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**CS61C : Machine Structures**

## Lecture 12 – Introduction to MIPS Procedures II, Logical and Shift Ops



**Lecturer PSOE Dan Garcia**

[www.cs.berkeley.edu/~ddgarcia](http://www.cs.berkeley.edu/~ddgarcia)

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# Review

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- Functions called with `jal`, return with `jr $ra`.
- The stack is your friend: Use it to save anything you need. Just be sure to leave it the way you found it.
- Instructions we know so far
  - Arithmetic: `add`, `addi`, `sub`, `addu`, `addiu`, `subu`
  - Memory: `lw`, `sw`
  - Decision: `beq`, `bne`, `slt`, `slti`, `sltu`, `sltiu`
  - Unconditional Branches (Jumps): `j`, `jal`, `jr`
- Registers we know so far
  - All of them!
  - There are **CONVENTIONS** when calling procedures!



# Register Conventions (1/4)

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- **CalleR**: the calling function
- **CalleE**: the function being called
- When callee returns from executing, the caller needs to know which registers may have changed and which are guaranteed to be unchanged.
- **Register Conventions**: A set of generally accepted rules as to which registers will be unchanged after a procedure call (ja1) and which may be changed.



## Register Conventions (2/4) - saved

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- **\$0: No Change.** Always 0.
- **\$s0-\$s7: Restore if you change.** Very important, that's why they're called saved registers. If the callee changes these in any way, it must restore the original values before returning.
- **\$sp: Restore if you change.** The stack pointer must point to the same place before and after the `jal` call, or else the caller won't be able to restore values from the stack.
- **HINT -- All saved registers start with S!**



## Register Conventions (3/4) - **volatile**

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- **\$ra: Can Change.** The `jal` call itself will change this register. Caller needs to save on stack if nested call.
- **\$v0-\$v1: Can Change.** These will contain the new returned values.
- **\$a0-\$a3: Can change.** These are volatile argument registers. Caller needs to save if they'll need them after the call.
- **\$t0-\$t9: Can change.** That's why they're called temporary: any procedure may change them at any time. Caller needs to save if they'll need them afterwards.



# Register Conventions (4/4)

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- **What do these conventions mean?**
  - If function R calls function E, then function R must save any temporary registers that it may be using onto the stack before making a `jal` call.
  - Function E must save any S (saved) registers it intends to use before garbling up their values
  - Remember: Caller/callee need to save only temporary/saved registers **they are using**, not all registers.



# Parents leaving for weekend analogy (1/5)

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- Parents (**main**) leaving for weekend
- They (**caller**) give keys to the house to kid (**callee**) with the rules (**calling conventions**):
  - You can trash the temporary room(s), like the den and basement (**registers**) if you want, we don't care about it
  - **BUT** you'd better leave the rooms (**registers**) that we want to **save** for the guests untouched. **“these rooms better look the same when we return!”**



Who hasn't heard this in their life?

# Parents leaving for weekend analogy (2/5)

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- Kid now “owns” rooms (**registers**)
- Kid wants to use the **saved** rooms for a wild, wild party (**computation**)
- What does kid (**callee**) do?
  - Kid takes what was in these rooms and puts them in the garage (**memory**)
  - Kid throws the party, **trashes everything** (except garage, who goes there?)
  - Kid restores the rooms the parents wanted **saved after the party** by **replacing the items from the garage (**memory**) back into those saved rooms**





## Parents leaving for weekend analogy (3/5)

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- Same scenario, except before parents return and kid replaces **saved** rooms...
- Kid (**callee**) has left valuable stuff (**data**) all over.
  - Kid's friend (**another callee**) wants the house for a party when the kid is away
  - Kid knows that friend might **trash the place** destroying valuable stuff!
  - Kid remembers rule parents taught and now becomes the “heavy” (**caller**), instructing friend (**callee**) on good rules (**conventions**) of house.



# Parents leaving for weekend analogy (4/5)

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- If kid had data in **temporary rooms** (which were going to be trashed), there are three options:
  - Move items directly to garage (**memory**)
  - Move items to **saved rooms** whose contents have already been moved to the garage (**memory**)
  - Optimize lifestyle (**code**) so that the amount you've got to shlep stuff back and forth from garage (**memory**) is minimized
- Otherwise: “Dude, where’s my data?!”



# Parents leaving for weekend analogy (5/5)

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- Friend now “owns” rooms (**registers**)
- Friend wants to use the **saved** rooms for a wild, wild party (**computation**)
- What does friend (**callee**) do?
  - Friend takes what was in these rooms and puts them in the garage (**memory**)
  - Friend throws the party, **trashes everything** (except garage)
  - Friend restores the rooms the kid wanted **saved after the party** by **replacing the items from the garage** (**memory**) **back into those saved rooms**



# Administrivia

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- **Project 1 due Friday @ 23:59**



# Bitwise Operations

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- Up until now, we've done arithmetic (add, sub, addi), memory access (lw and sw), and branches and jumps.
- All of these instructions view contents of register as a single quantity (such as a signed or unsigned integer)
- **New Perspective:** View register as 32 raw bits rather than as a single 32-bit number
- Since registers are composed of 32 bits, we may want to access individual bits (or groups of bits) rather than the whole.
- Introduce two new classes of instructions:
  - Logical & Shift Ops



# Logical Operators (1/3)

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- Two basic logical operators:
  - AND: outputs 1 only if **both** inputs are 1
  - OR: outputs 1 if **at least one** input is 1
- Truth Table: standard table listing all possible combinations of inputs and resultant output for each. E.g.,

A	B	A <b>AND</b> B	A <b>OR</b> B
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1



# Logical Operators (2/3)

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- **Logical Instruction Syntax:**

- 1 2,3,4

- where

- 1) operation name

- 2) register that will receive value

- 3) first operand (register)

- 4) second operand (register) or immediate (numerical constant)

- **In general, can define them to accept > 2 inputs, but in the case of MIPS assembly, these accept exactly 2 inputs and produce 1 output**



- **Again, rigid syntax, simpler hardware**

# Logical Operators (3/3)

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- **Instruction Names:**
  - **and, or:** Both of these expect the third argument to be a register
  - **andi, ori:** Both of these expect the third argument to be an immediate
- **MIPS Logical Operators are all bitwise**, meaning that bit 0 of the output is produced by the respective bit 0's of the inputs, bit 1 by the bit 1's, etc.
  - **C:** Bitwise AND is `&` (e.g., `z = x & y;`)
  - **C:** Bitwise OR is `|` (e.g., `z = x | y;`)





## Uses for Logical Operators (1/3)

- Note that anding a bit with 0 produces a 0 at the output while anding a bit with 1 produces the original bit.
- This can be used to create a **mask**.

- Example:

1011 0110 1010 0100 0011	1101 1001 1010
<b>mask:</b> 0000 0000 0000 0000 0000	1111 1111 1111

- The result of anding these:

0000 0000 0000 0000 0000	1101 1001 1010
--------------------------	----------------

**mask last 12 bits**



## Uses for Logical Operators (2/3)

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- The second bitstring in the example is called a **mask**. It is used to isolate the rightmost 12 bits of the first bitstring by masking out the rest of the string (e.g. setting it to all 0s).
- Thus, the **and** operator can be used to set certain portions of a bitstring to 0s, while leaving the rest alone.
  - In particular, if the first bitstring in the above example were in `$t0`, then the following instruction would mask it:

```
andi    $t0, $t0, 0xFFF
```



## Uses for Logical Operators (3/3)

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- Similarly, note that **oring** a bit with **1** produces a **1** at the output while **oring** a bit with **0** produces the original bit.
- This can be used to force certain bits of a string to **1s**.
  - For example, if `$t0` contains `0x12345678`, then after this instruction:  

```
ori $t0, $t0, 0xFFFF
```
  - ... `$t0` contains `0x1234FFFF` (e.g. the high-order 16 bits are untouched, while the low-order 16 bits are forced to **1s**).



# Shift Instructions (1/4)

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- Move (shift) all the bits in a word to the left or right by a number of bits.

- Example: shift right by 8 bits

0001 0010 0011 0100 0101 0110 0111 1000

0000 0000 0001 0010 0011 0100 0101 0110

- Example: shift left by 8 bits

0001 0010 0011 0100 0101 0110 0111 1000

0011 0100 0101 0110 0111 1000 0000 0000



# Shift Instructions (2/4)

---

- **Shift Instruction Syntax:**

1 2,3,4

- where

1) operation name

2) register that will receive value

3) first operand (register)

4) shift amount (constant < 32)

- **MIPS shift instructions:**

1. **sll** (shift left logical): shifts left and fills emptied bits with 0s

2. **srl** (shift right logical): shifts right and fills emptied bits with 0s

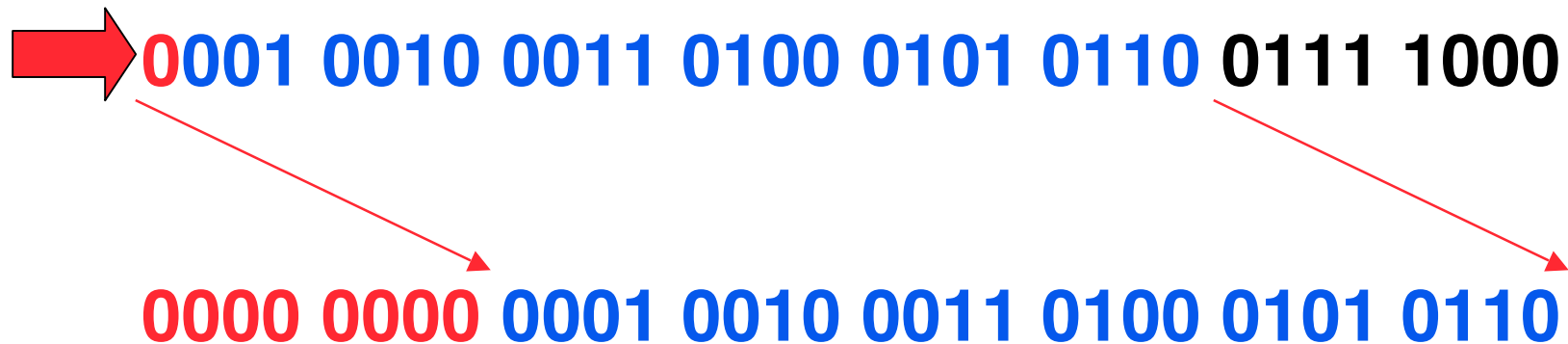
3. **sra** (shift right arithmetic): shifts right and fills emptied bits by sign extending



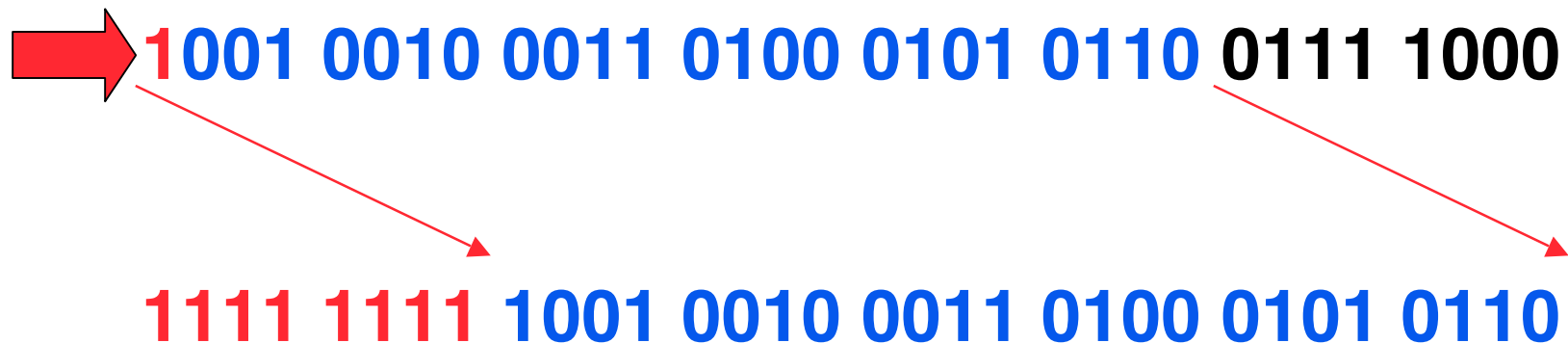
## Shift Instructions (3/4)

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- **Example: shift right arith by 8 bits**



- **Example: shift right arith by 8 bits**



# Shift Instructions (4/4)

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- Since shifting may be faster than multiplication, a good compiler usually notices when C code multiplies by a power of 2 and compiles it to a shift instruction:

`a *= 8; (in C)`

would compile to:

`sll $s0, $s0, 3 (in MIPS)`

- Likewise, shift right to divide by powers of 2
  - remember to use `sra`



# Peer Instruction

---

```
r:  ...      # R/W $s0, $v0, $t0, $a0, $sp, $ra, mem
      ...      ### PUSH REGISTER(S) TO STACK?
      jal e    # Call e
      ...      # R/W $s0, $v0, $t0, $a0, $sp, $ra, mem
      jr $ra   # Return to caller of r

e:  ...      # R/W $s0, $v0, $t0, $a0, $sp, $ra, mem
      jr $ra   # Return to r
```

What does `r` have to push on the stack before “`jal e`”?

- 1: 1 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)
- 2: 2 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)
- 3: 3 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)
- 4: 4 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)
- 5: 5 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)
- 6: 6 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)
- 7: 0 of (\$s0, \$sp, \$v0, \$t0, \$a0, \$ra)





# Peer Instruction Answer

```

r:  ...      # R/W $s0, $v0, $t0, $a0, $sp, $ra, mem
      ...      ### PUSH REGISTER(S) TO STACK?
      jal e    # Call e
      ...      # R/W $s0, $v0, $t0, $a0, $sp, $ra, mem
      jr $ra   # Return to caller of r

e:  ...      # R/W $s0, $v0, $t0, $a0, $sp, $ra, mem
      jr $ra   # Return to r
    
```

What does `r` have to push on the stack before “`jal e`”?  
**Saved Volatile! -- need to push**

	1:	1	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)
	2:	2	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)
	3:	3	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)
☺	4:	4	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)
	5:	5	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)
	6:	6	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)
	7:	0	of	(	\$s0,	\$sp,	\$v0,	\$t0,	\$a0,	\$ra)

**e can't return changed, e can return changed**  
**no need to push**



# “And in Conclusion...”

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- **Register Conventions**: Each register has a purpose and limits to its usage. Learn these and follow them, even if you’re writing all the code yourself.
- **Logical and Shift Instructions**
  - Operate on bits individually, unlike arithmetic, which operate on entire word.
  - Use to isolate fields, either by masking or by shifting back and forth.
  - Use shift left logical, `sll`, for multiplication by powers of 2
  - Use shift right arithmetic, `sra`, for division by powers of 2.
- **New Instructions:**  
`and, andi, or, ori, sll, srl, sra`



## Example: Fibonacci Numbers 1/8

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- The Fibonacci numbers are defined as follows:  $F(n) = F(n - 1) + F(n - 2)$ ,  $F(0)$  and  $F(1)$  are defined to be 1
- In scheme, this could be written:

```
(define (Fib n)
  (cond ((= n 0) 1)
        ((= n 1) 1)
        (else (+ (Fib (- n 1))
                  (Fib (- n 2))))))
```



## Example: Fibonacci Numbers 2/8

---

- Rewriting this in C we have:

```
int fib(int n) {  
    if(n == 0) { return 1; }  
    if(n == 1) { return 1; }  
    return (fib(n - 1) + fib(n - 2));  
}
```



## Example: Fibonacci Numbers 3/8

---

- Now, let's translate this to MIPS!
- You will need space for three words on the stack
- The function will use one \$s register, \$s0
- Write the Prologue:

fib:

addi \$sp, \$sp, -12

# Space for three words

sw \$ra, 8(\$sp)

# Save the return address

sw \$s0, 4(\$sp)

# Save \$s0



# Example: Fibonacci Numbers 4/8

---

◦ Now write the Epilogue:

`fin:`

`lw $s0, 4($sp)`

# Restore \$s0

`lw $ra, 8($sp)`

# Restore return address

`addi $sp, $sp, 12`

# Pop the stack frame

`jr $ra`

# Return to caller



# Example: Fibonacci Numbers 5/8

---

- Finally, write the body. The C code is below. Start by translating the lines indicated in the comments

```
int fib(int n) {  
    if(n == 0) { return 1; } /*Translate  
    Me!*/ if(n == 1) { return 1; }  
    /*Translate Me!*/ return (fib(n - 1) +  
    fib(n - 2));  
}
```

```
addi $v0, $zero, 1      # $v0 = 1  
beq $a0, $zero, fin    # if (n == 0) . . . .  
addi $t0, $zero, 1    # $t0 = 1  
beq $a0, $t0, fin      # if (n == 1) . . . .
```

Continued on next slide. .



# Example: Fibonacci Numbers 6/8

---

- Almost there, but be careful, this part is tricky!

```
int fib(int n) {  
    return (fib(n - 1) + fib(n - 2));  
}
```

```
addi $a0, $a0, -1      # $a0 = n - 1  
sw $a0, 0($sp)       # Need $a0 after jal  
jal fib                # fib(n - 1)  
lw $a0, 0($sp)       # Restore $a0  
addi $a0, $a0, -1    # $a0 = n - 2
```

Continued on next slide. . .





# Example: Fibonacci Numbers 7/8

---

- Remember that \$v0 is caller saved!

```
int fib(int n) {  
    return (fib(n - 1) + fib(n - 2));  
}
```

```
add $s0, $v0, $zero    # Place fib(n - 1)  
                        # somewhere it won't get  
                        # clobbered  
  
jal fib                # fib(n - 2)  
  
add $v0, $v0, $s0     # $v0 = fib(n-1) + fib(n-2)
```

To the epilogue and beyond.



# Example: Fibonacci Numbers 8/8

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◦ Here's the complete code for reference:

```
fib:                                lw $a0, 0($sp)
addi $sp, $sp, -12                 addi $a0, $a0, -1
sw $ra, 8($sp)                     add $s0, $v0, $zero
sw $s0, 4($sp)                     jal fib
addi $v0, $zero, 1                add $v0, $v0, $s0
beq $a0, $zero, fin               fin:
addi $t0, $zero, 1                lw $s0, 4($sp)
beq $a0, $t0, fin                 lw $ra, 8($sp)
addi $a0, $a0, -1                 addi $sp, $sp, 12
sw $a0, 0($sp)                    jr $ra
jal fib
```



## BONUS: Uses for Shift Instructions (1/4)

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- **Suppose we want to isolate byte 0 (rightmost 8 bits) of a word in \$t0. Simply use:**

```
andi    $t0, $t0, 0xFF
```

- **Suppose we want to isolate byte 1 (bit 15 to bit 8) of a word in \$t0. We can use:**

```
andi    $t0, $t0, 0xFF00
```

**but then we still need to shift to the right by 8 bits...**

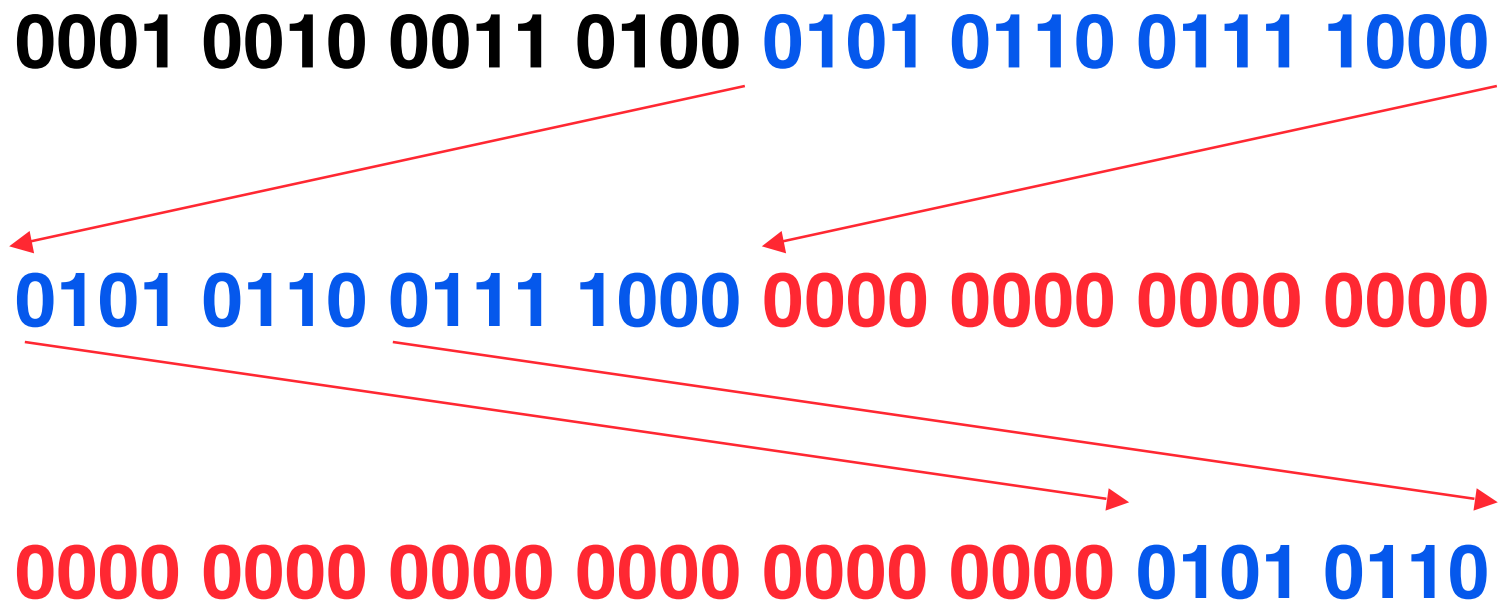


# BONUS: Uses for Shift Instructions (2/4)

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- Could use instead:

```
sll    $t0, $t0, 16  
srl    $t0, $t0, 24
```



## **BONUS: Uses for Shift Instructions (3/4)**

---

- **In decimal:**
  - **Multiplying by 10 is same as shifting left by 1:**
    - $714_{10} \times 10_{10} = 7140_{10}$
    - $56_{10} \times 10_{10} = 560_{10}$
  - **Multiplying by 100 is same as shifting left by 2:**
    - $714_{10} \times 100_{10} = 71400_{10}$
    - $56_{10} \times 100_{10} = 5600_{10}$
  - **Multiplying by  $10^n$  is same as shifting left by  $n$**



# **BONUS: Uses for Shift Instructions (4/4)**

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- **In binary:**
  - **Multiplying by 2 is same as shifting left by 1:**
    - $11_2 \times 10_2 = 110_2$
    - $1010_2 \times 10_2 = 10100_2$
  - **Multiplying by 4 is same as shifting left by 2:**
    - $11_2 \times 100_2 = 1100_2$
    - $1010_2 \times 100_2 = 101000_2$
  - **Multiplying by  $2^n$  is same as shifting left by n**



## Bonus Example: Compile This (1/5)

---

```
main() {
    int i,j,k,m; /* i-m:$s0-$s3 */
    . . .
    i = mult(j,k); ...
    m = mult(i,i); ...
}

int mult (int mcand, int mlier) {
    int product;

    product = 0;
    while (mlier > 0) {
        product += mcand;
        mlier -= 1; }
    return product;
}
```



## Bonus Example: Compile This (2/5)

---

\_\_start:

```
add $a0, $s1, $0      # arg0 = j
add $a1, $s2, $0      # arg1 = k
jal mult              # call mult
add $s0, $v0, $0      # i = mult()
```

...

```
add $a0, $s0, $0      # arg0 = i
add $a1, $s0, $0      # arg1 = i
jal mult              # call mult
add $s3, $v0, $0      # m = mult()
```

...

done

```
main() {
int i, j, k, m; /* i-m: $s0-$s3 */
...
i = mult(j, k); ...
m = mult(i, i); ... }

```





# Bonus Example: Compile This (3/5)

---

- **Notes:**

- **main function ends with `done`, not `jr $ra`, so there's no need to save `$ra` onto stack**
- **all variables used in `main` function are saved registers, so there's no need to save these onto stack**



## Bonus Example: Compile This (4/5)

---

mult:

```
    add    $t0, $0, $0        # prod=0
```

Loop:

```
    slt    $t1, $0, $a1      # mlr > 0?
```

```
    beq    $t1, $0, Fin      # no=>Fin
```

```
    add    $t0, $t0, $a0     # prod+=mc
```

```
    addi   $a1, $a1, -1      # mlr-=1
```

```
    j      Loop             # goto Loop
```

Fin:

```
    add    $v0, $t0, $0      # $v0=prod
```

```
    jr     $ra              # return
```

```
int mult (int mcand, int mlier) {  
    int product = 0;  
    while (mlier > 0) {  
        product += mcand;  
        mlier -= 1; }  
    return product;  
}
```



## Bonus Example: Compile This (5/5)

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- **Notes:**

- **no `jal` calls are made from `mult` and we don't use any saved registers, so we don't need to save anything onto stack**
- **temp registers are used for intermediate calculations (could have used `s` registers, but would have to save the caller's on the stack.)**
- **`$a1` is modified directly (instead of copying into a temp register) since we are free to change it**
- **result is put into `$v0` before returning (could also have modified `$v0` directly)**

