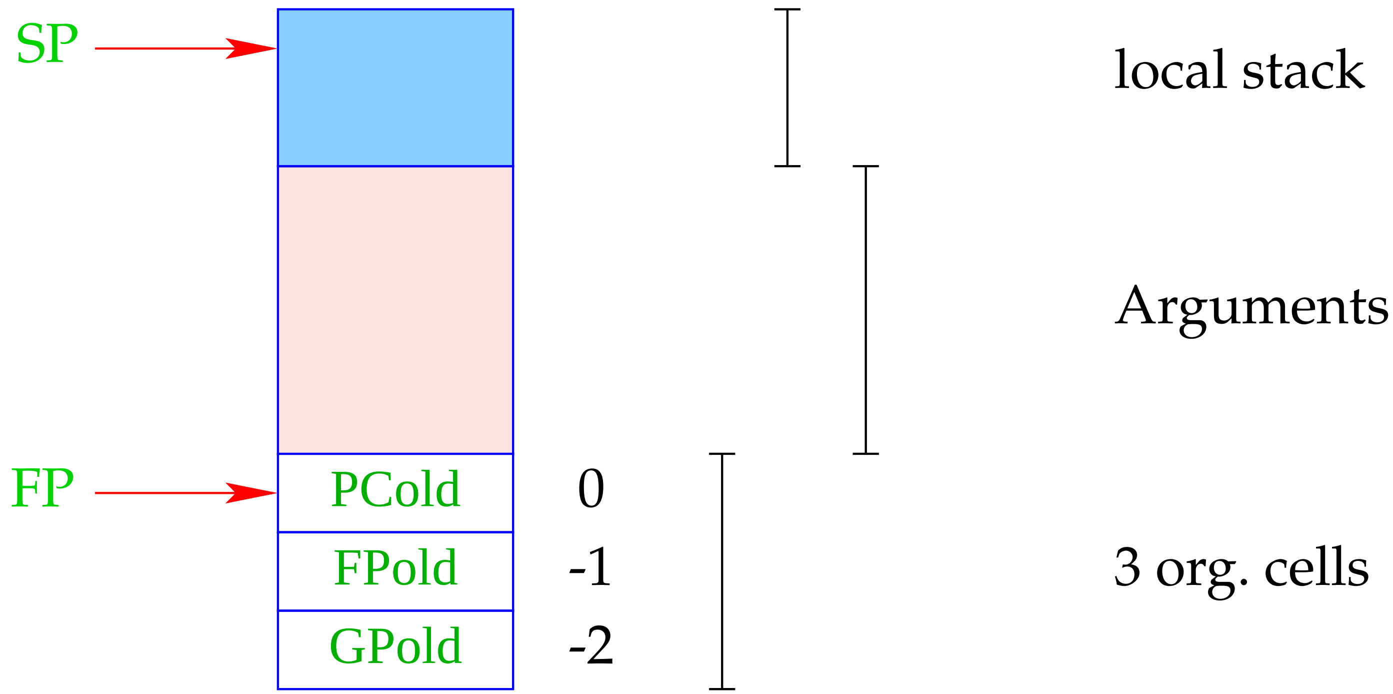
A Slightly Larger Example:

$$\textbf{let } a = 17 \textbf{ in let } f = \textbf{fun } b \to a + b \textbf{ in } f\ 42$$

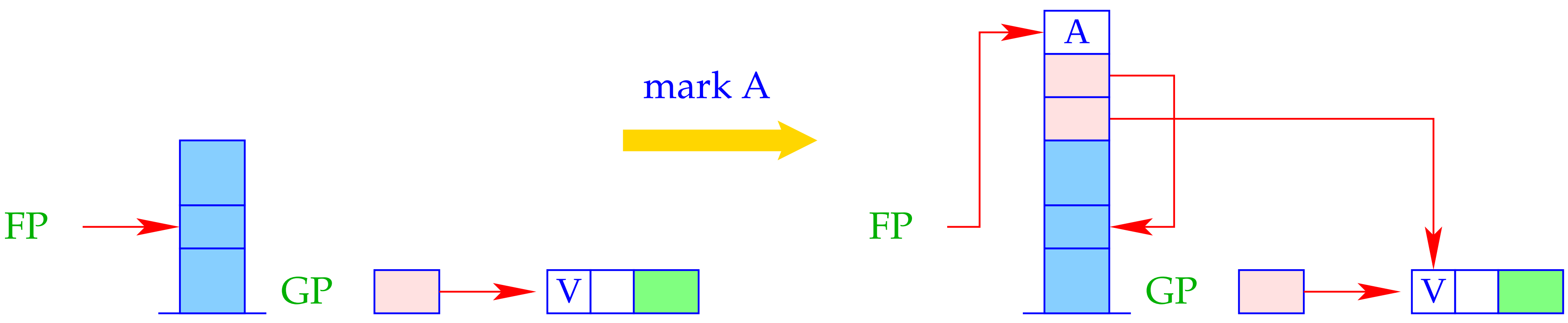
For CBV and $sd = 0$ we obtain:

0	loadc 17	2		jump B	2		getbasic	5		loadc 42
1	mkbasic	0	A:	targ 1	2		add	5		mkbasic
1	pushloc 0	0		pushglob 0	1		mkbasic	6		pushloc 4
2	mkvec 1	1		getbasic	1		return 1	7		apply
2	mkfunval A	1		pushloc 1	2	B:	mark C	3	C:	slide 2

For the implementation of the new instruction, we must fix the organization of a stack frame:

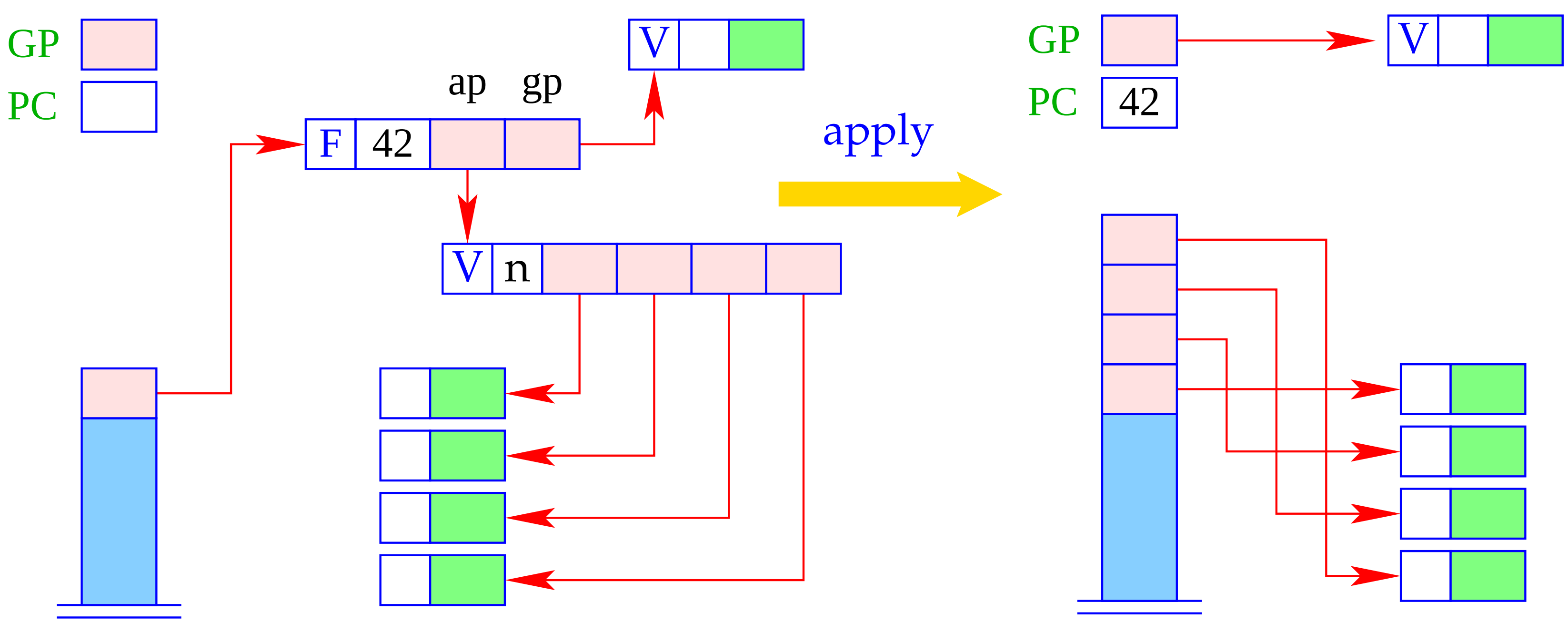


Different from the CMa, the instruction mark A already saves the return address:



S[SP+1] = GP;
S[SP+2] = FP;
S[SP+3] = A;
FP = SP = SP + 3;

The instruction apply unpacks the F-object, a reference to which (hopefully) resides on top of the stack, and continues execution at the address given there:




```
h = S[SP];
if (H[h] != (F,_,_))
    Error "no fun";
else {
```

```
GP = h→gp; PC = h→cp;
for (i=0; i< h→ap→n; i++)
    S[SP+i] = h→ap→v[i];
SP = SP + h→ap→n – 1;
}
```

Warning:

- The last element of the argument vector is the last to be put onto the stack. This must be the first argument reference.
- This should be kept in mind, when we treat the packing of arguments of an under-supplied function application into an F-object !!!