Compilers

CS414-2014S-08

Code Generation

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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.

Target Assembly

- Our compiler will produce MIPS code
  - RISC code is easier to generate
  - Can use your compiler to generate code that works on your chip (from Architecture)

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

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 $\neq$ rt, jump to the label $<$target$>$
blez rs, $<$target$>$	if rs $\leq$ 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 $\geq$ 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)

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

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

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

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?

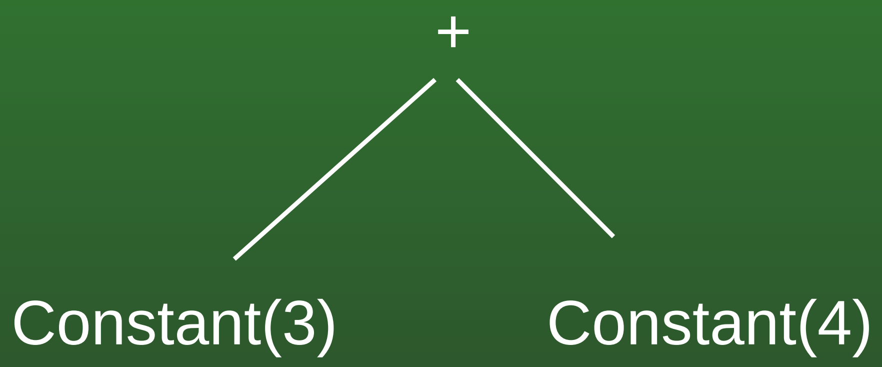
Expression Trees

- 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

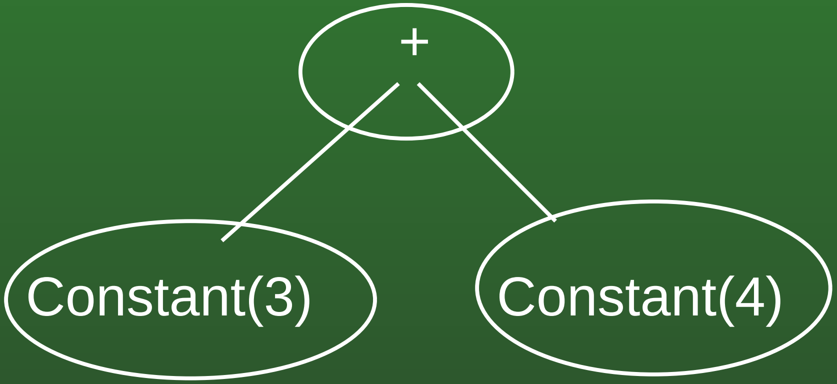
- Arithmetic Binary Operations



- 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

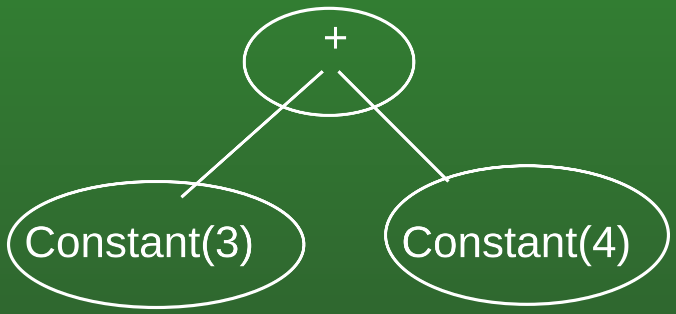
- Code is emitted in a post-order traversal of the tree
  - When code for + is executed
    - The values of the left and right sub-expressions are stored on the stack
    - Right sub-expression is on the top of the stack
- Pop the left and right sub-expressions of the stack
- Add their values
- Push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

08-21: Expression Trees

- Arithmetic Binary Operations
  - Code for a “+” tile:

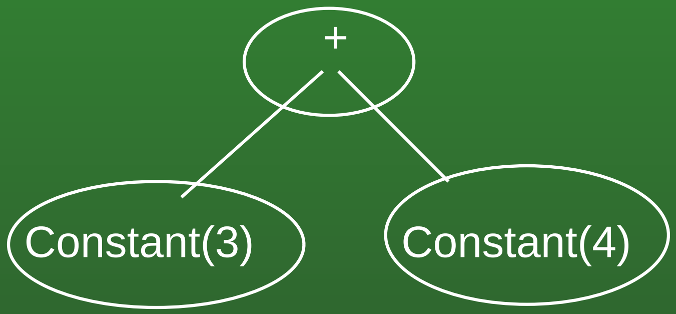
```
lw   $t1, 8($ESP)     % load first operand
lw   $t2, 4($ESP)     % load the second operand
add  $t1, $t1, $t2    % do the addition
sw   $t1, 8($ESP)     % store the result
add  $ESP, $ESP, 4    % update the ESP
```

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
```

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

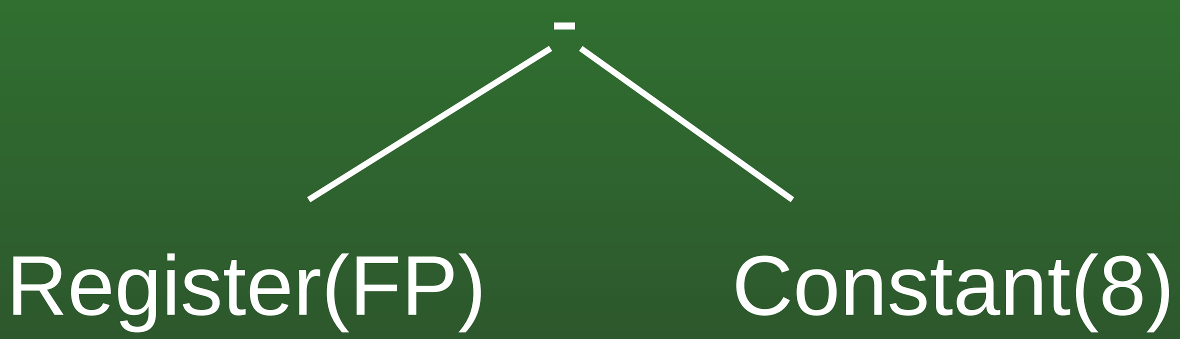
08-25: Expression Trees

- Register Trees
  - Register(FP)

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

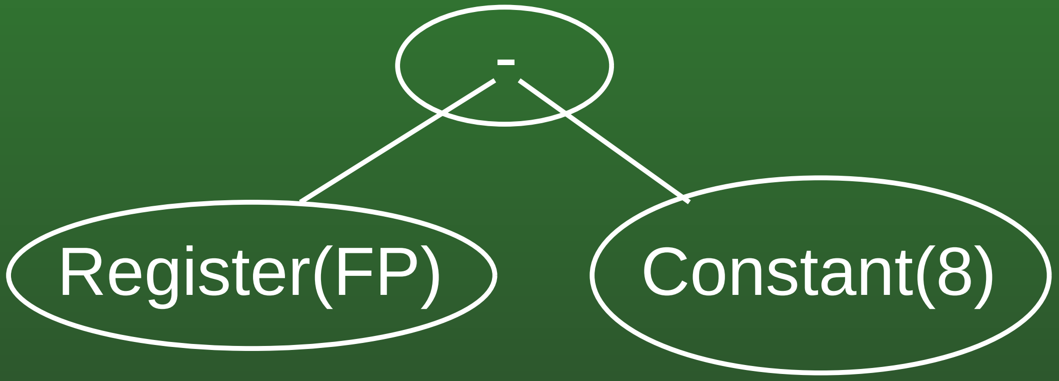
Expression Trees

- Tiling the tree:

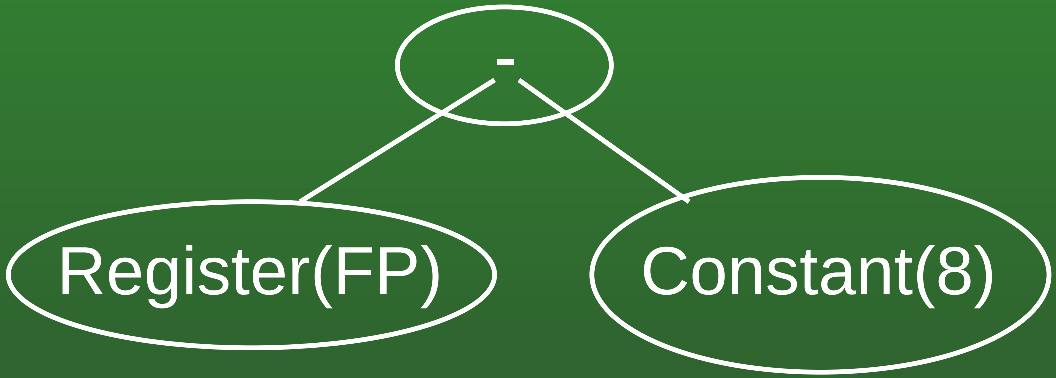


08-27: Expression Trees

- Tiling the tree:



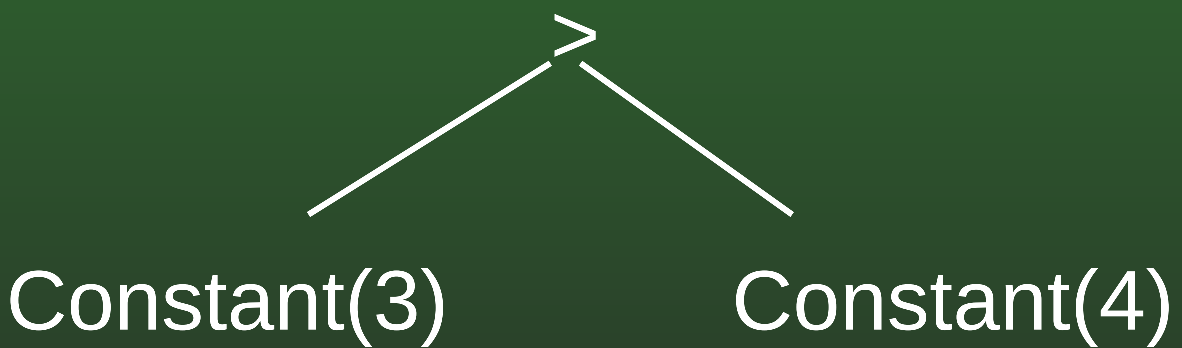
08-28: Expression Trees



```
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

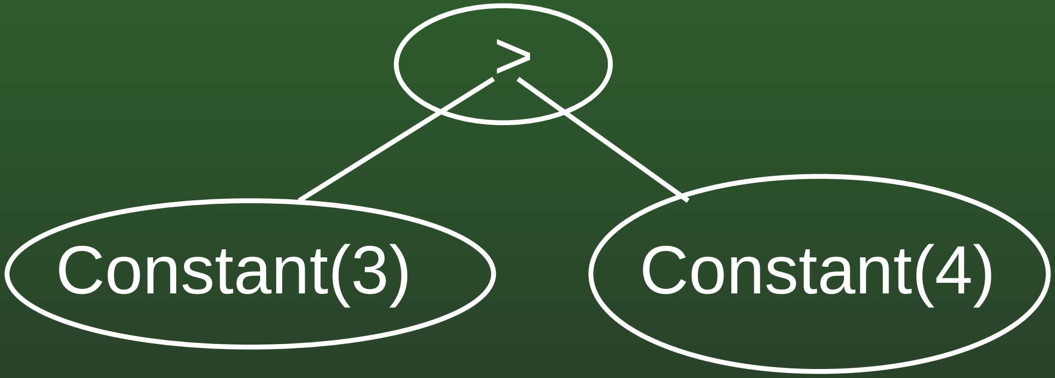
- Relational Operations
  - Relational operators – $<, >, =$, etc – produce boolean values
  - Assembly code for a relational operator tile needs to put a 0 or 1 on the expression stack



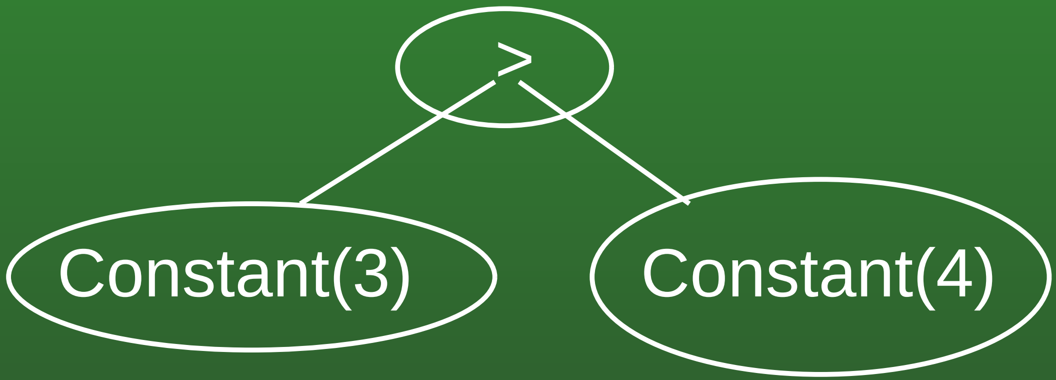
- If we tile the tree with one tile / tree node:

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



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

Expression Trees

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

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

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
```

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

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

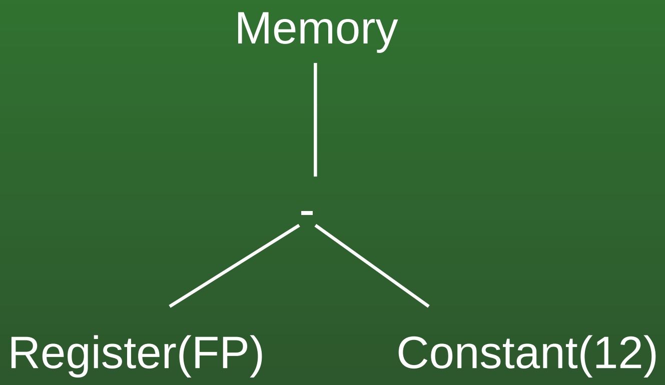
08-41: Expression Trees

- Memory Accesses

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

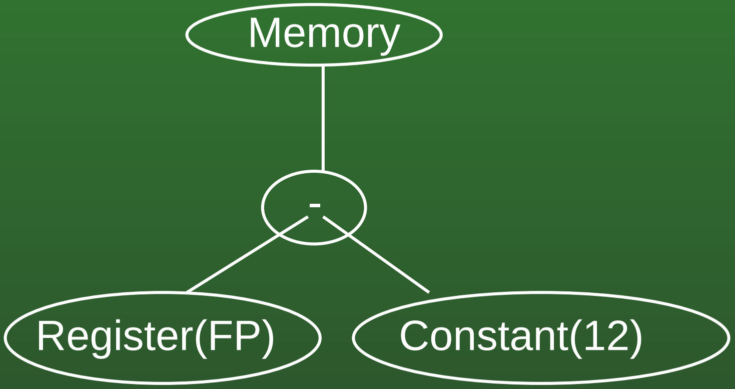
Expression Trees

- Memory Example

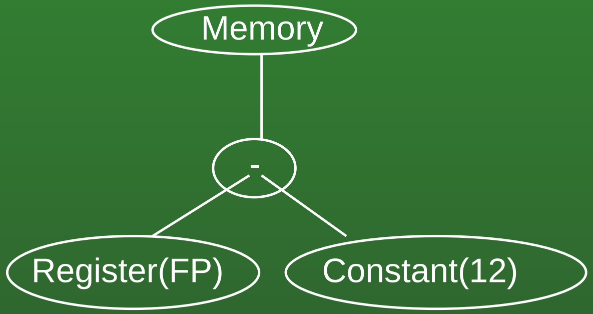


Expression Trees

- Memory Example



08-44: Expression Trees



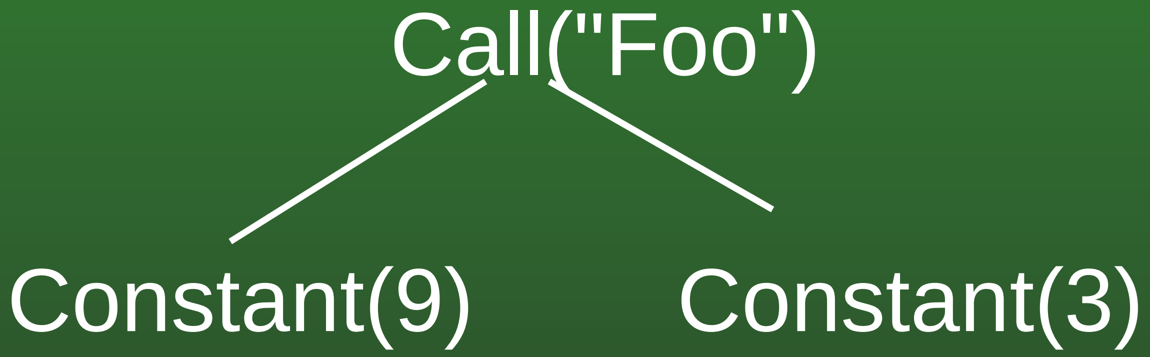
```
sw   $FP,  0($ESP)      % Store frame pointer on the top of the expressin stack
addi $ESP, $ESP,  -4    % Update the expression stack pointer
addi $t1,  $zero, 12    % Load the constant value 12 into the register $t1
sw   $t1,  0($ESP)      % Store $t1 on the top of the expression stack
addi $ESP, $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
```

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

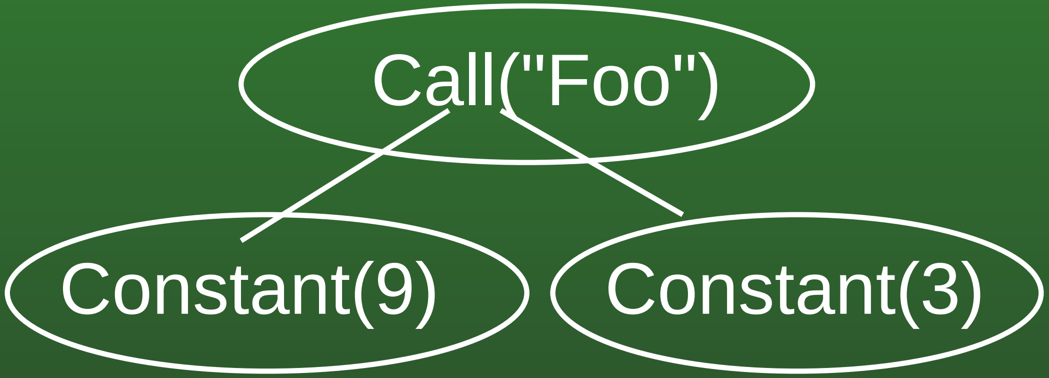
Expression Trees

- Function calls

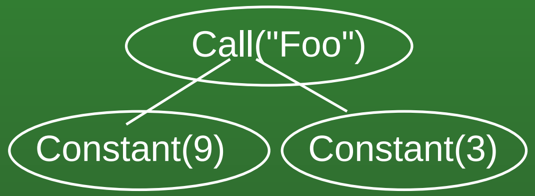


08-47: Expression Trees

- 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
```

Simple Tiling

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

Statement Trees

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

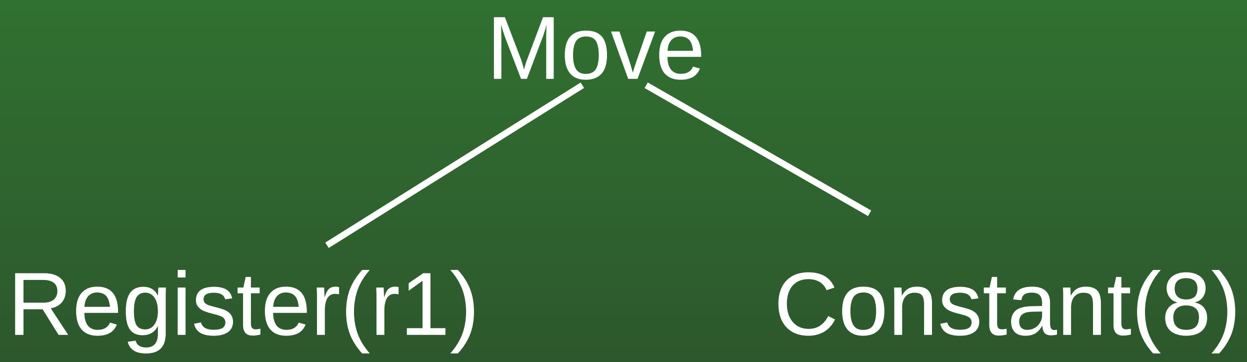
```
Label1:
```

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)

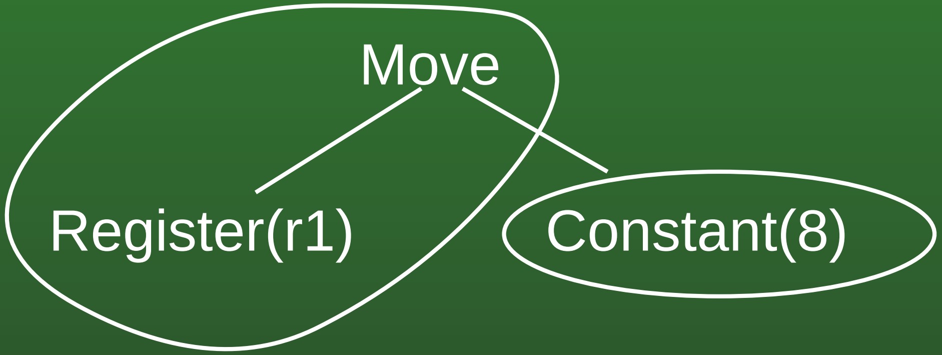
Statement Trees

- Move Trees (Moving into Registers)



Statement Trees

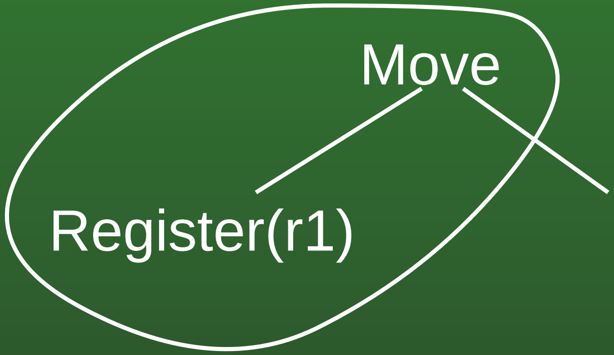
- Move Trees (Moving into Registers)



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

Statement Trees

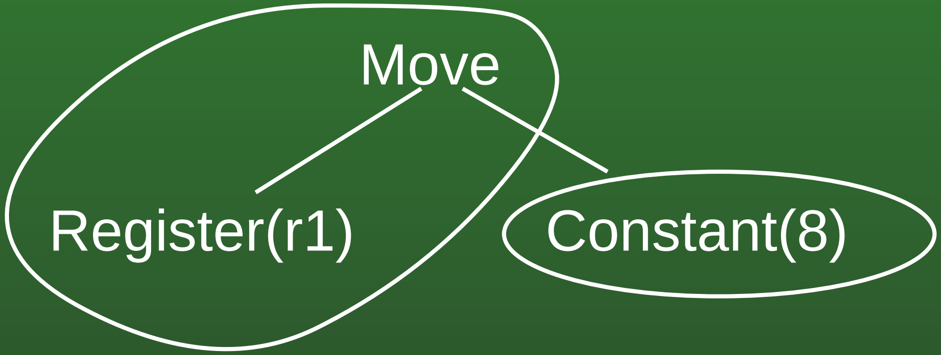
- Move Trees (Moving into Registers)



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

Statement Trees

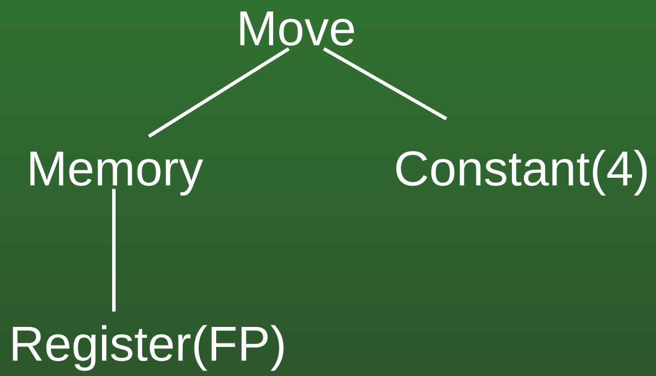
- Move Trees (Moving into Registers)



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

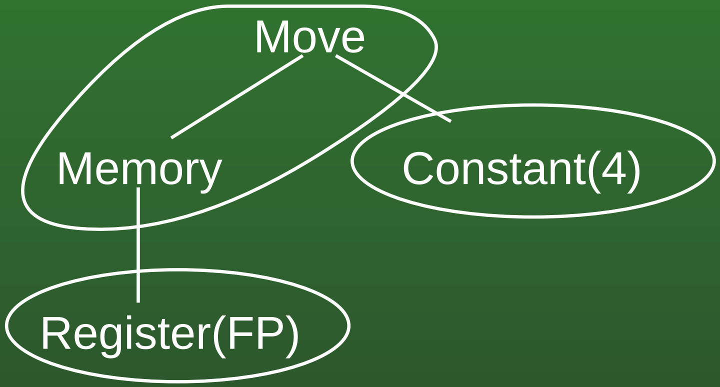
08-56: Statement Trees

- Move Trees (Moving into MEMORY locations)



Statement Trees

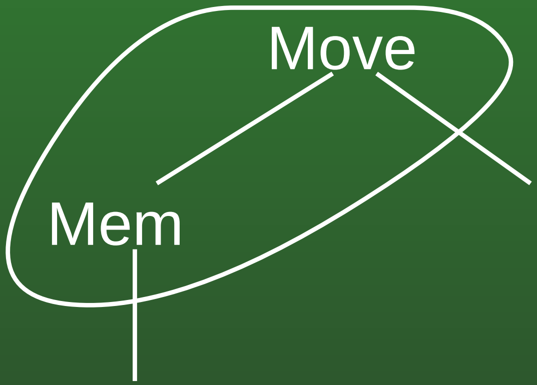
- Move Trees (Moving into MEMORY locations)



- 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

Statement Trees

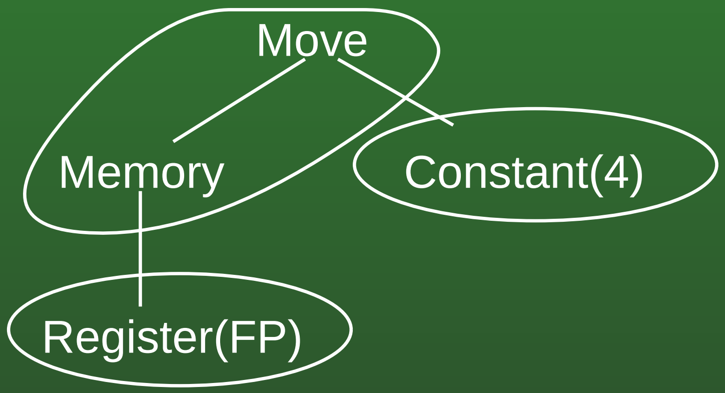
- Move Trees (Moving into MEMORY locations)



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

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
```

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:

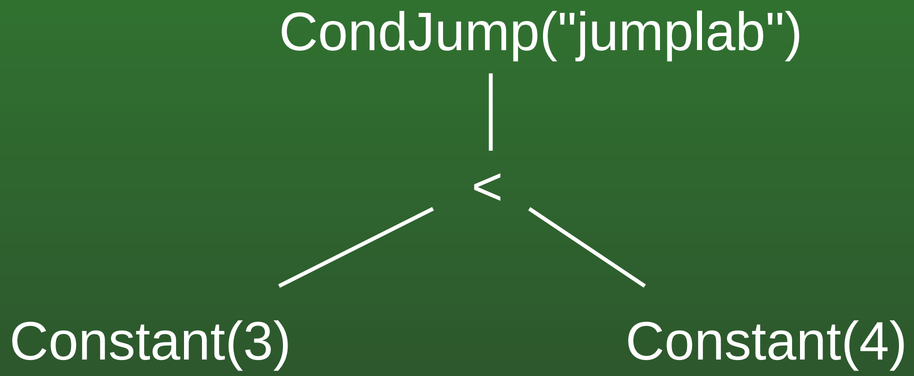
```
j jumplab
```

Statement Trees

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

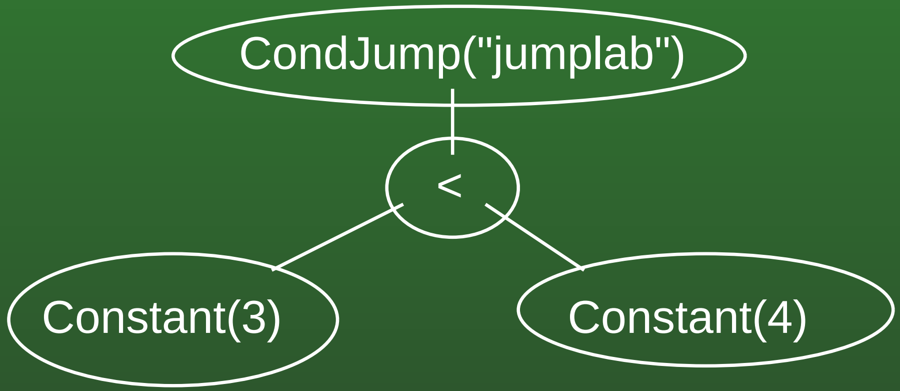
Statement Trees

- Conditional Jump Trees



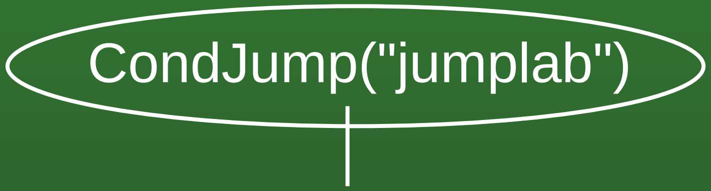
08-64: Statement Trees

- Conditional Jump Trees



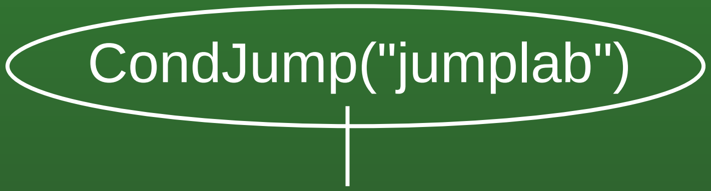
Statement Trees

- Conditional Jump Trees



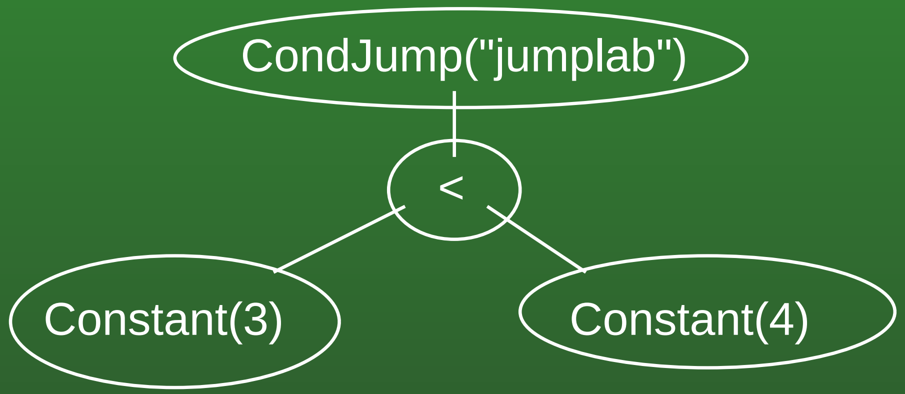
Statement Trees

- 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      %--
```

Statement Trees

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

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

Statement Trees

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

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:

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

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

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

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:

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

Accumulator Register

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

08-81: Accumulator Register

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

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

Accumulator Register

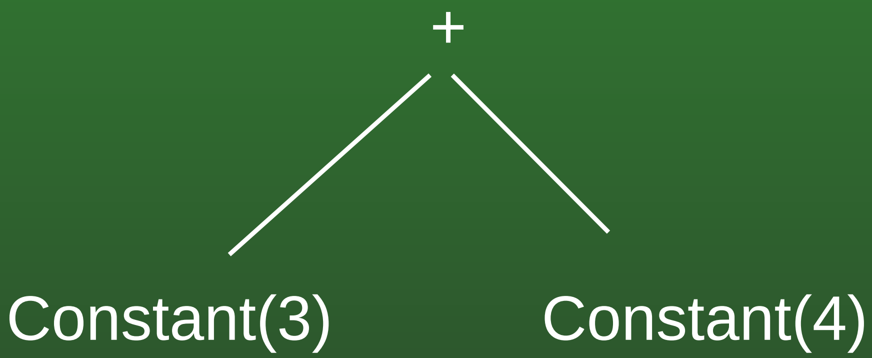
- Binary Operators (+, -, *, etc)
  - Slightly more complicated
  - Can no longer do a simple postorder traversal
    - Emit code for left subtree – stores value in ACC
    - Emit code for right subtree – stores value in ACC – overwriting old value
      - Oops!

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

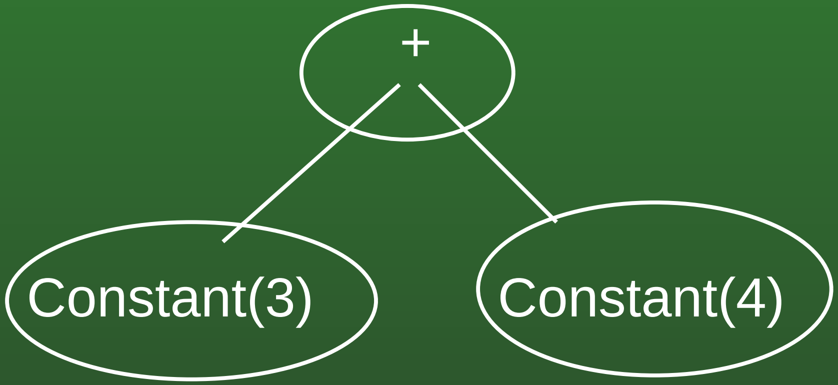
08-84: Accumulator Register

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



Accumulator Register

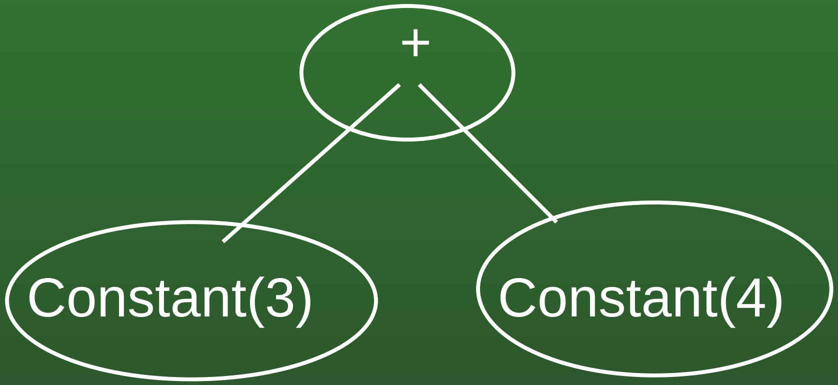
- Binary Operators (+, -, *, etc)



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

Accumulator Register

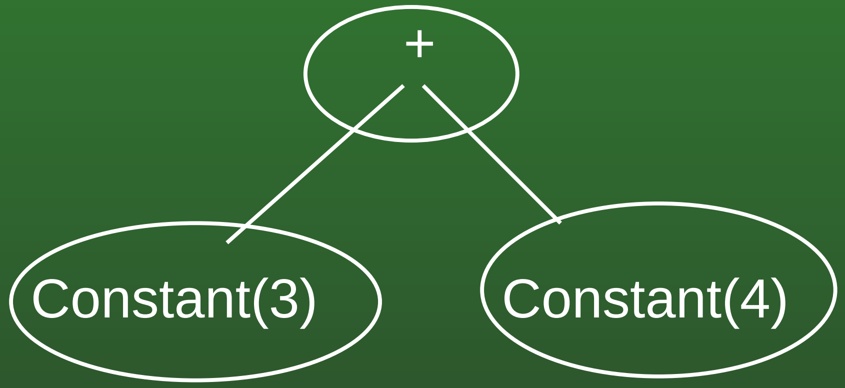
- Binary Operators (+, -, *, etc)



```
<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
```

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
```

Accumulator Register

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

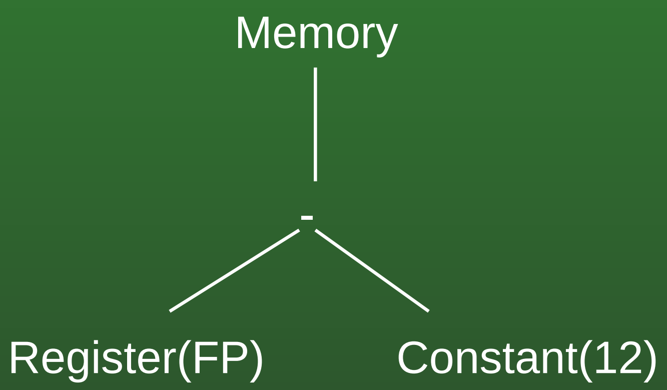
08-89: Accumulator Register

- Memory Expression Trees
  - Code for a Memory tile:

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

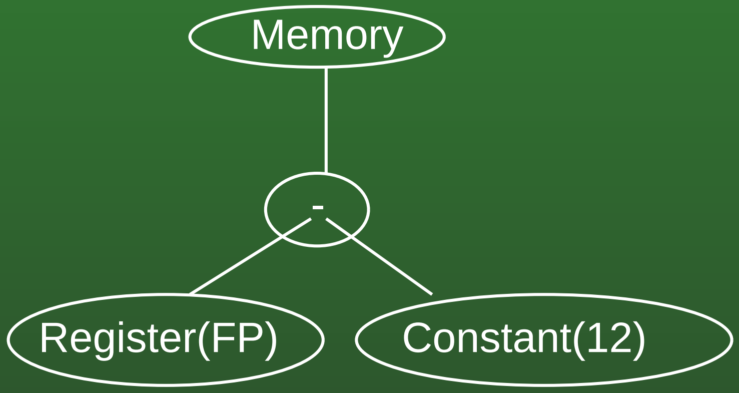
08-90: Accumulator Register

- Memory Example



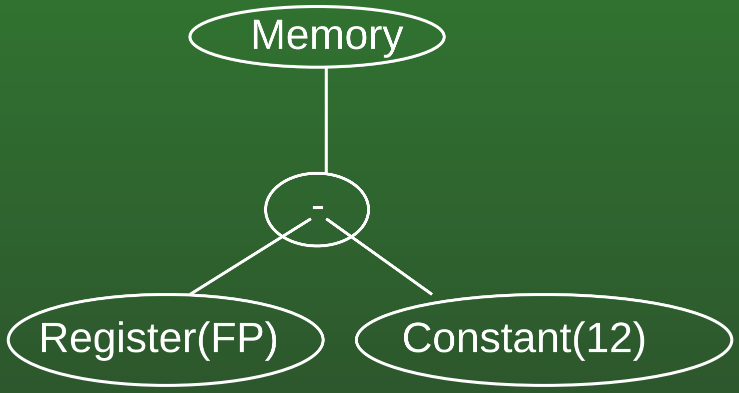
08-91: Accumulator Register

- Memory Example



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
```

Accumulator Register

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

Accumulator Register

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

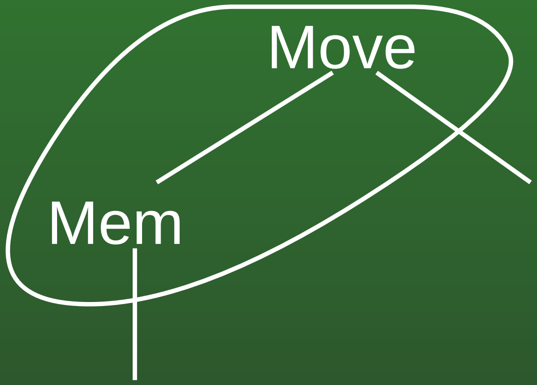
```
addi $r1, $ACC, 0
```

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

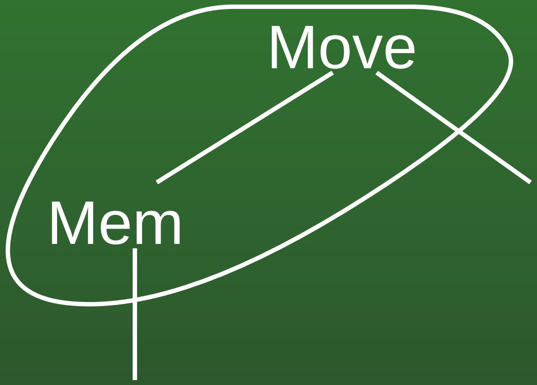
08-96: Accumulator Register

- Memory Move Statement Trees



Accumulator Register

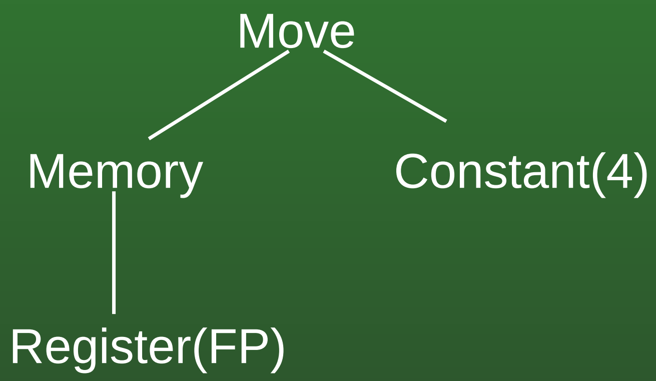
- Memory Move Statement Trees



```
<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)
```

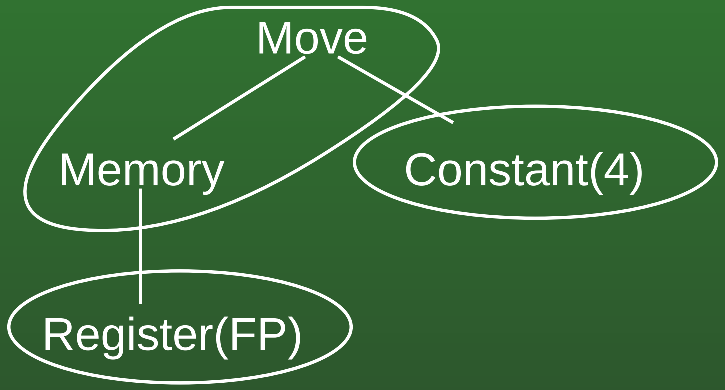
08-98: Accumulator Register

- Memory Move Example



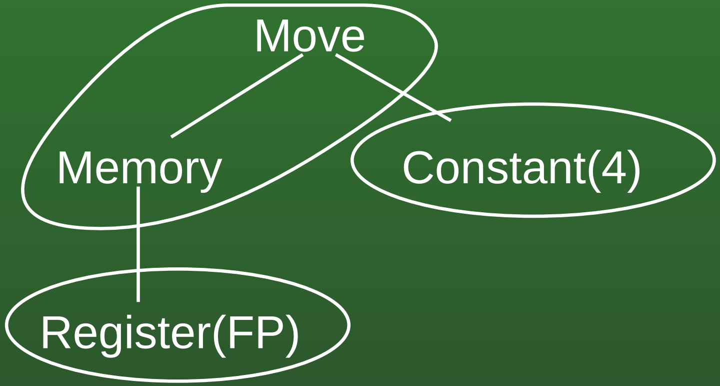
08-99: Accumulator Register

- Memory Move Example



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

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
```

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

Accumulator Register

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

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

Accumulator Register

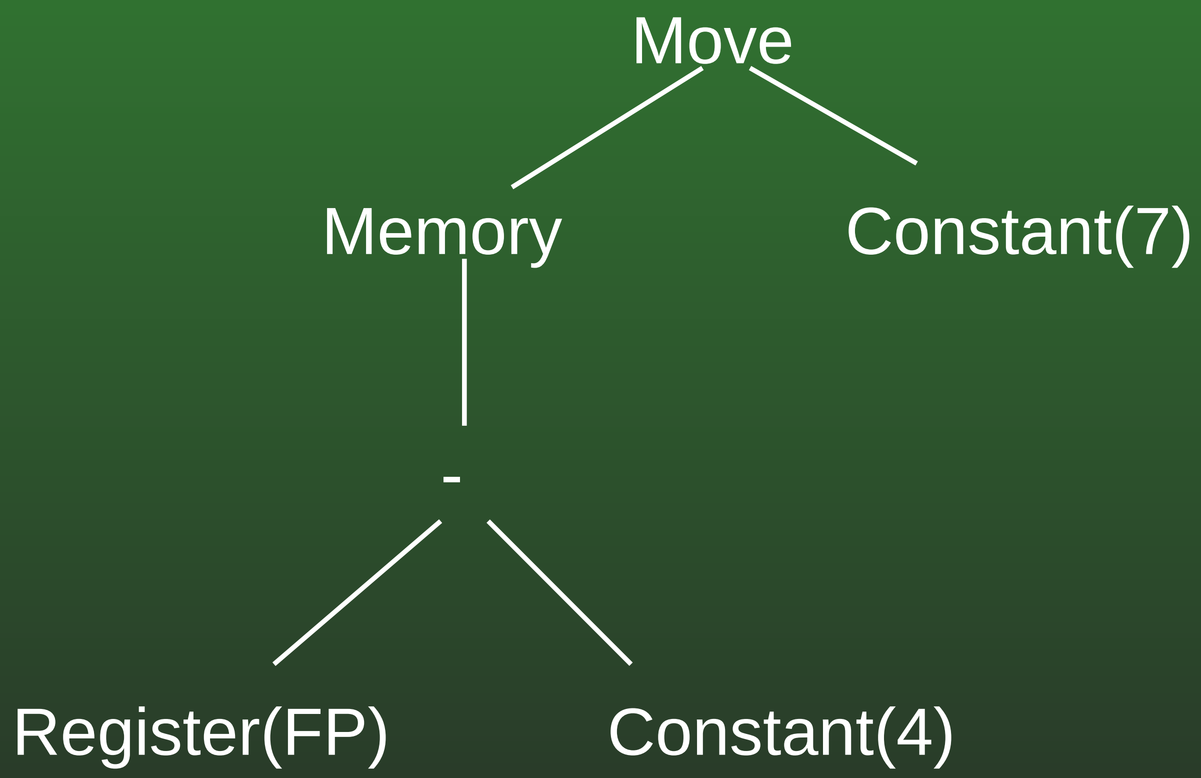
- Jumps, labels, sequential statements
  - Do not have subtrees with values
  - Code is the same as previously defined

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

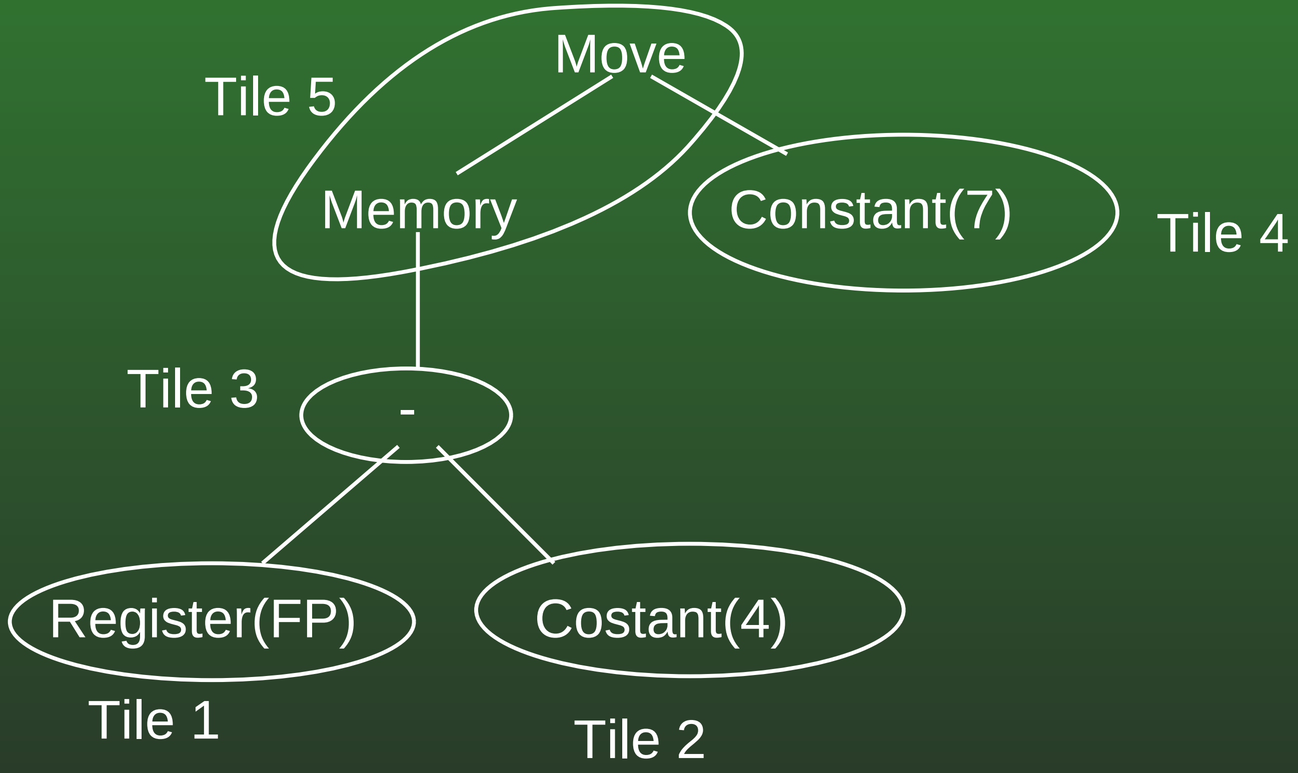
08-108: Larger Tiles Example

- Memory Move Expression



08-109: Larger Tiles Example

- Standard Tiling



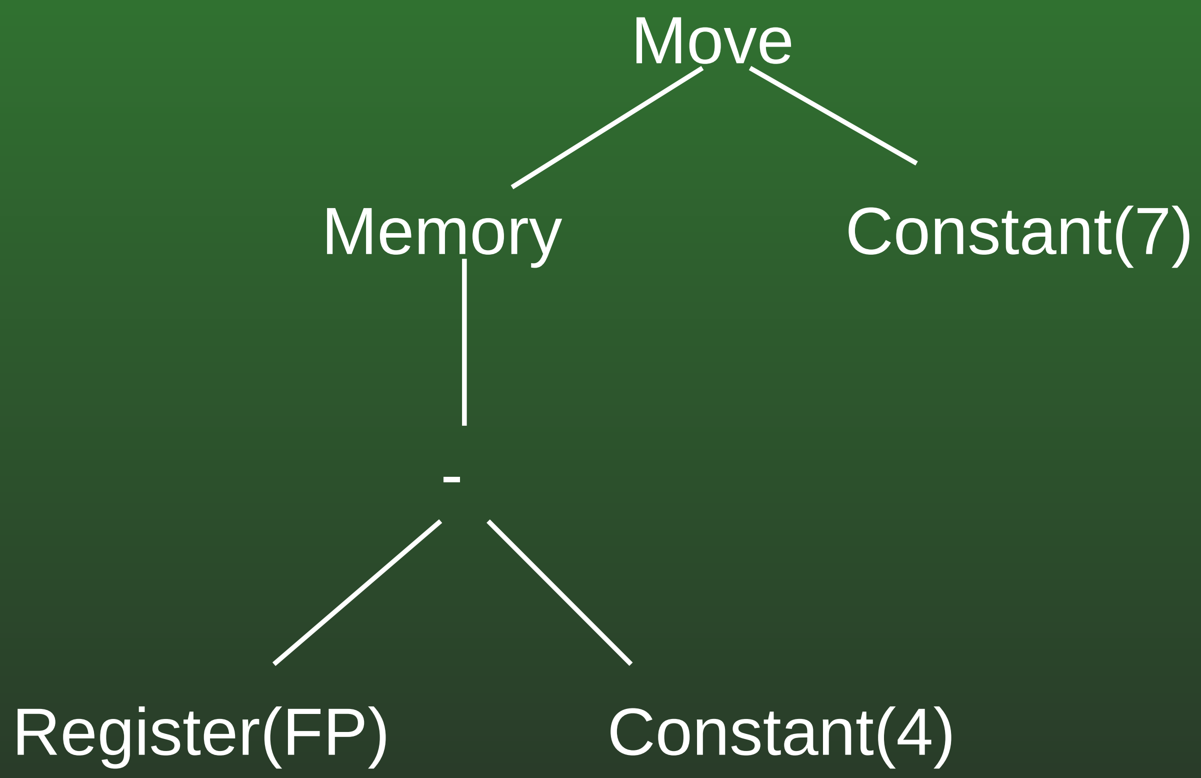
Larger Tiles Example

- 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
```

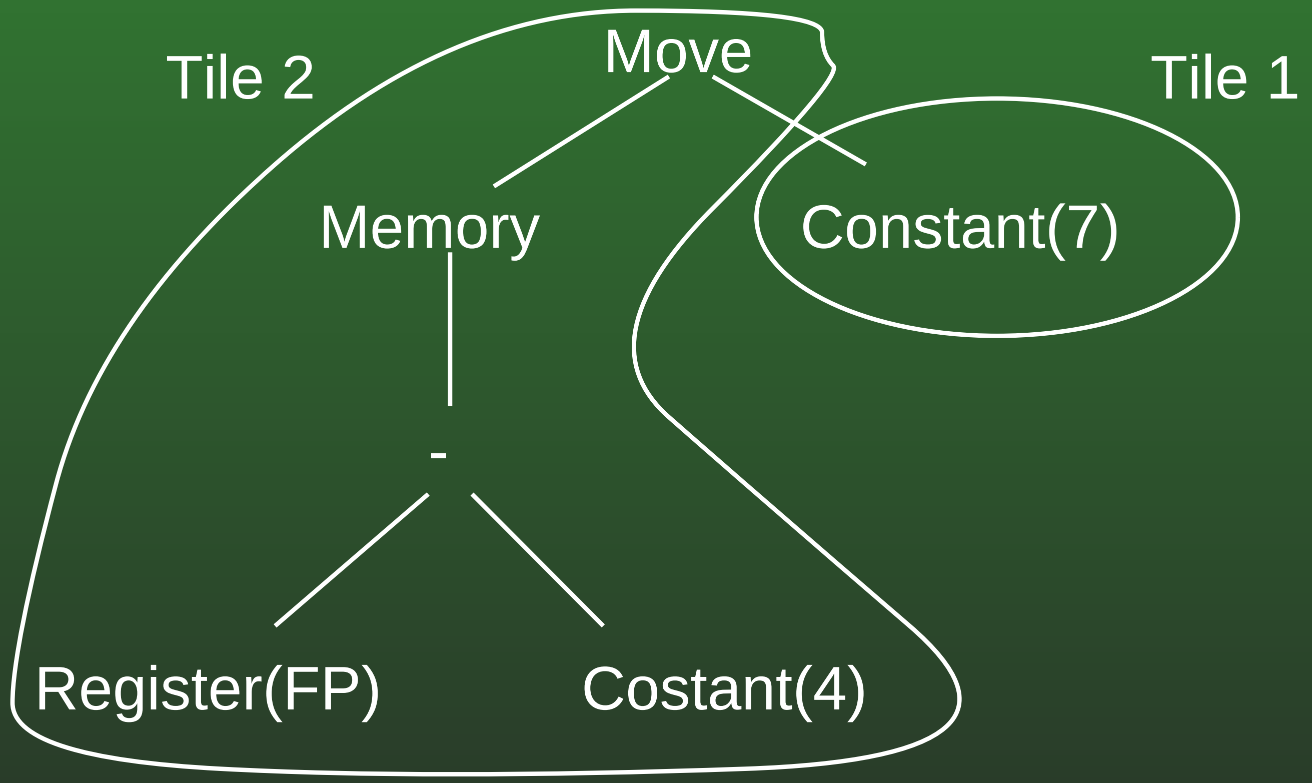
08-111: Larger Tiles Example

- Memory Move Expression

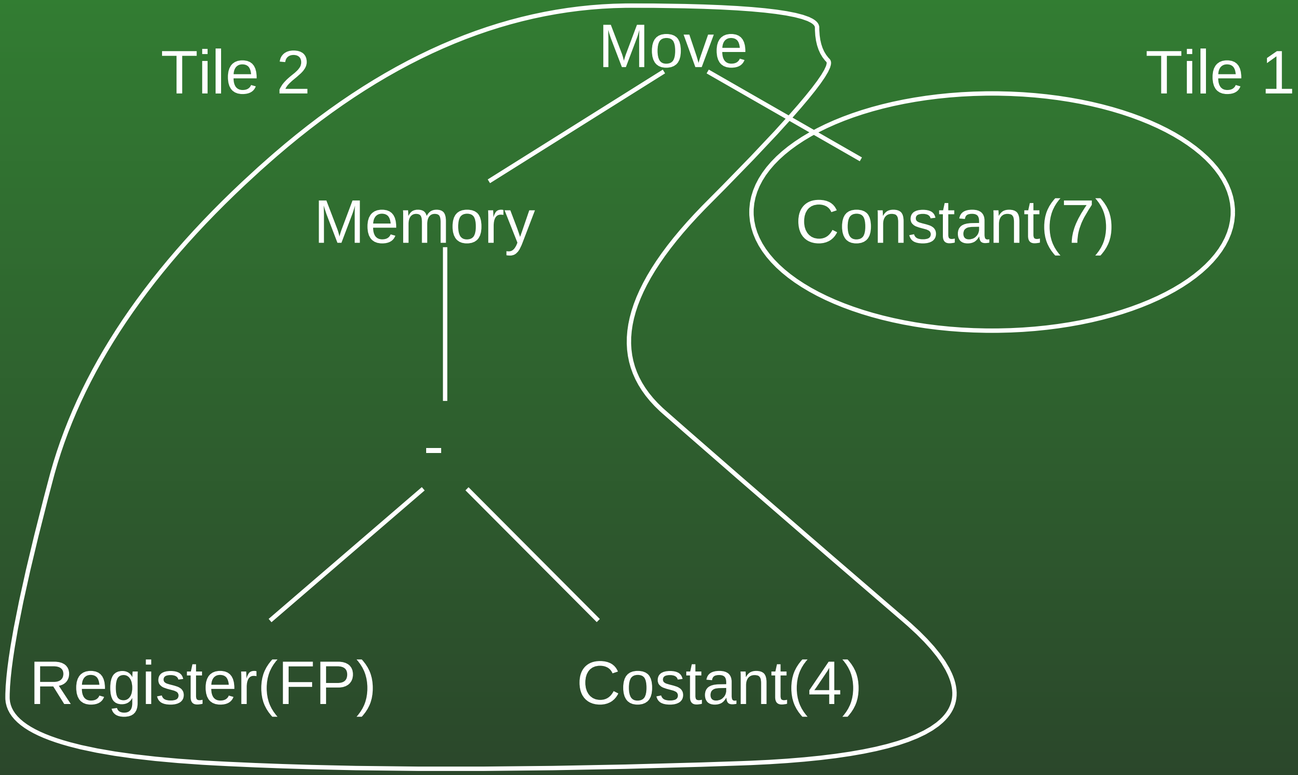


08-112: Larger Tiles Example

- Using Larger Tiles

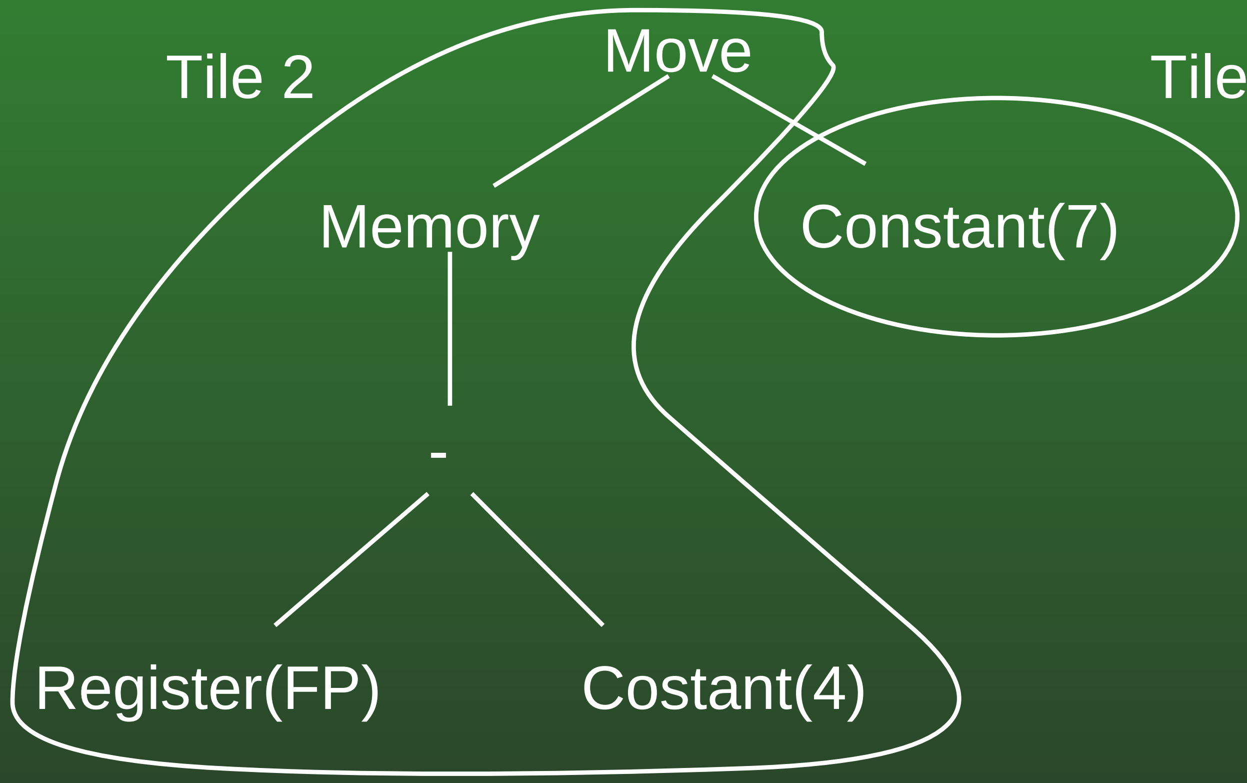


Larger Tiles Example



- Code for Tile 2?

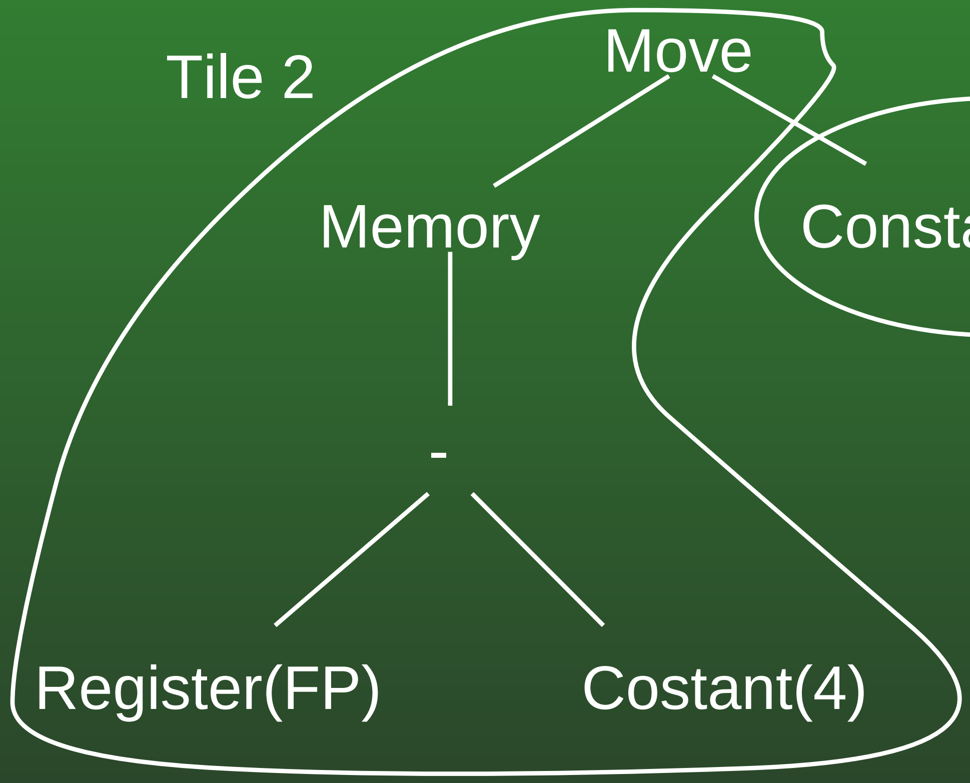
08-114: Larger Tiles Example



- 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
```

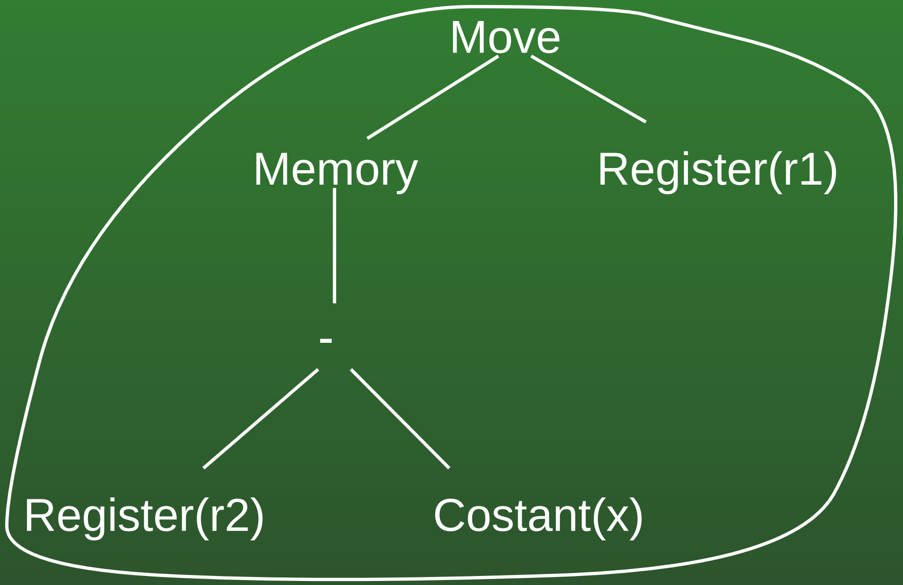
Larger Tiles

- 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

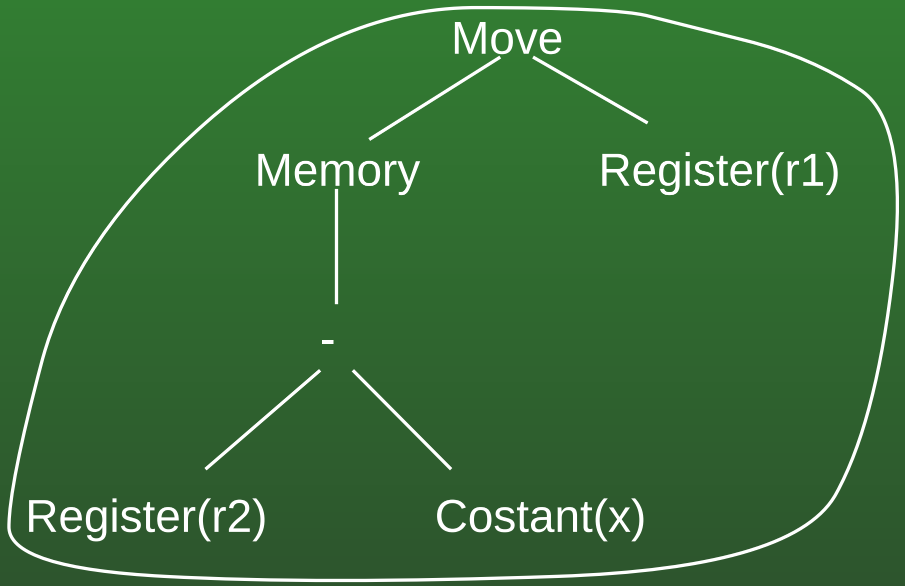
Larger Tiles

- 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

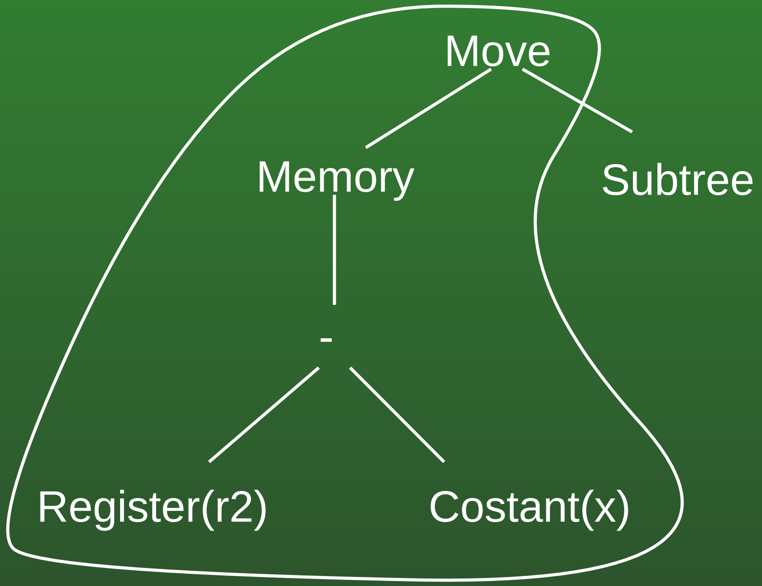


Larger Tiles – Examples

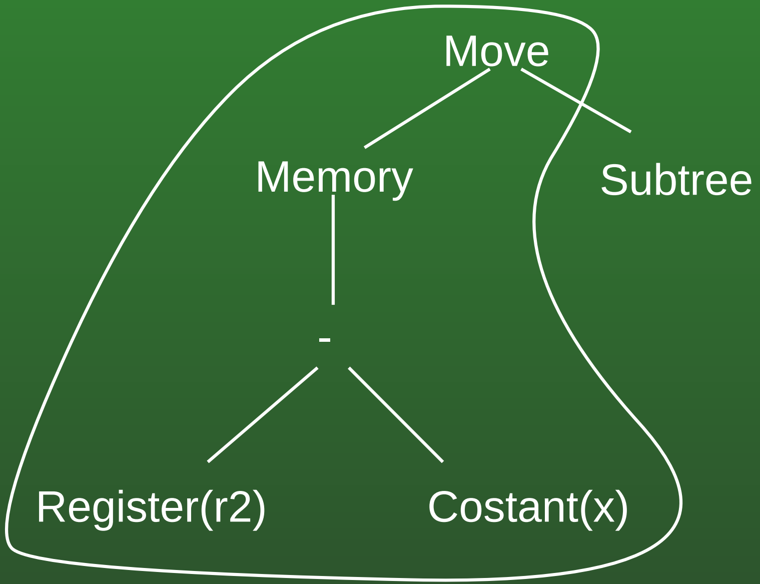


```
sw r1 -x(r2)
```

Larger Tiles – Examples

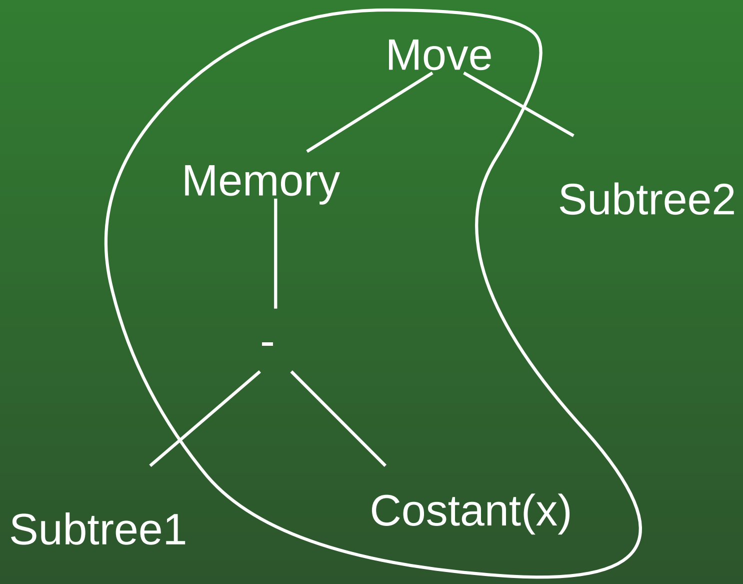


08-121: Larger Tiles – Examples

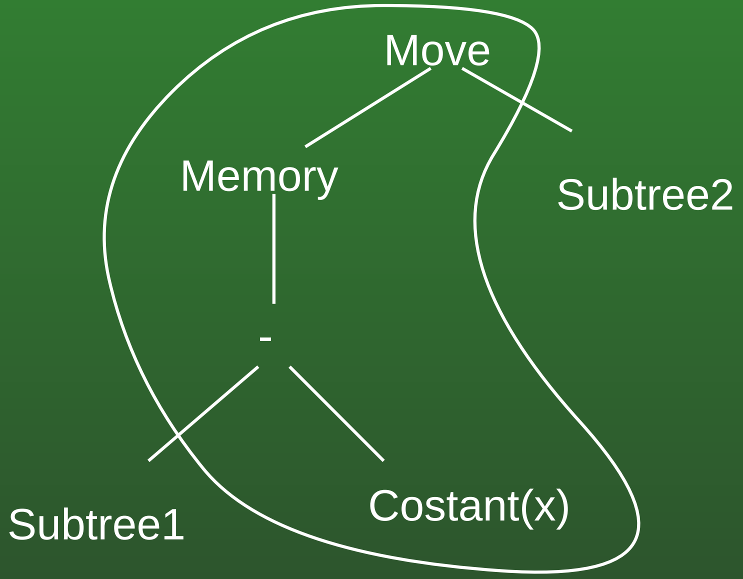


```
<code for Subtree>
sw $ACC, -x(r2)
```

Larger Tiles – Examples

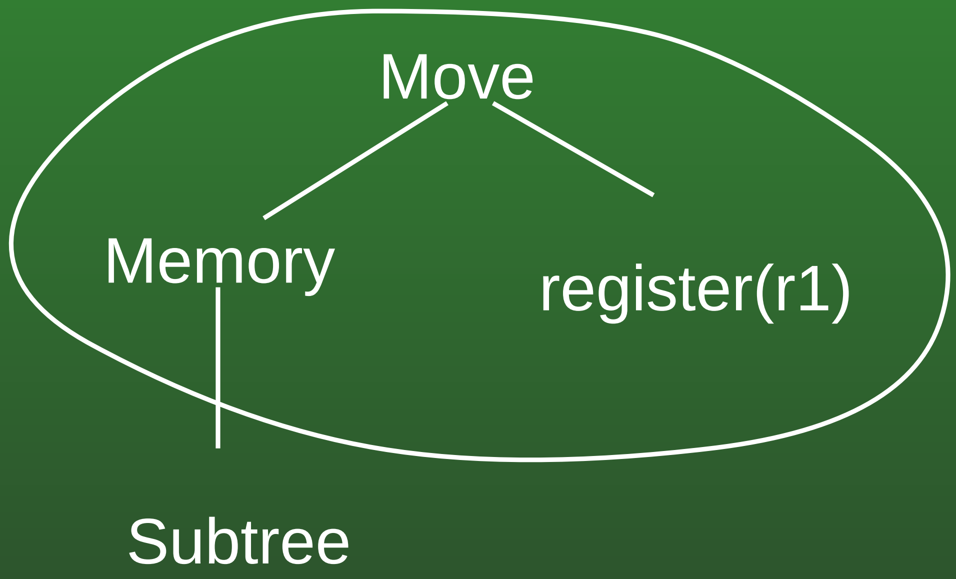


08-123: Larger Tiles – Examples

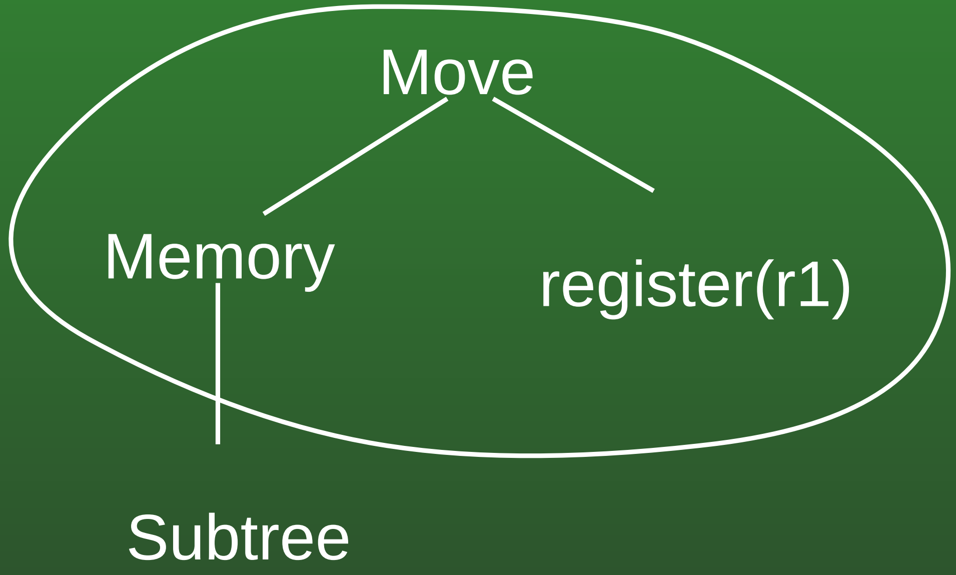


```
<code for Subtree1>
sw   $ACC, 0($ESP)
addi $ESP, $ESP
<code for Subtree2>
lw   $t1,   4($ESP)
addi $ESP, $ESP, 4
sw   $ACC, -x($t1)
```

Larger Tiles – Examples

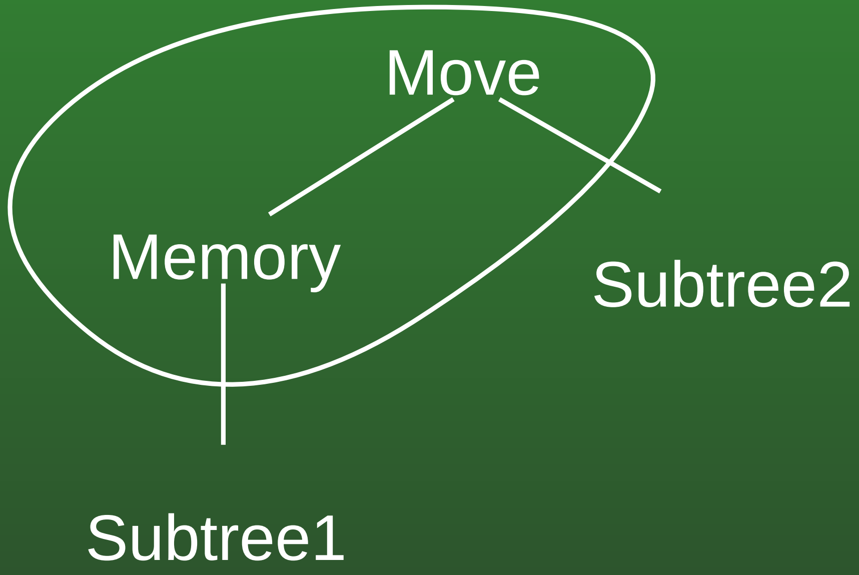


Larger Tiles – Examples

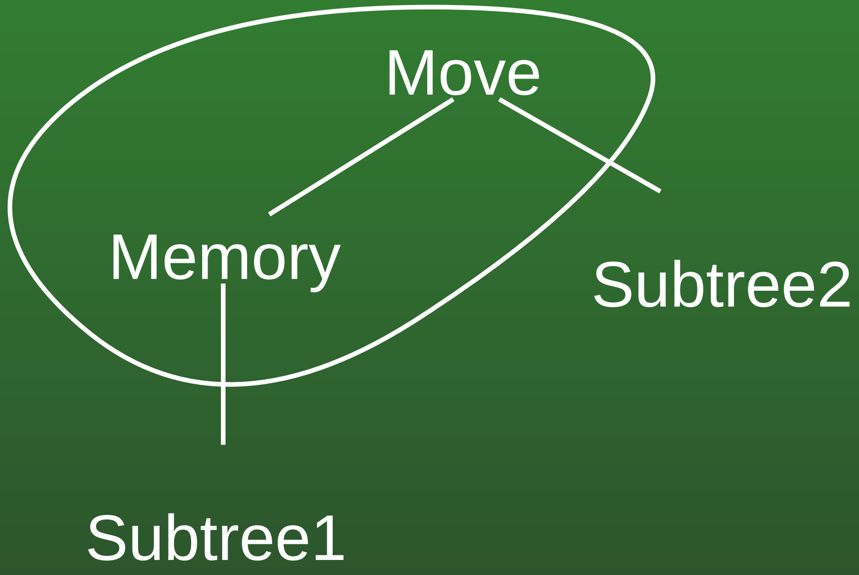


```
<code for Subtree>
sw   $r1, -x($ACC)
```

08-126: Larger Tiles – Examples



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

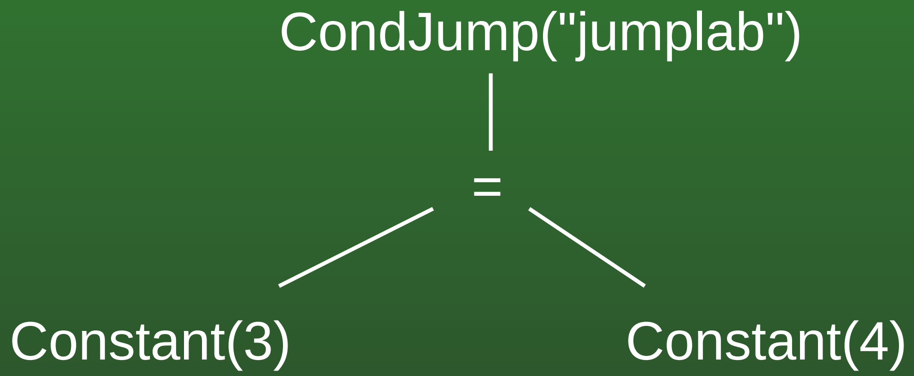
- Larger tiles are better
- Why design small tiles as well as large tiles?
  - Might not always be able to use largest tile
- Why design a range of tile sizes

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

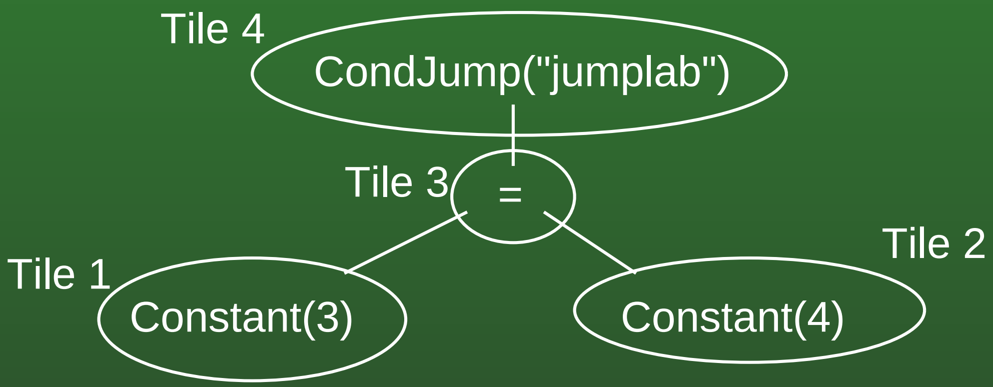
08-131: Larger Tiles

- Conditional Jump Trees



Larger Tiles

- Conditional Jump Trees



Larger Tiles

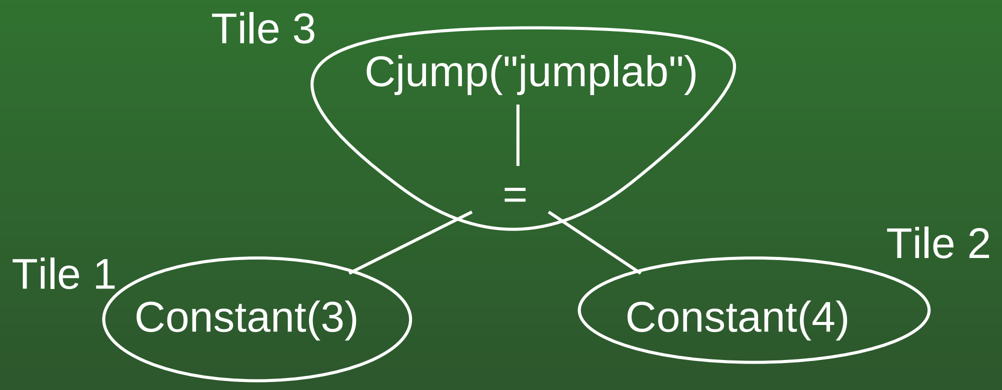
```
          addi $ACC, $zero 3          % Tile 1
          sw   $ACC, 0($ESP)          % Tile 3
          addi $ESP, $ESP, -4         % Tile 3
          addi $ACC, $zero, 4         % Tile 2
          lw   $t1,  4($ESP)          % Tile 3
          addi $ESP, $ESP, 4          % Tile 3
          beq 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

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

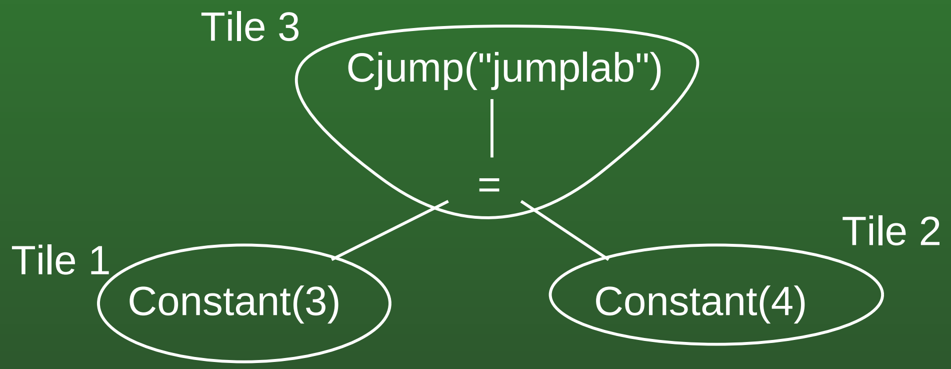
Larger Tiles

- Conditional Jump Trees



08-136: **Larger Tiles**

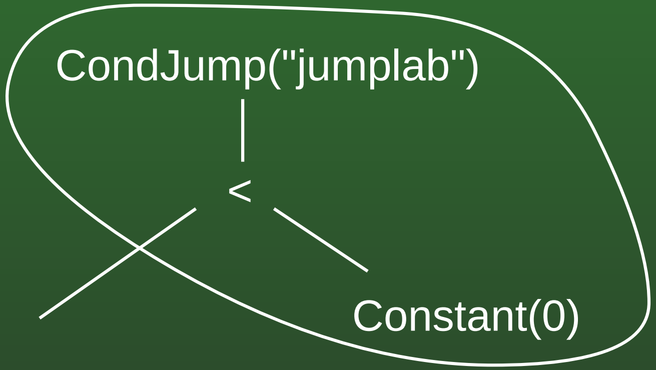
- Conditional Jump Trees



```
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
```

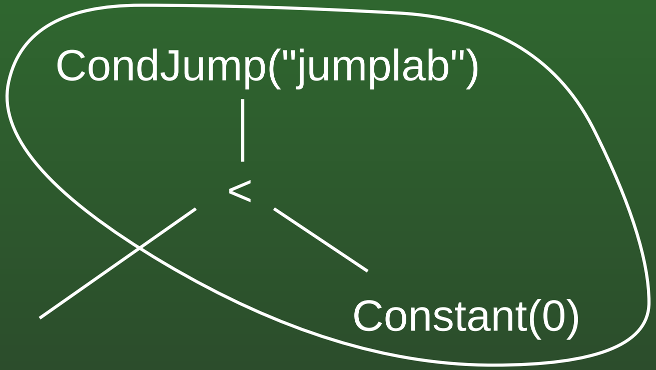
Larger Tiles

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



Larger Tiles

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



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

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

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

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)
  ```

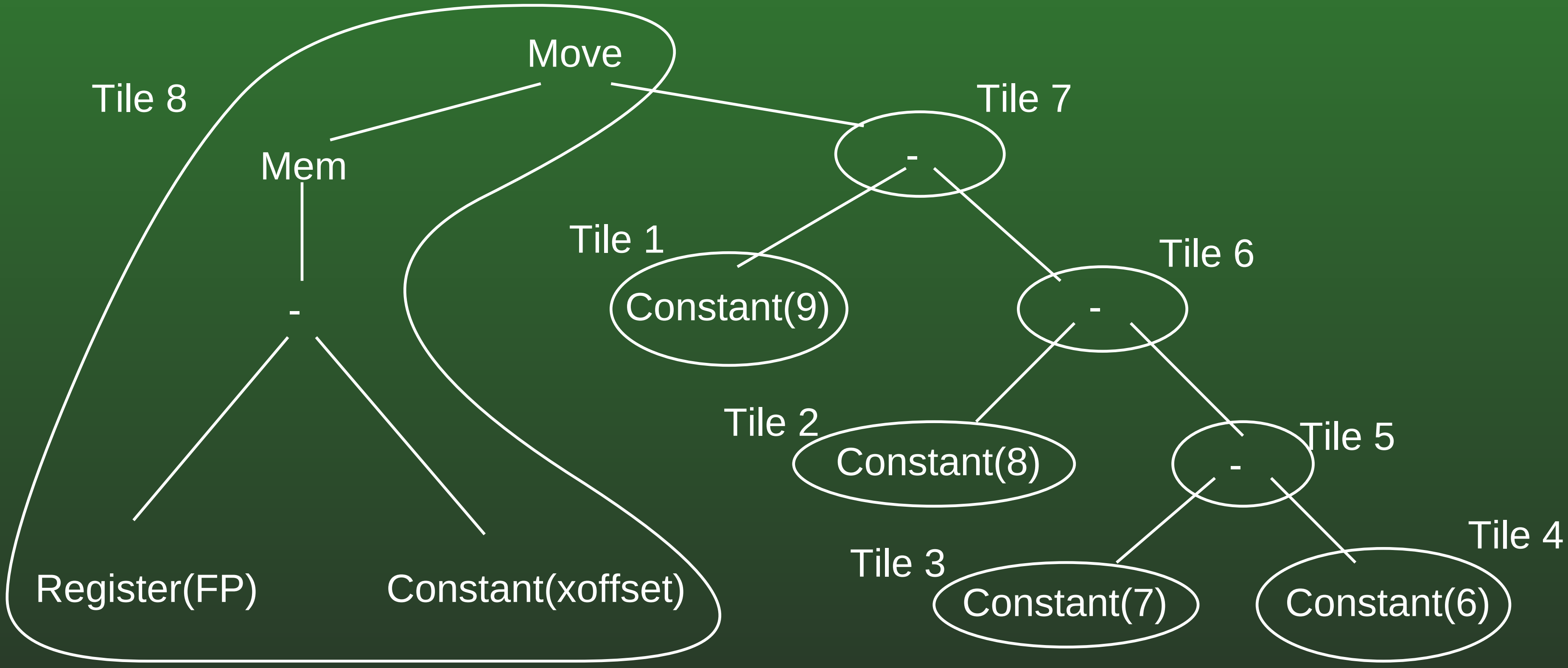
  (decement <offset> by 4)

- 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
```

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?

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 ..

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!

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:

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

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
```

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

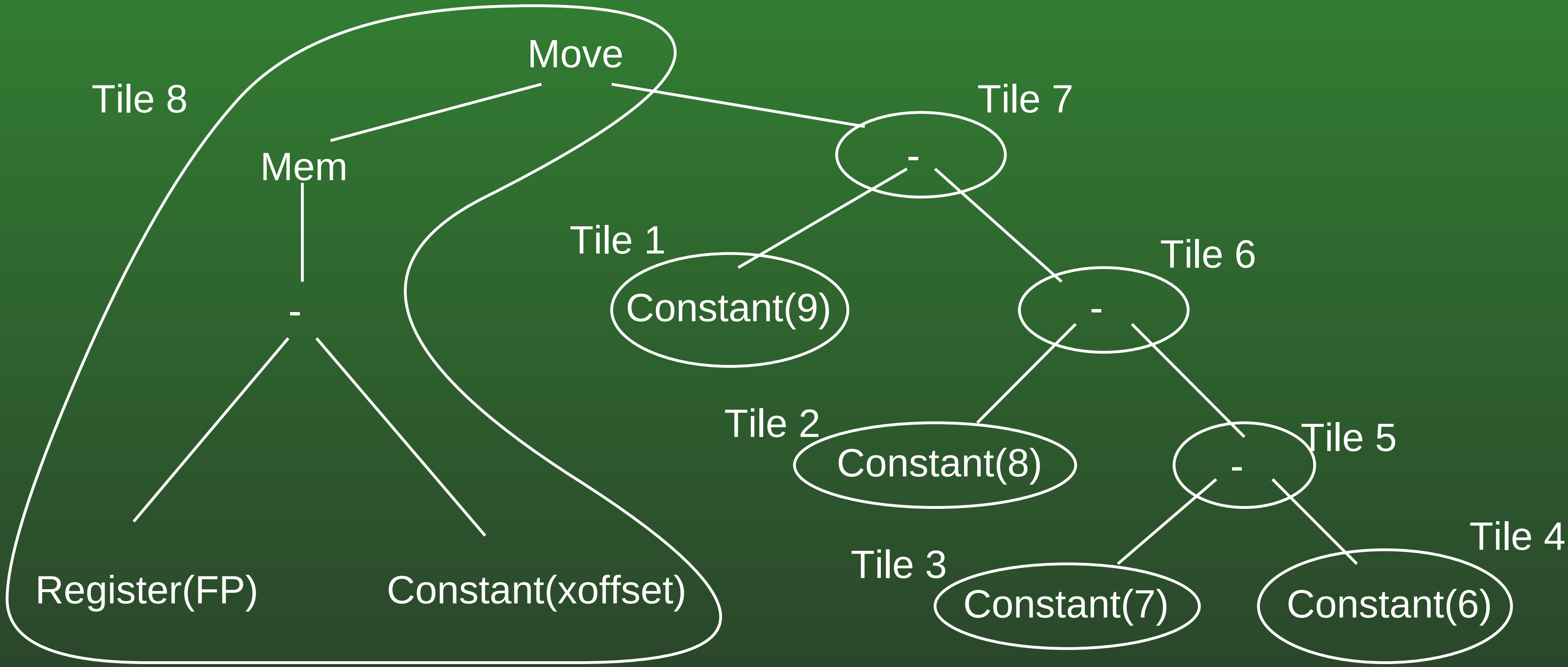
08-157: Using Registers

- 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

Using Registers



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
```

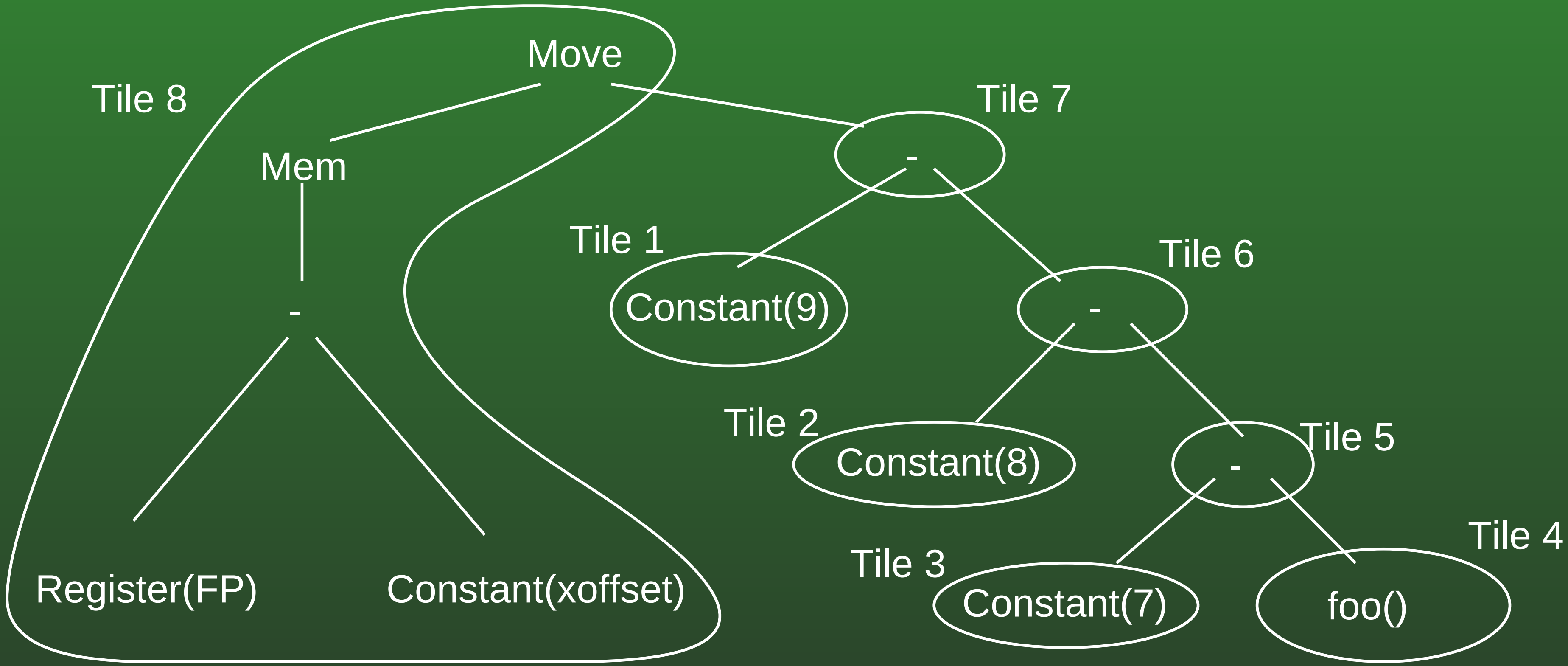
08-162: Using Registers

- 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?

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

Using Registers



08-165: Using Registers

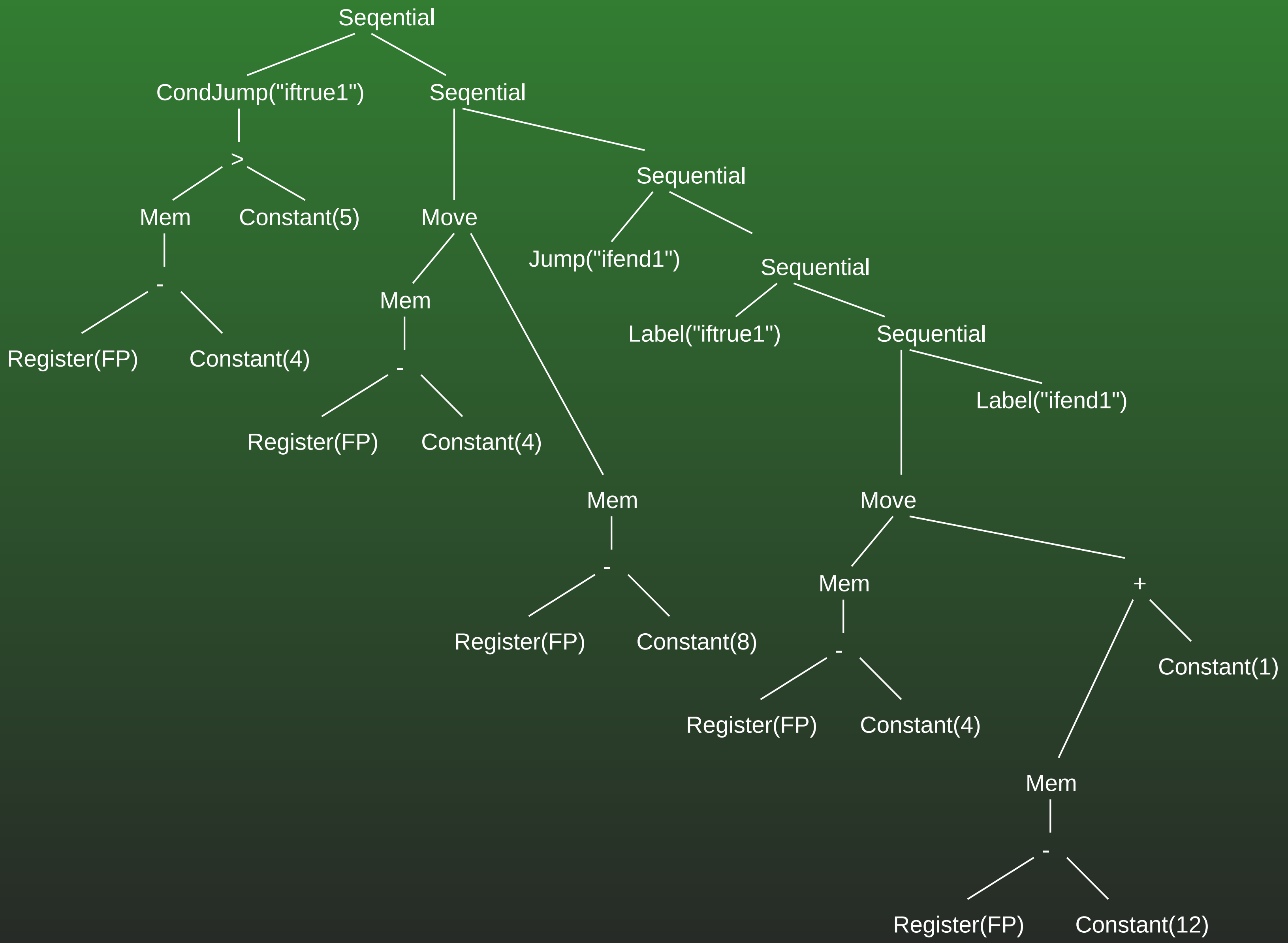
```
addi $ACC, $zero,  9         % Tile 1
addi $r2,  $ACC,   0         % Tile 7 -- pushing on expression stack
addi $ACC, $zero,  8         % Tile 2
addi $r3,  $ACC,   0         % Tile 6 -- pushing on expression stack
addi $ACC, $zero,  7         % Tile 3
sw   $ACC, 0($ESP)           % Tile 5 -- pushing 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

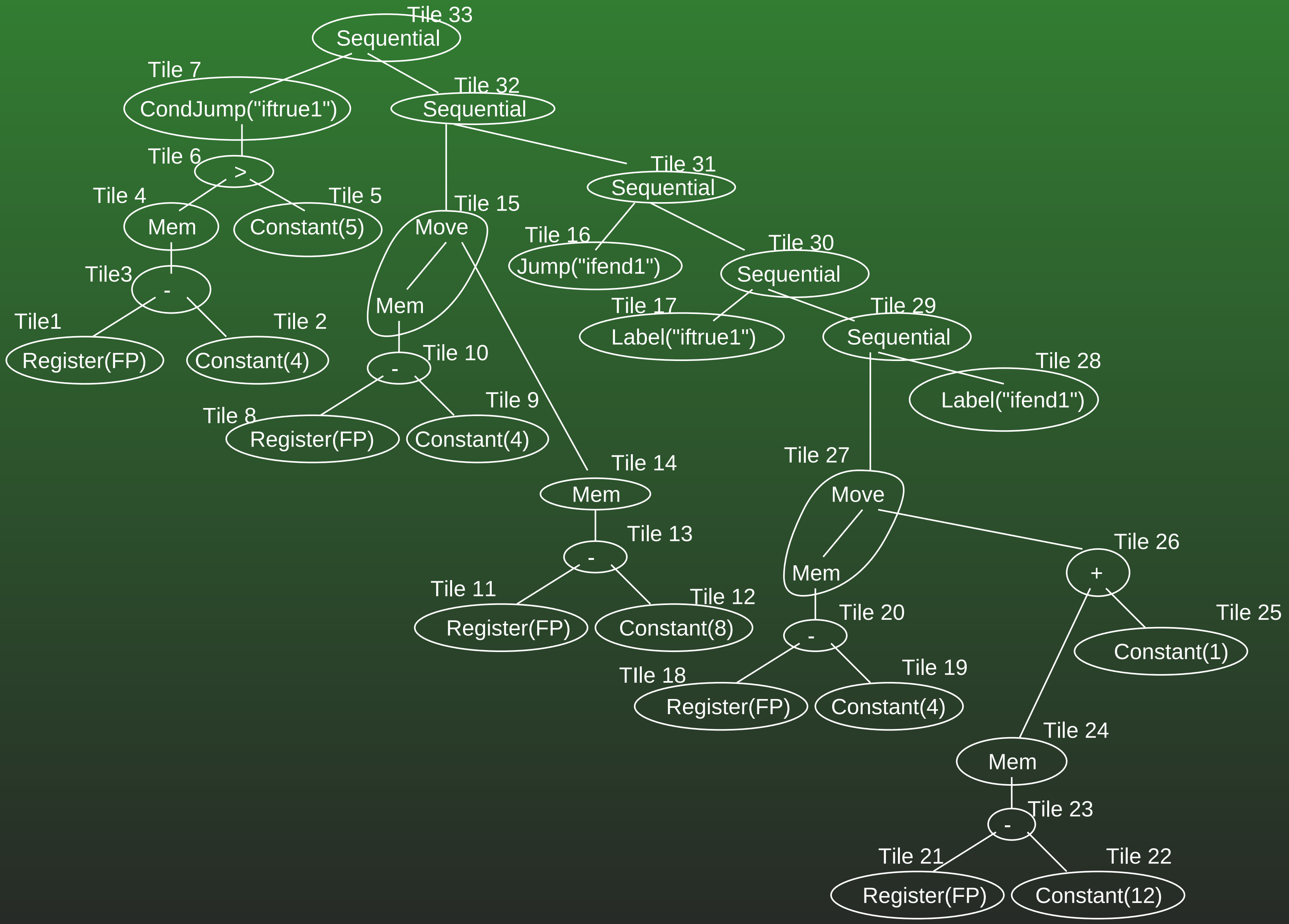
```
if (x > 1)
   x = z + 1;
else
   x = y;
```

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

08-167: Extended Example



Extended Example – Basic



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
```

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
```

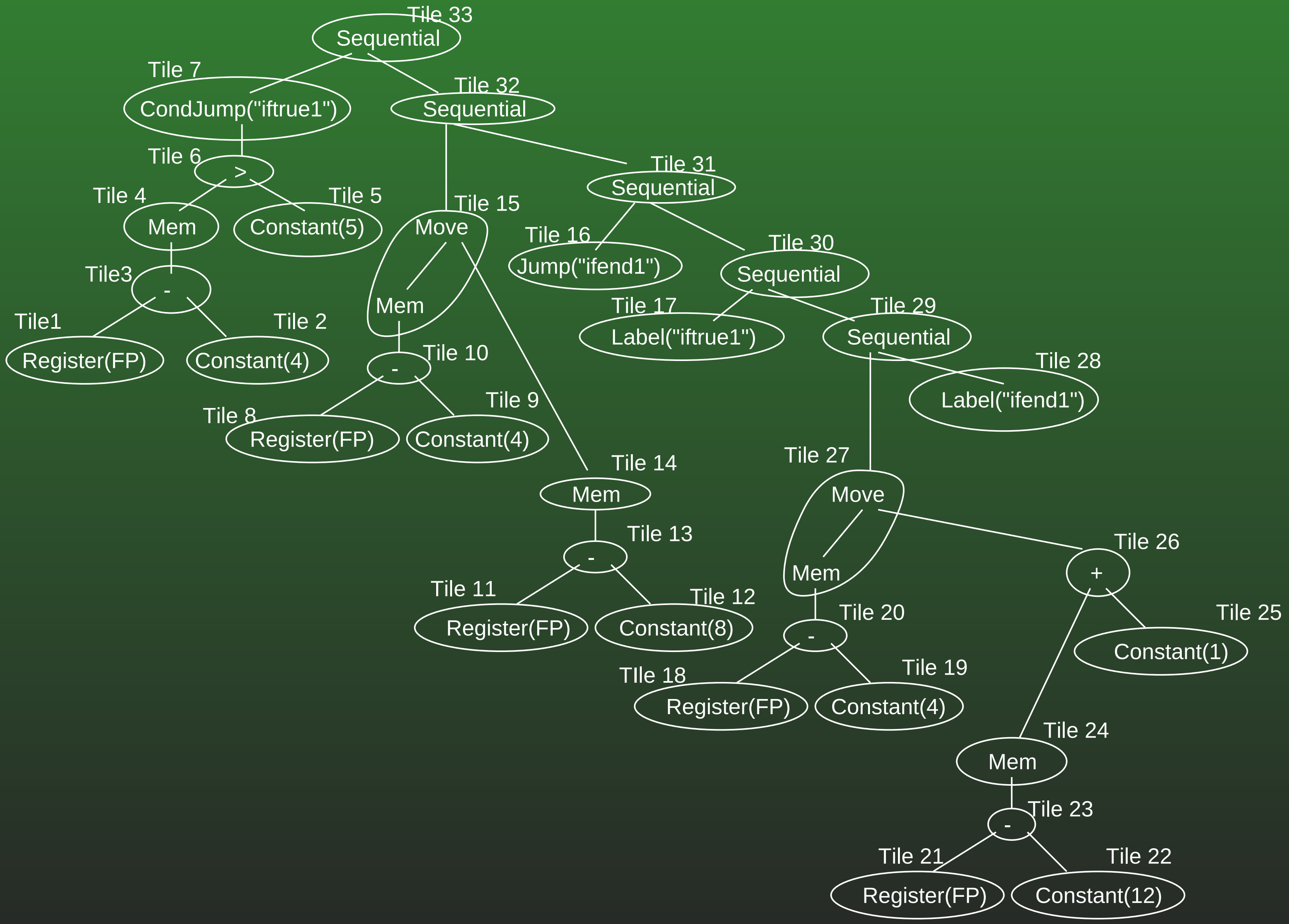
08-172: Extended Example – Basic

```
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
```

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
```

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
```

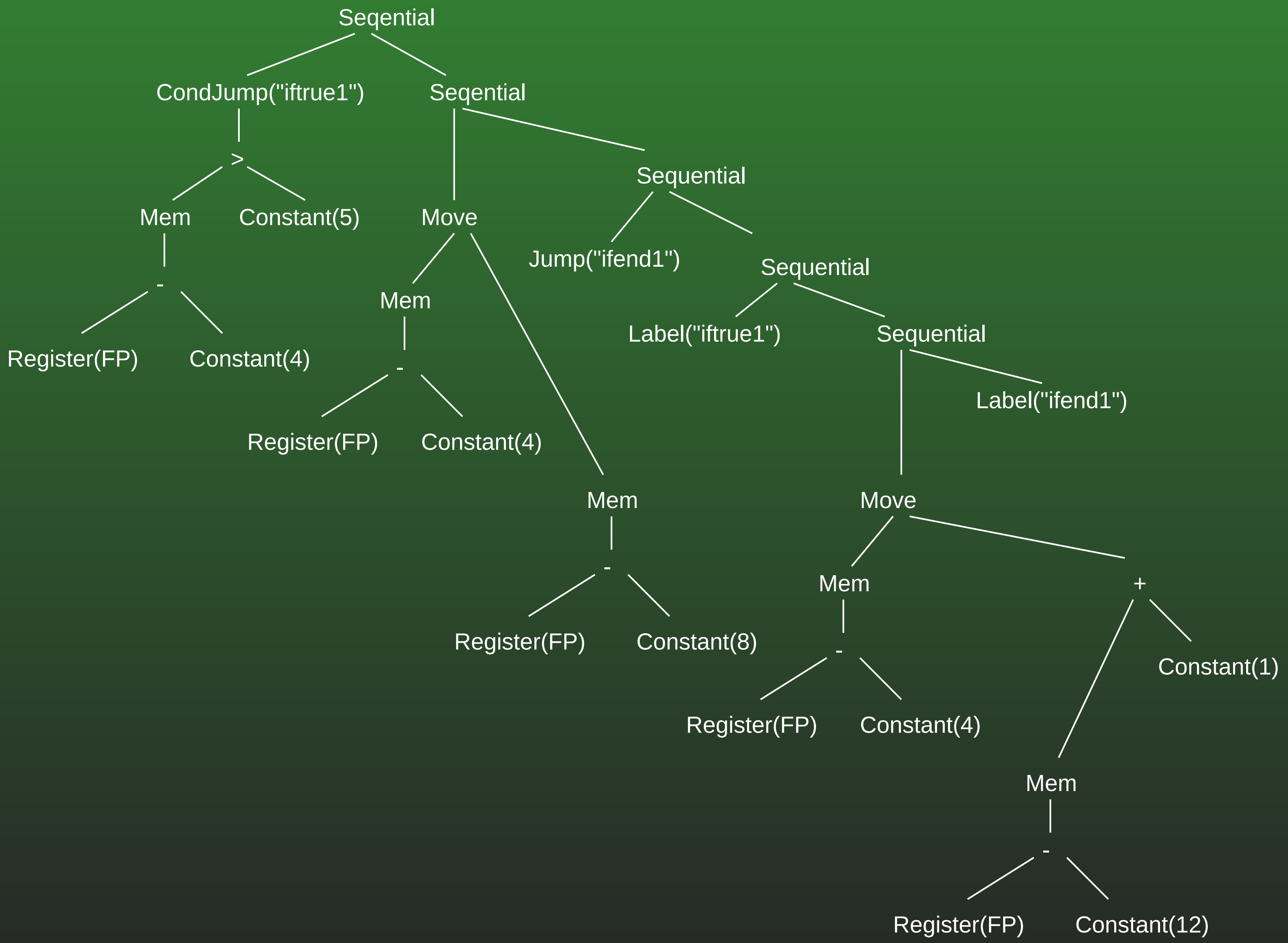
08-177: Extended Eg. – Accumulator

```
        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
```

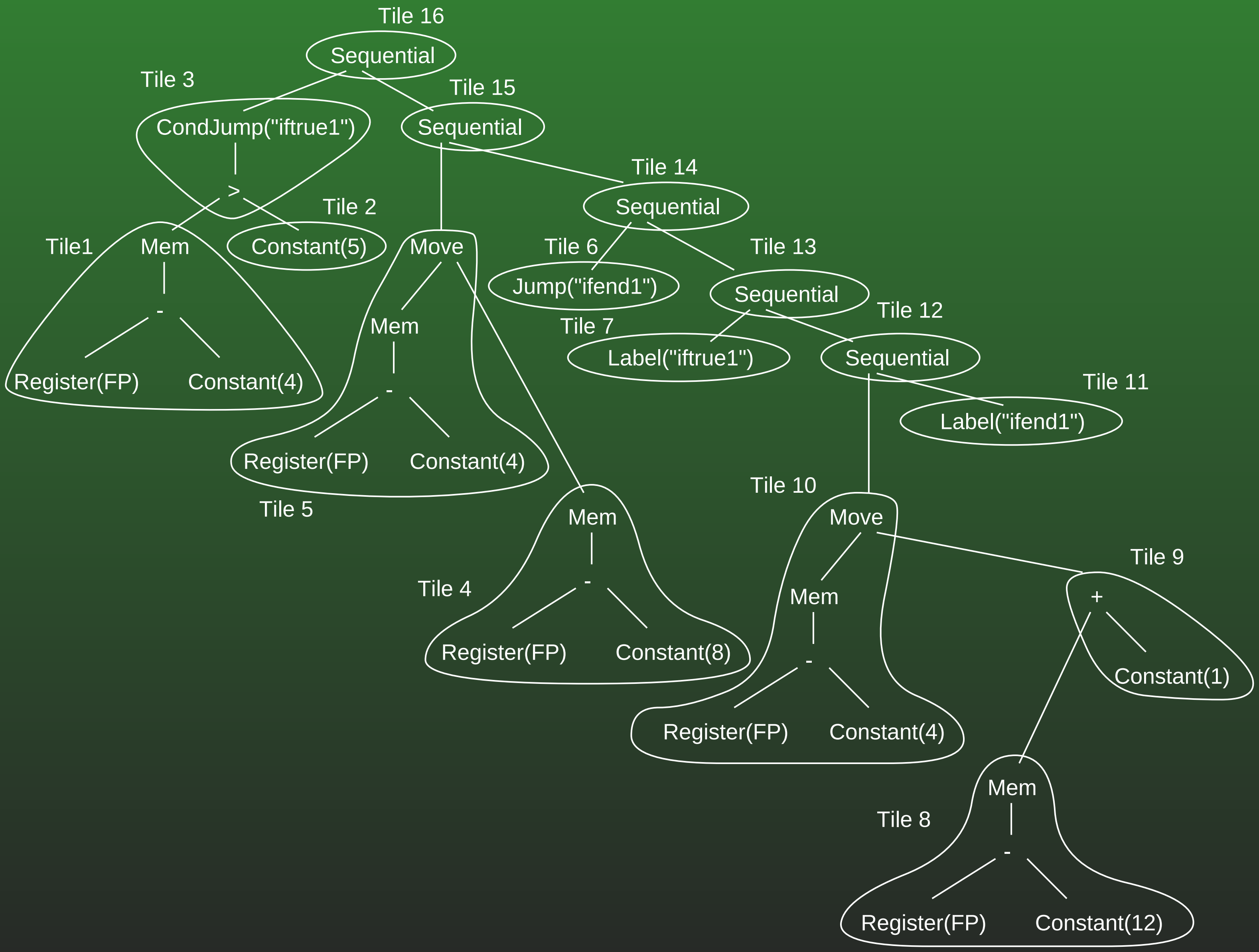
08-178: Extended Eg. – Accumulator

```
        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



Extended Eg. – Large Tiles



Extended Eg. – Large Tiles

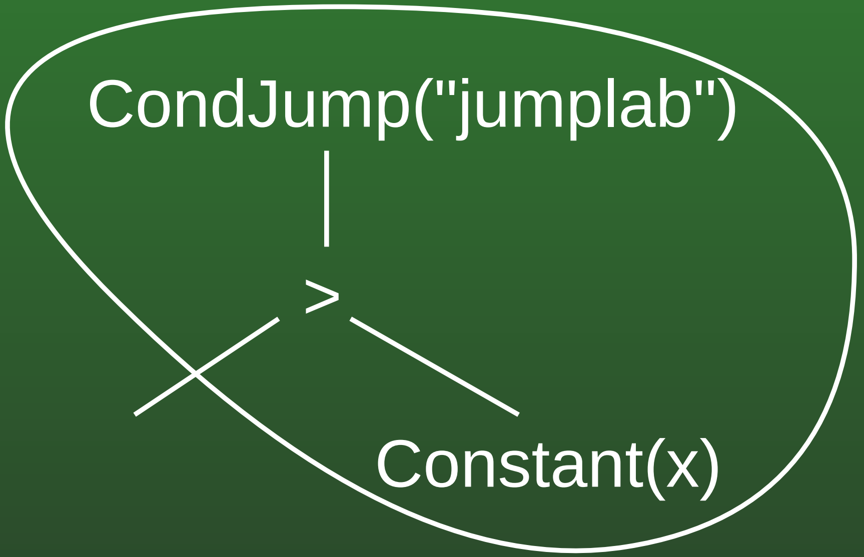
```
        lw   $ACC, -4($FP)          % Tile 1
        sw   $ACC, 0($ESP)          % Tile 3
        addi $ESP, $ESP,  -4        % Tile 3
        addi $ACC, $zero,  5        % Tile 2
        lw   $t1, 4($ESP)           % Tile 3
        addi $ESP, $ESP,   4        % Tile 3
        slt  $ACC, $ACC,  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

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
```

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
```

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)

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

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.