Script generated by TTT

Title: Seidl: Virtual_Machines (05.06.2013)

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Pages: 46

Example:

For our example term $f(g(\bar{X}, Y), a, Z)$ and $\rho = \{X \mapsto 1, Y \mapsto 2, Z \mapsto 3\}$ we obtain:

ustruct f/3 A_1		up B_2	B_2:	son 2		putvar 2
son 1				uatom a		putstruct g/2
ustruct g/2 A_2	A_2:	check 1		son 3		putatom a
son 1		putref 1		uvar 3		putvar 3
uref 1		putvar 2		up B_1		putstruct f/3
son 2		putstruct g/2	A_1:	check 1		bind
uvar 2		bind		putref 1	B_1:	...

Code size can grow quite considerably — for deep terms. In practice, though, deep terms are "rare" :-)

Example:

For our example term $f(g(\bar{X}, Y), a, Z)$ and $\rho = \{X \mapsto 1, Y \mapsto 2, Z \mapsto 3\}$ we obtain:

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son 1		putref 1		uvar 3		putvar 3
uref 1		putvar 2		up B_1		putstruct f/3
son 2		putstruct g/2	A_1:	check 1		bind
uvar 2		bind		putref 1	B_1:	...

Code size can grow quite considerably — for deep terms. In practice, though, deep terms are "rare" :-)

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31 Clauses

Clausal code must

- allocate stack space for locals;
- evaluate the body;
- free the stack frame (whenever possible :-)

Let r denote the clause: $p(X_1, \ldots, X_k) \leftarrow g_1, \ldots, g_n$.

Let $\{X_1, \ldots, X_m\}$ denote the set of locals of r and ρ the address environment:

$$\rho\ X_i = i$$

Remark: The first k locals are always the formals :-)

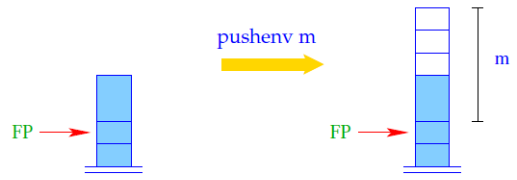
Then we translate:

$$\begin{array}{lll} \text{code}_C\ r & = & \text{pushenv m} \qquad // \text{ allocates space for locals} \\ & & \text{code}_G\ g_1\ \rho \\ & & \ldots \\ & & \text{code}_G\ g_n\ \rho \\ & & \text{popenv} \end{array}$$

The instruction popenv restores FP and PC and tries to pop the current stack frame.

It should succeed whenever program execution will never return to this stack frame :-)

The instruction pushenv m sets the stack pointer:



SP = FP + m;

Example:

Consider the clause r:

$$\mathsf{a}(X, Y) \leftarrow \mathsf{f}(\bar{X}, X_1), \mathsf{a}(\bar{X}_1, \bar{Y})$$

Then $\text{code}_C\ r$ yields:

pushenv 3	mark A	A:	mark B	B:	popenv
	putref 1		putref 3		
	putvar 3		putref 2		
	call f/2		call a/2		

32 Predicates

A predicate q/k is defined through a sequence of clauses $rr \equiv r_1 \ldots r_f$.

The translation of q/k provides the translations of the individual clauses r_i.

In particular, we have for $f = 1$:

$$\text{code}_P\ rr = \text{code}_C\ r_1$$

If q/k is defined through several clauses, the first alternative must be tried.

On failure, the next alternative must be tried

$\Longrightarrow$ backtracking :-)

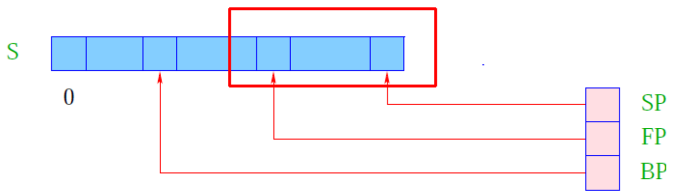
32.1 Backtracking

- Whenever unifcation fails, we call the run-time function `backtrack()`.
- The goal is to roll back the whole computation to the (dynamically :-) latest goal where another clause can be chosen $\Longrightarrow$ the last backtrack point.
- In order to undo intermediate variable bindings, we always have recorded new bindings with the run-time function `trail()`.
- The run-time function `trail()` stores variables in the data-structure trail:

TP == Trail Pointer

points to the topmost occupied Trail cell

The current stack frame where backtracking should return to is pointed at by the extra register BP:



A backtrack point is stack frame to which program execution possibly returns.

- We need the code address for trying the next alternative (negative continuation address);
- We save the old values of the registers HP, TP and BP.
- Note: The new BP will receive the value of the current FP :-)

For this purpose, we use the corresponding four organizational cells:

FP →	posCont.	0
	FPold	-1
	HPold	-2
	TPold	-3
	BPold	-4
	negCont.	-5

For more comprehensible notation, we thus introduce the macros:

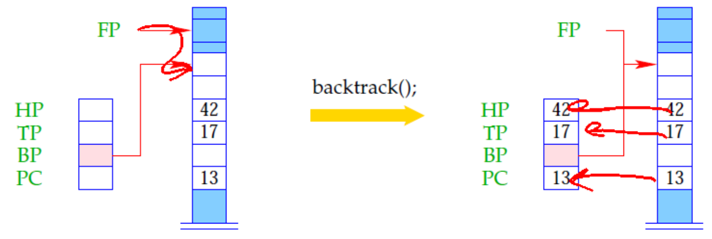
$$\begin{array}{lcl}
\text{posCont} & \equiv & S[\text{FP}] \\
\text{FPold} & \equiv & S[\text{FP} - 1] \\
\text{HPold} & \equiv & S[\text{FP} - 2] \\
\text{TPold} & \equiv & S[\text{FP} - 3] \\
\text{BPold} & \equiv & S[\text{FP} - 4] \\
\text{negCont} & \equiv & S[\text{FP} - 5]
\end{array}$$

for the corresponding addresses.

Remark:

Occurrence on the left	==	saving the register
Occurrence on the right	==	restoring the register

Calling the run-time function `void backtrack()` yields:




```
void backtrack() {
    FP = BP; HP = HPold;
    reset (TPold, TP);
    TP = TPold; PC = negCont;
}
```

where the run-time function `reset()` undoes the bindings of variables established since the backtrack point.

32.2 Resetting Variables

Idea:

- The variables which have been created since the last backtrack point can be removed together with their bindings by popping the heap !!! :-)
- This works fine if younger variables always point to older objects.
- Bindings of old variables to younger objects, though, must be reset manually :-(
- These are therefore recorded in the trail.

Functions `void trail(ref u)` and `void reset (ref y, ref x)` can thus be implemented as:

```
void trail (ref u) {
   if (u < S[BP-2]) {
      TP = TP+1;
      T[TP] = u;
   }
}
```

```
void reset (ref x, ref y) {
   for (ref u=y; x<u; u--)
      H[T[u]] = (R,T[u]);
}
```

Here, `S[BP-2]` represents the heap pointer when creating the last backtrack point.

32.3 Wrapping it Up

Assume that the predicate q/k is defined by the clauses $r_1, \ldots, r_f$ $(f > 1)$.
We provide code for:

- setting up the backtrack point;
- successively trying the alternatives;
- deleting the backtrack point.

This means:

$$
\begin{array}{rcll}
\text{code}_P\; rr & = & q/k: & \boxed{\text{setbtp}} \\
 & & & \boxed{\text{try } A_1} \\
 & & & \ldots \\
 & & & \text{try } A_{f-1} \\
 & & & \boxed{\text{delbtp}} \\
 & & & \text{jump } A_f \\
 & & A_1: & \text{code}_C\; r_1 \\
 & & & \ldots \\
 & & A_f: & \text{code}_C\; r_f
\end{array}
$$

Note:

- We delete the backtrack point before the last alternative :-)
- We jump to the last alternative — never to return to the present frame :-))

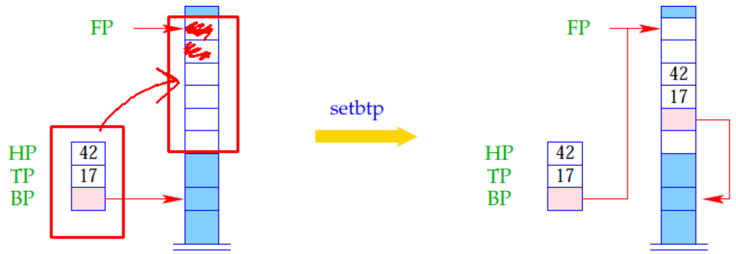
Example:

$$
\begin{array}{lcl}
\text{s}(X) & \leftarrow & \text{t}(\bar{X}) \\
\text{s}(X) & \leftarrow & \bar{X} = a
\end{array}
$$

The translation of the predicate s yields:

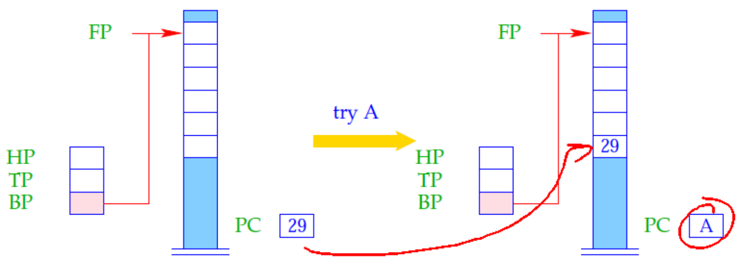
s/1:	setbtp	A:	pushenv 1	B:	pushenv 1
	try A		mark C		putref 1
	delbtp		putref 1		uatom a
	jump B		call t/1		popenv
		C:	popenv		

The instruction setbtp saves the registers HP, TP, BP:



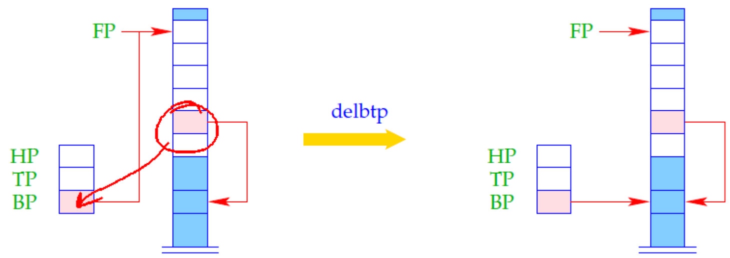
HPold = HP;
TPold = TP;
BPold = BP;
BP = FP;

The instruction try A tries the alternative at address A and updates the negative continuation address to the current PC:



negForts = PC;
PC = A;

The instruction delbtp restores the old backtrack pointer:



BP = BPold;

32.4 Popping of Stack Frames

Recall the translation scheme for clauses:

$$\begin{array}{lcl} \text{code}_C\ r & = & \text{pushenv m} \\ & & \text{code}_G\ g_1\ \rho \\ & & \ldots \\ & & \text{code}_G\ g_n\ \rho \\ & & \text{popenv} \end{array}$$

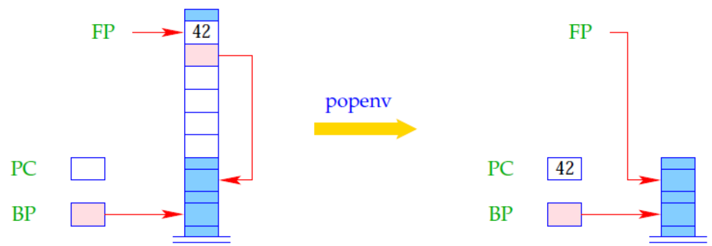
The present stack frame can be popped ...

- if the applied clause was the last (or only); and
- if all goals in the body are definitely finished.

$\Longrightarrow$ the backtrack point is older :-)

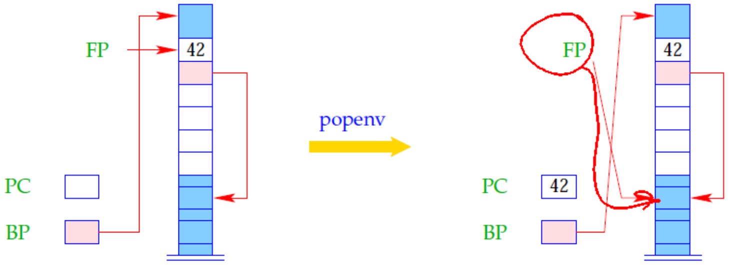
$\Longrightarrow$ FP > BP

The instruction popenv restores the registers FP and PC and possibly pops the stack frame:



if (FP > BP) SP = FP - 6;
PC = posCont;
FP = FPold;

Warning: popenv may fail to de-allocate the frame !!!



if (FP > BP) SP = FP - 6;
PC = posCont;
FP = FPold;

If popping the stack frame fails, new data are allocated on top of the stack. When returning to the frame, the locals still can be accessed through the FP :-))

33 Queries and Programs

The translation of a program: $p \equiv rr_1 \dots rr_h ? g$
consists of:

- an instruction no for failure;
- code for evaluating the query g;
- code for the predicate definitions rr_i.

Preceding query evaluation:

$\Longrightarrow$ initialization of registers
$\Longrightarrow$ allocation of space for the globals

Succeeding query evaluation:

$\Longrightarrow$ returning the values of globals

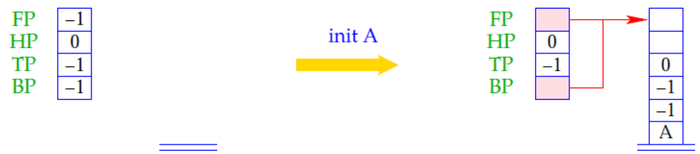
code p = init A
pushenv d
$\text{code}_G\ g\ \rho$
halt d
A: no
$\text{code}_P\ rr_1$
...
$\text{code}_P\ rr_h$

where $free(g) = \{X_1, \dots, X_d\}$ and ρ is given by $\rho\ X_i = i$.

The instruction halt d ...

- ... terminates the program execution;
- ... returns the bindings of the d globals;
- ... causes backtracking — if demanded by the user :-)

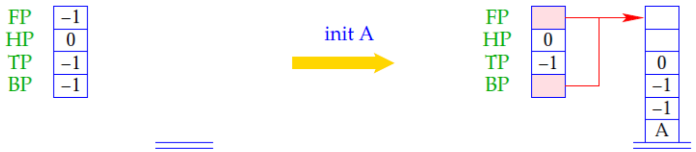
The instruction init A is defined by:



BP = FP = SP = 5;
S[0] = A;
S[1] = S[2] = -1;
S[3] = 0;
BP = FP;

At address "A" for a failing goal we have placed the instruction no for printing no to the standard output and halt :-)

The instruction init A is defined by:



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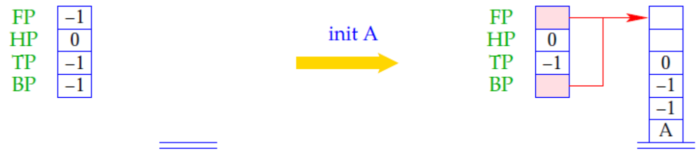

The Final Example:

$$t(X) \leftarrow \bar{X} = b \qquad q(X) \leftarrow s(\bar{X}) \qquad s(X) \leftarrow \bar{X} = a$$
$$p \leftarrow q(X), t(\bar{X}) \qquad s(X) \leftarrow t(\bar{X}) \qquad ?\ \ p$$

The translation yields:

	init N		popenv	q/1:	pushenv 1	E:	pushenv 1
	pushenv 0	p/0:	pushenv 1		mark D		mark G
	mark A		mark B		putref 1		putref 1
	call p/0		putvar 1		call s/1		call t/1
A:	halt 0		call q/1	D:	popenv	G:	popenv
N:	no	B:	mark C	s/1:	setbtp	F:	pushenv 1
t/1:	pushenv 1		putref 1		try E		putref 1
	putref 1		call t/1		delbtp		uatom a
	uatom b	C:	popenv		jump F		popenv

34 Last Call Optimization

Consider the app predicate from the beginnning:

$$\text{app}(X, Y, Z) \leftarrow X = [\,],\ Y = Z$$
$$\text{app}(X, Y, Z) \leftarrow X = [H|X'],\ Z = [H|Z'],\ \text{app}(X', Y, Z')$$

We observe:

- The recursive call occurs in the last goal of the clause.
- Such a goal is called last call.

  $\Longrightarrow$ we try to evaluate it in the current stack frame !!!

  $\Longrightarrow$ after (successful) completion, we will not return to the current caller !!!

Consider a clause r: $p(X_1, \ldots, X_k) \leftarrow g_1, \ldots, g_n$ with m locals where $g_n \equiv q(t_1, \ldots, t_h)$. The interplay between code_C and code_G:

$$
\begin{array}{lll}
\text{code}_C\ r & = & \text{pushenv m} \\
 & & \text{code}_G\ g_1\ \rho \\
 & & \ldots \\
 & & \text{code}_G\ g_{n-1}\ \rho \\
 & & \text{mark B} \\
 & & \text{code}_A\ t_1\ \rho \\
 & & \ldots \\
 & & \text{code}_A\ t_h\ \rho \\
 & & \text{call q/h} \\
 & \text{B}: & \text{popenv}
\end{array}
$$

Replacement:			
	mark B	$\Longrightarrow$	lastmark
	call q/h; popenv	$\Longrightarrow$	lastcall q/h m

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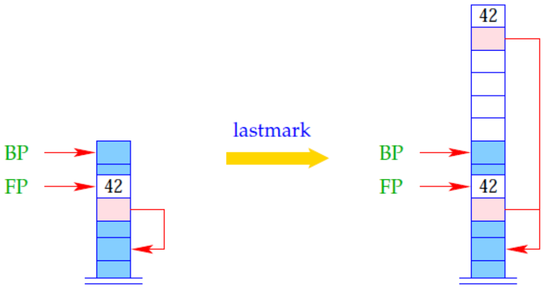
\begin{array}{lll}
\text{code}_C\ r & = & \text{pushenv m} \\
 & & \text{code}_G\ g_1\ \rho \\
 & & \ldots \\
 & & \text{code}_G\ g_{n-1}\ \rho \\
 & & \text{lastmark} \\
 & & \text{code}_A\ t_1\ \rho \\
 & & \ldots \\
 & & \text{code}_A\ t_h\ \rho \\
 & & \text{lastcall q/h m}
\end{array}
$$

Replacement:			
	mark B	$\Longrightarrow$	lastmark
	call q/h; popenv	$\Longrightarrow$	lastcall q/h m

If the current clause is not last or the $g_1, \ldots, g_{n-1}$ have created backtrack points, then FP $\leq$ BP :-)

Then lastmark creates a new frame but stores a reference to the predecessor:




```
if (FP ≤ BP) {
    SP = SP + 6;
    S[SP] = posCont; S[SP-1] = FPold;
}
```

If FP > BP then lastmark does nothing :-)

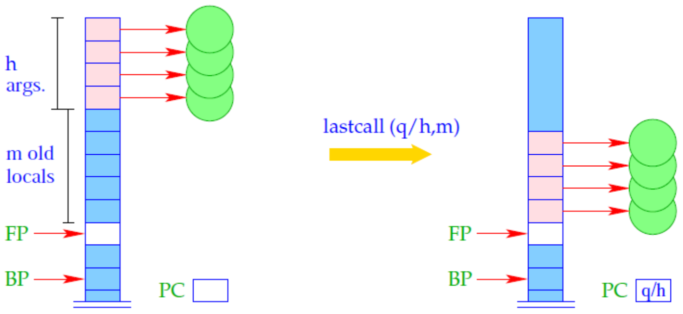
If FP $\leq$ BP, then lastcall q/h m behaves like a normal call q/h.

Otherwise, the current stack frame is re-used. This means that:

- the cells S[FP+1], S[FP+2], ..., S[FP+h] receive the new values and
- q/h can be jumped to :-)

```
lastcall q/h m  =  if (FP ≤ BP)  call q/h;
                   else {
                      move m h;
                      jump q/h;
                   }
```

The difference between the old and the new addresses of the parameters m just equals the number of the local variables of the current clause :-))



Example:

Consider the clause:

$$\mathsf{a}(X, Y) \leftarrow \mathsf{f}(\bar{X}, X_1), \mathsf{a}(\bar{X}_1, \bar{Y})$$

The last-call optimization for code$_C$ r yields:

```
                mark A          A:  lastmark
pushenv 3       putref 1            putref 3
                putvar 3            putref 2
                call f/2            lastcall a/2 3
```


Example:

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The last-call optimization for code$_C$ r yields:

```
                mark A          A:  lastmark
pushenv 3       putref 1            putref 3
                putvar 3            putref 2
                call f/2            lastcall a/2 3
```

Note:

If the clause is last and the last literal is the only one, we can skip lastmark and can replace lastcall q/h m with the sequence move m n; jump p/n :-))

Example:

Consider the last clause of the app predicate:

$$\mathsf{app}(X, Y, Z) \leftarrow \bar{X} = [H|X'],\ \bar{Z} = [\bar{H}|Z'],\ \mathsf{app}(\bar{X}', \bar{Y}, \bar{Z}')$$

Here, the last call is the only one :-) Consequently, we obtain:

```
A:  pushenv 6                                uref 4              bind
    putref 1          B:  putvar 4           son 2          E:   putref 5
    ustruct [|]/2 B       putvar 5           uvar 6              putref 2
    son 1                 putstruct [|]/2    up E                putref 6
    uvar 4                bind           D:  check 4             move 6 3
    son 2             C:  putref 3           putref 4            jump app/3
    uvar 5                ustruct [|]/2 D    putvar 6
    up C                  son 1              putstruct [|]/2
```

Example:

Consider the last clause of the app predicate:

$$\text{app}(X, Y, Z) \quad \leftarrow \quad \bar{X} = [H|X'],\ \bar{Z} = [\bar{H}|Z'],\ \text{app}(\bar{X}', \bar{Y}, \bar{Z}')$$

Here, the last call is the only one :-) Consequently, we obtain:

```
A:  pushenv 6              uref 4              bind
    putref 1        B:  putvar 4        son 2         E:  putref 5
    ustruct [|]/2 B     putvar 5        uvar 6            putref 2
    son 1               putstruct [|]/2 up E              putref 6
    uvar 4              bind        D:  check 4           move 6 3
    son 2           C:  putref 3        putref 4          jump app/3
    uvar 5              ustruct [|]/2 D putvar 6
    up C                son 1           putstruct [|]/2
```


35 Trimming of Stack Frames

Idea:

- Order local variables according to their life times;
- Pop the dead variables — if possible :-}

35 Trimming of Stack Frames

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- Order local variables according to their life times;
- Pop the dead variables — if possible :-}

Example:

Z

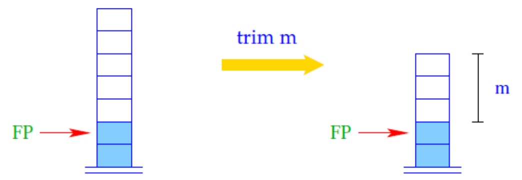
Consider the clause:

$$\text{a}(X, Z) \leftarrow \text{p}_1(\bar{X}, X_1), \text{p}_2(\bar{X}_1, X_2), \text{p}_3(\bar{X}_2, X_3), \text{p}_4(\bar{X}_3, \bar{Z})$$

X X1 X2

X3

After every non-last goal with dead variables, we insert the instruction trim :




```
if (FP ≥ BP)
    SP = FP + m;
```

Example (continued):

$$\mathsf{a}(X, Z) \leftarrow \mathsf{p}_1(\bar{X}, X_1), \mathsf{p}_2(\bar{X}_1, X_2), \mathsf{p}_3(\bar{X}_2, X_3), \mathsf{p}_4(\bar{X}_3, \bar{Z})$$

Ordering of the variables:

d

$$\rho = \{X \mapsto 1, Z \mapsto 2, X_3 \mapsto 3, X_2 \mapsto 4, X_1 \mapsto 5\}$$

The resulting code:

pushenv 5	A:	mark B		mark C	lastmark
mark A		putref 5		putref 4	putref 3
putref 1		putvar 4		putvar 3	putref 2
putvar 5		call $\mathsf{p}_2/2$		call $\mathsf{p}_3/2$	lastcall $\mathsf{p}_4/2$ 3
call $\mathsf{p}_1/2$	B:	trim 4	C:	trim 3	

app(X, Y, Z)

36 Clause Indexing

Observation:

Often, predicates are implemented by case distinction on the first argument.

$\Longrightarrow$ Inspecting the first argument, many alternatives can be excluded :-)

$\Longrightarrow$ Failure is earlier detected :-)

$\Longrightarrow$ Backtrack points are earlier removed. :-))

$\Longrightarrow$ Stack frames are earlier popped :-)))

Example:

The app-predicate:

$$\begin{array}{lll} \mathsf{app}(X, Y, Z) & \leftarrow & X = [\,],\ Y = Z \\ \mathsf{app}(X, Y, Z) & \leftarrow & X = [H|X'],\ Z = [H|Z'],\ \mathsf{app}(X', Y, Z') \end{array}$$

- If the root constructor is $[\,]$, only the first clause is applicable.
- If the root constructor is $[|]$, only the second clause is applicable.
- Every other root constructor should fail !!
- Only if the first argument equals an unbound variable, both alternatives must be tried ;-)