Compilers and computer architecture: A realistic compiler to MIPS

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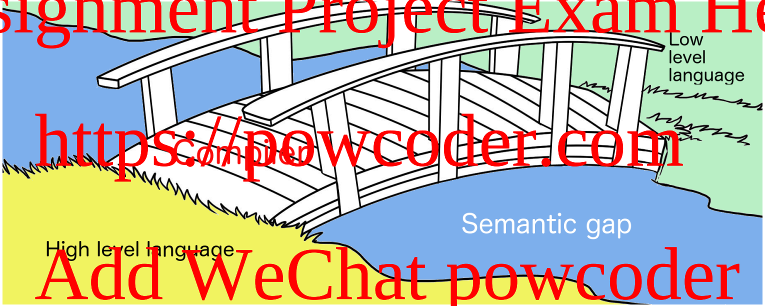
November 2017

Recall the function of compilers



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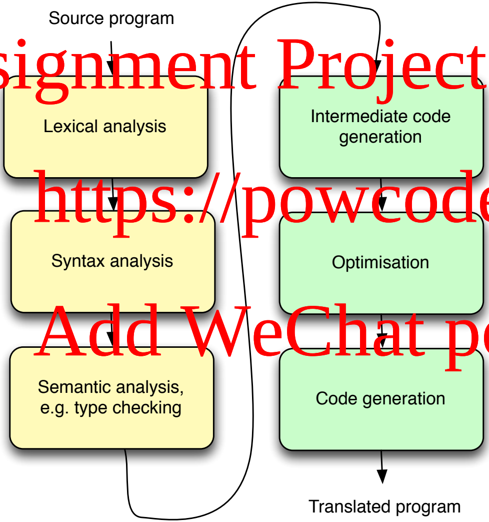

Introduction

Now we look at more realistic code generation. In the previous two lectures we investigated key issues in compilation for more realistic source and target languages, such as procedures and memory alignment. We also introduced the MIPS architecture, which has an especially clean instruction set architecture, is widely used (embedded systems, PS2, PSP), and has deeply influenced other CPU architectures (e.g. ARM).

Source language

The language we translate to MIPS is a simple imperative language with integers as sole data type and **recursive** procedures with arguments. Here's its grammar.

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\begin{array}{lcl}
P & \rightarrow & D\, P \mid D \\
D & \rightarrow & \texttt{def}\ \mathit{ID}\,(A) = E \\
A & \rightarrow & A_{ne} \mid \epsilon \\
A_{ne} & \rightarrow & \mathit{ID}, A_{ne} \mid \mathit{ID} \\
E & \rightarrow & \mathit{INT} \mid \mathit{ID} \mid \texttt{if}\ E = E\ \texttt{then}\ E\ \texttt{else}\ E \\
 & \mid & E + E \mid E - E \mid \mathit{ID}(EA) \mid x := E \\
EA & \rightarrow & \epsilon \mid EA_{ne} \\
EA_{ne} & \rightarrow & E \mid E, EA_{ne}
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All variables are of type integer and procedures return integers. We assume that the program passed semantic analysis.

Example program

```
def myFirstProg () = fib ( 3 );

def fib ( n ) =
   if n = 0 then
      1
   else if n = 1 then
      1
   else
      fib ( n-1 ) + fib ( n-2 )
```

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- the first argument is assumed to be in the accumulator;
- all remaining arguments sit on the (top of the) stack;
- the result of the operation is stored in the accumulator;
- after finishing the operation, all arguments are removed from the stack.

The code generator we will be presenting guarantees that all these assumptions always hold.

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- The stack grows downwards.

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We could have made other choices.

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For simplicity, we won't worry about over/underflow of arithmetic operations.

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As with the translation to an idealised accumulator machine a few weeks ago, we compile expressions by recursively walking the AST. We want to write the following:

```
def genExp ( e : Exp ) =
  if e is of form
    IntLiteral ( n ) then ...
    Variable ( x ) then ...
    If ( cond , thenBody, elseBody ) then ...
    Add ( l, r ) then ...
    Sub ( l, r ) then ...
    Call ( f, args ) then ... } }
```

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This preserves all invariants to do with the stack and the accumulator as required. Recall that li is a pseudo instruction and will be expanded by the assembler into several real MIPS instructions.

Code generation: addition

```
def genExp ( e : Exp ) =
  if e is of form
    Add ( l, r ) then
      genExp ( l )
      sw $a0 0($sp)
      addiu $sp $sp -4
      genExp ( r )
      lw $t1 4($sp)
      add $a0 $t1 $a0
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Note that this evaluates from left to right! Recall also that the stack grows downwards and that the stack pointer points to the first free memory cell above the stack.

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Question: Why not store the result of compiling the left argument directly in `$t0`? Consider 1+(2+3)

Code generation: minus

We want to translate $e - e'$. We need new MIPS command:

```
sub reg1 reg2 reg3
```


It subtracts the content of `reg3` from the content of `reg2` and stores the result in `reg1`. I.e. `reg1 := reg2 - reg3`.

Code generation: minus


```
def genExp ( e : Exp ) =
  if e is of form
    Minus ( l, r ) then
      genExp ( l )
      sw $a0 0($sp)
      addiu $sp $sp -4
      genExp ( r )
      lw $t1 4($sp)
      sub $a0 $t1 $a0 // only change from addition
      addiu $sp $sp 4
```


Note that `sub $a0 $t1 $a0` deducts `$a0` from `$t1`.

Code generation: conditional

We want to translate `if` $e_1 = e_2$ `then` e `else` e'. We need two new MIPS commands:


```
beq reg1 reg2 label
```

```
b label
```


`beq` branches (= jumps) to `label` if the content of `reg1` is identical to the content of `reg2`. Otherwise it does nothing and moves on to the next command.

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In contrast `b` makes an unconditional jump to `label`.

Code generation: conditional

```
def genExp ( e : Exp ) =
   if e is of form
    If ( l, r, thenBody, elseBody ) then
      val elseBranch = newLabel () // not needed
      val thenBranch = newLabel ()
      val exitLabel = newLabel ()
        genExp ( l )
        sw $a0 0($sp)
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        beq $a0 $t1 thenBranch
     elseBranch + ":"
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`newLabel` returns new, distinct string every time it is called.

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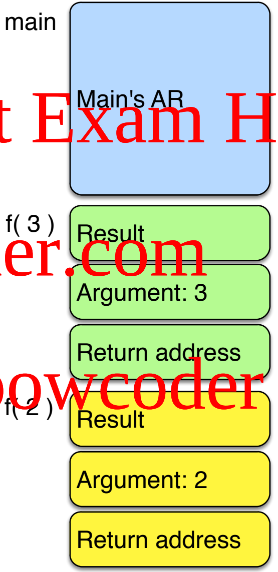
Note that invocation result and (some) procedure arguments are often passed in register not in AR (for efficiency)



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The stack calling discipline ensures that on procedure exit `$sp` is the same as on procedure entry.

Also: no registers need to be preserved in accumulator machines. Why? Because no register is used except for the accumulator and `$t0`, and when a procedure is invoked, all previous evaluations of expressions are already discharged or ’tucked away’ on the stack.

Code generation: procedure calls/declarations

So ARs for a procedure with *n* arguments look like this:

caller's FP
argument n
...
argument 1
return address

A pointer to the **top** of current AR (i.e. where the return address sits) is useful (though not necessary) see later. This pointer is called **frame pointer** and lives in register `$fp`. We need to restore the caller's FP on procedure exit, so we store it in the AR upon procedure entry. The FP makes accessing variables easier (see later).

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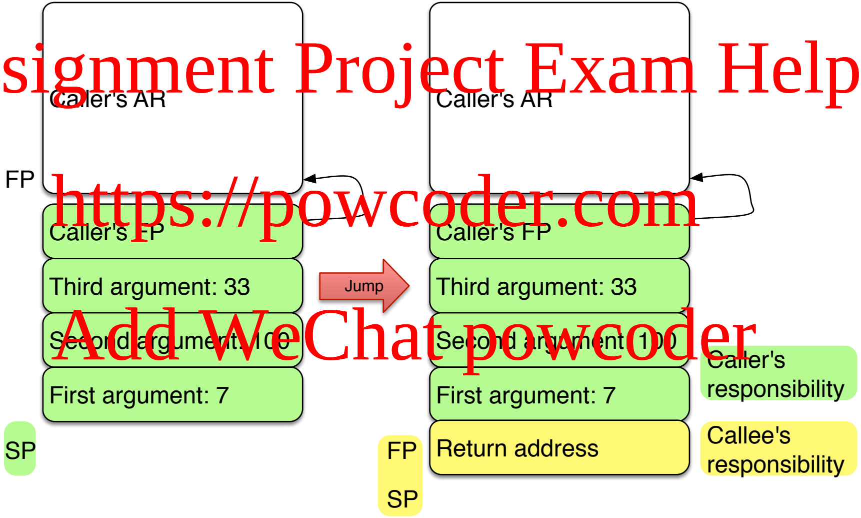
Arguments are stored in reverse order to make indexing a bit easier.

Code generation: procedure calls/declarations

Let's look at an example: assume we call $f(7, 100, 33)$



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Note that `jal` stands for **jump and link.** This instruction does the following:

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On MIPS we must push the return address on stack explicitly. This can only be done by callee, because address is available only after `jal` has executed.

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```
case Call ( f, List ( e1, e2, e3 ) ) then
  sw $fp 0($sp) // save FP on stack
  addiu $sp $sp -4
  genExp ( e3 ) // we choose right-to-left ev. order
  sw $a0 0($sp) // save 3rd argument on stack
  addiu $sp $sp -4
  genExp ( e2 )
  sw $a0 0($sp) // save 2nd argument on stack
  addiu $sp $sp -4
  genExp ( e1 )
  sw $a0 0($sp) // save 1st argument on stack
  addiu $sp $sp -4
  jal ( f + "_entry" )  // jump to f, save return
                        // addr in $ra
```

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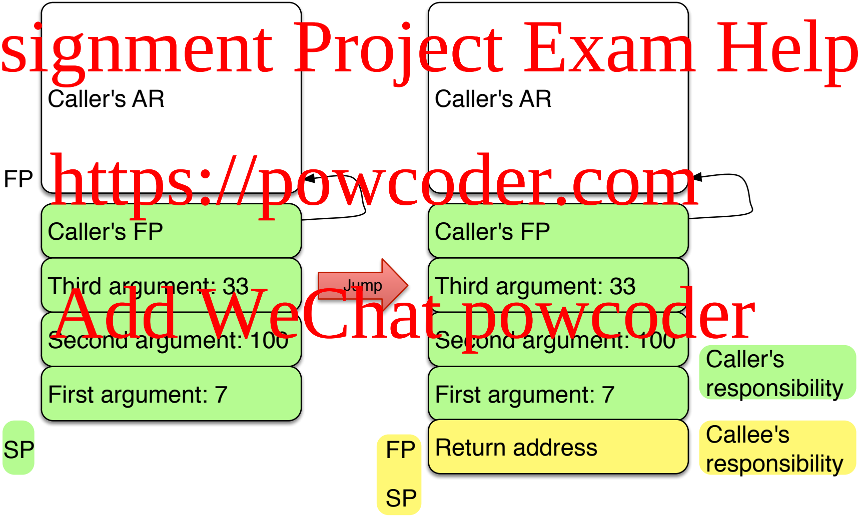
- How big is the AR? For a procedure with n arguments the AR (without return address) is $4 + 4 * n = 4(n + 2)$ bytes long. This is **know at compile time** and is important for the compilation of procedure bodies.
- The translation of procedure invocations is generic in the number of procedure arguments, nothing particular about 3.

Code generation: procedure calls

So far we perfectly adhere to the lhs of this picture (except 33, 100, 7).



Code generation: procedure calls, callee's side

In order to compile a declaration `d` like

```
def f ( x1, ..., xn ) = body
```


we use a procedure for compiling declarations like so:

```
def genDecl ( d ) = ...
```

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We need two new MIPS instructions:


```
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```

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The former (`jr reg`) jumps to the address stored in register `reg`.

The latter (`move reg reg'`) moves the content of register `reg'` into the register `reg`.

Code generation: procedure calls, callee's side

```
def genDecl ( d : Declaration ) =
  val sizeAR = ( 2 + d.args.size ) * 4
         // each procedure argument takes 4 bytes
         // in addition the AR stores the return
         // address and old FP
  d.id + "_entry:" // label to jump to
    move $fp $sp // FP points to top of current AR
    sw $ra 0($sp) // put return address on stack
    addiu $sp $sp -4  // now AR is fully created
    genExp ( d.body )
    lw $ra 4($sp) // load return address into $ra
                  // could also use $fp
    addiu $sp $sp sizeAR // pop AR off stack in one go
    lw $fp 0($sp) // restore old FP
    jr $ra  // hand back control to caller
```

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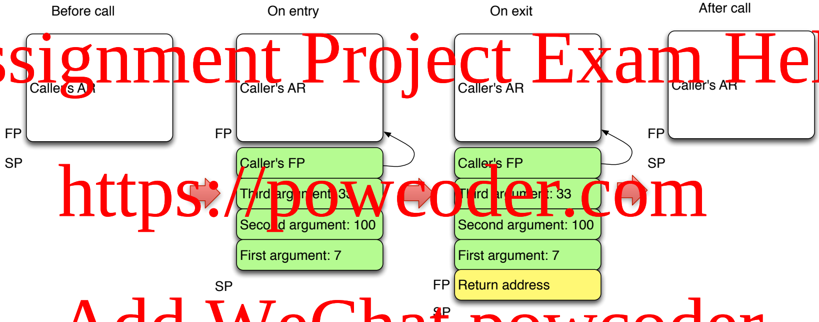
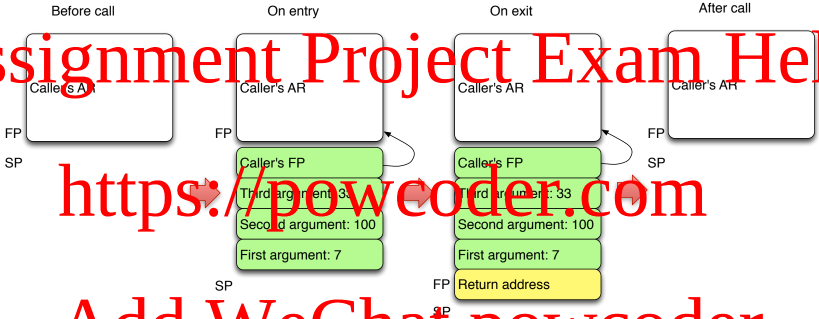


Code generation: procedure calls, callee's side



So we preserve the invariant that the stack looks exactly the same before and after a procedure call!

Code generation: frame pointer

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- Always points to the top of current AR as long as invocation is active.
- The FP does not (appear to) move, so we can find all variables at a fixed offset from `$fp`.

Code generation: variable use

Let's compile *x* which is the i-th (starting to count from 1) parameter of `def f(x1, x2, ..., xn) = body` works like this (using offset in AR):


```
def genExp ( e : Exp ) =
   if e is of form Variable ( x ) then
      val offset = 4*i
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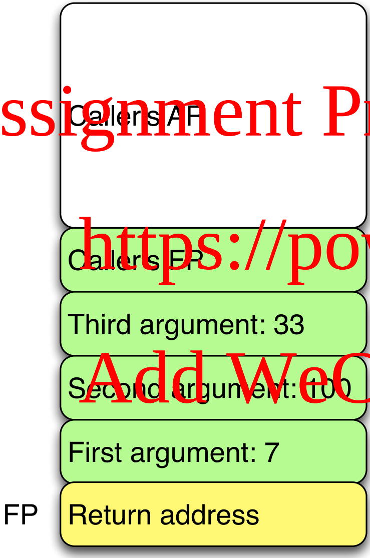
Key insight: access at **fixed offset** relative to a dynamically changing pointer. Offset and pointer location are known at compile time.

This idea is pervasive in compilation.

Code generation: variable use



In the declaration `def f (x, y, z) = ...`, we have:

- x is at address `$fp + 4`
- y is at address `$fp + 8`
- z is at address `$fp + 12`

Note that this work because indexing begins at 1 in this case, and arguments are pushed on stack from right to left.

Translation of variable assignment

Given that we know now that reading a variable is translated as

```
if e is of form Variable ( x ) then
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How would you translate an assignment

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Easy!

Code generation: summary remarks

The code of variable access, procedure calls and declarations depends totally on the layout of the AR, so the AR must be designed together with the code generator, and all parts of the code generator must agree on AR conventions. It's just as important to be clear about the nature of the stack (grows upwards or downwards), frame pointer etc.

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Industrial strength compilers are more complicated:

- Try to keep values in registers, especially the current stack frame. E.g. compilers for MIPS usually pass first four procedure arguments in registers `$a0 - $a3`.
- Intermediate values, local variables are held in registers, not on the stack.

Non-integer procedure arguments

What we have not covered is procedures taking non integer arguments.

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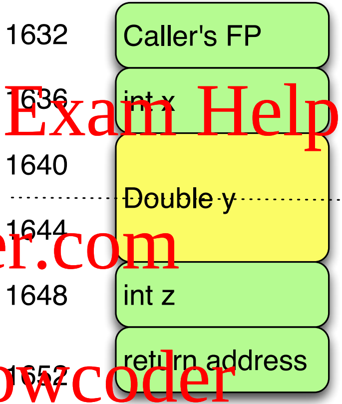
This is easy: the only difference from a code generation perspective between integer types and other types as procedure arguments is the **size** of the data. But that size is known at compile-time (at least for languages that are statically typed). For example the type `double` is often 64 bits. So we reserve 8 bytes for arguments of that type in the procedure's AR layout. We may have to use two calls to `lw` and `sw` to load and store such arguments, but otherwise code generation is unchanged.

Non-integer procedure arguments

Consider a procedure with the following signature:

```
int f ( int x,
        double y,
        int z ) = { ... }
```

(Not valid in our mini-language).
Assuming that `double` is stored as 64 bits, then the AR would look like on the right.



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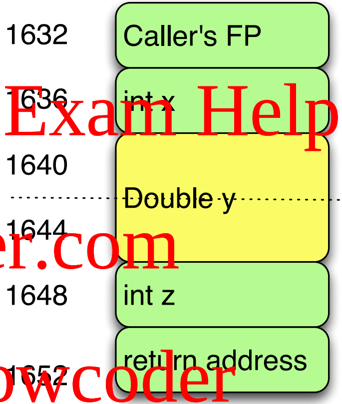

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1632	Caller's FP
1636	int x
1640	Double y
1644	
1648	int z
1652	return address

How does the code generator know what size the variables have?

Using the information stored in the symbol table, which was created by the type checker and passed to the code-generator.

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Due to the simplistic accumulator machine approach, cannot do the same with the return value, e.g.


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double f ( int x, double y, int z ) = ...
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In this case we'd have to move to an approach that holds the return value also in the AR (either for all arguments, or only for arguments that don't fit in a register – we know at compile time which is which).

Example `def sumto(n) = if n=0 then 0 else n+sumto(n-1)`


```
sumto_entry:
   move $fp $sp
   sw $ra 0($sp)
   addiu $sp $sp -4
   lw $a0 4($fp)
   sw $a0 0($sp)
   addiu $sp $sp -4
   li $a0 0
   lw $t1 4($sp)
   addiu $sp $sp 4
   beq $a0 $t1 then1
else0:
   lw $a0 4($fp)
   sw $a0 0($sp)
   addiu $sp $sp -4
   sw $fp 0($sp)
   addiu $sp $sp -4
   lw $a0 4($fp)
   sw $a0 0($sp)
   addiu $sp $sp -4
   li $a0 1
   lw $t1 4($sp)
   sub $a0 $t1 $a0
   addiu $sp $sp 4
   sw $a0 0($sp)
   addiu $sp $sp -4
   jal sumto_entry
   lw $t1 4($sp)
   add $a0 $t1 $a0
   addiu $sp $sp 4
   b exit2
then1:
   li $a0 0
exit2:
   lw $ra 4($sp)
   addiu $sp $sp 12
   lw $fp 0($sp)
   jr $ra
```

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Interesting observations

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Stack allocated memory is much **faster** than heap allocation, because (1) acquiring stack memory is just a constant-time push operation, and (2) the whole AR can be 'deleted' (= popped off the stack) in a single, constant-time operation. We will soon learn about heap-allocation (section on garbage-collection), which is much more expensive. This is why low-level language (C, C++, Rust) don't have garbage collection (by default).

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The source language has recursion. The target language (MIPS) does not. What is recursion translated to? Jumping! But what kind of jumping? **Backwards jumping**.

Another interesting observation: inefficiency of the translation

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lw $a0 4($fp)       // first we load n into the
                    // accumulator from the stack
sw $a0 0($sp)       // then we push n back onto
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It's possible to do much better, e.g. saving it directly in `$t1` using better compilation strategies and optimisation techniques.

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  1. Creating (the caller's side of) an activation record.
  2. Jump-and-link'ing to the first procedure.
  3. Code that hands back control gracefully to the OS after program termination. Termination means doing a return to the place after (2). This part is highly OS specific.

Compiling whole programs

Say we had a program declaring 4 procedures `f1`, `f2`, `f3`, and `f4` in this order. Then a fully formed compiler would typically generate code as follows.


```
preamble
   ...// e.g. alignment commands if needed
entry_point: // this is where the OS jumps to
             // at startup
   ... // create AR for initial call to f1
   jal f1_entry // jump to f1
   ... // cleanup, hand back control to OS
f1_entry:
   ... // f1 body code
f2_entry:
   ... // f2 body code
f3_entry:
   ... // f3 body code
f4_entry:
   ... // f4 body code
```