Script generated by TTT

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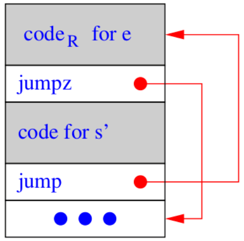
Iterating Statements

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

$$\text{code}^i\ \texttt{while}(e)\ s\ \rho \quad = \quad \begin{array}{ll} A: & \text{code}^i_R\ e\ \rho \\ & \text{jumpz}\ R_i\ B \\ & \text{code}^i\ s\ \rho \\ & \text{jump}\ A \\ B: & \end{array}$$



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) */
}
```

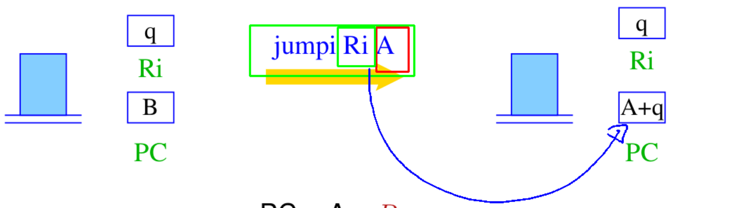
Then $\text{code}^i\ s\ \rho$ evaluates to:

	(i)	(ii)	(iii)
$A:$	move R_i R_7	move R_i R_9	move R_i R_7
	loadc R_{i+1} 0	loadc R_{i+1} 1	move R_{i+1} R_8
	gr R_i R_i R_{i+1}	add R_i R_i R_{i+1}	sub R_i R_i R_{i+1}
	jumpz R_i B	move R_9 R_i	move R_7 R_i
			jump A
		$B:$	

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



PC = A + R_i;

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;**
}

$0 \leq R_i \leq k$

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

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

Translation of the $check^i$ Macro

The macro $check^i\ l\ u\ B$ 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

we define:

$$
\begin{array}{lll}
check^i\ l\ u\ B & = & \text{loadc}\ R_{i+1}\ l \\
 & & \text{geq}\ R_{i+2}\ R_i\ R_{i+1} \\
 & & \text{jumpz}\ R_{i+2}\ E \\
 & & \text{sub}\ R_i\ R_i\ R_{i+1} \\
 & & \text{loadc}\ R_{i+1}\ u \\
 & & \text{geq}\ R_{i+2}\ R_i\ R_{i+1} \\
 & & \text{jumpz}\ R_{i+2}\ D \\
 & E: & \text{loadc}\ R_i\ u - l \\
 & D: & \text{jumpi}\ R_i\ B
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 & \text{jump}\ A_k \\
C:
\end{array}
$$

Note: a jump $\text{jumpi}\ R_i\ B$ with $R_i = u$ winds up at $B + u$, the default case

Improvements for Jump Tables

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

- In case the table starts with 0 instead of u l 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 $\leadsto O(\log n)$ 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

Chapter 4:

Functions

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:

$$\mathrm{code}_R^i\ f\ \rho \quad = \quad \mathrm{loadc}\ R_i\ \_f \quad \text{with } \_f \text{ starting address of } f$$

Observe:

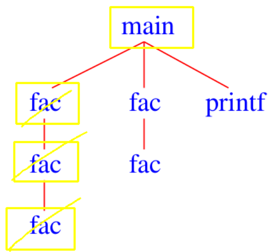
- function names must have an address assigned to them
- since the size of functions is unknown before they are translated, the addresses of forward-declared functions must be inserted later

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

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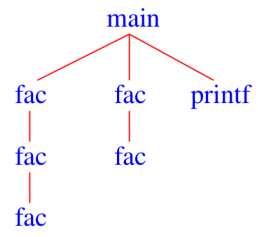

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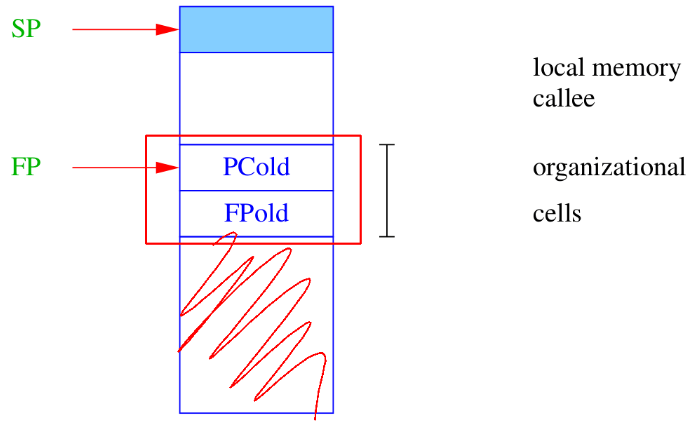
Organization of a Stack Frame

- 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

(steps 1–6 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

(steps 1–3 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

Translation of Function Calls

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

$$\text{code}^i_R\ g(e_1, \ldots e_n)\ \rho \quad = \quad \text{code}^i_R\ g\ \rho$$

$\text{code}^{i+1}_R\ e_1\ \rho$
$\vdots$
$\text{code}^{i+n}_R\ e_n\ \rho$
move R_{-1} R_{i+1}
$\vdots$
move R_{-n} R_{i+n}
saveloc R_1 R_{i-1}
mark
call R_i
restoreloc R_1 R_{i-1}
move R_i R_0

Rescuing the FP

The instruction mark allocates stack space for the ~~return value~~ and the organizational cells and backs up FP.

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

Result of a Function

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

$$\text{code}^i\ \boxed{\texttt{return}\ e}\ \rho \quad = \quad \boxed{\text{code}^i_{\text{R}}\ e\ \rho}$$
$$\text{move}\ R_0\ \boxed{R_i}$$
$$\text{return}$$

alternative without result value:

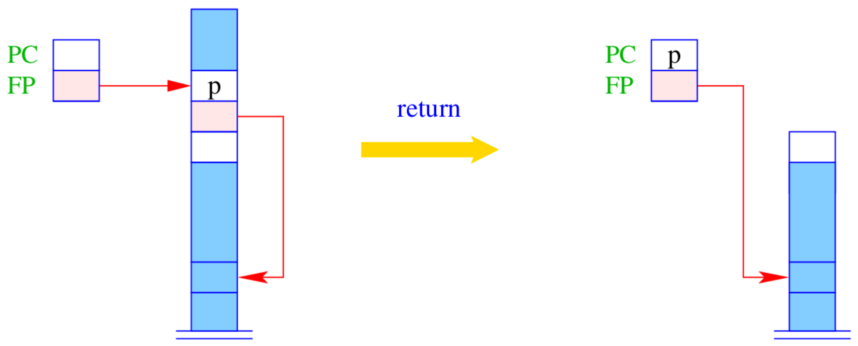
$$\text{code}^i\ \texttt{return}\ \rho \quad = \quad \text{return}$$

global registers are otherwise not used inside a function body:

- advantage: at any point in the body another function can be called without backing up *global* registers
- disadvantage: on entering a function, all *global* registers must be saved

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:

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

Assumptions:

- the function has n parameters
- the local variables are stored in registers $R_1, \ldots R_l$
- the parameters of the function are in $\boxed{R_{-1}, \ldots R_{-n}}$
- ρ' is obtained by extending ρ with the bindings in $decls$ and the function parameters $args$
- return is not always necessary

Are the move instructions always necessary?

Translation of Whole Programs

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

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

Assumptions:

- $\rho = \emptyset$ assuming that we have no global variables
- ρ_{f_i} contain the addresses the local variables
- $\rho_1 \oplus \rho_2 = \lambda x \,.\, \begin{cases} \rho_2(x) & \text{if } x \in \text{dom}(\rho_2) \\ \rho_1(x) & \text{otherwise} \end{cases}$

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	