The University of Texas at Dallas

Erik Jonsson School of Engineering and Computer Science

Roll Call

Requirements for Test #3 Exemption

1. **No unexcused absences to end of semester (written excuse required—must be MD-verified illness or work-related, with written excuse from supervisor).**
2. **Turn in all required homeworks for rest of year. Miss one and you take the test.**
3. **Make grade of 100 on semester project.**
4. **Maintain your average at 90 or above.**

Final Programming Lecture

- **We conclude our SPIM study with a more difficult example that addresses the recursive loop; that is, a loop that can (and does) call itself during program execution.**
- **While you will not have many recursive loop problems in EE 2310, it is worthwhile to understand the structure of a recursive loop and how to successfully construct one.**
- **You have been doing a lot of programming so far (including loops). If you can understand today's concepts and build a recursive loop on your own, you are entitled to consider that you have completed the required assembly language learning process in EE 2310.**

Desired Program

- **We would like to choose a program that is simple enough to compose in a reasonable time, but challenging enough to be interesting to construct.**
- **For this example, we choose a program that will arrange lower-case letters in a group of characters into alphabetical order.**
- **We could input the phrase using syscall 8 ("input an ASCII string"). However, since we would like the program to alphabetize a string of different letters, we declare them in the program rather than trusting to a keyboard entry that might not have all 26 letters in it.**
- **We will do the letter placement loop as a procedure call, using jal and jr plus $ra, in order to "keep our place" in the loop. This is a good example of useful recursive programming.**

Program Specification

- **Our program will alphabetize a group of letters which starts out in arbitrary order.**
- **Each new letter in the string is compared to the previous letter.**
- **If the new letter is nearer the beginning of the alphabet than the previous letter, the program goes into a recursive comparison loop that moves it "upstream" to its proper position.**
- **Each move upstream, or backwards, evokes another recursive call of the comparison program.**
- **Each procedure call requires storing $ra on the stack and decrementing the stack pointer ($sp).**
- **The reverse (jr action) returns the comparison process to the correct place in the line to get the next letter to be compared.**

Thoughts on the Program

- We will not need a counter for our letter sort, since we will know when we get to the end of the loop by the null character (".asciiz").
- In terms of finding our way back to the next letter to compare, we will not need a counter either – the jal/jr twins take care of that when we use recursive procedure calls.
- Since the letter string we declare will be all lower-case letters (only), we do not have to have a routine to check and discard non-lower-case letters.

Basic Program Flow

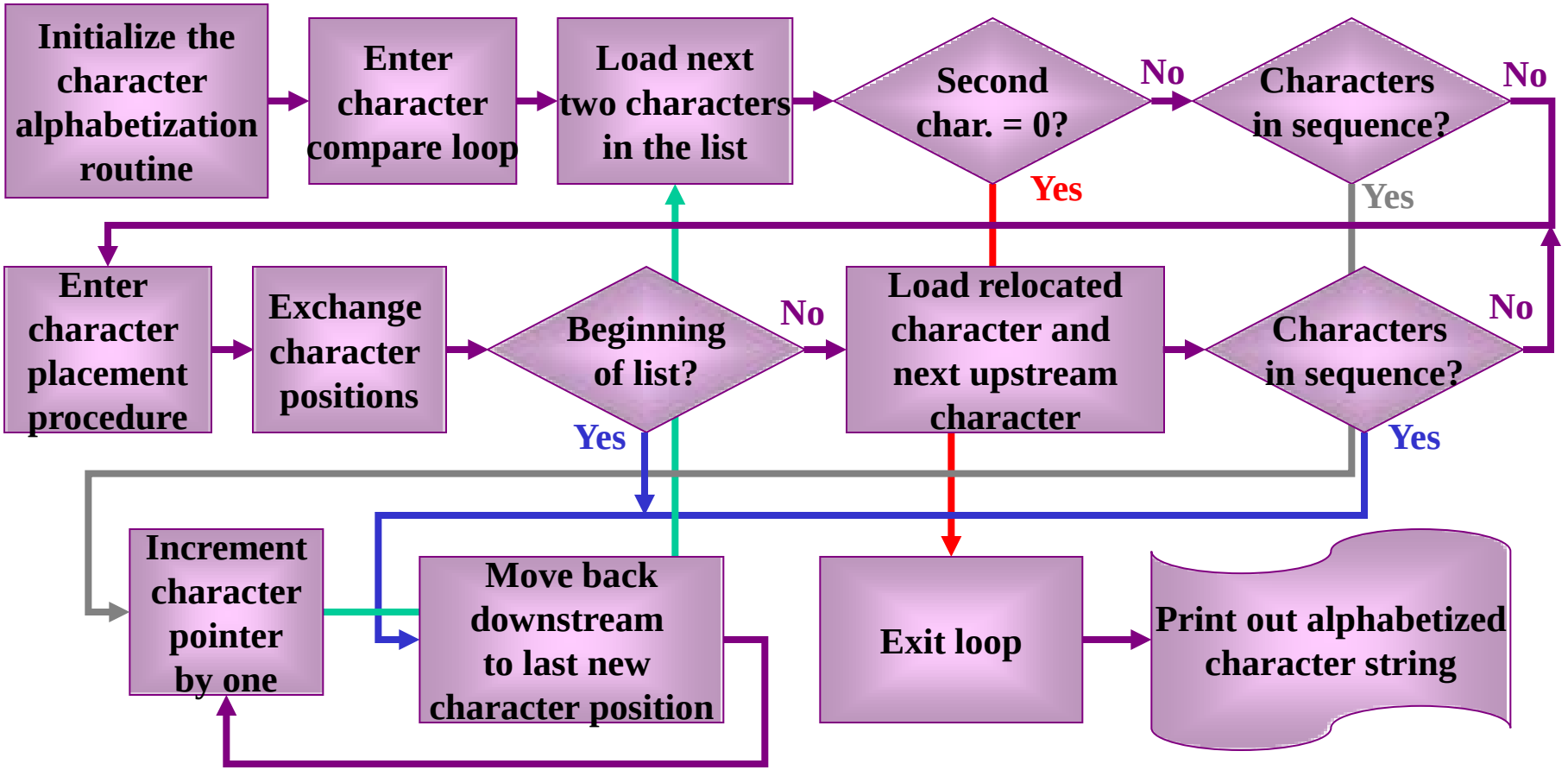
- Initialize program by setting up two character pointers.
- Enter character compare loop:
  - Load first two characters in string to compare.
  - If characters are in order, compare next two characters.
  - If characters should be exchanged, go to placement procedure.
  - If newest character is 0, go to output routine.
- Character placement routine (procedure call using jal):
  - Store $ra on stack and decrement stack pointer.
  - Exchange places of two characters.
  - Decrement the letter pointer and test for first position.
  - Load two characters one position "upstream," and compare.
  - If in correct order, go to "find your place" routine (jr function).
  - If not, call placement procedure again (using another jal).
- "Find your place" routine.
  - Go through successive jr's until we unspool back to current letter position.
  - Go back into character compare loop.
- "Done" = print-out routine and syscall 10.

Procedure

Required Variables

- **The following variables are required:**
  - **Pointer to the current position -- Use $t0**
  - **"Upstream compare character" -- Use $t1**
  - **Current character being analyzed -- Use $t2**
  - **Pointer to the first character in the string – Use $t7**

Basic Flow Chart



Further Analysis

- **We now understand the basic elements of our program.**
- **We need to expand on several activities within the actual procedure to completely define the operation of the procedure.**
- **There are two loops in the program:**
  - **A non-recursive loop that is a sort of "outer loop" that takes us down the list of characters, gathering a new one to compare after we have finished with the last character.**
  - **An inner, recursive loop that, when a character is discovered out of order, proceeds back "upstream" in the character list until it places the character in its proper alphabetical position.**
  - **The inner loop is made recursive to assist us in finding our way back to the proper position in the list to get the next letter to compare.**

Outer Loop

- **The outer or "get letter" loop loads two adjacent letters in the unalphabetized list into registers $t1 and $t2.**
- **The letter in $t1 is one space "upstream" from the one in $t2. The letter in $t2 is the letter being evaluated.**
- **ASCII codes for the two letters are then compared.**
- **If $t1 has the smaller number, (smaller ASCII code), then the numbers are in alphabetical order, and the outer loop simply increments the pointer ($t0) by 1 and repeats itself.**
- **If $t2 is smaller, that letter must be moved "upstream" to be alphabetized, so that the program enters the inner, recursive loop.**

Inner Loop

- **The inner loop is called as a recursive procedure (via jal).**
- **After storing the two letters in reverse order in the string, the pointer is decremented, and two adjacent letter are loaded again.**
- **Note that the letter being compared will still be in $t2.**
- **Another comparison is made. If $t1<$t2, the letters are now in alphabetical order. The inner loop is exited.**
- **If $t1>$t2, the letter in $t2 is still not properly placed. The inner loop procedure is called again via a jal.**

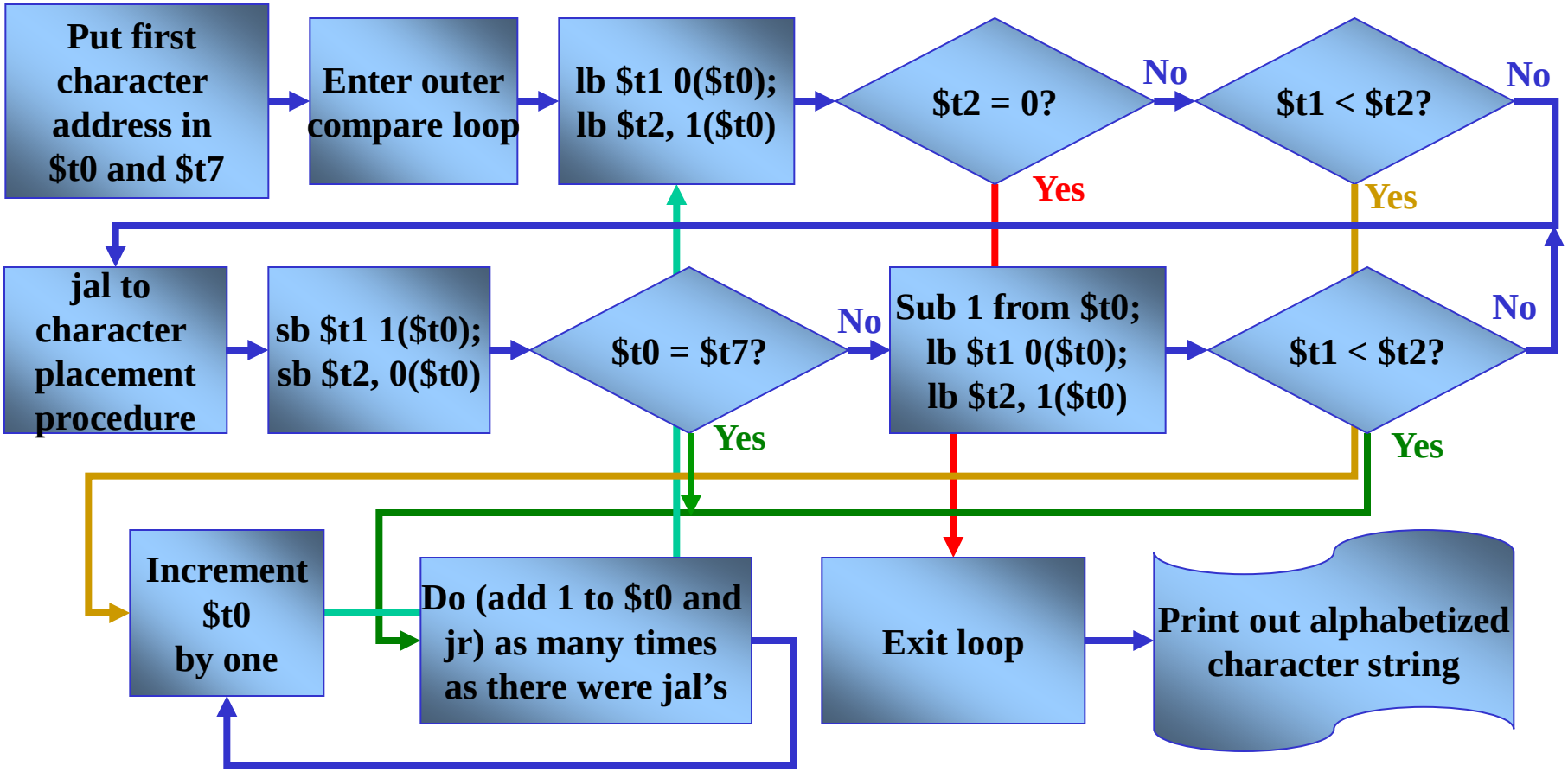
Inner Loop Details

- **We use a "jal" to enter the inner loop each time.**
  - **Inside the loop, we save the contents of $ra (next instruction after the jal) by pushing it onto the stack, since the procedure will probably call itself more than once. Then we decrement the stack pointer (remember, it doesn't decrement itself).**
  - **Each time we find the letter still out of position, we recall the loop again (jal) and move one character further upstream.**
- **When the letter is properly placed, we use a series of jr's to retrace our steps to where we started.**
  - **Each time we execute a jr, we increment $t0 (move pointer back toward the spot of the current letter under analysis), increment the stack pointer, pop the stack (putting the latest stack entry back in $ra), and do jr $ra.**
  - **When jr's = jal's, we are back where we started the inner loop.**

Inner Loop Details (2)

- **Thus, for procedure entry:**
  - **Do jal "label" ("label" is start of inner letter placement loop).**
- **Immediately inside the loop:**
  - **sw $ra,0(sp)**
  - **sub $sp,$sp,4**
  - **Proceed with loop (do not need to store any of the s-registers)**
- **For the procedure exit:**
  - **addi $t0,$t0,1 (move pointer back toward current place)**
  - **addi $sp,$sp,4**
  - **lw $ra,0($sp)**
  - **jr $ra**
- **We jr at exit as many times as we did a jal.**

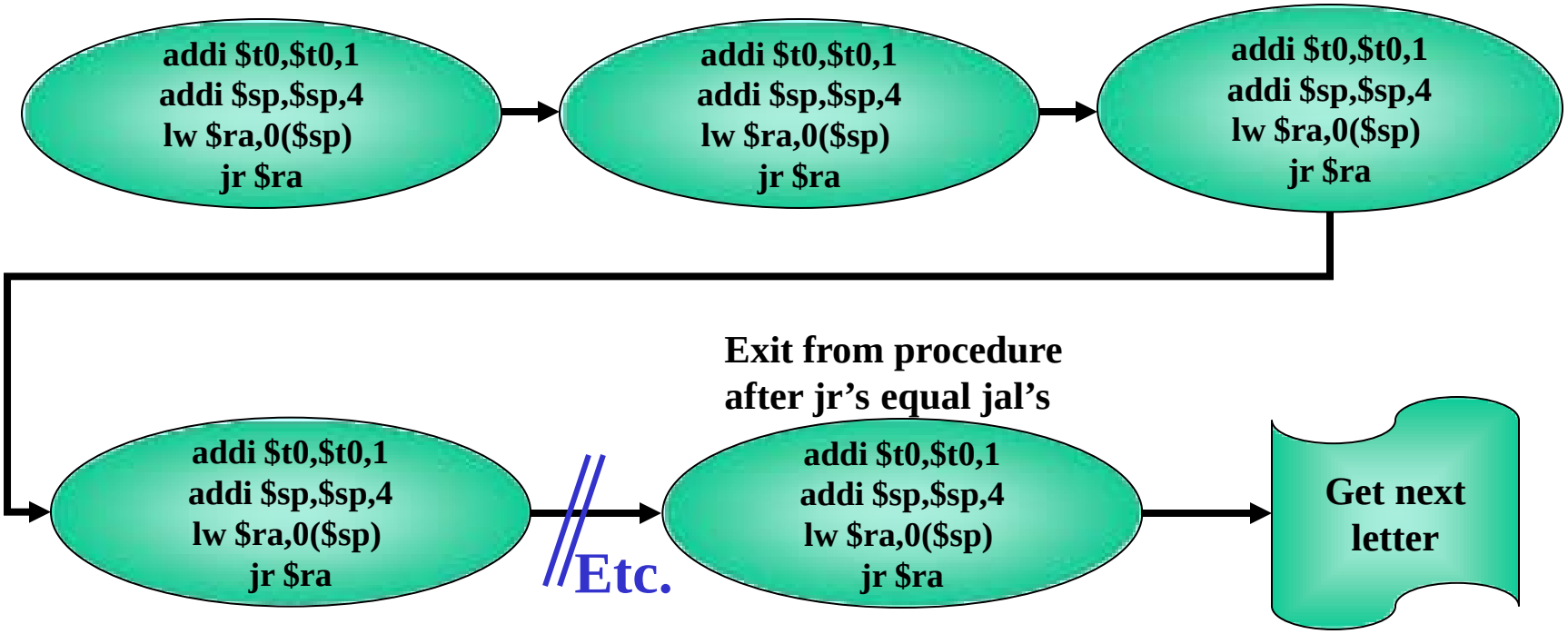
Program Flow with Additional Detail



Revision of Procedure Exit on Diagram

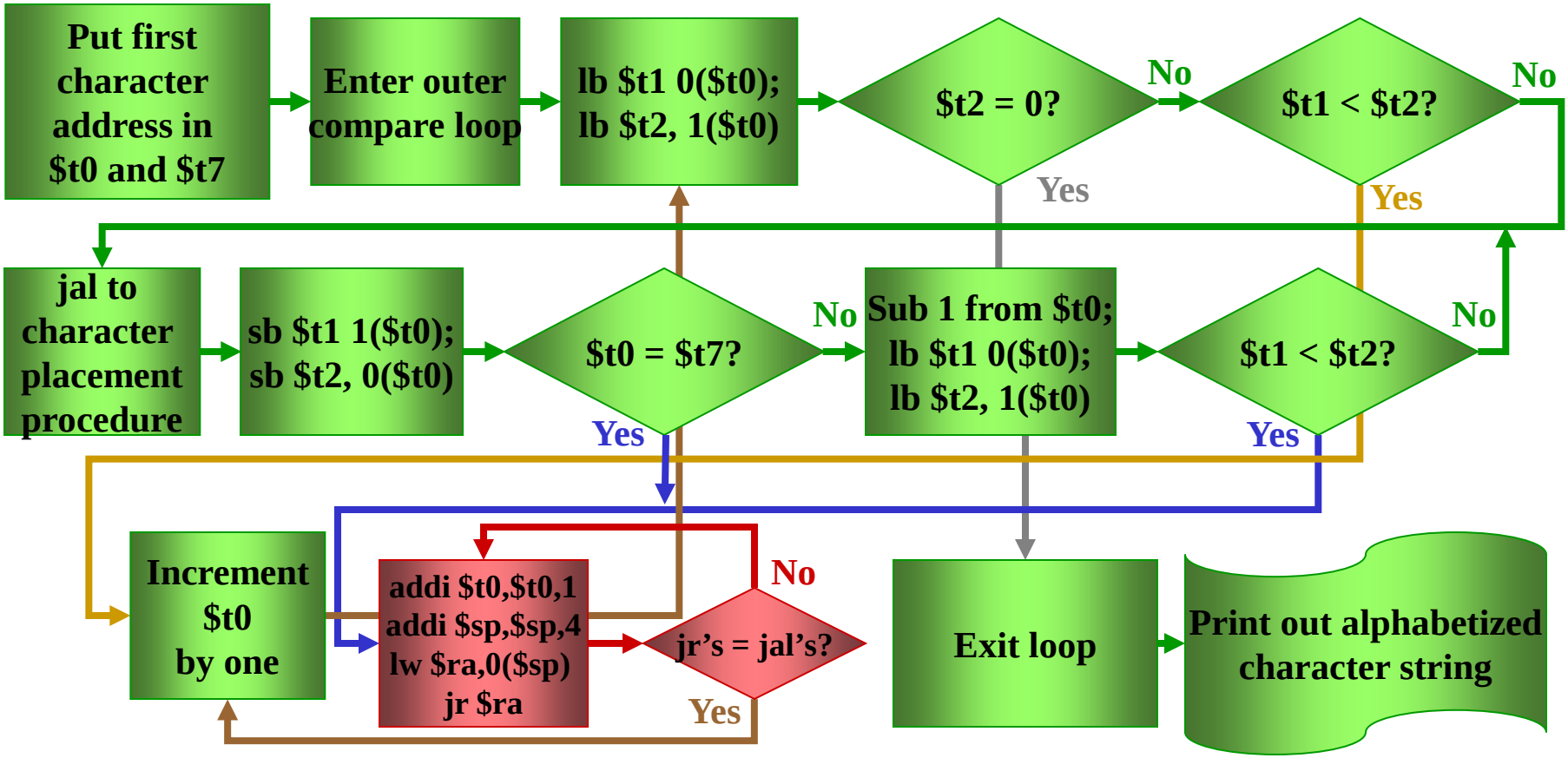
- The previous flow chart does not accurately convey that the jr loop must be done as many times as the recursive procedure was called.
- As our inner loop calls itself, it builds up a series of "nested loops" from which it must extricate itself.
- This jr "unwind" procedure lets the program find its way back to the current position in the string of letters.
- The "unwind" increments $sp, pops the stack to $ra, and performs a jr until there has been a jr for each jal.
- The jr loop looks like this:

"jr" Loop



Thus a more accurate flow chart would be: →

Final Loop Flow Chart



Writing the Program

- We have a good program flow chart, so we can proceed to compose the program at this point.
- Once again, we write the program in Notepad in order to avoid the text formatting characters inserted by Word®.
  - First we write program header information.
  - We define our data with data declarations.
  - Finally, we complete the program segments.
- We did not show detail of the print routine on the flow chart, since by now, hopefully, this is a familiar task.

Program "Prolog" and Data Declaration

```
##  Lecture 18 Demo Program 1, Character List Alphabetization
##  Alphabetizes a sequence of ASCII lower-case letters
##    and prints out the resulting alphabetized list.
##  Note that the list is made in the data declaration and
##    starts with all 26 letters of the alphabet in random order.

##  $t0 is the variable pointer.
##  $t1 holds the "upstream compare character."
##  $t2 holds the current character being analyzed.
##  $t7 is the fixed pointer (always points to the first character
##    in the string).

                    .data
string:   .asciiz "qwertyuiopasdfghjklzxcvbnm"   # Characters to be
                                                 #   alphabetized.
```

Program name and description

Definition of register roles

Initiation and Outer-Loop Setup

```
        .text
main:   la $t0,string       # Load address of string in $t0.
        la $t7,string       # Load address of string in $t7.
comp:   lb $t1,0($t0)       # Load first two characters to be compared.
        lb $t2,1($t0)
        beqz $t2,done       # If the new character is 0, we are done.
        ble $t1,$t2,count   # If characters are in the correct order, get
                            #     the next character.
        jal rev             # Characters not in correct sequence;
                            #   go to rearrangement routine.
        j comp              # When character is placed in correct
                            #   position, get next character.
```

Sets up fixed and variable pointers

Outer loop; gets next char. in list and compares it to previous char.

Outer Loop (Concluded) and End Routine

```
count:  addi $t0,$t0,1      # Increment current character address.
        j comp              # Compare next two characters.

done:   la $a0,string       # When finished, print out the alphabetized
        li $v0,4            #    string in correct order.
        syscall
        li $v0,10           # Done; end program.
        syscall
```

End of outer loop (pointer increment)

End routine which prints the alphabetized string and halts the program

Inner (Positioning) Loop

```
rev:    sub $sp,$sp,4      # Decrement stack pointer.
        sw $ra,($sp)       # Store contents of $ra on the stack.
        sb $t1,1($t0)      # Exchange positions of the two characters
        sb $t2,0($t0)      #  in the string.
        beq $t0,$t7,goback # If position is first in the string,
                           #   we are done -- get next letter.
        sub $t0,$t0,1      # Decrement the letter pointer.
        lb $t1,0($t0)      # Compare current letter in placement
        lb $t2,1($t0)      #  to the next letter "upstream."
        ble $t1,$t2,goback # If letter properly placed, return to
                           #    current outer loop position
                           #    position to get next letter.
        jal rev            # Not done yet; go back “upstream” one
                           #   character and do next compare.
```

Store $ra on the stack

Move letter back one position

Top of the list?

Compare letter to the next “upstream” letter to see if it needs to be moved further up.

Recall inner loop

"Rewind" Loop Using jr

```
goback:  addi $t0,$t0,1        # Placement done; move the
         lw $ra,($sp)          #    pointer "downstream" until
         addi $sp,$sp,4        #    we find our correct
         jr $ra                #    position to get next letter.
```

This loop repeats as many times as necessary, until the number of jr's equals the number of jal's. Note that once in the inner loop, since the instruction before the line labeled "goback" was the jal, each jr will return the program to "goback" until the last jr, which sends the program back to the outer loop ("comp").

```
#  Lecture 17 Demo Program 1, Character List Alphabetization
#  Alphabetizes a sequence of ASCII lower-case letters and prints out the resulting
#  alphabetized list.
#  The list of letters is in the data declaration and contains all 26 alphabet letters in
#  random order.

#  $t0 -- Pointer to current spot in letters
#  $t1 -- Holds the "upstream compare character"
#  $t2 -- Holds the current character being analyzed
#  $t7 -- Pointer to the first character in string

            .text
main:       la $t0,string          # Load the string address into $t0
            la $t7,string          # Load the string address into $t7
comp:       lb $t1,0($t0)          # Load first two characters to be compared
            lb $t2,1($t0)
            beqz $t2,done          # If the new character = 0, done
            ble $t1,$t2,count      # If characters in correct order, get next character
            jal rev                # Characters not in correct order; go to reverse
            j comp                 # Character in correct position; get next character
count:  addi $t0,$t0,1             # Increment current character address
            j comp                 # Return to next character compare
```

```
done:   la $a0,string       # Print out alphabetized string + CR
        li $v0,4
        syscall
        li $v0,10           # Done; end program.
        syscall
# Character reverse routine follows

rev:    sub $sp,$sp,4       # Store contents of $ra on the stack
        sw $ra,($sp)        # Decrement stack pointer.
        sb $t1,1($t0)       # Exchange two character positions
        sb $t2,0($t0)
        beq $t0,$t7,goback  # If at first position in the string, done
        sub $t0,$t0,1       # Decrement the letter pointer.
        lb $t1,0($t0)       # Compare letter to next "upstream" letter
        lb $t2,1($t0)
        ble $t1,$t2,goback  # If letter is properly placed, done
        jal rev             # Not done yet; move back another position

goback: addi $t0,$t0,1      # Reverse done; move back to current position
        lw $ra,($sp)
        addi $sp,$sp,4
        jr $ra

        .data
string: .asciiz "qwertyuiopasdfghjklzxcvbnm"    # Character list

#  End of Lecture 17 Demo Program 1.
```

Summary

- **Once again, we have gone through the "thought process" of defining, flow-charting, coding, and checking out a MIPS assembly-language program (and this one was the most complicated by far).**
- **When you can understand the preceding program and compose similar software in SPIM, you have completed the learning process we began in Lecture 11.**
- **If you still have questions about this program or about how to write a recursive loop, now is the time to visit office hours, complete the homework and lab assignments, and polish your assembly language skills.**

Program 2

- **This problem is not a recursive loop, but it will give you more loop practice.**
- **The text and data declarations for this program are given.**
- **Write a brief loop program to compare the numerical value of the ASCII bytes that represent the characters in "Hello,_world!\n" and output the largest one as a decimal number.**
- **This is a short program – mine took 20 instructions in all.**

```
        .text
main:
```

```
        .data
str:    .asciiz "Hello, world!\n"
```

Final Practice Programming Problem

- **Copy the example program into Notepad and single-step it, watching especially, in the inner loop, how recursion is used to track the position in the list.**
- **Change the program so that the list of letters is input from the keyboard (using system call 8) and then alphabetized.**

Bonus Material 2

- **What follows is some miscellaneous material on how computers start up their operation and how operating systems work in general.**
- **We do not have time for this material in class, but as it is a worthwhile set of information to be aware of, it is offered as a second bonus homework (as in Lecture 11).**
- **Turning in this homework is worth 100 points, but it does not count as a homework when the overall homework grade is calculated. It therefore adds 100 to the numerator of your homework average but nothing to the denominator.**

Miscellaneous Topics

- **In this bonus material on computers in general, we discuss several miscellaneous topics:**
  - **Operating systems**
  - **Starting up or "booting" a computer**
  - **How a computer operating system (OS) manages the execution of user programs in a multi-tasking environment**
  - **Multiprogramming and virtual memory**
  - **Processes; launching a process; process switching**
  - **Exceptions**

Operating Systems

- An operating system (OS) is a program that supervises computer system functions.
- The OS runs application programs (e.g., Word) and input/output (I/O) like printing.
- Examples are Unix®, Linux®, Windows®, and MacOS®.
- The OS relieves users from operational details:
  - Controls all process operations (i.e., it is "the boss").
  - Protects each process from damage by another.
  - Activates processes and supervises peripheral access (printer, CRT, disk memory. DVD-ROM, etc.).
  - Prioritizes process operation and access to peripherals.
  - Sets up and monitors communication with other processes, network input/output, etc.

Operating Systems (2)

- **Since the OS handles fundamental operations, users do not have to deal with these details.**
  - **Example: printing a Word® file under Windows® -- When the user "prints" a Word file, Word converts the document to a standard data format and passes it to Windows, which activates a "print driver" (printer software) to output data to the printer.**
- **Programs issue system calls to request OS service.**
- **The OS call handler uses information passed in the system call to decide what action to take.**
- **After servicing a system call, the OS resumes, suspends, or terminates the process that called it. It can schedule other tasks while a process awaits the results of a system call (e.g., an application awaiting data from the disk).**

Operating Systems (3)

- **A modern operating system provides other important services:**
  - **Allocates memory segments to programs (processes) that are active.**
  - **Supervises starting, running and termination of all programs.**
  - **Determines priority of all operations.**
  - **Provides interprocess communication and access to I/O devices (CRT screen, mouse, keyboard, printer, disk, etc.) as noted previously.**
  - **Detects and handles events that interrupt program execution (interrupts, exceptions, protection faults – covered in detail below).**
  - **On a large system, can provide accounting functions (usage or time running for a customer when computer time is "bought").**

Starting or "Booting" a Computer

- At computer power-up (think PC), there is a short (~1-3 sec) "power settle" delay, then an all-system reset.
- OS load is then initiated.
  - Long ago (circa 1950-1970), a "bootstrap" load might be put into memory using switches on the computer front panel.
  - Later, it was input from paper tape, magnetic tape, or disk.
- Today, an OS load usually starts with a small ("micro") OS, which may be in read-only memory (ROM).
- The micro OS (PC "Bios" or "CMOS") checks system hardware, then initiates an OS loader.
  - For Windows™, this is a program called "command.com," which is on the lowest sector of the hard drive.
  - Once in operation, the loader loads the OS and starts it.

How the OS Runs Programs

- **Single-task operating systems were the first OS's (1950's IBM systems; 1960 mini-computers, 1970 PC-DOS).**
- **These primitive OS's ran one program at a time.***
  - **User programs issued commands directly to the hardware (!).**
  - **Users had "free reign" within the computer, and could do just about anything ("FORMAT C:" for example).**
  - **User programs could overwrite and destroy the OS.**
- **Today, a multi-tasking OS is the norm (Large IBM systems, MacOS, Windows).**
  - **Many programs reside in main memory at the same time.**
  - **The OS protects itself and user program vigorously.**
  - **Programs obtain services only via system calls.**

*** Anybody remember printing a document in DOS?**

Processes

- A program is an executable file (e.g., a SPIM NotePad file). A process is an instance of a program in execution (e.g., that NotePad file assembled and running).
- In a modern OS, processes execute "simultaneously."
- "Simultaneously" is in quotes since only one process can be executed by a single CPU at a time.
  - Although processes execute serially, many can be in memory at the same time. Since in a given second, the OS runs parts of many processes, we say that the execution is "simultaneous," since they are simultaneous in our perception.
  - The OS runs a process until it no longer can run, due to:
    - Process completion.
    - Process suspension (awaiting disk load or print completion).
    - Process abort (stopped by the OS due to a problem).

Launching a Process

- **To launch a user process or application, the OS:**
  - **Reserves space in operating memory for the process.**
  - **Copies the executable text module into the address space.**
  - **Pushes "command-line and environment arguments" onto the stack (process identification and priority or scheduling information, relationship to other processes, process communication requirements) in a "frame" assigned to it.**
  - **Allocates process space for data and text (program) segments (as in PCSPIM), and expansion room for storage of data generated within the process.**
  - **Initiates the process (e.g., calls "main" in SPIM).**
- **A process is protected within system memory from other "predatory" processes.**

Process Switching

- When a process terminates or is suspended (perhaps awaiting disk I/O), the OS makes a process switch.
- In making the switch, the OS will:
  - Push the contents of registers and other information about the curtailed process onto the stack
  - Use a "scheduling algorithm" (process priority according to relative importance) to find the highest pending process.
  - Retrieve (pop) the context of this process (register contents, etc.) from its stack frame.
  - Restore the context (registers, stack pointer, mode) to the CPU.
  - Re-initiate the process.

Exceptions

- An exception is an event that causes the OS to halt or suspend normal operation.
- Many exceptions are benign – most are interrupts.
  - Interrupts are often caused by external events, such as a signal from a peripheral that it needs to communicate with the CPU.
  - A good example is the disk drive on a computer. It is a mechanical device that must be serviced immediately.
  - The current process will be halted for interrupt service.
- Some exceptions may be system problems :
  - Bus (data I/O) error, Syscall timeout, bad memory address.
  - Protection exception (memory violation).
  - CPU error.

Exceptions (2)

- **In the R2000, exceptions are handled by Coprocessor 0.**
- **For most exceptions:**
  - **The processor exits user mode and enters executive mode.**
  - **A subroutine is initiated (usually via memory location 0x80000080 in OS memory).**
  - **This subroutine, called an exception handler, takes control, determines the exception, processes it (possibly by executing I/O), and resumes normal operation.**
- **For more serious exceptions, such as application errors, the operating system usually deletes the offending process (with proper information to the user).**

Bonus Questions 2

1. **What is the difference between an exception and an interrupt?**
2. **What is the difference between a process and a program?**
3. **What is the real definition of "simultaneous processing" in a multi-tasking system?**
4. **In a multi-process system, what happens when the current process suspends?**
5. **How does an application program request service from the OS?**
6. **To facilitate process switching, where is the process context kept?**
7. **When a computer is turned on, what is the first software that activates?**
8. **What is a one-sentence description of an operating system?**