08-0: **Code Generation**

- Next Step: Create actual assembly code.
- Use a tree tiling strategy:
  - Create a set of tiles with associated assembly code.
  - Cover the AST with these tiles.
  - Output the code associated with each tiles.
- As long as we are clever about the code associated with each tile, and how we tile the tree, we will create correct actual assembly.

08-1: **Target Assembly**

- Our compiler will produce MIPS code
  - RISC code is easier to generate than x86
  - You are more familiar with RISC assembly (from Architecture and/or cs220)

08-2: **MIPS**

| Instruction | Description |
|---|---|
| lw rt, <offset> (base) | Add the constant value <*offset*> to the register *base* to get an address. Load the contents of this address into the register *rt*. rt = M[base + <offset>] |
| sw rt, <offset> (base) | Add the constant value <offset> to the register base to get an address. Store the contents of rt into this address. M[base + <offset>] = rt |
| add rd, rs, rt | Add contents of registers rs and rt, put result in register rd |

08-3: **MIPS**

| Instruction | Description |
|---|---|
| sub rd, rs, rt | Subtract contents of register rt from rs, put result in register rd |
| addi rt, rs, <val> | Add the constant value <val> to register rs put result in register rt |
| mult rs, rt | Multiply contents of register rs by register rt, put the low order bits in register LO, and the high bits in register HI |
| div rs, rt | Divide contents of register rs by register rt, put the quotient in register LO, and the remainder in register HI |

08-4: **MIPS**

| Instruction | Description |
|---|---|
| mflo rd | Move contents of the special register LOW into the register rd |
| j <target> | Jump to the assembly label <*target*> |
| jal <target> | Jump and link. Put the address of the next instruction in the *Return* register, and then jump to the address <target>. Used for function and procedure calls |
| jr rs | Jump to the address stored in register rs. Used in conjunction with jal to return from function and procedure calls |

08-5: **MIPS**

| Instruction | Description |
|---|---|
| slt rd, rs, rt | if rs < rt, rd = 1, else rd = 0 |
| beq rs, rt, <target> | if rs = rt, jump to the label <target> |
| bne rs, rt, <target> | if rs ≠ rt, jump to the label <target> |
| blez rs, <target> | if rs ≤ 0, jump to label <target> |
| bgtz rs, <target> | if rs > 0, jump to label <target> |
| bltz rs, <target> | if rs < 0, jump to the label <target> |
| bgez rs, <target> | if rs ≥ 0, jump to the label <target> |

08-6: **Registers**

- MIPS processors use 32 different registers
- We will only use a subset for this project
  - (Though you can increase the number of registers used for temporary values fairly easily)

08-7: **Registers**

| Mnemonic Name | SPIM Name | Description |
|---|---|---|
| $FP | $fp | Frame Pointer – Points to the top of the current activation record |
| $SP | $sp | Stack Pointer – Used for the activation record (stack frame) stack |
| $ESP | | Expression Stack Pointer – The expression stack holds temporary values for expression evaluations |
| $result | $v0 | Result Register – Holds the return value for functions |

08-8: **Registers**

| Mnemonic Name | SPIM Name | Description |
|---|---|---|
| $return | $ra | Return Register – Holds the return address for the current function |
| $zero | $zero | Zero Register – This register always has the value 0 |
| $ACC | $t0 | Accumulator Register – Used for calculating the value of expressions |
| $t1 | $t1 | General Purpose Register |
| $t2 | $t2 | General Purpose Register |
| $t3 | $t3 | General Purpose Register |

08-9: **Expression Stack**

- Long expressions – a * b + c * d * foo(x) – will require us to store several temporary values
- Since expressions can be arbitrarily long, we will need to store an unlimited number of partial solutions
  - Can't always use registers – not enough of them
  - Use a stack instead

08-10: **Expression Stack**

- For now, we will use an entirely different stack than the one for activation records
  - Make debugging easier
  - Later on, we can combine the stacks

08-11: **Tree Tilings**

- We will explore several different tree tiling strategies:
  - Simple tiling, that is easy to understand but produces inefficient code

- More complex tiling, that relies less on the expression stack
- Modifications to complex tilings, to increase efficiency

08-12: **Simple Tiling**

- Based on a post-order traversal of the tree
- Cover the tree with tiles
  - Each tile associated with actual assembly
- Emit the code associated with the tiles in a left-to-right, post-order traversal of the tree

08-13: **Simple Tiling**

- Expression Trees
  - The code associated with an expression tree will place the value of that expression on the top of the expression stack

08-14: **Expression Trees**

- Constant Expressions
  - Constant(5)
    - Push the constant 5 on the top of the expression stack

08-15: **Expression Trees**

- Constant Expressions
  - How can we push the constant $x$ on top of the expression stack, using MIPS assembly?

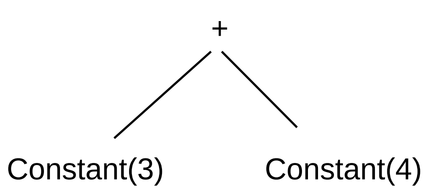
08-16: **Expression Trees**

- Constant Expressions
  - How can we push the constant $x$ on top of the expression stack, using MIPS assembly?

```
addi $t1, $zero, x
sw   $t1, 0($ESP)
addi $ESP, $ESP, -4
```

08-17: **Expression Trees**

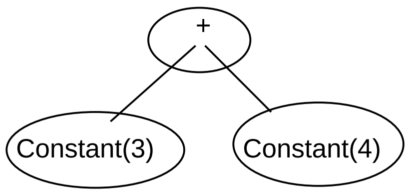
- Arithmetic Binary Operations




- Instead of using a single tile to cover this tree, we will use three.

08-18: **Expression Trees**

- Arithmetic Binary Operations




- What should the code for the + tile be?
  - Code for entire tree needs to push *just* the final sum on the stack
  - Code for Constant Expressions push constant values on top of the stack

08-19: **Expression Trees**

- Code is emitted in a post-order traversal of the tree
  - When code for + is executed
    - The values of the left and right sub-expressions are stored on the stack
    - Right sub-expression is on the top of the stack

08-20: **Expression Trees**

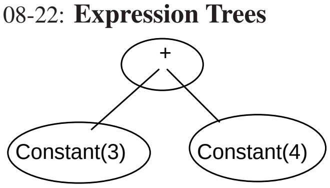
- Code is emitted in a post-order traversal of the tree
  - When code for + is executed
    - The values of the left and right sub-expressions are stored on the stack
    - Right sub-expression is on the top of the stack
- Pop the left and right sub-expressions of the stack
- Add their values
- Push the result on the stack

08-21: **Expression Trees**

- Arithmetic Binary Operations
  - Code for a "+" tile:

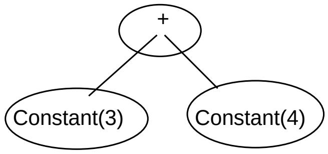
```
lw   $t1, 8($ESP)     % load first operand
lw   $t2, 4($ESP)     % load the second operand
add  $t1, $t1, $t2    % do the addition
sw   $t1, 8($ESP)     % store the result
add  $ESP, $ESP, 4    % update the ESP
```

08-22: **Expression Trees**



- Complete Assembly:

08-23: **Expression Trees**




```
addi $t1, $zero, 3      % Load the constant value 3 into the register $t1
sw   $t1, 0($ESP)       % Store $t1 on the top of the expression stack
addi $ESP, $ESP, -4     % update the expression stack pointer
addi $t1, $zero, 4      % Load the constant value into 4 the register $t1
sw   $t1, 0($ESP)       % Store $t1 on the top of the expression stack
addi $ESP, $ESP, -4     % update the expression stack pointer
lw   $t1, 8($ESP)       % load the first operand into temporary $t1
lw   $t2, 4($ESP)       % load the second operand into temparary $t2
add  $t1, $t1, $t2      % do the addtion, storing result in $t1
sw   $t1, 8($ESP)       % store the result on the expression stack
add  $ESP, $ESP, 4      % update the expression stack pointer
```

08-24: **Expression Trees**

- Register Trees
  - Register(FP)
  - We will cover this tree with a single tile
  - Code for the tree needs to store the register on top of the stack

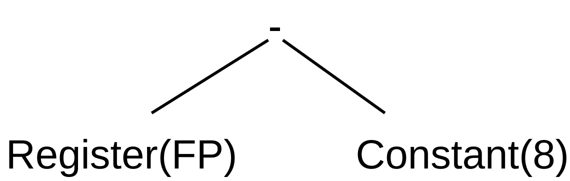
08-25: **Expression Trees**

- Register Trees
  - Register(FP)

```
sw   $FP,  0($ESP)     % Store frame pointer
addi $ESP, ESP, -4     % Update the ESP
```

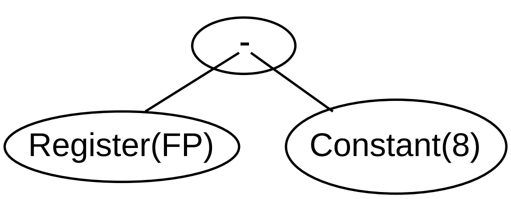
08-26: **Expression Trees**

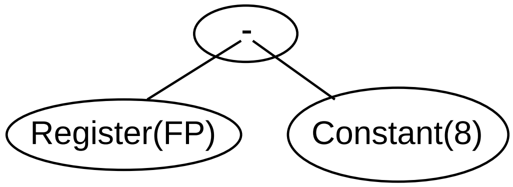
- Tiling the tree:




08-27: **Expression Trees**

- Tiling the tree:



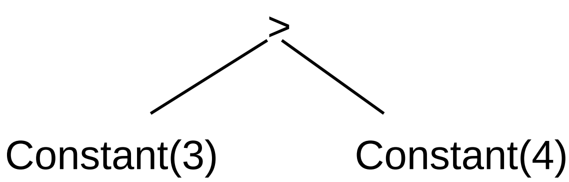



08-28: **Expression Trees**

```
sw   $FP,  0($ESP)    % Store frame pointer on the top of the expression stack
addi $ESP, $ESP, -4   % Update the expression stack pointer
addi $t1, $zero, 8    % Load the constant value 8 into the register $t1
sw   $t1, 0($ESP)     % Store $t1 on the top of the expression stack
addi $ESP, $ESP, -4   % update the expression stack pointer
lw   $t1, 8($ESP)     % load the first operand into temporary $t1
lw   $t2, 4($ESP)     % load the second operand into temparary $t2
sub  $t1, $t1, $t2    % do the subtraction, storing result in $t1
sw   $t1, 8($ESP)     % store the result on the expression stack
add  $ESP, $ESP, 4    % update the expression stack pointer
```

08-29: **Expression Trees**

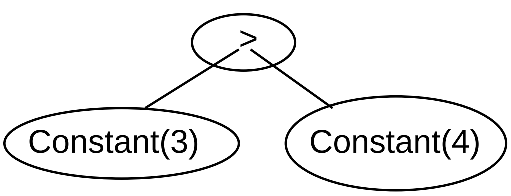
- Relational Operations
  - Relational operators – $<$, $>$, $=$, etc – produce boolean values
  - Assembly code for a relational operator tile needs to put a 0 or 1 on the expression stack



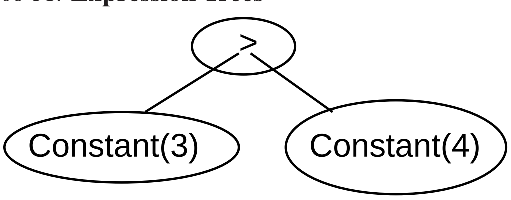

- If we tile the tree with one tile / tree node:

08-30: **Expression Trees**

- Relational Operations
  - Relational operators – $<$, $>$, $=$, etc – produce boolean values
  - Assembly code for a relational operator tile needs to put a 0 or 1 on the expression stack




08-31: **Expression Trees**




- Tile for $>$ should:

    - Pop the left & right operands off the top of the stack
    - Push a 1 on the stack if the first operand is greater than the second operand
    - Push a 0 on the stack otherwise
        - Remember that the *second* operand is on the top of the stack

08-32: **Expression Trees**

- Tile for >:
    - Store the left and right operands in registers $t1 and $t2
    - $t1 > $t2 iff $t2 < $t1
        - Use slt
    - Store result on the top of the stack

08-33: **Expression Trees**

- Tile for >:

```
lw   $t1, 8($ESP)
lw   $t2, 4($ESP)
slt  $t1, $t2, $t1
sw   $t1, 8($ESP)
addi $ESP, $ESP, 4
```

08-34: **Expression Trees**

- Relational Operations
    - <=, >=
        - SimpleJava uses all integer operands
        - x <= y iff (x-1) < y

08-35: **Expression Trees**

- Relational Operations
    - ==, ! =
        - Can't use `slt` easily
        - Use beq instead

08-36: **Expression Trees**

- Relational Operations
    - ==, ! =
        - Store the left and right operands of == in registers $t1 and $t2
        - If $t1 == $t2, jump to a code segment that stores 1 on top of the stack.
        - Otherwise, store a 0 on the top of the stack

08-37: **Expression Trees**

- Code for == tile:

```
        lw   $t1, 8($ESP)
        lw   $t2, 4($ESP)
        beq  $t1, $t2,    truelab
        addi $t1, 0
        j    endlab
truelab:
        addi $t1, 1
endlab:
        sw   $t1, 8,($ESP)
        addi $ESP, $ESP, 4
```

08-38: **Expression Trees**

- Boolean Operations
  - AND, OR, NOT
  - Take as operators boolean values
  - Return boolean values
  - Pop off the operands, push value back on the stack

08-39: **Expression Trees**

- If we use 0 for false, 1 for true
  - Implement (NOT x) as 1-x
  - Implement (x OR y), (x AND y) in a similar fashion to $<$, $>$, etc.
    - Use `slt` to calculate return value
- If we use 0 for false, non-zero for true
  - Implement (x OR y) as x + y
  - Implement (X AND y) as x*y
  - Use `slt` for NOT

08-40: **Expression Trees**

- Memory Accesses
  - Memory node is a memory dereference
    - Pop operand into a register
    - Dereference register
    - Push result back on stack

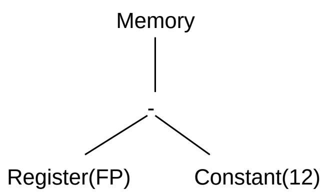
08-41: **Expression Trees**

- Memory Accesses

```
lw $t1, 4($ESP)
lw $t1, 0($t1)
sw $t1, 4($ESP)
```

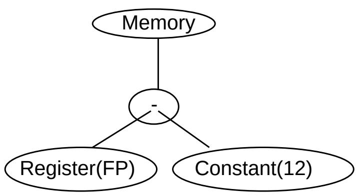
08-42: **Expression Trees**

- Memory Example

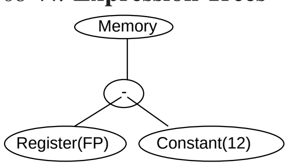



08-43: **Expression Trees**

- Memory Example




08-44: **Expression Trees**



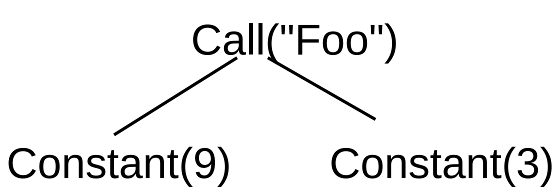

```
sw   $FP,  0($ESP)     % Store frame pointer on the top of the expressin stack
addi $ESP, $ESP,  -4   % Update the expression stack pointer
addi $t1,  $zero, 12   % Load the constant value 12 into the register $t1
sw   $t1,  0($ESP)     % Store $t1 on the top of the expression stack
addi $ESP, $ESP,  -4   % update the expression stack pointer
lw   $t1,  8($ESP)     % load the first operand into temporary $t1
lw   $t2,  4($ESP)     % load the second operand into temparary $t2
sub  $t1,  $t1,    $t2 % do the subtraction, storing result in $t1
sw   $t1,  8($ESP)     % store the result on the expression stack
add  $ESP, $ESP,   4   % update the expression stack pointer
lw   $t1,  4($ESP)     % Pop the address to dereference off the top of
                       % the expression stack
lw   $t1, 0($t1)       % Dereference the pointer
sw   $t1, 4($ESP)      % Push the result back on the expression stack
```

08-45: **Expression Trees**

- Function calls
  - Pop off all actual parameters of the Expression Stack
  - Push actual parameters onto activation record stack
  - Jump to the start of the function (jal)
  - After function returns, push $Result register onto the Expression Stack

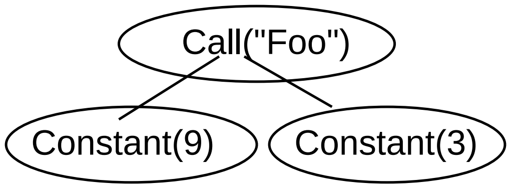
08-46: **Expression Trees**

- Function calls

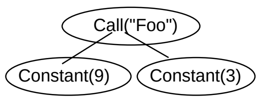



08-47: **Expression Trees**

- Function calls




08-48: **Expression Trees**




- Code for the Call tile

```
lw   $t1   4($ESP)
sw   $t1   0($SP)
lw   $t1   8($ESP)
sw   $t1   -4($SP)
addi $SP,  $SP, -8
addi $ESP, $ESP, 8
jal  foo
addi $SP,  $SP,  8
sw   $result,0($ESP)
addi $ESP, $ESP, -4
```

08-49: **Simple Tiling**

- Statement Trees
  - The code associated with a statement tree implements the statement described by the tree

08-50: **Statement Trees**

- Label Trees
  - We just need to output the label
- Tree: Label(“Label1”)
- Associated code:

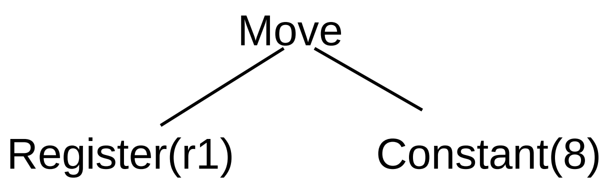
```
Label1:
```

08-51: **Statement Trees**

- Move Trees
  - Left-hand side of move must be a MEMORY node or a REGISTER node
  - MOVE tiles cover two nodes
    - MOVE node
    - Left child (MEMORY node or REGISTER node)

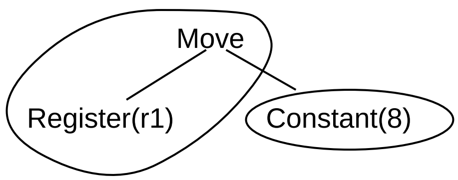
08-52: **Statement Trees**

- Move Trees (Moving into Registers)




08-53: **Statement Trees**

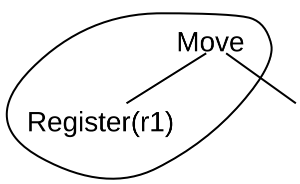
- Move Trees (Moving into Registers)




- The code for the MOVE tile needs to:
    - Pop the value to move off the stack
    - Store the value in the appropriate register

08-54: **Statement Trees**

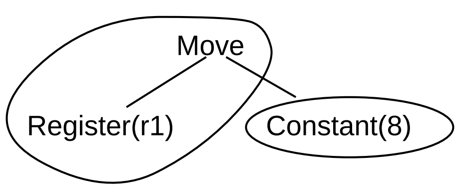
- Move Trees (Moving into Registers)




```
lw   $r1,  4($ESP)
addi $ESP, $ESP, 4
```

08-55: **Statement Trees**

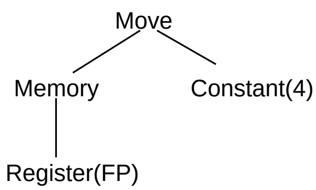
- Move Trees (Moving into Registers)



```
addi $t1,  $zero, 8
sw   $t1,  0($ESP)
addi $ESP, $ESP,  -4
lw   $r1,  4($ESP)
addi $ESP, $ESP, 4
```

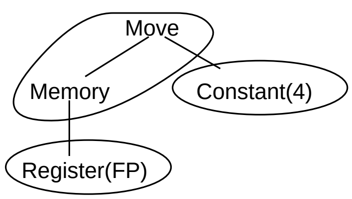
08-56: **Statement Trees**

- Move Trees (Moving into MEMORY locations)




08-57: **Statement Trees**

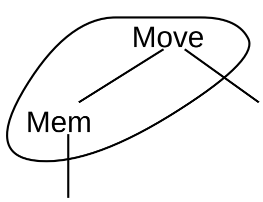
- Move Trees (Moving into MEMORY locations)




- The code for the MOVE tile needs to:
  - Pop the value to move off the stack
  - Pop the destination of the move off the stack
  - Store the value in the destination

08-58: **Statement Trees**

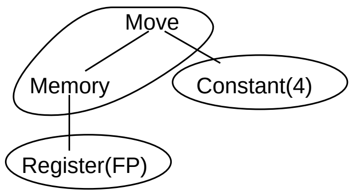
- Move Trees (Moving into MEMORY locations)




```
lw   $t1,  8($ESP)
lw   $t2,  4($ESP)
sw   $t2,  0($t1)
addi $ESP, $ESP, 8
```

08-59: **Statement Trees**

- Move Trees (Moving into MEMORY locations)




```
sw   $FP,  0($ESP)    % Store the frame pointer on the expression stack
addi $ESP, $ESP, -4   % Update the expression stack pointer
addi $t1,  $ZERO, 4   % Put constant 4 into a register
sw   $t1,  0($ESP)    % Store resgister on the expression stack
addi $ESP, $ESP, -4   % Update expression stack pointer
lw   $t1,  8($ESP)    % Store the address of the lhs of the move in a regiter
lw   $t2,  4($ESP)    % Store value of the rhs of the move in a register
sw   $t2,  0($t1)     % Implement the move
addi $ESP, $ESP, 8    % update the expression stack pointer
```

08-60: **Statement Trees**

- Jump Trees
  - Jump trees modify the flow of control of the program
  - Can be implemented with a single `j` instruction

08-61: **Statement Trees**

- Jump Trees
  - Tree: jump("jumplab")
  - Code:

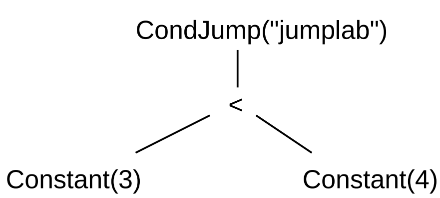
```
j jumplab
```

08-62: **Statement Trees**

- Conditional Jump Trees
  - Evaluate the expression
  - Jump if the expression != 0

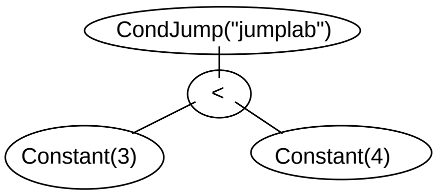
08-63: **Statement Trees**

- Conditional Jump Trees



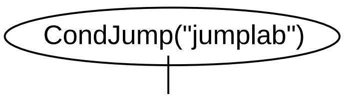

08-64: **Statement Trees**

- Conditional Jump Trees



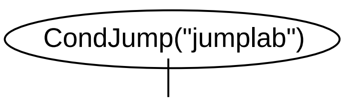

08-65: **Statement Trees**

- Conditional Jump Trees



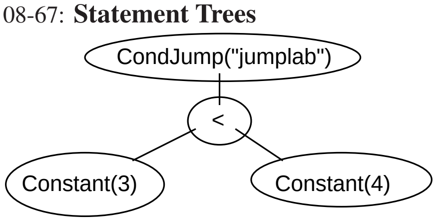

08-66: **Statement Trees**

- Conditional Jump Trees




```
lw   $t1,  4($ESP)
addi $ESP, $ESP, 4
bgtz $t1, jumplab
```

08-67: **Statement Trees**




08-68: **Statement Trees**

```
addi $t1,  $zero, 3    %--
sw   $t1,  0($ESP)     %  Tile for const(3)
addi $ESP, $ESP, -4    %--
addi $t1,  $zero, 4    %--
sw   $t1,  0($ESP)     %  Tile for const(4)
addi $ESP, $ESP -4     %--
lw   $t1, 8($ESP)      %--
lw   $t2, 4($ESP)      %
slt  $t1, $t1,  $t2    %  Tile for <
sw   $t1, 8($ESP)      %
addi $ESP, $ESP, 4     %--
lw   $t1,  4($ESP)     %--
addi $ESP, $ESP, 4     %  Tile for CJUMP
bgtz $t1, jumplab      %--
```

08-69: **Statement Trees**

- Sequential Trees
  - After we have emitted code for the left and right subtrees, what do we need to do?

08-70: **Statement Trees**

- Sequential Trees
  - After we have emitted code for the left and right subtrees, what do we need to do?

- Nothing!
  - Sequential trees have no associated code

08-71: **Statement Trees**

- Empty Statement Trees
  - No action is required
  - No code associated with tile for empty trees

08-72: **Improved Tiling**

- Tiling we've seen so far is correct – but inefficient
  - Generated code is much longer than it needs to be
  - Too heavy a reliance on the stack (main memory accesses are slow)
- We can improve our tiling in three ways:

08-73: **Improved Tiling**

- Decrease reliance on the expression stack
- Use large tiles
- Better management of the expression stack
  - Including storing the bottom of the expression stack in registers

08-74: **Improved Tiling**

- Decrease reliance on the expression stack
  - Every expression is stored on the stack – even when we do not need to store partial results
  - Instead, we will only use the stack when we need to store partial results – and use registers otherwise

08-75: **Accumulator Register**

- Code for expression trees will no longer place the value on the top of the expression stack
- Instead, code for expression trees will place the value of the expression in an accumulator register (ACC)
- Stack will still be necessary (in some cases) to store partial values

08-76: **Accumulator Register**

- Constant trees
  - Code for a constant tree needs to place the value of the constant in the accumulator register
  - Can be accomplished by a single assembly language instruction

08-77: **Accumulator Register**

- Constant trees
  - Tree: Constant(15)

- Code:

08-78: **Accumulator Register**

- Constant trees
  - Tree: Constant(15)
  - Code:

```
addi $ACC, $zero, 15
```

08-79: **Accumulator Register**

- Register trees
  - Code for a register tree needs to move the contents of the register into the accumulator register
  - Can also be accomplished by a single assembly language instruction

08-80: **Accumulator Register**

- Register trees
  - Tree: Register(r1)
  - Code:

08-81: **Accumulator Register**

- Register trees
  - Tree: Register(r1)
  - Code:

```
addi $ACC, $r1, 0
```

08-82: **Accumulator Register**

- Binary Operators (+, -, *, etc)
  - Slightly more complicated
  - Can no longer do a simple postorder traversal
    - Emit code for left subtree – stores value in ACC
    - Emit code for right subtree – stores value in ACC – overwriting old value
      - Oops!

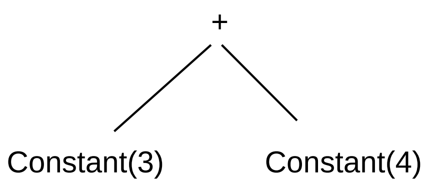
08-83: **Accumulator Register**

- Binary Operators (+, -, *, etc)
  - Use an INORDER traversal instead
    - Emit code for left subtree
    - Store this value on the stack
    - Emit code for the right subtree
    - Pop value of left operand off stack

- Do the operation, storing result in ACC

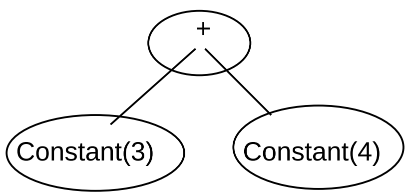
08-84: **Accumulator Register**

- Binary Operators (+, -, *, etc)




08-85: **Accumulator Register**

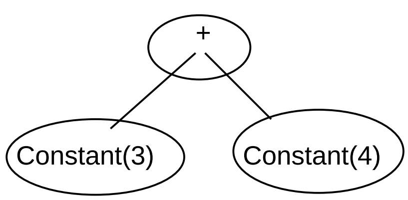
- Binary Operators (+, -, *, etc)




- Emit code for left subtree
- Push value on stack
- Emit code for right subtree
- Do arithmetic, storing result in ACC

08-86: **Accumulator Register**

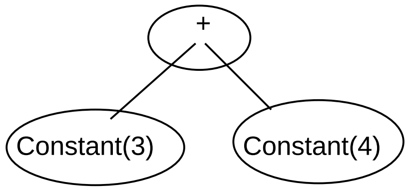
- Binary Operators (+, -, *, etc)




```
<code for left operand>
sw   $ACC, 0($ESP)
addi $ESP, $ESP, -4
<code for right operand>
lw   $t1,  4($ESP)
addi $ESP, $ESP, 4
add  $ACC, $t1, $ACC
```

08-87: **Accumulator Register**

- Binary Operators (+, -, *, etc)




```
addi $ACC, $zero, 3
sw   $ACC, 0($ESP)
addi $ESP, $ESP, -4
addi $ACC, $zero, 4
lw   $t1,  4($ESP)
addi $ESP, $ESP, 4
add  $ACC, $t1, $ACC
```

08-88: **Accumulator Register**

- Memory Expression Trees
  - ACC points to a memory location
  - Load the contents of that memory location into the ACC

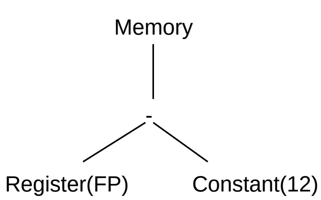
08-89: **Accumulator Register**

- Memory Expression Trees
  - Code for a Memory tile:

```
lw $ACC, 0($ACC)
```

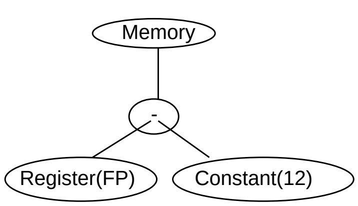
08-90: **Accumulator Register**

- Memory Example



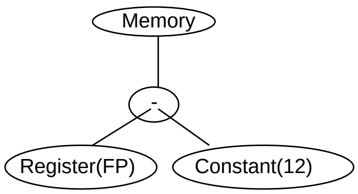

08-91: **Accumulator Register**

- Memory Example




08-92: **Accumulator Register**

- Memory Example




```
addi $ACC, $FP, 0         % Store the FP in the accumulator
sw   $ACC, 0($ESP)        % Store left operand on expression stack
addi $ESP, $ESP, -4       % Update expression stack pointer
addi $ACC, $zero, 12      % Store constant 4 in the accumulator
lw   $t1,  4($ESP)        % Pop left operand off expression stack
addi $ESP, $ESP, 4        % Update expression stack pointer
sub  $ACC, $t1, $ACC      % Do the addition
lw $ACC, 0($ACC)          % Dereference the ACC
```

08-93: **Accumulator Register**

- Register Move Statement Trees
  - Almost the same as Register expressions
  - Move value to an arbitrary register, instead of ACC

08-94: **Accumulator Register**

- Register Move Statement Trees
  - Almost the same as Register expressions
  - Move value to an arbitrary register, instead of ACC

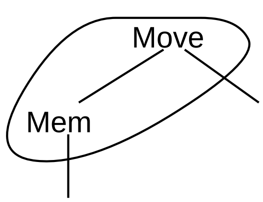
```
addi $r1, $ACC, 0
```

08-95: **Accumulator Register**

- Memory Move Statement Trees
  - Calculate the source & destination of the move
  - Like operator expressions, will need to store values on stack
  - Once source & destination are stored in registers, can use a `sw` statement

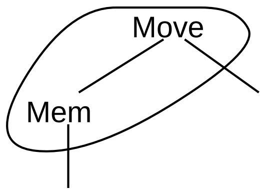
08-96: **Accumulator Register**

- Memory Move Statement Trees




08-97: **Accumulator Register**

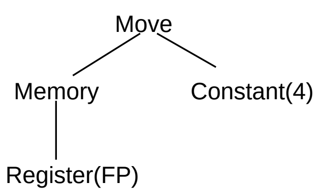
- Memory Move Statement Trees




```
<code for left subtree (destination)>
sw   $ACC,  0($ESP)
addi $ESP, $ESP,   -4
<code for right subtree (value to move)>
lw   $t1,  4($ESP)
addi $ESP, $ESP,   4
sw   $ACC, 0($t1)
```

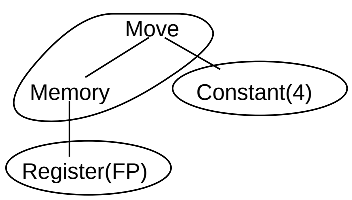
08-98: **Accumulator Register**

- Memory Move Example



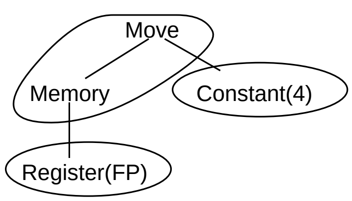

08-99: **Accumulator Register**

- Memory Move Example




08-100: **Accumulator Register**

- Memory Move Example




```
addi $ACC, $FP, 0        %  Code for Register(FP) tile
sw   $ACC,  0($ESP)      %  Store destination on expression stack
addi $ESP, $ESP,   -4    %  Update expression stack pointer
addi $ACC, $zero, 4      %  Code for Constant(4) tile
lw   $t1,  4($ESP)       %  Load destination into a register
addi $ESP, $ESP,   4     %  Update expression stack pointer
sw   $ACC, 0($t1)        %  Implement the move
```

08-101: **Accumulator Register**

- Function & Procedure Calls
    - Move arguments to the call stack as they are computed
        - No need to use the expression stack at all

08-102: **Accumulator Register**

- Function Calls

```
sw   $ACC,    -<4n-4>($SP)   %  Store first argument on the call stack
<Code for second argument>
sw   $ACC,   -<4n-8>($SP)    %  Store second argument on the call stack
...
<Code for nth argument>
sw   $ACC, 0($SP)            %  Store nth argument on the call stack
addi $SP,  $SP,  -<4n>       %  Update call stack pointer
jal  foo                     %  Make the function call
addi $SP,  $SP,   <4n>       %  Update call stack pointer
addi $ACC, $result,0         %  Store result of function in accumulator
```

08-103: **Accumulator Register**

- Procedure Calls

```
sw   $ACC,    <-4n-4>($SP)   %  Store first argument on the call stack
<Code for second argument>
sw   $ACC,   -<4n-8>($SP)    %  Store second argument on the call stack
...
<Code for nth argument>
sw   $ACC, 0($SP)            %  Store nth argument on the call stack
addi $SP,  $SP,  -<4n>       %  Update call stack pointer
jal  foo                     %  Make the function call
addi $SP,  $SP,   <4n>       %  Update call stack pointer
```

08-104: **Accumulator Register**

- Conditional Jumps
    - No temporary values need to be saved
    - Jump if ACC is not zero

08-105: **Accumulator Register**

- Conditional Jumps
    - No temporary values need to be saved
    - Jump if ACC is not zero

```
<Code for conditional expression>
bgtz $ACC, jumplab
```

08-106: **Accumulator Register**

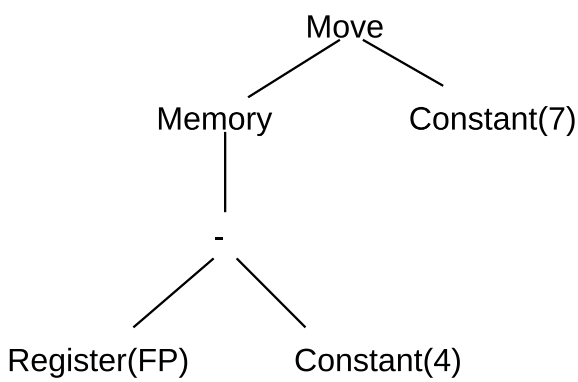
- Jumps, labels, sequential statements
    - Do not have subtrees with values
    - Code is the same as previously defined

08-107: **Larger Tiles**

- Instead of covering a single node for each tile, cover several nodes with the same tile
- As long as the code associated with the larger tile is more efficient than the code associated with all of the smaller tiles, we gain efficiency

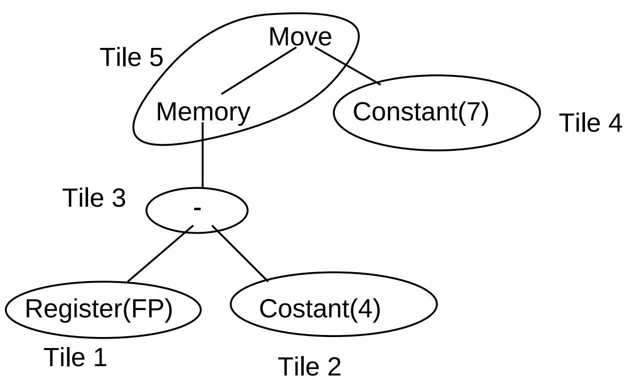
08-108: **Larger Tiles Example**

- Memory Move Expression




08-109: **Larger Tiles Example**

- Standard Tiling



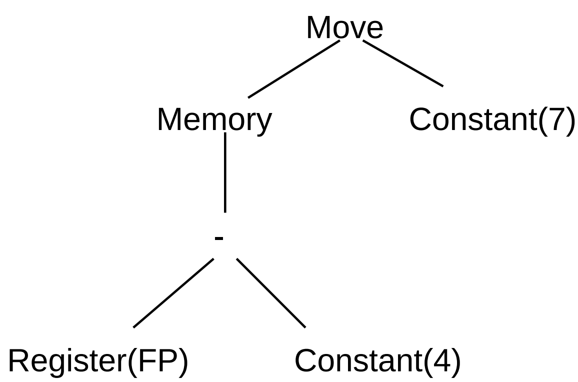

08-110: **Larger Tiles Example**

- Standard Tiling

```
addi  $ACC, $FP, 0      % code for tile 1
sw    $ACC, $ESP, 0     % code for tile 3
addi  $ESP, $ESP, -4    % code for tile 3
addi  $ACC, $zero, 4    % code for tile 2
lw    $t1,  4($ESP)     % code for tile 3
addi  $ESP, $ESP, 4     % code for tile 3
sub   $ACC, $t1, $ACC   % code for tile 3
sw    $ACC, $ESP, 0     % code for tile 5
addi  $ESP, $ESP, -4    % code for tile 5
addi  $ACC, $zero, 7    % code for tile 4
lw    $t1,  4($ESP)     % code for tile 5
addi  $ESP, $ESP,4      % code for tile 5
sw    $ACC, 0($t1)      % code for tile 5
```

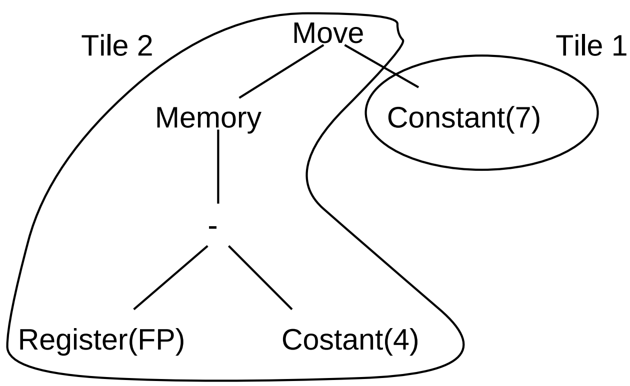
08-111: **Larger Tiles Example**

- Memory Move Expression

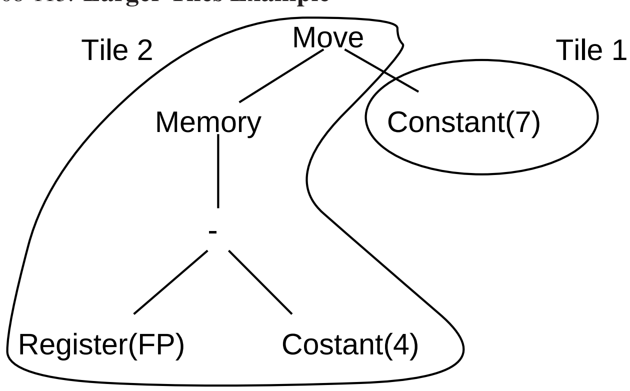



08-112: **Larger Tiles Example**

- Using Larger Tiles

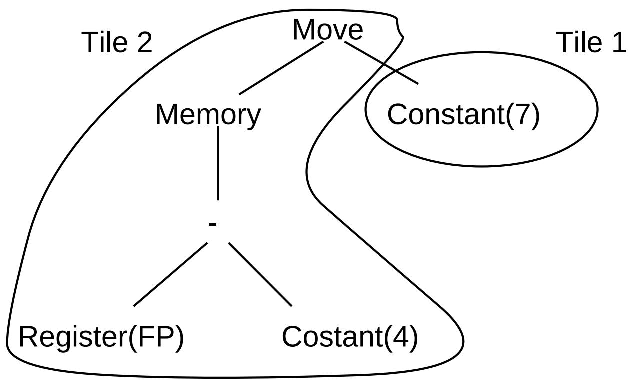



08-113: **Larger Tiles Example**




- Code for Tile 2?

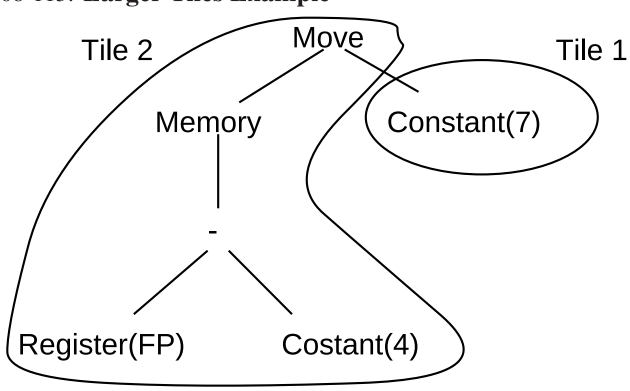
08-114: **Larger Tiles Example**




- Code for Tile 2?

```
sw  $ACC, -4($FP)
```

08-115: **Larger Tiles Example**




```
addi   $ACC, $zero 7      % tile 1
sw     $ACC, -4($FP)      % tile 2
```

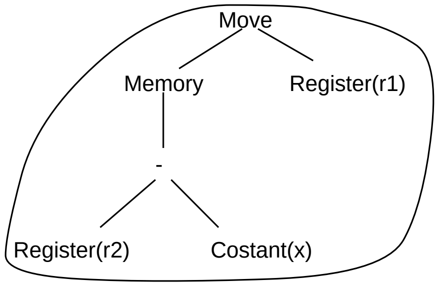
08-116: **Larger Tiles**

- Can get a huge saving using larger tiles
- Especially if tile size is geared to functionality of the actual assembly
  - `sw` Stores the value in a register in a memory location pointed to by an offset off a different register
  - Tile that takes full advantage of this functionality will lead to efficient assembly

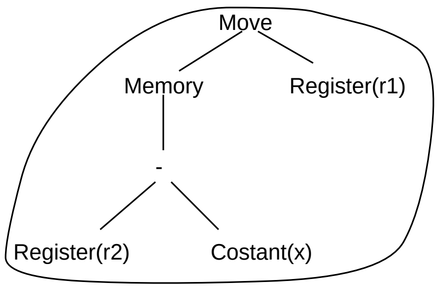
08-117: **Larger Tiles**

- Design tiles based on the actual assembly language
- Take advantage of as many feature of the language as possible
- Create tiles that are as large as possible, that can be implemented with a single assembly language instruction
  - Plus some extra instructions to do stack maintenance

08-118: **Larger Tiles – Examples**

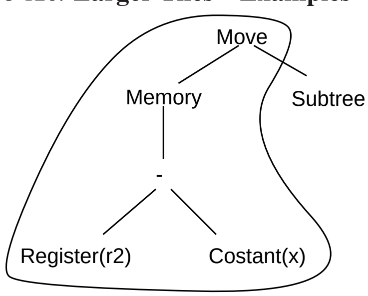



08-119: **Larger Tiles – Examples**

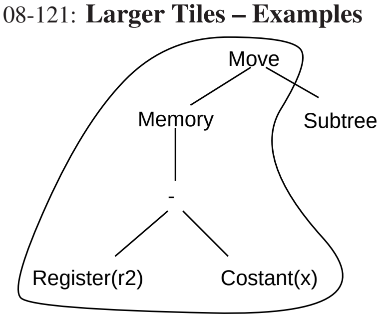



```
sw r1 -x(r2)
```

08-120: **Larger Tiles – Examples**

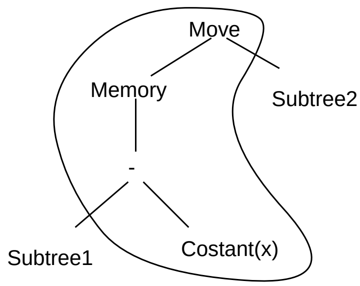



08-121: **Larger Tiles – Examples**

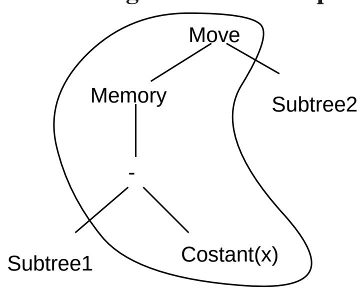



```
<code for Subtree>
sw $ACC, -x(r2)
```

08-122: **Larger Tiles – Examples**

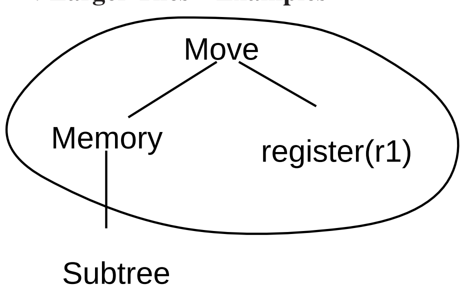



08-123: **Larger Tiles – Examples**

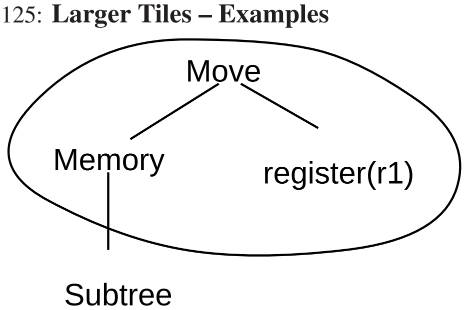



```
<code for Subtree1>
sw   $ACC, 0($ESP)
addi $ESP, $ESP
<code for Subtree2>
lw   $t1,   4($ESP)
addi $ESP, $ESP, 4
sw   $ACC, -x($t1)
```

08-124: **Larger Tiles – Examples**

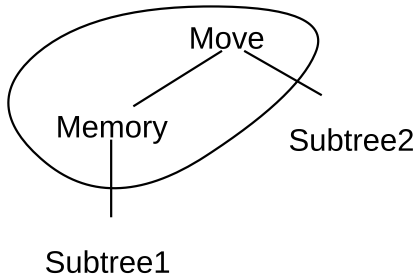



08-125: **Larger Tiles – Examples**

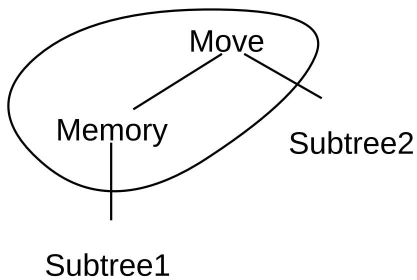



```
<code for Subtree>
sw   $r1, -x($ACC)
```

08-126: **Larger Tiles – Examples**




08-127: **Larger Tiles – Examples**




```
<code for Subtree1>
sw   $ACC, 0($ESP)
addi $ESP, $ESP
<code for Subtree2>
lw   $t1,   4($ESP)
addi $ESP, $ESP, 4
sw   $ACC, 0($t1)
```

08-128: **Larger Tiles**

- Larger tiles are better
- Why design small tiles as well as large tiles?

08-129: **Larger Tiles**

- Larger tiles are better
- Why design small tiles as well as large tiles?
    - Might not always be able to use largest tile
- Why design a range of tile sizes

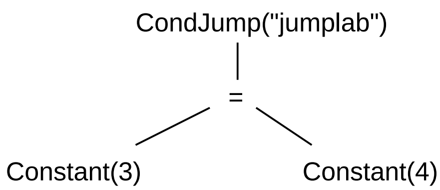
08-130: **Larger Tiles**

- Larger tiles are better
- Why design small tiles as well as large tiles?
    - Might not always be able to use largest tile
- Why design a range of tile sizes

- Most efficient tiling of any tree

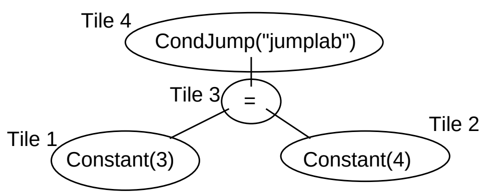
08-131: **Larger Tiles**

- Conditional Jump Trees




08-132: **Larger Tiles**

- Conditional Jump Trees




08-133: **Larger Tiles**

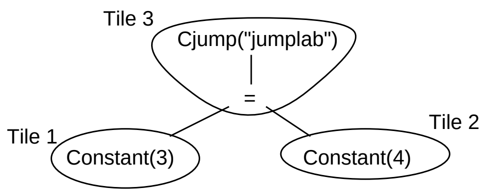
```
           addi $ACC, $zero 3         % Tile 1
           sw   $ACC, 0($ESP)         % Tile 3
           addi $ESP, $ESP, -4        % Tile 3
           addi $ACC, $zero, 4        % Tile 2
           lw   $t1,  4($ESP)         % Tile 3
           addi $ESP, $ESP, 4         % Tile 3
           beq  $t1,  $ACC, truelab1  % Tile 3
           addi $ACC, $zero, 0        % Tile 3
           j    endlab1               % Tile 3
truelab1:                             % Tile 3
           addi $ACC, $zero, 1        % Tile 3
endlab1:                              % Tile 3
           bgtz $ACC, jumplab         % Tile 4
```

08-134: **Larger Tiles**

- We are doing **two** conditional jumps
  - Set the boolean value, 0 or 1
  - Implement the actual jump
- Using larger tiles, we can remove one of them:
  - Jump directly to “jumplab” if the expression is true

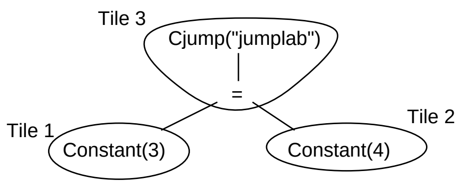
08-135: **Larger Tiles**

- Conditional Jump Trees




08-136: **Larger Tiles**

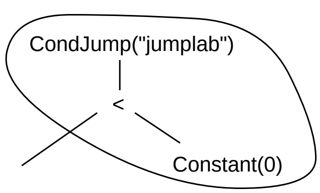
- Conditional Jump Trees




```
addi $ACC, $zero 3       % Tile 1
sw   $ACC, 0($ESP)       % Tile 3
addi $ESP, $ESP, -4      % Tile 3
addi $ACC, $zero, 4      % Tile 2
lw   $t1,  4($ESP)       % Tile 3
addi $ESP, $ESP, 4       % Tile 3
beq  $t1,  $ACC, jumplab % Tile 3
```

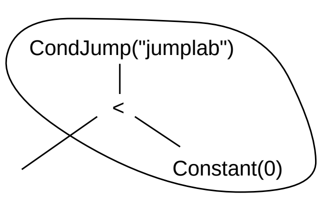
08-137: **Larger Tiles**

- Conditional Jump Trees
  - For some conditional jump trees, we can do even better




08-138: **Larger Tiles**

- Conditional Jump Trees
  - For some conditional jump trees, we can do even better




```
<Code for left subtree>
bltz $ACC, jumplab
```

08-139: **Larger Tiles**

- Given a range of tiles, we have a choice as to which tile to pick
- How do we decide which tiles to use, to minimize the total number of tiles?
  - Under the assumption that each tile uses about the same amount of assembly

08-140: **Tiling the Tree**

- Greedy Strategy:
  - Cover the root of the tree with the largest possible tile
  - Recursively tile subtrees
- Are we always guaranteed that we will find a tiling this way (that is, can we ever get stuck?)

08-141: **Tiling the Tree**

- Greedy Strategy:
  - Cover the root of the tree with the largest possible tile
  - Recursively tile subtrees
- Are we always guaranteed that we will find a tiling this way (that is, can we ever get stuck?)
  - We **can** always find a tiling this way – provided we include all unit-sized tiles in our tile set

08-142: **Optimizing Expression Stack**

- We spend more operations than necessary manipulating the expression stack
- Streamlining stack operations will save us some assembly language instructions (and thus some time)

08-143: **Constant Stack Offsets**

- Every time we push an item on the Expression Stack, need to increment the $ESP
- Every time we pop an item off the Expression Stack, need to increment the $ESP
- We know at compile time how deep the stack is
  - Can use a constant offset off the $ESP
  - Never need to change the $ESP

08-144: **Constant Stack Offsets**

- Pushing an expression:

```
sw   $ACC, 0($ESP)
addi $ESP, $ESP,   -4
```

- Popping an expression:

```
addi $ESP, $ESP,   4
lw   $ACC, 0($ESP)
```

08-145: **Constant Stack Offsets**

- Pushing an expression:

  ```
  sw   $ACC, <offset>($ESP)
  ```

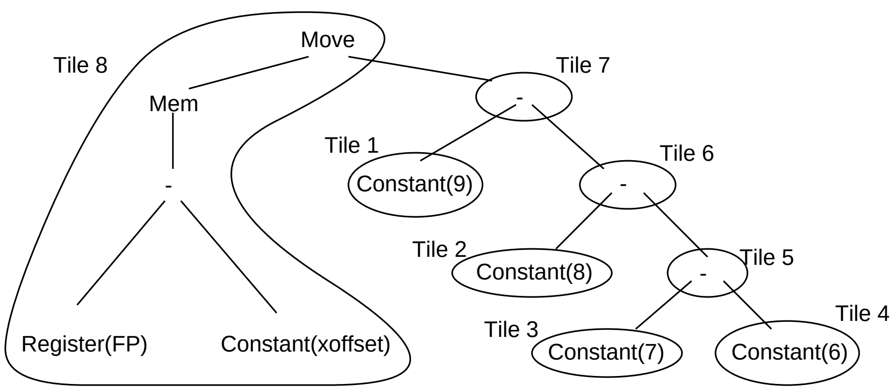
  (decement <offset> by 4)

- Popping an expression:
  (increment <offset> by 4)

  ```
  lw   $ACC, <offset>($ESP)
  ```

08-146: **Constant Stack Offsets**

- Example:




08-147: **Constant Stack Offsets**

```
addi $ACC, $zero,  9          % Tile 1
sw   $ACC, 0($ESP)            % Tile 7 -- pushing a value on the
addi $ESP, $ESP,  -4          % Tile 7          expression stack
addi $ACC, $zero,  8          % Tile 2
sw   $ACC, 0($ESP)            % Tile 6 -- pushing a value on the
addi $ESP, $ESP,  -4          % Tile 6          expression stack
addi $ACC, $zero,  7          % Tile 3
sw   $ACC, 0($ESP)            % Tile 5 -- pushing a value on the
addi $ESP, $ESP,  -4          % Tile 5          expression stack
addi $ACC, $zero,  6          % Tile 4
addi $ESP, $ESP,   4          % Tile 5 -- popping a value off the
lw   $t1,  0($ESP)            % Tile 5          expression stack
sub  $ACC, $t1, $ACC          % Tile 5
addi $ESP, $ESP,   4          % Tile 6 -- popping a value off the
lw   $t1,  0($ESP)            % Tile 6          expression stack
sub  $ACC, $t1, $ACC          % Tile 6
addi $ESP, $ESP,   4          % Tile 7 -- popping a value off the
lw   $t1,  0($ESP)            % Tile 7          expression stack
sub  $ACC, $t1, $ACC          % Tile 7
lw   $ACC, xoffset($FP)       % Tile 8
```

08-148: **Constant Stack Offsets**

```
addi $ACC, $zero,  9          % Tile 1
sw   $ACC, 0($ESP)            % Tile 7 -- pushing on expression stack
addi $ACC, $zero,  8          % Tile 2
sw   $ACC, -4($ESP)           % Tile 6 -- pushing on expression stack
addi $ACC, $zero,  7          % Tile 3
sw   $ACC, -8($ESP)           % Tile 5 -- pushing on expression stack
addi $ACC, $zero,  6          % Tile 4
lw   $t1,  -8($ESP)           % Tile 5 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 5
lw   $t1,  -4($ESP)           % Tile 6 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 6
lw   $t1,  0($ESP)            % Tile 7 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 7
lw   $ACC, xoffset($FP)       % Tile 8
```

08-149: **Constant Stack Offsets**

- Using constant offsets off the $ESP words well most of the time
- There are problems with function calls, however
    - `x = y + (z + bar(2))`

08-150: **Constant Stack Offsets**

- `x = y + (z + bar(2))`

```
lw   $ACC, -8($FP)      % Load y into the ACC
sw   $ACC, 0($ESP)      % Store value of y on the expression stack
lw   $ACC, -12($FP)     % Load z into the ACC
sw   $ACC, -4($ESP)     % Store value of z on the expression stack
addi $ACC, $zero,   2   % Load actual parameter (2) into ACC
sw   $ACC, 0($SP)       % Store actual parameter on the stack
addi $SP,  $SP,    -4   % Adjust the stack pointer
jal  bar                % Make the function call
addi $SP,  $SP,     4   % Adjust the stack pointer
addi $ACC, $result, 0   % Store result of function call in the ACC
lw   $t1,  -4($ESP)     % Load stored value of z into t1
add  $ACC, $t1, $ACC    % Do the addtion z + bar(2)
lw   $t1,  0($ESP)      % Load stored value of y into t1
addi $ACC, $t1, $ACC    % Do the addition y + (z + bar(2))
sw   $ACC, -4($FP)      % Store value of addition in x
```

- What's wrong with this code?

08-151: **Constant Stack Offsets**

- What's wrong with this code?
    - When we call the function, constant offset is -8.
        - There are 2 expressions stored *beyond* the top of the $ESP
    - In the body of the function, constant offset is ..

08-152: **Constant Stack Offsets**

- What's wrong with this code?
    - When we call the function, constant offset is -8.
        - There are 2 expressions stored *beyond* the top of the $ESP
    - In the body of the function, constant offset is 0!
    - If `bar` uses the expression stack, it will clobber the values we've stored on it!

08-153: **Constant Stack Offsets**

- Problem:
    - Function calls expect constant offset to be 0 at start of the function
    - Actual constant offset may not be 0
        - May be *arbitrarily large* (why?)
- Solution:

08-154: **Constant Stack Offsets**

- Problem:

  - Function calls expect constant offset to be 0 at start of the function
  - Actual constant offset may not be 0
    - May be *arbitrarily large* (why?)
- Solution:
  - Before a function call, decrement the $ESP by constant offset
    - Constant offset is now 0 again
  - After the function call, increment the $ESP again

08-155: **Constant Stack Offsets**

- `x = y + (z + bar(2))` (Corrected)

```
lw   $ACC, -8($FP)      % Load y into the ACC
sw   $ACC, 0($ESP)      % Store value of y on the expression stack
lw   $ACC, -12($FP)     % Load z into the ACC
sw   $ACC, -4($ESP)     % Store value of z on the expression stack
addi $ACC, $zero,   2   % Load actual parameter (2) into ACC
sw   $ACC, 0($SP)       % Store actual parameter on the stack
addi $SP,  $SP,    -4   % Adjust the stack pointer
addi $ESP, $ESP, -8     % ** Adjust the expression stack pointer **
jal  bar                % Make the function call
addi $ESP, $ESP, 8      % ** Adjust the expression stack pointer **
addi $SP,  $SP,     4   % Adjust the stack pointer
addi $ACC, $result, 0   % Store result of function call in the ACC
lw   $t1,  -4($ESP)     % Load stored value of z into t1
add  $ACC, $t1, $ACC    % Do the addtion z + bar(2)
lw   $t1,  0($ESP)      % Load stored value of y into t1
addi $ACC, $t1, $ACC    % Do the addition y + (z + bar(2))
sw   $ACC, -4($FP)      % Store value of addition in x
```

08-156: **Optimizing Expression Stack**

- Like to store temporary values in Registers instead of in main memory
- Can't store *all* temporary values in Registers
  - Arbitrarily large number of temporary values may be required
  - Limited number of registers
- Can store *some* temporary values in registers

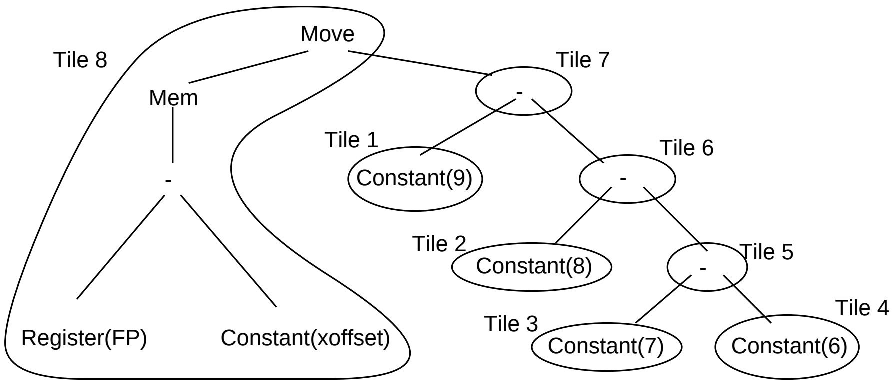
08-157: **Using Registers**

- Store the bottom of the expression stack in registers
  - For small expressions, we will not need to use main memory for temporary values
  - Retain the flexibility to handle large expressions
- Bottom $x$ elements of the expression stack in registers

08-158: **Using Registers**

- Example:
  - Use two temporary registers $r2 & $r3
  - If we only need two temporary values, use $r2 and $r3
  - When more values are required, use stack

08-159: **Using Registers**




08-160: **Using Registers**

- Constant stack offsets (no registers)

```
addi $ACC, $zero,  9          % Tile 1
sw   $ACC, 0($ESP)            % Tile 7 -- pushing on expression stack
addi $ACC, $zero,  8          % Tile 2
sw   $ACC, -4($ESP)           % Tile 6 -- pushing on expression stack
addi $ACC, $zero,  7          % Tile 3
sw   $ACC, -8($ESP)           % Tile 5 -- pushing on expression stack
addi $ACC, $zero,  6          % Tile 4
lw   $t1,  -8($ESP)           % Tile 5 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 5
lw   $t1,  -4($ESP)           % Tile 6 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 6
lw   $t1,  0($ESP)            % Tile 7 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 7
lw   $ACC, xoffset($FP)       % Tile 8
```

08-161: **Using Registers**

- Bottom of expression stack in registers

```
addi $ACC, $zero,  9          % Tile 1
addi $r2,  $ACC,   0          % Tile 7 -- pushing on expression stack
addi $ACC, $zero,  8          % Tile 2
addi $r3,  $ACC,   0          % Tile 6 -- pushing on expression stack
addi $ACC, $zero,  7          % Tile 3
sw   $ACC, 0($ESP)            % Tile 5 -- pushing on expression stack
addi $ACC, $zero,  6          % Tile 4
lw   $t1,  0($ESP)            % Tile 5 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 5
addi $t1   $t3,    0          % Tile 6 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 6
addi $t1,  $t2,    0          % Tile 7 -- popping from expresssion stack
sub  $ACC, $t1, $ACC          % Tile 7
lw   $ACC, xoffset($FP)       % Tile 8
```

08-162: **Using Registers**

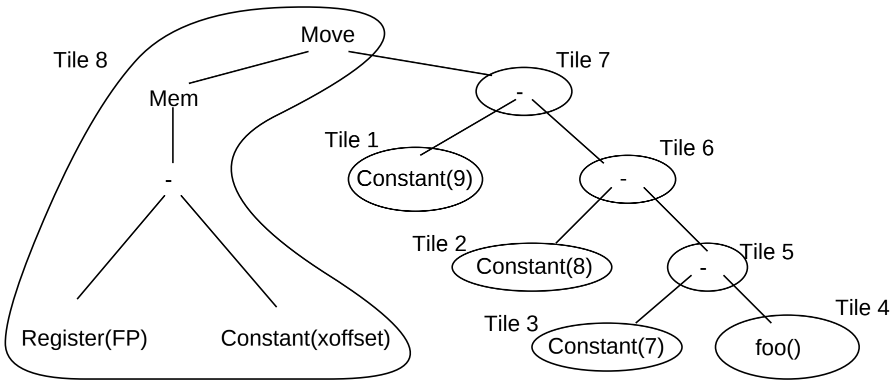
- If we store the bootom of the expression stack in regisers, we have a problem with function calls:
  - x = foo(a,b) + foo(c,d)
- What can we do?

08-163: **Using Registers**

- If we store the bootom of the expression stack in regisers, we have a problem with function calls:
  - x = foo(a,b) + foo(c,d)
- What can we do?
  - On a function call, push all registers onto the expression stack, and update the expression stack pointer.

- After a function call, pop all values back into the registers, and update the expression stack pointer

08-164: **Using Registers**




08-165: **Using Registers**

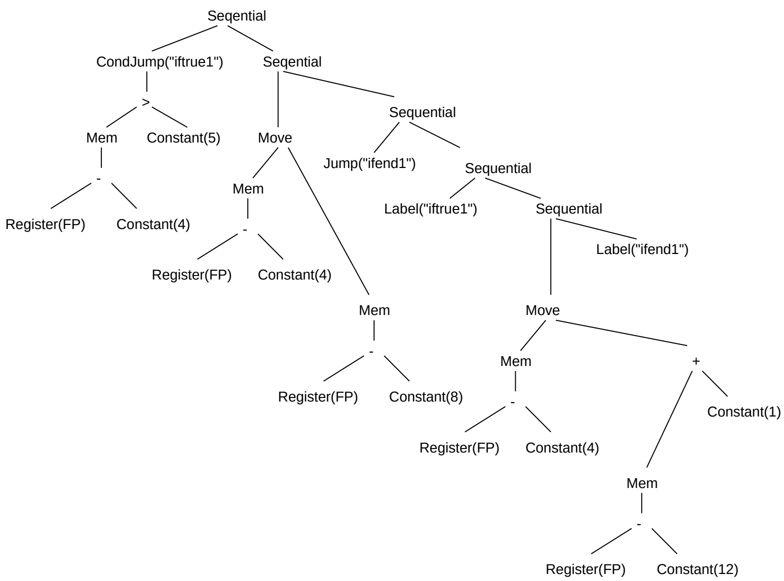
```
addi $ACC, $zero,  9         % Tile 1
addi $r2,  $ACC,   0         % Tile 7 -- pushing on expression stack
addi $ACC, $zero,  8         % Tile 2
addi $r3,  $ACC,   0         % Tile 6 -- pushing on expression stack
addi $ACC, $zero,  7         % Tile 3
sw   $ACC, 0($ESP)           % Tile 5 -- pushing on expression stack
sw   $r2, -4($ESP)           % Tile 4 -- Push register on ESP
sw   $r3, -8($ESP)           % Tile 4 -- Push register on ESP
addi $ESP, $ESP, -12         % Tile 4 -- Update ESP
jal  foo                     % Tile 4
addi $ACC, $result, 0        % Tile 4
addi $ESP, $ESP, 12          % Tile 4 -- Update ESP
lw   $r2,  -4($ESP)          % Tile 4 -- Pop register off ESP
lw   $r3,  -8($ESP)          % Tile 4 -- Pop register off ESP
lw   $t1,  0($ESP)           % Tile 5 -- popping from expresssion stack
sub  $ACC, $t1, $ACC         % Tile 5
addi $t1   $t3,    0         % Tile 6 -- popping from expresssion stack
sub  $ACC, $t1, $ACC         % Tile 6
addi $t1,  $t2,    0         % Tile 7 -- popping from expresssion stack
sub  $ACC, $t1, $ACC         % Tile 7
lw   $ACC, xoffset($FP)      % Tile 8
```

08-166: **Extended Example**

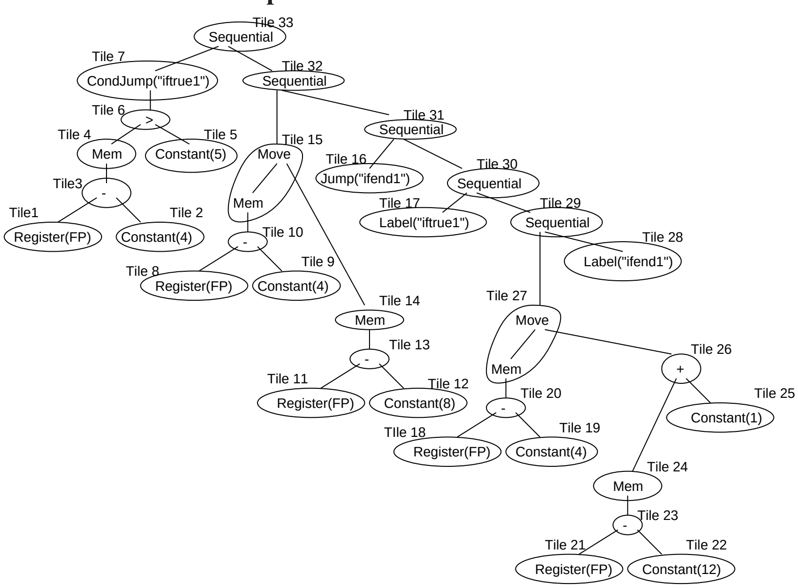
```
if (x > 1)
   x = z + 1;
else
   x = y;
```

- x has offset 4
- y has offset 8
- z has offset 12

08-167: **Extended Example**




## 08-168: **Extended Example – Basic**




## 08-169: **Extended Example – Basic**

```
sw   $FP,  0($ESP)       % Tile 1
addi $ESP, $ESP,  -4     % Tile 1
addi $t1,  $zero,  4     % Tile 2
sw   $t1,  0($ESP)       % Tile 2
addi $ESP, $ESP,  -4     % Tile 2
lw   $t1,  4($ESP)       % Tile 3
lw   $t2,  8($ESP)       % Tile 3
sub  $t1,  $t2,   $t1    % Tile 3
sw   $t1,  8($ESP)       % Tile 3
addi $ESP, $ESP,   4     % Tile 3
lw   $t1,  4($ESP)       % Tile 4
lw   $t1,  0($t1)        % Tile 4
sw   $t1,  4($ESP)       % Tile 4
addi $t1,  $zero,  5     % Tile 5
sw   $t1,  0($ESP)       % Tile 5
addi $ESP, $ESP,  -4     % Tile 5
lw   $t1,  8($ESP)       % Tile 6
lw   $t2,  4($ESP)       % Tile 6
slt  $t1,  $t2, $t1      % Tile 6
addi $ESP, $ESP,   4     % Tile 6
```

## 08-170: **Extended Example – Basic**

```
        lw   $t1,  4($ESP)       % Tile 7
        addi $ESP, $ESP,   4     % Tile 7
        bgtz $t1,  iftrue1       % Tile 7
        sw   $FP,  0($ESP)       % Tile 8
        addi $ESP, $ESP,  -4     % Tile 8
        addi $t1,  $zero,  4     % Tile 9
        sw   $t1,  0($ESP)       % Tile 9
        addi $ESP, $ESP,  -4     % Tile 9
        lw   $t1,  4($ESP)       % Tile 10
        lw   $t2,  8($ESP)       % Tile 10
        sub  $t1,  $t2,   $t1    % Tile 10
```

## 08-171: **Extended Example – Basic**

```
        sw   $t1,  8($ESP)       % Tile 10
        addi $ESP, $ESP,   4     % Tile 10
        sw   $FP,  0($ESP)       % Tile 11
        addi $ESP, $ESP,  -4     % Tile 11
        addi $t1,  $zero,  8     % Tile 12
        sw   $t1,  0($ESP)       % Tile 12
        addi $ESP, $ESP,  -4     % Tile 12
        lw   $t1,  4($ESP)       % Tile 13
        lw   $t2,  8($ESP)       % Tile 13
        sub  $t1,  $t2,   $t1    % Tile 13
        sw   $t1,  8($ESP)       % Tile 13
        addi $ESP, $ESP,   4     % Tile 13
        lw   $t1,  4($ESP)       % Tile 14
        lw   $t1,  0($t1)        % Tile 14
        sw   $t1,  4($ESP)       % Tile 14
        lw   $t1,  8($ESP)       % Tile 15
        lw   $t2,  4($ESP)       % Tile 15
        sw   $t2,  0($t1)        % Tile 15
        addi $ESP, $ESP,   8     % Tile 15
        j    Ifend1              % Tile 16
```

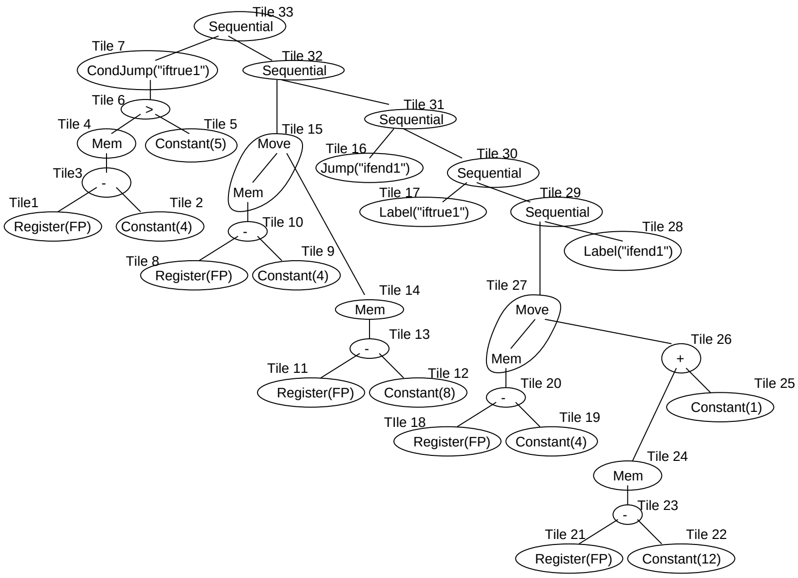
## 08-172: **Extended Example – Basic**

```
iftrue1:                         % Tile 17
        sw   $FP,  0($ESP)       % Tile 18
        addi $ESP, $ESP,  -4     % Tile 18
        addi $t1,  $zero,  4     % Tile 19
        sw   $t1,  0($ESP)       % Tile 19
        addi $ESP, $ESP,  -4     % Tile 19
        lw   $t1,  4($ESP)       % Tile 20
        lw   $t2,  8($ESP)       % Tile 20
        sub  $t1,  $t2,   $t1    % Tile 20
        sw   $t1,  8($ESP)       % Tile 20
        addi $ESP, $ESP,   4     % Tile 20
        sw   $FP,  0($ESP)       % Tile 21
        addi $ESP, $ESP,  -4     % Tile 21
        addi $t1,  $zero,  8     % Tile 22
        sw   $t1,  0($ESP)       % Tile 22
        addi $ESP, $ESP,  -4     % Tile 22
        lw   $t1,  4($ESP)       % Tile 23
        lw   $t2,  8($ESP)       % Tile 23
        sub  $t1,  $t2,   $t1    % Tile 23
        sw   $t1,  8($ESP)       % Tile 23
```

## 08-173: **Extended Example – Basic**

```
        addi $ESP, $ESP,   4     % Tile 23
        lw   $t1,  4($ESP)       % Tile 24
        lw   $t1,  0($t1)        % Tile 24
        sw   $t1,  4($ESP)       % Tile 24
        addi $t1,  $zero,  4     % Tile 25
        sw   $t1,  0($ESP)       % Tile 25
        addi $ESP, $ESP,  -4     % Tile 25
        lw   $t1,  4($ESP)       % Tile 26
        lw   $t2,  8($ESP)       % Tile 26
        add  $t1,  $t2,   $t1    % Tile 26
        sw   $t1,  8($ESP)       % Tile 26
        addi $ESP, $ESP,   4     % Tile 26
        lw   $t1,  8($ESP)       % Tile 27
        lw   $t2,  4($ESP)       % Tile 27
        sw   $t2,  0($t1)        % Tile 27
        addi $ESP, $ESP,   8     % Tile 27
Ifend1:                          % Tile 28
                                 %  No code for tiles 29 -- 33
```

## 08-174: **Extended Eg. – Accumulator**




## 08-175: **Extended Eg. – Accumulator**

```
        addi $ACC, $FP, 0        % Tile 1
        sw   $ACC, 0($ESP)       % Tile 3
        addi $ESP, $ESP,  -4     % Tile 3
        addi $ACC, $zero,  4     % Tile 2
        lw   $t1,  4($ESP)       % Tile 3
        addi $ESP, $ESP,   4     % Tile 3
        sub  $ACC, $t1,    $ACC  % Tile 3
        lw   $ACC, 0($ACC)       % Tile 4
        sw   $ACC, 0($ESP)       % Tile 6
        addi $ESP, $ESP,  -4     % Tile 6
        addi $ACC, $zero, 5      % Tile 5
        lw   $t1,  4($ESP)       % Tile 6
        addi $ESP, $ESP,   4     % Tile 6
        slt  $ACC, $ACC, $t1     % Tile 6
        bgtz $ACC, iftrue1       % Tile 7
        addi $ACC, $FP,    0     % Tile 8
```

## 08-176: **Extended Eg. – Accumulator**

```
        sw   $ACC, 0($ESP)       % Tile 10
        addi $ESP, $ESP,  -4     % Tile 10
        addi $ACC, $zero,  4     % Tile 9
        lw   $t1, 4($ESP)        % Tile 10
        sub  $ACC, $t1,   $ACC   % Tile 10
        sw   $ACC, 0($ESP)       % Tile 15
        addi $ESP, $ESP,  -4     % Tile 15
        addi $ACC, $FP, 0        % Tile 11
        sw   $ACC, 0($ESP)       % Tile 13
        addi $ESP, $ESP   -4     % Tile 13
        addi $ACC, $zero,  8     % Tile 12
        lw   $t1,  4($ESP)       % Tile 13
        addi $ESP, $ESP,   4     % Tile 13
        sub  $ACC, $t1,   $ACC   % Tile 13
        lw   $ACC, 0($ACC)       % Tile 14
        lw   $t1,  4($ESP)       % Tile 15
        addi $ESP, $ESP,   4     % Tile 15
        sw   $ACC, 0($t1)        % Tile 15
```

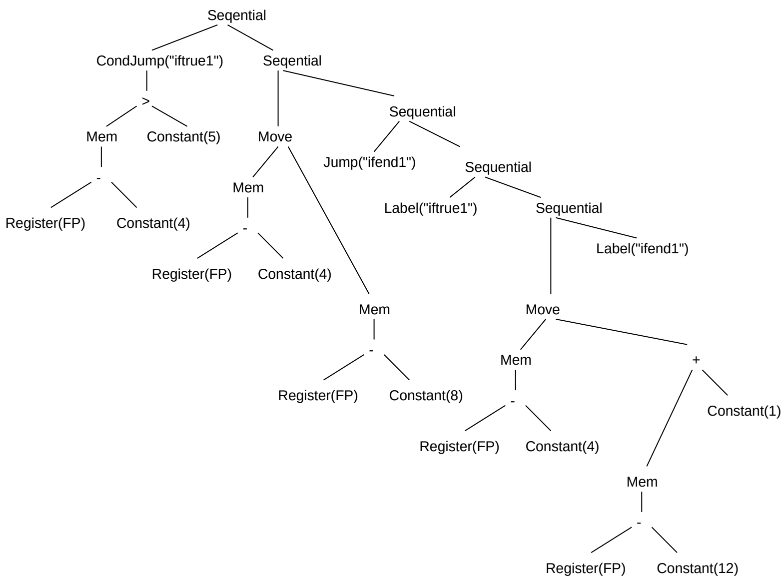
## 08-177: **Extended Eg. – Accumulator**

```
        j    ifend1              % Tile 16
iftrue:                          % Tile 17
        addi $ACC, $FP,    0     % Tile 18
        sw   $ACC, 0($ESP)       % Tile 20
        addi $ESP, $ESP   -4     % Tile 20
        addi $ACC, $zero   4     % Tile 19
        lw   $t1,  0($ESP)       % Tile 20
        addi $ESP, $ESP    4     % Tile 20
        sub  $ACC, $t1,   $ACC   % Tile 20
        sw   $ACC, 0($ESP)       % Tile 27
        addi $ESP, $ESP,  -4     % Tile 27
        addi $ACC, $FP,    0     % Tile 21
        sw   $ACC, 0($ESP)       % Tile 23
        addi $ESP, $ESP,  -4     % Tile 23
        addi $ACC, $zero,  12    % Tile 22
        lw   $t1,  4($ESP)       % Tile 23
        addi $ESP, $ESP,   4     % Tile 23
        add  $ACC, $t1,   $ACC   % Tile 23
        lw   $ACC, 0($ACC)       % Tile 24
        sw   $ACC, 0($ESP)       % Tile 26
```

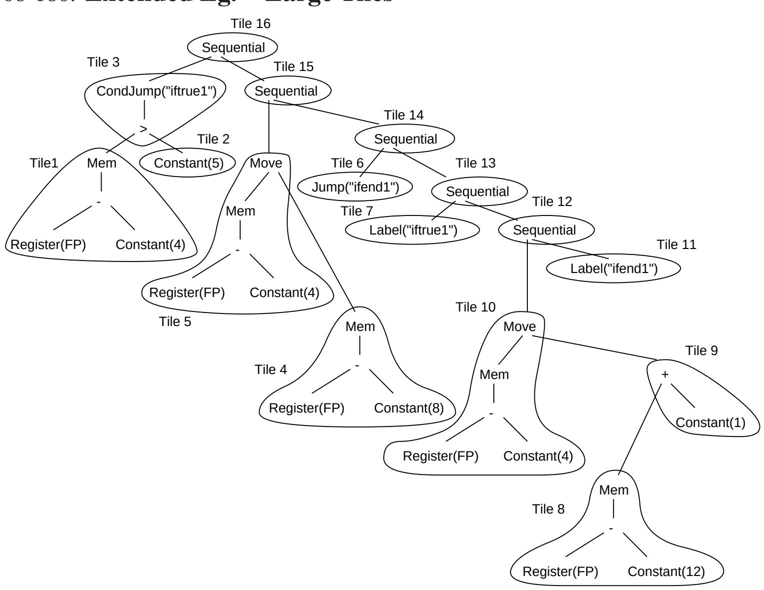
## 08-178: Extended Eg. – Accumulator

```
       addi $ESP, $ESP,  -4     % Tile 26
       addi $ACC, $zero   1     % Tile 25
       lw   $t1,  4($ESP)       % Tile 26
       addi $ESP, $ESP,   4     % Tile 26
       add  $ACC, $t1,   $ACC   % Tile 26
       lw   $t1,  4($ESP)       % Tile 27
       addi $ESP, $ESP,   4     % Tile 27
       sw   $ACC, 0($t1)        % Tile 27
ifend1:                         % Tile 28
                                %  No code for tiles 29 -- 33
```

## 08-179: Extended Eg. – Large Tiles




## 08-180: Extended Eg. – Large Tiles




## 08-181: Extended Eg. – Large Tiles

```
       lw   $ACC, -4($FP)       % Tile 1
       sw   $ACC, 0($ESP)       % Tile 3
       addi $ESP, $ESP,  -4     % Tile 3
       addi $ACC, $zero,  5     % Tile 2
       lw   $t1, 4($ESP)        % Tile 3
```

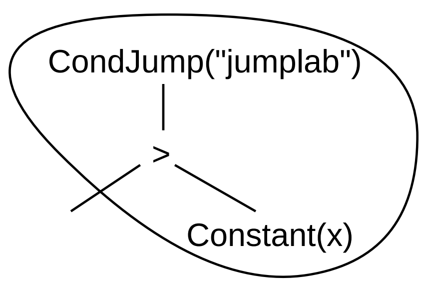
```
        addi $ESP, $ESP,   4     % Tile 3
        slt  $ACC, $ACC,   $t1   % Tile 3
        bgtz $ACC, iftrue1       % Tile 3
        lw   $ACC, -8($FP)       % Tile 4
        sw   $ACC, -4($FP)       % Tile 5
        j    ifend               % Tile 6
iftrue1:                         % Tile 7
        lw   $ACC, -12($FP)      % Tile 8
        addi $ACC, $ACC,   1     % Tile 9
        sw   $ACC, -4($FP)       % Tile 10
ifend:                           % Tile 11
                                 %  No code for tiles 12 -- 16
```

08-182: **Optimized Expression Stack**

```
        lw   $ACC, -4($FP)       % Tile 1
        addi $t2, $ACC,    0     % Tile 3
        addi $ACC, $zero,  5     % Tile 2
        addi $t1,  $t2,    0     % Tile 3
        slt  $ACC, $ACC,   $t1   % Tile 3
        bgtz $ACC, iftrue1       % Tile 3
        lw   $ACC, -8($FP)       % Tile 4
        sw   $ACC, -4($FP)       % Tile 5
        j    ifend               % Tile 6
iftrue1:                         % Tile 7
        lw   $ACC, -12($FP)      % Tile 8
        addi $ACC, $ACC,   1     % Tile 9
        sw   $ACC, -4($FP)       % Tile 10
ifend:                           % Tile 11
                                 %  No code for tiles 12 -- 16
```

08-183: **Further Optimizations**

- Tiles 2 and 3 could be covered by a single tile:




```
addi $ACC, $ACC, -x
bgtz $ACC, jumplab
```

08-184: **Further Optimizations**

```
        lw   $ACC, -4($FP)       % Tile 1
        addi $ACC, $ACC,  -5     % Tile 2/3
        bgtz $ACC, iftrue1       % Tile 2/3
        lw   $ACC, -8($FP)       % Tile 4
        sw   $ACC, -4($FP)       % Tile 5
        j    ifend               % Tile 6
iftrue1:                         % Tile 7
        lw   $ACC, -12($FP)      % Tile 8
        addi $ACC, $ACC,   1     % Tile 9
        sw   $ACC, -4($FP)       % Tile 10
ifend:                           % Tile 11
                                 %  No code for tiles 12 -- 16
```

08-185: **Implementation Details**

- Implementing in Java
  - Implement AATVisitor to do code generation
    - Don’t always call “accept” on children
    - Sometimes call “accept” on grandchildren, great-grandchildren, etc.
    - Will need to use “instance of” (slightly more ugly than semantic analysis)

08-186: **Implementation Details**

- Don't always call "accept" on children
  - Use "instance of" to decide which "tile" to use
  - Call "accept" to tile the subtrees
  - Output code with the "emit" function

08-187: **Implementation Details**

- Start will small tiles, slowly adding larger tiles to make the code more efficient
- Unfortunately, generated code using small tiles is hard to debug
- Plan on spending **at least** 50% of your time debugging rather than coding
  - Much more so with this project than with prior projects!
- Hopefully all early bugs have been worked out, so you only need to deal with getting codegen to work without going back and modifying SemanticAnalyzer.java, BuildTree.java, etc.
  - It'd be nice to win the lottery, too.