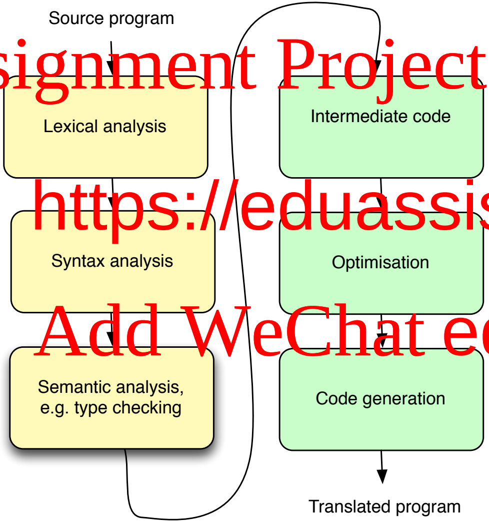
Compilers and computer architecture:
A realistic compiler to MIPS

November 20

Recall the function of compilers

Recall the structure of compilers



Now we look at more realistic code generation. In the previous
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whic
widely used (embedded systems, PS2, PS
influenced other CPU architectures (e.g. A

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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$$D \rightarrow \texttt{def}\ ID\,(A) = E$$

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first declared procedure is the entry point (i.e. will be executed when the program is run) and must take **0 arguments**. Procedure names must be **distinct**.

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first declared procedure is the entry point (i.e. will be executed when the program is run) and must take **0 arguments**. Procedure names must be **distinct**.

All variables are of type integer and procedures return integers. We assume that the program passed semantic analysis.

Example program


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

        1
    else
        fib ( n-1 ) + fib ( n-2 )
```

Generating code for the language

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- after finishing the operation, all argum from the stack.

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

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To use MIPS as an accumulator machine we need to decide what registers to use as stack pointer and accumulator.

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We could have made other choices.

Assumption about data types

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Code generation

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As with the translation to an idealised accumulator machine a few w

the A


```
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 ... } }
```

Code generation: integer literals

Let's start with the simplest case.

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def genExp ( e : Exp ) =
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This preserves all invariants to do with the sta 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

      addiu $sp $sp 4
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Note that this evaluates from left to right! Reca stack grows downwards and that the stack p 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`?

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first free memory cell above the stack.

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:

It sub 2 and stores the result in reg1. I.e. reg1 := r

Code generation: minus


```
def genExp ( e : Exp ) =
  if e is of form
    Minus ( l, r ) then
```



```
      lw $t1 4($sp)
      sub $a0 $t1 $a0 // only change from a
      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:


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beq reg1 reg2 label
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`beq` branches (= jumps) to `label` if t
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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 ()

        lw $t1 4($sp)
        addiu $sp $sp 4
        beq $a0 $t1 thenBranch
     elseBranch + ":"
        genExp ( elseBody )
        b exitLabel
     thenBranch + ":"
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   elseBranch + ":"
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      genExp ( thenBody )
   exitLabel +  ":" }
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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 p `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
...
arg
ret

A poi
address sits) is useful (though not necessar
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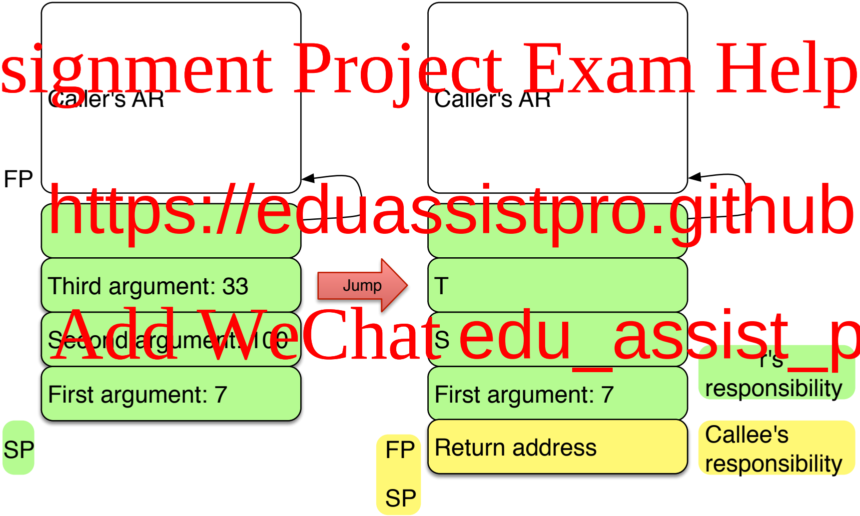
Arguments are stored in reverse order to make indexing a bit easier.

Code generation: procedure calls/declarations

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



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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.

Code generation: procedure calls

Example of procedure call with 3 arguments. General case is similar.

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```
case Call ( f, List ( e1, e2, e3 ) ) then
  sw $fp 0($sp) // save FP on stack
  a
  g
  s
  a
  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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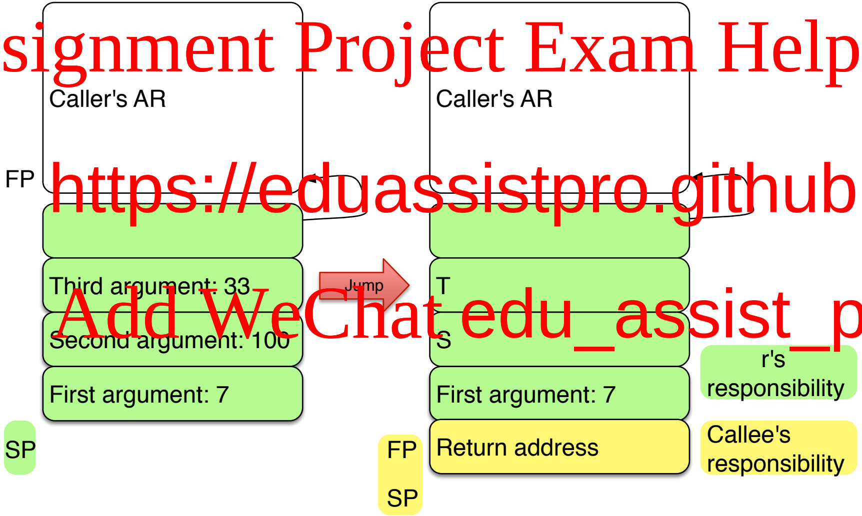
- The translation of procedure invocations is generic in the number of procedure arguments, nothing particular about 3.

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

```
d
```

we us


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

Code generation: procedure calls, callee's side

We need two new MIPS instructions: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The former (`jr reg`) jumps to the addre

`reg`.

The latter (`move reg reg'`) moves th

`reg'` into the register `reg`.

```
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
```



```
    addiu $sp $sp -4  // now AR is fully created
    genExp ( d.body )
    lw $ra 4($sp)  // load return address in
                   // could also use $
    addiu $sp $sp sizeAR // pop AR off stack in o
    lw $fp 0($sp) // restore old FP
    jr $ra  // hand back control to caller
```

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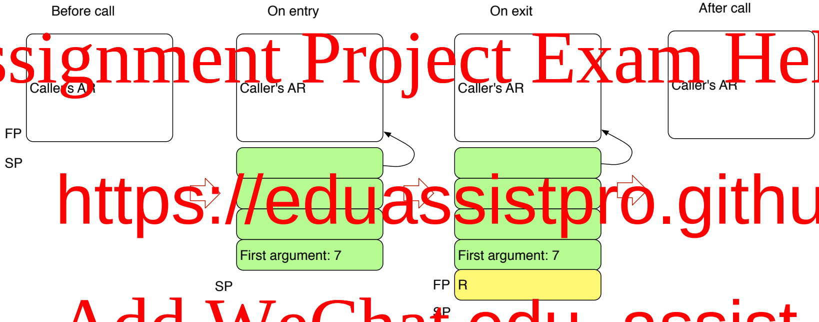

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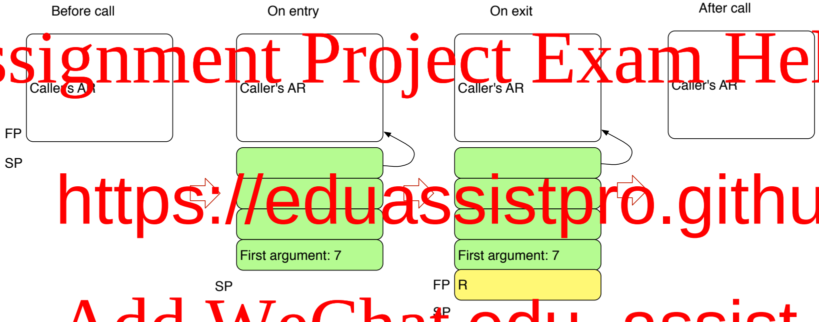

So we preserve the invariant that the stack loo
same before and after a procedure call!

Code generation: frame pointer

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Solution: Use **frame pointer** `$fp`.

- 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
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Key insight: access at **fixed offset** r changing pointer. Offset and pointer location are known at compile time.

This idea is pervasive in compilation.

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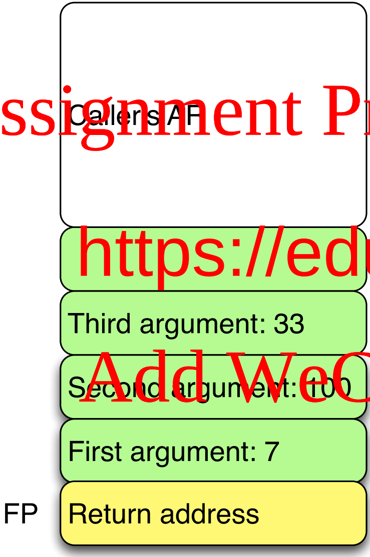

In the declaration `def f (x, y, z) = ...`, we have:

Note th
indexi
and ar
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
    val offset = 4*i
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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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Code generation happens by recursive AS

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.

Acc [illegible] er.
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Code and layout also depends on CPU.

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- 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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typed). For example the type `doubl`
reserve 8 bytes for arguments of that type in th
AR layout. We may have to use two calls to
and store such arguments, but otherwise co
unchanged.

Non-integer procedure arguments

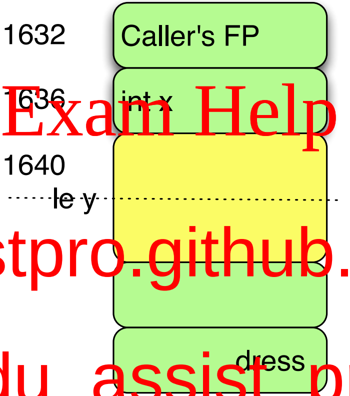
Consider a procedure with the following signature:

```
int f ( int x,
        double y,
```

(Not v

Assu

64 bits, then the AR would look like on the right.



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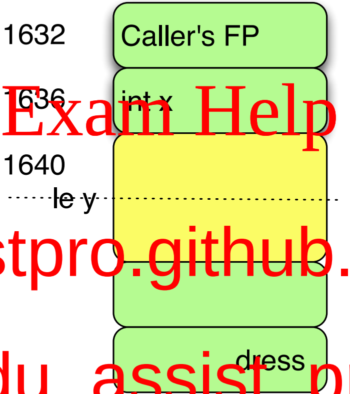

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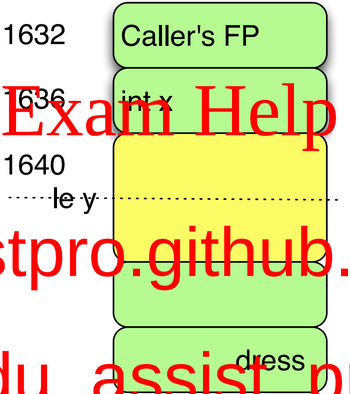

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How does the code generator know what size the variables have?

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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proc

In this case we'd have to move to an approach t return value also in the AR (either for all argum arguments that don't fit in a register – we know a 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)
```



```
    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)
```

```
exit2:
    lw $ra 4($sp)
    addiu $sp $sp 12
    lw $fp 0($sp)
    jr $ra
```

Interesting observations

Several points are worth thinking about.

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Stack allocated memory is much **faster** than heap allocation, because (1) acquiring stack memory is just a constant-time

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Another interesting observation: inefficiency of the translation

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lw $a0 4($fp)       // first we load n into the
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addiu $sp $sp -4
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This is the price we pay for the simplicity of compilation strategy.

It's possible to do much better, e.g. saving it directly in `$t1` using better compilation strategies and optimisation techniques.

Compiling whole programs

So far we have only compiled expressions and single declarations, but a program is a sequence of declarations, and it is called from, and returns to the OS. To compile a whole program we do the following:

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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
```



```
    ... // 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
```