Script **generated by TTT**

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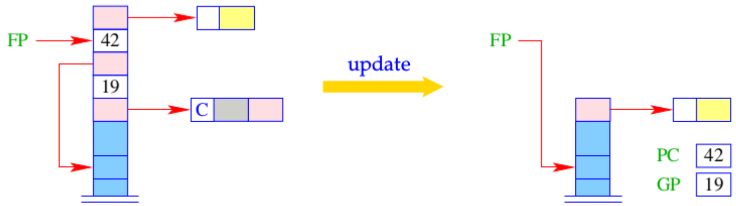
In fact, the instruction update is the combination of the two actions:

popenv
rewrite 1

It overwrites the closure with the computed value.



21 Optimizations I: Global Variables

Observation

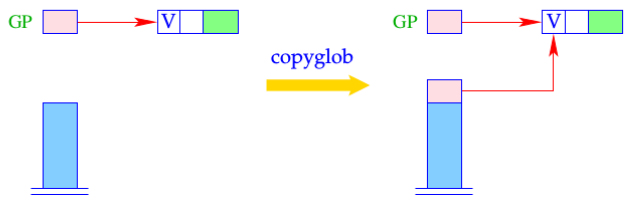
- Functional programs construct many F- and C-objects.
- This requires the inclusion of (the bindings of) all global variables.
  Recall, e.g., the construction of a closure for an expression e ...

$$
\begin{array}{rll}
\text{code}_C\ e\ \rho\ \text{sd} & = & \text{getvar}\ z_0\ \rho\ \text{sd} \\
 & & \text{getvar}\ z_1\ \rho\ (\text{sd}+1) \\
 & & \dots \\
 & & \text{getvar}\ z_{g-1}\ \rho\ (\text{sd}+g-1) \\
 & & \text{mkvec g} \\
 & & \text{mkclos A} \\
 & & \text{jump B} \\
 & \text{A}: & \text{code}_V\ e\ \rho'\ 0 \\
 & & \text{update} \\
 & \text{B}: & \dots
\end{array}
$$

where $\{z_0, \dots, z_{g-1}\} = \mathit{free}(e)$ and $\rho' = \{z_i \mapsto (G, i) \mid i = 0, \dots, g-1\}$.

Idea

- Reuse Global Vectors, i.e. share Global Vectors!
- Profitable in the translation of **let**-expressions or function applications: Build one Global Vector for the union of the free-variable sets of all **let**-definitions resp. all arguments.
- Allocate (references to) global vectors with multiple uses in the stack frame like local variables!
- Support the access to the current GP, e.g., by an instruction copyglob :




```
SP++;
S[SP] = GP;
```


- The optimization will cause Global Vectors to contain more components than just references to the free the variables that occur in one expression ...

Disadvantage: Superfluous components in Global Vectors prevent the deallocation of already useless heap objects ⟹ Space Leaks

Potential Remedy: Deletion of references from the global vector at the end of their life times.

22 Optimizations II: Closures

In some cases, the construction of closures can be avoided, namely for

- Basic values,
- Variables,
- Functions.

Basic Values

The construction of a closure for the value is at least as expensive as the construction of the B-object itself!

Therefore:

$$\text{code}_C\ b\ \rho\ \text{sd} \quad = \quad \text{code}_V\ b\ \rho\ \text{sd} \quad = \quad \begin{array}{l}\text{loadc } b \\ \text{mkbasic}\end{array}$$

This replaces:

mkvec 0		jump B	mkbasic	B:	...
mkclos A	A:	loadc b	update		

Variables

Variables are either bound to values or to C-objects. Constructing another closure is therefore superfluous. Therefore:

$$\text{code}_C\ x\ \rho\ \text{sd} \quad = \quad \text{getvar}\ x\ \rho\ \text{sd}$$

This replaces:

getvar x ρ sd	mkclos A	A:	pushglob 0		update
mkvec 1	jump B		eval	B:	...

Example

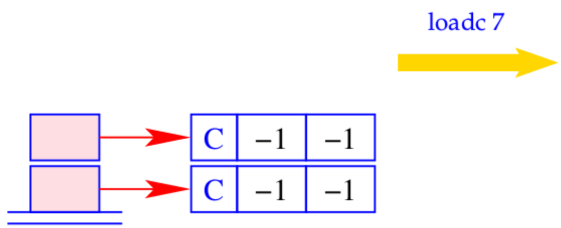
Consider $\quad e \equiv \textbf{let rec}\ a = b\ \textbf{and}\ b = 7\ \textbf{in}\ a.$

$\text{code}_V\ e\ \emptyset\ 0$ produces:

0	alloc 2	3	rewrite 2	3	mkbasic	2	pushloc 1
2	pushloc 0	2	loadc 7	3	rewrite 1	3	eval
						3	slide 2

The execution of this instruction sequence should deliver the basic value 7 ...

0	alloc 2	3	rewrite 2	3	mkbasic	2	pushloc 1
2	pushloc 0	2	loadc 7	3	rewrite 1	3	eval
						3	slide 2



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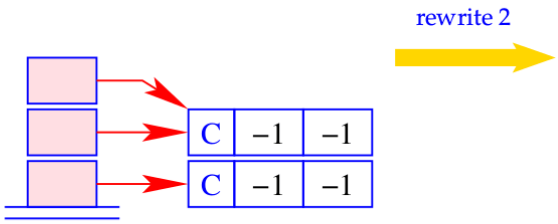

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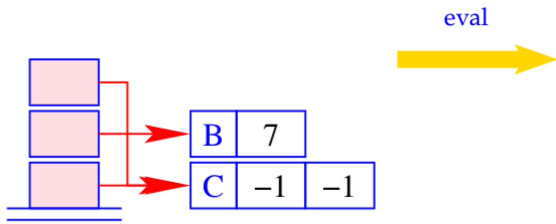

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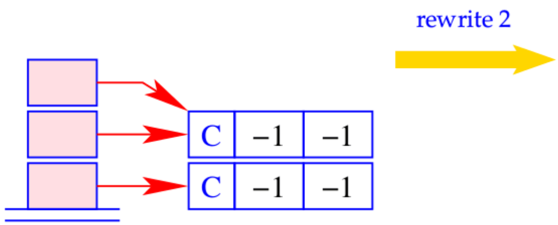


Example

Consider $e \equiv$ **let rec** $a = b$ **and** $b = 7$ **in** a.

$\text{code}_V\ e\ \emptyset\ 0$ produces:

0	alloc 2	3	rewrite 2	3	mkbasic	2	pushloc 1
2	pushloc 0	2	loadc 7	3	rewrite 1	3	eval
						3	slide 2

The execution of this instruction sequence should deliver the basic value 7 ...

Apparently, this optimization was not quite correct.

The Problem

Binding of variable y to variable x before x's dummy node is replaced!!

$$\Longrightarrow$$

The Solution

cyclic definitions: reject sequences of definitions like
let rec $a = b$ **and** $\ldots b = a$ **in** $\ldots$.

acyclic definitions: order the definitions $y = x$ such that the dummy node for the right side of x is already overwritten.

Functions

Functions are values, which are not evaluated further. Instead of generating code that constructs a closure for an F-object, we generate code that constructs the F-object directly.

Therefore:

$$\text{code}_C\ (\textbf{fun}\ x_0 \ldots x_{k-1} \to e)\ \rho\ \text{sd} \quad = \quad \text{code}_V\ (\textbf{fun}\ x_0 \ldots x_{k-1} \to e)\ \rho\ \text{sd}$$

23 The Translation of a Program Expression

Execution of a program e starts with

$$\text{PC} = 0 \qquad \text{SP} = \text{FP} = \text{GP} = -1$$

The expression e must not contain free variables.

The value of e should be determined and then a halt instruction should be executed.

$$\begin{aligned}\text{code}\ e \quad = \quad & \text{code}_V\ e\ \emptyset\ 0\\ & \text{halt}\end{aligned}$$

Remarks

- The code schemata as defined so far produce Spaghetti code.
- Reason: Code for function bodies and closures placed directly behind the instructions mkfunval resp. mkclos with a jump over this code.
- Alternative: Place this code somewhere else, e.g. following the halt-instruction:

  Advantage: Elimination of the direct jumps following mkfunval and mkclos.

  Disadvantage: The code schemata are more complex as they would have to accumulate the code pieces in a Code-Dump.

$$\Longrightarrow$$

Solution

Disentangle the Spaghetti code in a subsequent optimization phase.

Example $\quad$ **let** $a = 17$ **in let** $f =$ **fun** $b \to a + b$ **in** $f\ 42$

Disentanglement of the jumps produces:

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

24 Structured Data

In the following, we extend our functional programming language by some datatypes.

24.1 Tuples

Constructors: $(.,\ldots,.)$, k-ary with $k \geq 0$;

Destructors: $\#j$ for $j \in \mathbb{N}_0$ $\qquad$ (Projections)

We extend the syntax of expressions correspondingly:

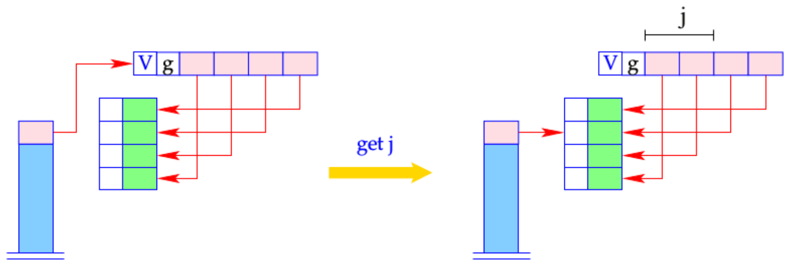
$$\begin{array}{lcl} e & ::= & \ldots \mid (e_0,\ldots,e_{k-1}) \mid \#j\ e \\ & & \mid \ \mathbf{let}\ (x_0,\ldots,x_{k-1}) = e_1\ \mathbf{in}\ e_0 \end{array}$$

- In order to construct a tuple, we collect sequence of references on the stack. Then we construct a vector of these references in the heap using mkvec
- For returning components we use an indexed access into the tuple.

$$\begin{array}{lcl} \text{code}_V\ (e_0,\ldots,e_{k-1})\ \rho\ \text{sd} & = & \text{code}_C\ e_0\ \rho\ \text{sd} \\ & & \text{code}_C\ e_1\ \rho\ (\text{sd}+1) \\ & & \ldots \\ & & \text{code}_C\ e_{k-1}\ \rho\ (\text{sd}+k-1) \\ & & \text{mkvec k} \end{array}$$

$$\begin{array}{lcl} \text{code}_V\ (\#j\ e)\ \rho\ \text{sd} & = & \text{code}_V\ e\ \rho\ \text{sd} \\ & & \text{get j} \\ & & \text{eval} \end{array}$$

In the case of CBV, we directly compute the values of the e_i.




```
if (S[SP] == (V,g,v)) if (j<g)
   S[SP] = v[j];
else Error "Vector index out of bounds!";
else Error "Vector expected!";
```

Inversion: Accessing all components of a tuple simulataneously:

$$e \equiv \mathbf{let}\ (y_0, \ldots, y_{k-1}) = e_1\ \mathbf{in}\ e_0$$

This is translated as follows:

$$\begin{array}{lll} \text{code}_V\ e\ \rho\ \text{sd} & = & \text{code}_V\ e_1\ \rho\ \text{sd} \\ & & \text{getvec k} \\ & & \text{code}_V\ e_0\ \rho'\ (\text{sd}+k) \\ & & \text{slide k} \end{array}$$

where $\rho' = \rho \oplus \{y_i \mapsto (L, sd+i+1) \mid i = 0, \ldots, k-1\}$.

The instruction getvec k pushes the components of a vector of length k onto the stack:

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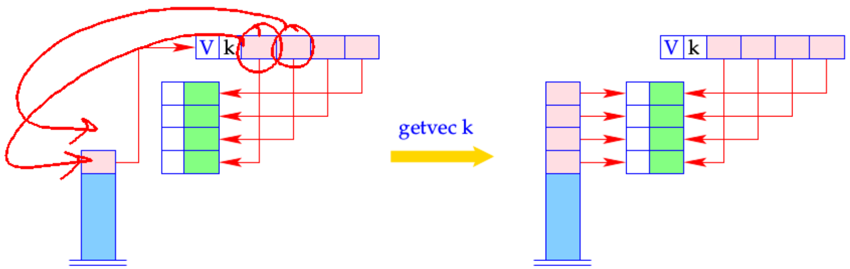
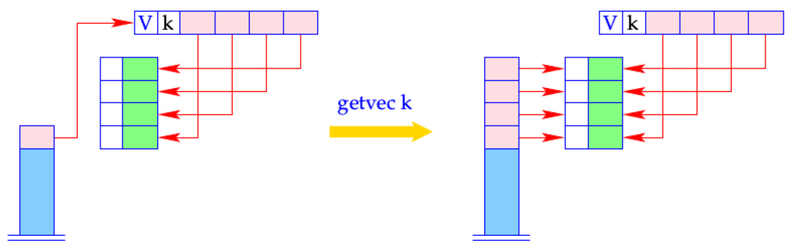



```
if (S[SP] == (V,k,v)) {
  SP--;
  for(i=0; i<k; i++) {
     SP++; S[SP] = v[i];
  }
} else Error "Vector expected!";
```

if (S[SP] == (V,k,v)) {
  SP--;
  for(i=0; i<k; i++) {
     SP++; S[SP] = v[i];
  }
} else Error "Vector expected!";

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24.2 Lists

Lists are constructed by the constructors:

[] "Nil", the empty list;

"::" "Cons", right-associative, takes an element and a list.

Access to list components is possible by **match**-expressions ...

Example The append function app:

$$\begin{array}{lllll} \text{app} & = & \textbf{fun } l\ y \rightarrow \textbf{match } l \textbf{ with} & & \\ & & \mid\ [] & \rightarrow & y \\ & & \mid\ h :: t & \rightarrow & h :: (\text{app } t\ y) \end{array}$$

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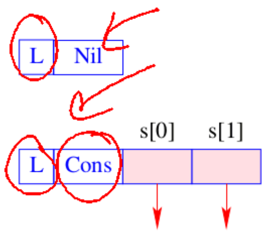
accordingly, we extend the syntax of expressions:

$$\begin{array}{lll} e & ::= & \ldots \mid [] \mid (e_1 :: e_2) \\ & & \mid (\textbf{match } e_0 \textbf{ with } [] \rightarrow e_1 \mid h :: t \rightarrow e_2) \end{array}$$

Additionally, we need new heap objects:

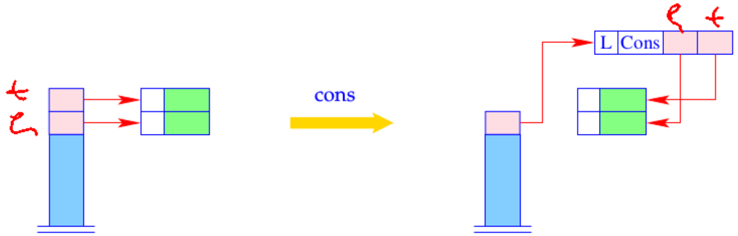


empty list

non–empty list

SP++; S[SP] = new (L,Nil);

SP++; S[SP] = new (L,Nil);



S[SP-1] = new (L,Cons, S[SP-1], S[SP]);
SP- -;

24.4 Pattern Matching

Consider the expression $e \equiv \textbf{match}\ e_0\ \textbf{with}\ [\,] \rightarrow e_1 \mid h :: t \rightarrow e_2$.

Evaluation of e requires:

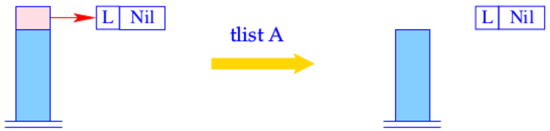
- evaluation of e_0;
- check, whether resulting value v is an L-object;
- if v is the empty list, evaluation of e_1 ...
- otherwise storing the two references of v on the stack and evaluation of e_2. This corresponds to binding h and t to the two components of v.

In consequence, we obtain (for CBN as for CBV):

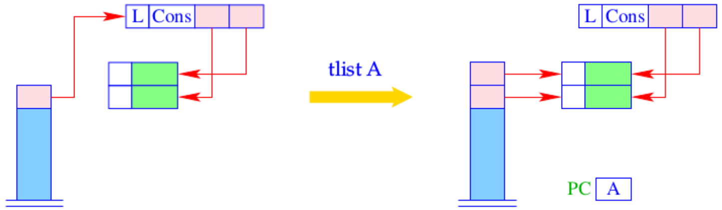
$$
\begin{array}{rrl}
\text{code}_V\ e\ \rho\ \text{sd} & = & \text{code}_V\ e_0\ \rho\ \text{sd} \\
 & & \text{tlist A} \\
 & & \text{code}_V\ e_1\ \rho\ \text{sd} \\
 & & \text{jump B} \\
 & \text{A}: & \text{code}_V\ e_2\ \rho'\ (\text{sd}+2) \\
 & & \text{slide 2} \\
 & \text{B}: & \ldots
\end{array}
$$

where $\rho' = \rho \oplus \{h \mapsto (L, sd+1), t \mapsto (L, sd+2)\}$.

The new instruction tlist A does the necessary checks and (in the case of Cons) allocates two new local variables:




```
h = S[SP];
if (H[h] != (L,...))
    Error “no list!”;
if (H[h] == (_,Nil)) SP- -;
    ...
```


```
... else {
  S[SP+1] = S[SP]→s[1];
  S[SP] = S[SP]→s[0];
  SP++; PC = A;
}
```


Example The (disentangled) body of the function app with $\text{app} \mapsto (G, 0)$:

0		targ 2	3		pushglob 0	0	C:	mark D
0		pushloc 0	4		pushloc 2	3		pushglob 2
1		eval	5		pushloc 6	4		pushglob 1
1		tlist A	6		mkvec 3	5		pushglob 0
0		pushloc 1	4		mkclos C	6		eval
1		eval	4		cons	6		apply
1		jump B	3		slide 2	1	D:	update
2	A:	pushloc 1	1	B:	return 2			

Remark

Datatypes with more than two constructors need a generalization of the tlist instruction, corresponding to a `switch`-instruction.

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Remark

Datatypes with more than two constructors need a generalization of the tlist instruction, corresponding to a `switch`-instruction.

24.5 Closures of Tuples and Lists

The general schema for code_C can be optimized for tuples and lists:

$$
\begin{array}{lllll}
\text{code}_C\ (e_0, \ldots, e_{k-1})\ \rho\ \text{sd} & = & \text{code}_V\ (e_0, \ldots, e_{k-1})\ \rho\ \text{sd} & = & \text{code}_C\ e_0\ \rho\ \text{sd} \\
 & & & & \text{code}_C\ e_1\ \rho\ (\text{sd} + 1) \\
 & & & & \ldots \\
 & & & & \text{code}_C\ e_{k-1}\ \rho\ (\text{sd} + k - 1) \\
 & & & & \text{mkvec k} \\
\text{code}_C\ []\ \rho\ \text{sd} & = & \text{code}_V\ []\ \rho\ \text{sd} & = & \text{nil} \\
\text{code}_C\ (e_1 :: e_2)\ \rho\ \text{sd} & = & \text{code}_V\ (e_1 :: e_2)\ \rho\ \text{sd} & = & \text{code}_C\ e_1\ \rho\ \text{sd} \\
 & & & & \text{code}_C\ e_2\ \rho\ (\text{sd} + 1) \\
 & & & & \text{cons}
\end{array}
$$