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UCB CS61C : Machine Structures

Lecture 11 – Introduction to MIPS Procedures II & Logical Ops

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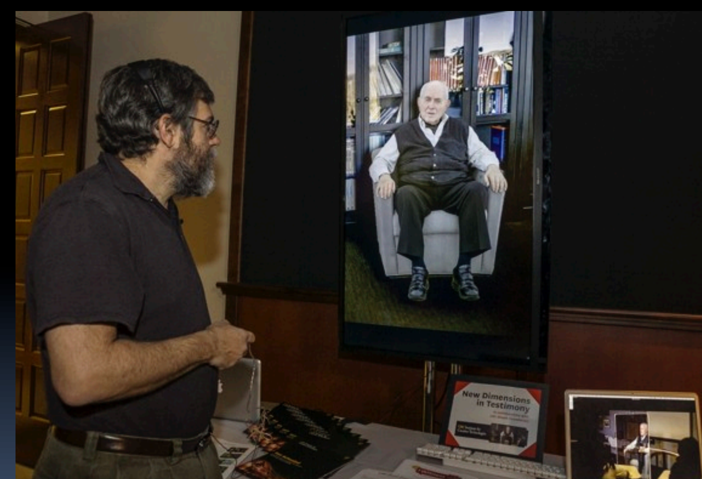
VIRTUAL HUMANS…

Prof Paul Debevec (UC Berkeley PhD 1996) at USC has been working to create virtual humans to keep alive the memory AND INTERACTIONS w/people into a 3D hologram. He is recording the Holocaust survivors, who tell their story, answering 500 questions about themselves. They're in a race against time…



www.washingtonpost.com/national/holograms-seen-as-tools-to-teach-future-generations-about-holocaust-retell-survivors-stories/2013/02/02/558cab32-6d58-11e2-8f4f-2abd96162ba8_story_1.html

Review

- Functions called with `jal`, return with `jr $ra`.
- The stack is your friend: Use it to save anything you need. Just leave it the way you found it!
- Instructions we know so far…

  Arithmetic: `add, addi, sub, addu, addiu, subu`

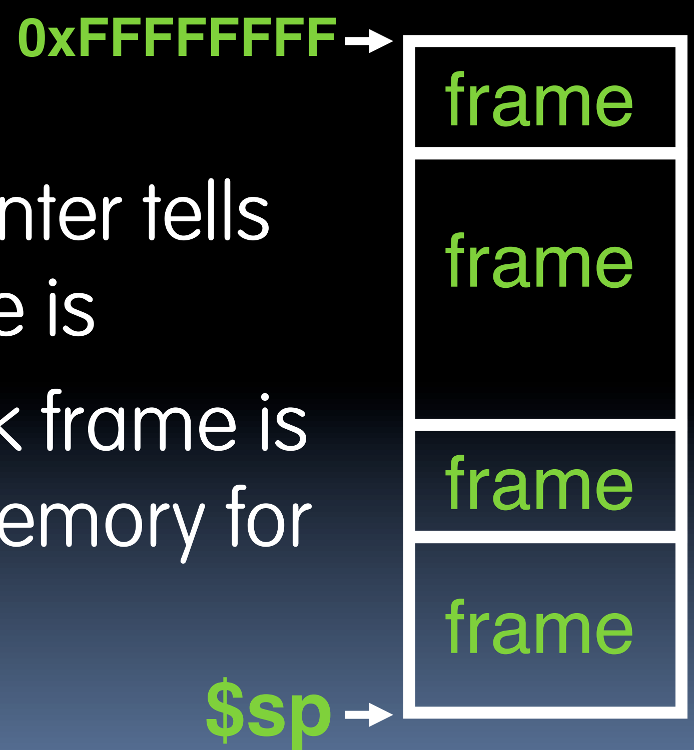
  Memory: `lw, sw, lb, sb`

  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!

The Stack (review)

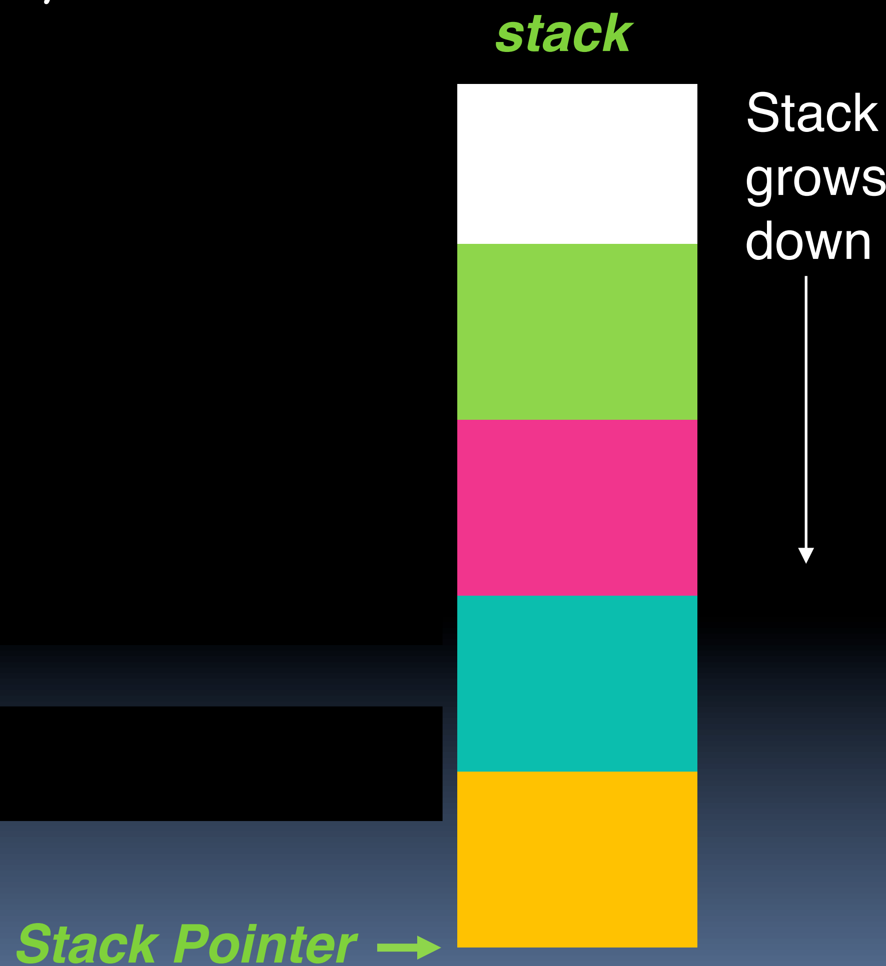
- Stack frame includes:
  - Return "instruction" address
  - Parameters
  - Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer tells where bottom of stack frame is
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



Stack

- Last In, First Out (LIFO) data structure

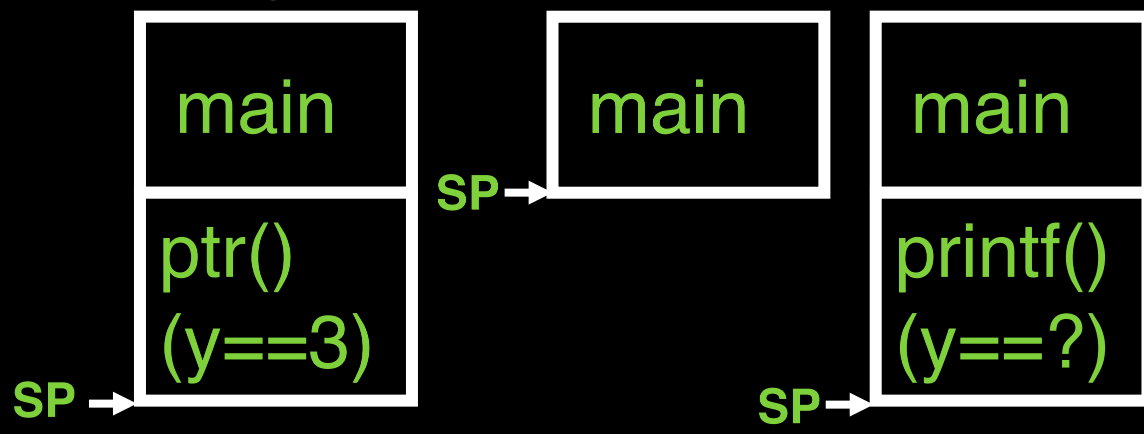
```
main ()
{ a(0);
}
  void a (int m)
  { b(1);
  }
    void b (int n)
    { c(2);
    }
      void c (int o)
      { d(3);
      }
        void d (int p)
        {
        }
```



Who cares about stack management?

- Pointers in C allow access to deallocated memory, leading to hard-to-find bugs !

```
int *ptr () {
    int y;
    y = 3;
    return &y; }
 main () {
    int *stackAddr,content;
    stackAddr = ptr();
    content = *stackAddr;
    printf("%d", content);  /* 3 */
    content = *stackAddr;
    printf("%d", content); }/*13451514 */
```



Memory Management

- How do we manage memory?
- Code, Static storage are easy: they never grow or shrink
- Stack space is also easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- Managing the heap is tricky: memory can be allocated / deallocated at any time

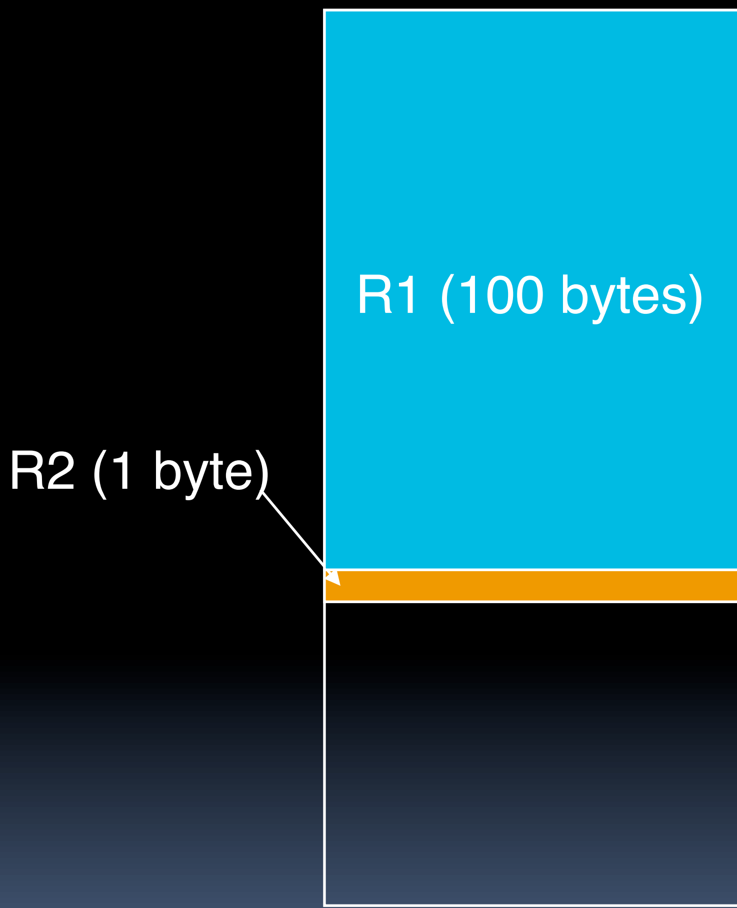
Heap Management Requirements

- Want **`malloc()`** and **`free()`** to run quickly.
- Want minimal memory overhead
- Want to avoid *fragmentation** –
  when most of our free memory is in many small chunks
  - In this case, we might have many free bytes but not be able to satisfy a large request since the free bytes are not contiguous in memory.

* This is technically called *external fragmention*

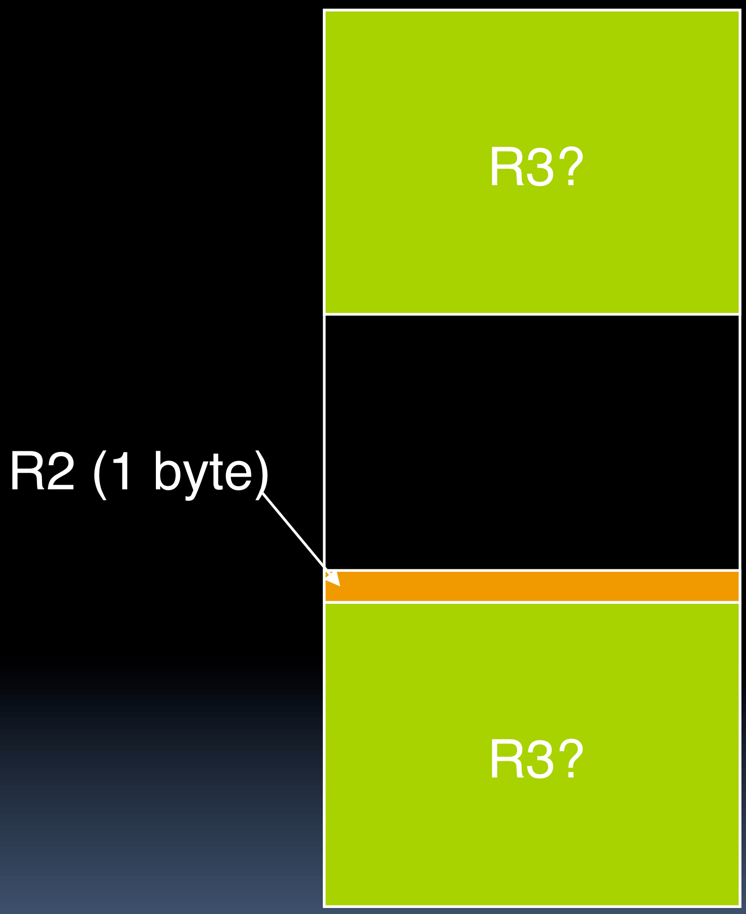
Heap Management

- An example
  - Request R1 for 100 bytes
  - Request R2 for 1 byte
  - Memory from R1 is freed
  - Request R3 for 50 bytes



Heap Management

- An example
  - Request R1 for 100 bytes
  - Request R2 for 1 byte
  - Memory from R1 is freed
    - Memory has become fragmented!
    - We have to keep track of the two *freespace* regions
  - Request R3 for 50 bytes
    - We have to search the data structures holding the freespace to find one that will fit! Choice here...



Administrivia

- Project (Pt 1) due Sunday @ 23:59:59pm
  - Quick Peer Instruction question: how are you doing on part 1 of the project?
    a) [0, 20%) done
    b) [20, 40%) done
    c) [40, 60%) done
    d) [60, 80%) done
    e) [80, 100%] done
- TAs, anything?

Register Conventions (1/4)

- 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 (`jal`) and which may be changed.

Register Conventions (2/4) – saved

- **`$0`**: No Change. Always `0`.
- **`$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 (2/4) – volatile

- `$ra`: Can Change. The `jal` call itself will change this register. Caller needs to save on stack if nested call.
- `$v0-$v1`: Can Change. These will contain the new returned values.
- `$a0-$a3`: Can change. These are volatile argument registers. Caller needs to save if they are needed after the call.
- `$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)

- 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, and restore them after done garbling
- Remember: calle<u>r</u>/calle<u>e</u> need to save only temporary/saved registers they are using, not all registers.

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`**"?

```
a)  1 of ($s0,$sp,$v0,$t0,$a0,$ra)
b)  2 of ($s0,$sp,$v0,$t0,$a0,$ra)
c)  3 of ($s0,$sp,$v0,$t0,$a0,$ra)
d)  4 of ($s0,$sp,$v0,$t0,$a0,$ra)
e)  5 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: $s0, $sp — Volatile! -- need to push: $v0, $t0, $a0, $ra

```
a)  1 of ($s0,$sp,$v0,$t0,$a0,$ra)
b)  2 of ($s0,$sp,$v0,$t0,$a0,$ra)
c)  3 of ($s0,$sp,$v0,$t0,$a0,$ra)
☺ d)  4 of ($s0,$sp,$v0,$t0,$a0,$ra)
e)  5 of ($s0,$sp,$v0,$t0,$a0,$ra)
```

"And in Conclusion…"

- 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 logical, `srl`, for division by powers of 2 of unsigned numbers (**`unsigned int`**)
  - Use shift right arithmetic, `sra`, for division by powers of 2 of signed numbers (**`int`**)
- New Instructions:
  `and, andi, or, ori, sll, srl, sra`

Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the "bonus" area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Bitwise Operations

- So far, we've done arithmetic (`add`, `sub`,`addi`), mem access (`lw` and `sw`), & branches and jumps.
- All of these instructions view contents of register as a single quantity (e.g., signed or unsigned int)
- New Perspective: View register as 32 raw bits rather than as a single 32-bit number
  - Since registers are composed of 32 bits, wish 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)

- Two basic logical operators:
  - AND: outputs 1 only if all 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

a	b	a AND b	a OR b
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1

=

a	a AND b	a OR b
0	0	b
1	b	1

Logical Operators (2/3)

- 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)

- 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 **and**ing a bit with **0** produces a **0** at the output while **and**ing 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
mask: 0000 0000 0000 0000 0000 1111 1111 1111
```

  - The result of **and**ing these:

```
      0000 0000 0000 0000 0000 1101 1001 1010
```

mask last 12 bits

Uses for Logical Operators (2/3)

- 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 to all **0**s).
- Thus, the **and** operator can be used to set certain portions of a bitstring to **0**s, 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)

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

```
ori  $t0, $t0, 0xFFFF
```

  … **`$t0`** will contain **`0x1234FFFF`**
    - (i.e., the high-order 16 bits are untouched, while the low-order 16 bits are forced to `1`s).

Example: Fibonacci Numbers 1/8

- 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 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    #
addi $t0, $zero, 1      # $t0 = 1
beq  $a0, $t0, fin      #
```

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
```

Example: Fibonacci Numbers 7/8

- Remember that $vo 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

- Here's the complete code for reference:

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

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()
  ...
  j __exit
```

```
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 a jump to **`__exit`**, 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)

- 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)

Parents leaving for weekend analogy (1/5)

- 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)

- 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 ever goes in 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)

- 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)

- 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.
    - Mantra: "Minimize register footprint"
- Otherwise: "Dude, where's my data?!"

Parents leaving for weekend analogy (5/5)

- 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

Shift Instructions (review) (1/4)

- 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)

- Example: shift right arithmetic by 8 bits

`0001 0010 0011 0100 0101 0110 0111 1000`

`0000 0000 0001 0010 0011 0100 0101 0110`

- Example: shift right arithmetic by 8 bits

`1001 0010 0011 0100 0101 0110 0111 1000`

`1111 1111 1001 0010 0011 0100 0101 0110`

Shift Instructions (4/4)

- 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 (rounds towards $-\infty$)
  - remember to use `sra`