Script generated by TTT

Title: Petter: Compilerbau (11.07.2016)

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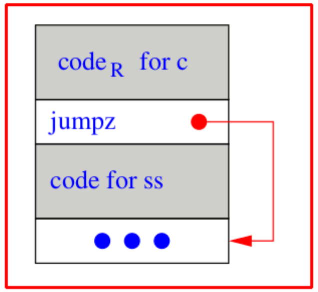
Simple Conditional

We first consider $s \equiv \texttt{if}\ (\boxed{c})\ \boxed{ss}$.
...and present a translation without basic blocks.

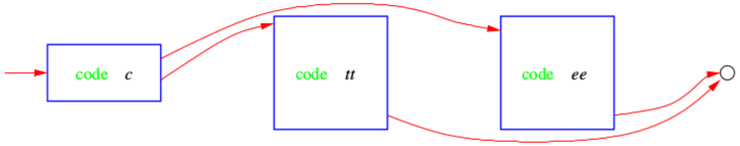
Idea:

- emit the code of c and ss in sequence
- insert a jump instruction in-between, so that correct control flow is ensured

$$
\begin{aligned}
\text{code}^i\ s\ \rho \quad = \quad & \boxed{\text{code}^i_R\ c\ \rho} \\
& \boxed{\text{jumpz}\ R_i\ A} \\
& \text{code}^i\ ss\ \rho \\
\boxed{A}: \quad & \dots
\end{aligned}
$$

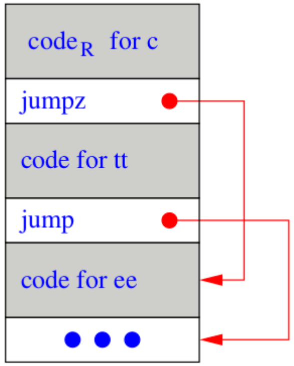


General Conditional



Translation of $\texttt{if}\ (\ c\ )\ tt\ \texttt{else}\ ee$.

$$
\begin{aligned}
\text{code}^i\ \texttt{if}(c)\ tt\ \texttt{else}\ ee\ \rho \quad = \quad & \boxed{\text{code}^i_R\ c\ \rho} \\
& \boxed{\text{jumpz}\ R_i\ A} \\
& \text{code}^i\ tt\ \rho \\
& \boxed{\text{jump}\ B} \\
\boxed{A:} \quad & \boxed{\text{code}^i\ ee\ \rho} \\
\boxed{B:} \quad &
\end{aligned}
$$



Example for if-statement

Let $\rho = \{x \mapsto 4, y \mapsto 7\}$ and let s be the statement

```
if (x>y) {          /* (i)   */
   x = x - y;       /* (ii)  */
} else {
   y = y - x;       /* (iii) */
}
```

Then $\text{code}^i\ s\ \rho$ yields:

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```

Then $\text{code}^i\ s\ \rho$ yields:

(i)

move R_i R_4

move R_{i+1} R_7

gr R_i R_i R_{i+1}

jumpz R_i A

(ii)

move R_i R_4

move R_{i+1} R_7

sub R_i R_i R_{i+1}

move R_4 R_i

jump B

(iii)

A : move R_i R_7

move R_{i+1} R_4

sub R_i R_i R_{i+1}

move R_7 R_i

B :

Iterating Statements

We only consider the loop $s \equiv$ **while** (e) s'. For this statement we define:

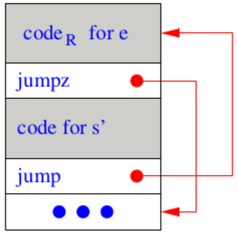
code^i `while`(e) s ρ $= A$: code^i_R e ρ

jumpz R_i B

code^i s ρ

jump A

B :



Example: Translation of Loops

Let $\rho = \{a \mapsto 7, b \mapsto 8, c \mapsto 9\}$ and let s be the statement:

```
while (a>0) {       /* (i) */
    c = c + 1;      /* (ii) */
    a = a - b;      /* (iii) */
}
```

Then $\text{code}^i\ s\ \rho$ evaluates to:

Example: Translation of Loops

Let $\rho = \{a \mapsto 7, b \mapsto 8, c \mapsto 9\}$ and let s be the statement:

```
while (a>0) {       /* (i) */
    c = c + 1;      /* (ii) */
    a = a - b;      /* (iii) */
}
```

Then $\text{code}^i\ s\ \rho$ evaluates to:

(i)

A : move R_i R_7

loadc R_{i+1} 0

gr R_i R_i R_{i+1}

jumpz R_i B

(ii)

move R_i R_9

loadc R_{i+1} 1

add R_i R_i R_{i+1}

move R_9 R_i

(iii)

move R_i R_7

move R_{i+1} R_8

sub R_i R_i R_{i+1}

move R_7 R_i

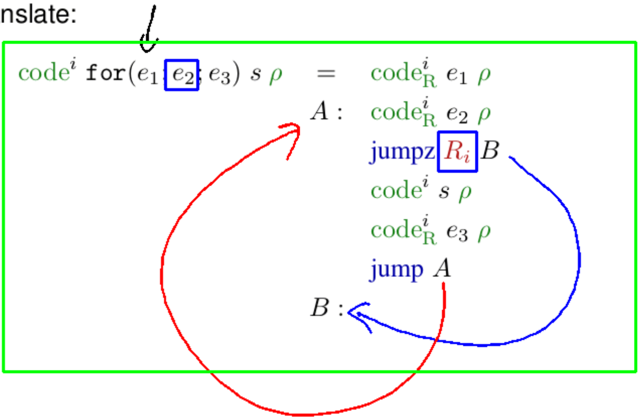
jump A

B :

for-Loops

The **for**-loop $s \equiv$ **for** $(e_1; e_2; e_3)\ s'$ is equivalent to the statement sequence $e_1;\ \textbf{while}\ (e_2)\ \{s'\ e_3;\}$ – as long as s' does not contain a **continue** statement.

Thus, we translate:



$$\begin{array}{rcl}
\text{code}^i\ \texttt{for}(e_1;\boxed{e_2};e_3)\ s\ \rho & = & \text{code}^i_{\text{R}}\ e_1\ \rho \\
A: & & \text{code}^i_{\text{R}}\ e_2\ \rho \\
 & & \text{jumpz}\ \boxed{R_i}\ B \\
 & & \text{code}^i\ s\ \rho \\
 & & \text{code}^i_{\text{R}}\ e_3\ \rho \\
 & & \text{jump}\ A \\
B: & &
\end{array}$$

The switch-Statement

Idea:

- Suppose choosing from multiple options in *constant time* if possible
- use a *jump table* that, at the ith position, holds a jump to the ith alternative
- in order to realize this idea, we need an *indirect jump* instruction

---

The switch-Statement

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- Suppose choosing from multiple options in *constant time* if possible
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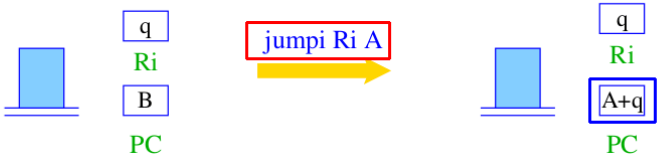


PC = A + R_i;

Consecutive Alternatives

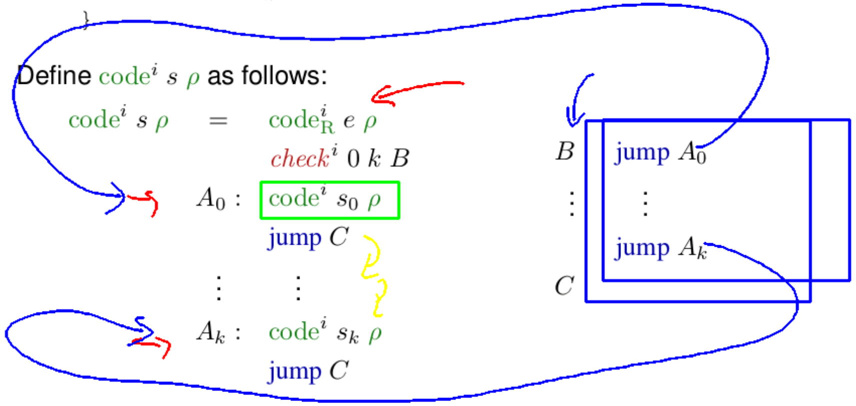
Let `switch` s be given with k consecutive `case` alternatives:

```
switch (e) {
  case 0: s0; break;
  ⋮
  case k-1: sk-1; break;
  default: sk; break;
}
```

Consecutive Alternatives

Let **switch** s be given with k consecutive **case** alternatives:

switch (e) {
case 0: s_0; ~~**break**~~;
$\vdots$
case $k-1$: s_{k-1}; ~~**break**~~;
default: s_k; **break**;
}



Define $\text{code}^i\ s\ \rho$ as follows:

$$\begin{array}{rrl} & \text{code}^i\ s\ \rho \quad = & \text{code}^i_{\text{R}}\ e\ \rho \\ & & \mathit{check}^i\ 0\ k\ B \\ & A_0: & \boxed{\text{code}^i\ s_0\ \rho} \\ & & \text{jump}\ C \\ & \vdots & \vdots \\ & A_k: & \text{code}^i\ s_k\ \rho \\ & & \text{jump}\ C \end{array}$$

$$\begin{array}{rl} B & \text{jump}\ A_0 \\ \vdots & \quad\vdots \\ & \text{jump}\ A_k \\ C & \end{array}$$

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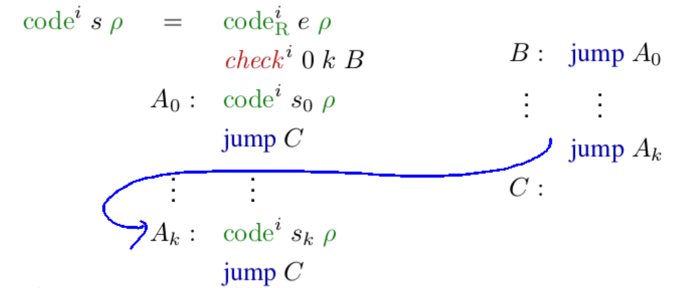

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$$\begin{array}{rl} B: & \text{jump}\ A_0 \\ \vdots & \quad\vdots \\ & \text{jump}\ A_k \\ C: & \end{array}$$

$\mathit{check}^i\ l\ u\ B$ checks if $l \leq R_i < u$ holds and jumps accordingly.

Translation of the check^i Macro

The macro $\mathit{check}^i\ l\ u\ B$ checks if $l \leq R_i < u$. Let $k = u - l$.

- if $l \leq R_i < u$ it jumps to $B + R_i - l$
- if $R_i < l$ or $R_i \geq u$ it jumps to A_k

$$\begin{array}{rl} B: & \text{jump}\ A_0 \\ \vdots & \quad\vdots \\ & \text{jump}\ A_k \\ C: & \end{array}$$

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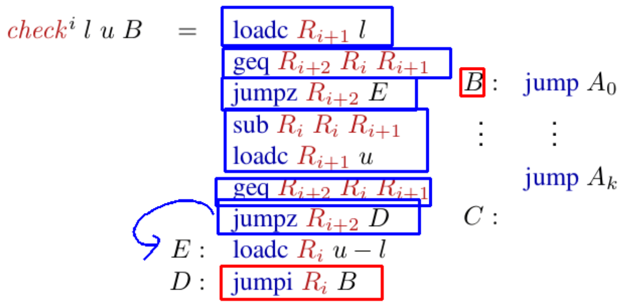
we define:



$$\begin{array}{rrl} \mathit{check}^i\ l\ u\ B \quad = & & \boxed{\text{loadc}\ R_{i+1}\ l} \\ & & \boxed{\text{geq}\ R_{i+2}\ R_i\ R_{i+1}} \\ & & \boxed{\text{jumpz}\ R_{i+2}\ E} \\ & & \text{sub}\ R_i\ R_i\ R_{i+1} \\ & & \text{loadc}\ R_{i+1}\ u \\ & & \boxed{\text{geq}\ R_{i+2}\ R_i\ R_{i+1}} \\ & & \boxed{\text{jumpz}\ R_{i+2}\ D} \\ & E: & \text{loadc}\ R_i\ u - l \\ & D: & \boxed{\text{jumpi}\ R_i\ B} \end{array}$$

$$\begin{array}{rl} \boxed{B}: & \text{jump}\ A_0 \\ \vdots & \quad\vdots \\ & \text{jump}\ A_k \\ C: & \end{array}$$

Improvements for Jump Tables

This translation is only suitable for *certain* **`switch`**-statement.

- In case the table starts with 0 instead of u we don't need to subtract it from e before we use it as index
- if the value of e is guaranteed to be in the interval $[l, u]$, we can omit check

---

General translation of switch-Statements

In general, the values of the various cases may be far apart:

- generate an **`if`**-ladder, that is, a sequence of **`if`**-statements
- for n cases, an **`if`**-cascade (tree of conditionals) can be generated $\rightsquigarrow O(\log n)$ tests
- if the sequence of numbers has small gaps (≤ 3), a jump table may be smaller and faster
- one could generate several jump tables, one for each sets of consecutive cases
- an **`if`** cascade can be re-arranged by using information from *profiling*, so that paths executed more frequently require fewer tests

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Ingredients of a Function

The definition of a function consists of

- a name with which it can be called;
- a specification of its formal parameters;
- possibly a result type;
- a sequence of statements.

In C we have:

$$\text{code}^i_{\text{R}}\ f\ \rho \quad = \quad \text{loadc}\ R_i\ \_f \qquad \text{with } \_f \text{ starting address of } f$$

Observe:

- function names must have an address assigned to them
- since the size of functions is unknown before they are translated, the addresses of forward-declared functions must be inserted later

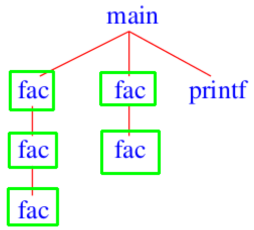
---

Memory Management in Functions

```
int fac(int x) {
  if (x<=0) return 1;
  else return x*fac(x-1);
}
```

```
int main(void) {
  int n;
  n = fac(2) + fac(1);
  printf("%d", n);
}
```

At run-time several instances may be active, that is, the function has been called but has not yet returned.
The recursion tree in the example:



Memory Management in Function Variables

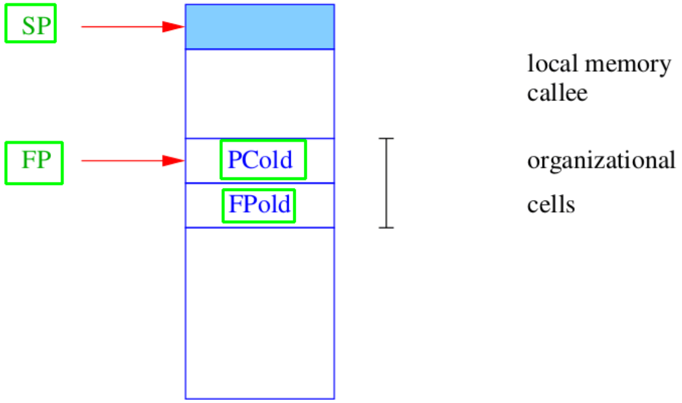
The formal parameters and the local variables of the various instances of a function must be kept separate

Idea for implementing functions:

- set up a region of memory each time it is called
- in sequential programs this memory region can be allocated on the stack
- thus, each instance of a function has its own region on the stack
- these regions are called stack frames

Organization of a Stack Frame

- stack representation: grows upwards
- SP points to the last used stack cell



Split of Obligations

Definition

Let f be the current function that calls a function g.

- f is dubbed *caller*
- g is dubbed *callee*

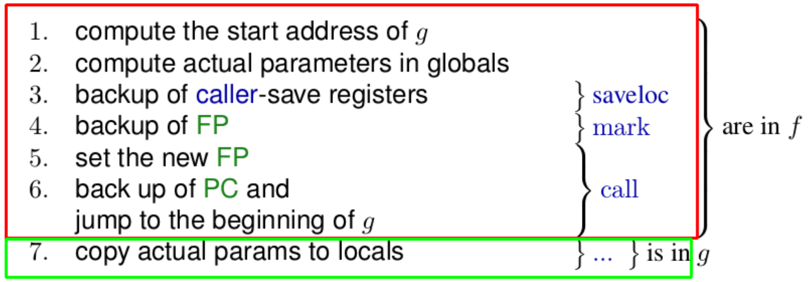
The code for managing function calls has to be split between caller and callee.
This split cannot be done arbitrarily since some information is only known in that caller or only in the callee.

Observation:

The space requirement for parameters is only know by the caller:
Example: `printf`

Principle of Function Call and Return

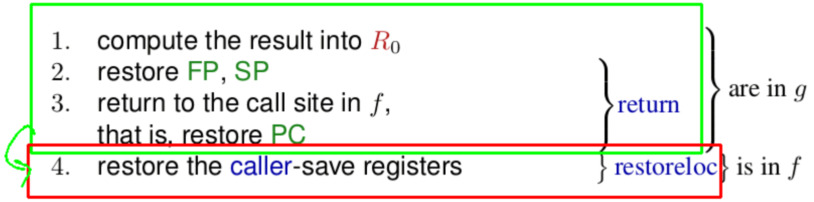
actions taken on entering g:



1. compute the start address of g
2. compute actual parameters in globals
3. backup of caller-save registers } saveloc
4. backup of FP } mark
5. set the new FP
6. back up of PC and jump to the beginning of g } call
7. copy actual params to locals } ... } is in g

} are in f

actions taken on leaving g:



1. compute the result into R_0
2. restore FP, SP
3. return to the call site in f, that is, restore PC } return
4. restore the caller-save registers } restoreloc } is in f

} are in g

Managing Registers during Function Calls

The two register sets (global and local) are used as follows:

- automatic variables live in *local* registers R_i
- intermediate results also live in *local* registers R_i
- parameters live in *global* registers R_i (with $i \leq 0$)
- global variables: let's suppose there are none

convention:

- the i th argument of a function is passed in register R_{-i}
- the result of a function is stored in R_0
- local registers are saved before calling a function

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Definition

Let f be a function that calls g. A register R_i is called

- *caller-saved* if f backs up R_i and g may overwrite it
- *callee-saved* if f does not back up R_i, and g must restore it before returning

---

Translation of Function Calls

A function call $\mathrm{g}(e_1, \ldots e_n)$ is translated as follows:

$$\begin{array}{lll}
\mathrm{code}^i_{\mathrm{R}}\ \mathrm{g}(e_1, \ldots e_n)\ \rho & = & \mathrm{code}^i_{\mathrm{R}}\ \mathrm{g}\ \rho \\
 & & \mathrm{code}^{i+1}_{\mathrm{R}}\ e_1\ \rho \\
 & & \vdots \\
 & & \mathrm{code}^{i+n}_{\mathrm{R}}\ e_n\ \rho \\
 & & \mathrm{move}\ R_{-1}\ R_{i+1} \\
 & & \vdots \\
 & & \mathrm{move}\ R_{-n}\ R_{i+n} \\
 & & \mathrm{saveloc}\ R_1\ R_{i-1} \\
 & & \mathrm{mark} \\
 & & \mathrm{call}\ R_i \\
 & & \mathrm{restoreloc}\ R_1\ R_{i-1} \\
 & & \mathrm{move}\ R_i\ R_0
\end{array}$$

g

Calling a Function

The instruction call rescues the value of PC+1 onto the stack and sets FP and PC.

SP = SP+1;
S[SP] = PC;
FP = SP;
PC = Ri;

Result of a Function

The global register set is also used to communicate the result value of a function:

$$\begin{aligned} \text{code}^i\ \texttt{return}\ e\ \rho &= \text{code}_R^i\ e\ \rho \\ &\quad \text{move}\ R_0\ R_i \\ &\quad \text{return} \end{aligned}$$

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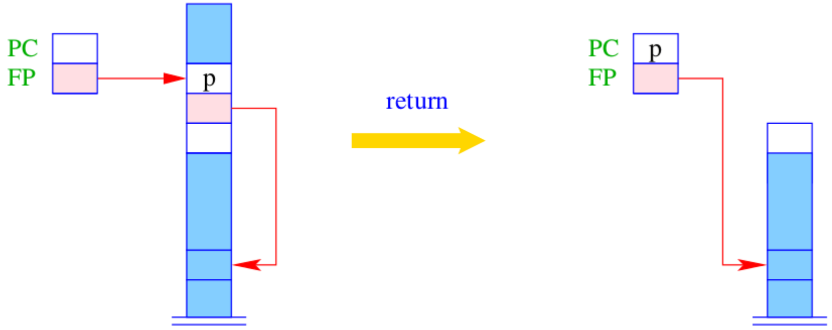
alternative without result value:

$$\text{code}^i\ \texttt{return}\ \rho = \text{return}$$

Return from a Function

The instruction return relinquishes control of the current stack frame, that is, it restores PC and FP.



PC = S[FP];
SP = FP-2;
FP = S[SP+1];

Translation of Functions

The translation of a function is thus defined as follows:

$$\begin{aligned} \text{code}^1\ t_r\ \texttt{f}(args)\{decls\ \ ss\}\ \rho &= \text{move}\ R_{l+1}\ R_{-1} \\ &\quad \vdots \\ &\quad \text{move}\ R_{l+n}\ R_{-n} \\ &\quad \text{code}^{l+n+1}\ ss\ \rho' \\ &\quad \text{return} \end{aligned}$$

Assumptions:

Translation of Whole Programs

A program $P = F_1; \ldots F_n$ must have a single `main` function.

$$
\begin{array}{lll}
\text{code}^1\; P\; \rho & = & \text{loadc}\; R_1\; \texttt{\_main} \\
 & & \text{mark} \\
 & & \text{call}\; R_1 \\
 & & \text{halt} \\
 & \_f_1 : & \text{code}^{\boxed{1}}\; F_1\; \rho \oplus \rho_{f_1} \\
 & & \vdots \\
 & \_f_n : & \text{code}^{\boxed{1}}\; F_n\; \rho \oplus \rho_{f_n}
\end{array}
$$

Translation of the `fac`-function

Consider:

```
int fac(int x) {
 if (x<=0) then
   return 1;
 else
   return x*fac(x-1);
}
```

```
_fac:     move $R_1$ $R_{-1}$      save param.
$i = 2$   move $R_2$ $R_1$         if (x<=0)
          loadc $R_3$ 0
          leq $R_2$ $R_2$ $R_3$
          jumpz $R_2$ $\_A$        to else
          loadc $R_2$ 1            return 1
          move $R_0$ $R_2$
          return
          jump $\_B$               code is dead

_A:       move $R_2$ $R_1$         x*fac(x-1)
$i = 3$   move $R_3$ $R_1$         x-1
$i = 4$   loadc $R_4$ 1
          sub $R_3$ $R_3$ $R_4$
$i = 3$   move $R_{-1}$ $R_3$      fac(x-1)
          loadc $R_3$ $\_fac$
          saveloc $R_1$ $R_2$
          mark
          call $R_3$
          restoreloc $R_1$ $R_2$
          move $R_3$ $R_0$
          mul $R_2$ $R_2$ $R_3$
          move $R_0$ $R_2$         return x*...
          return
_B:       return
```

End of presentation. Click to exit.