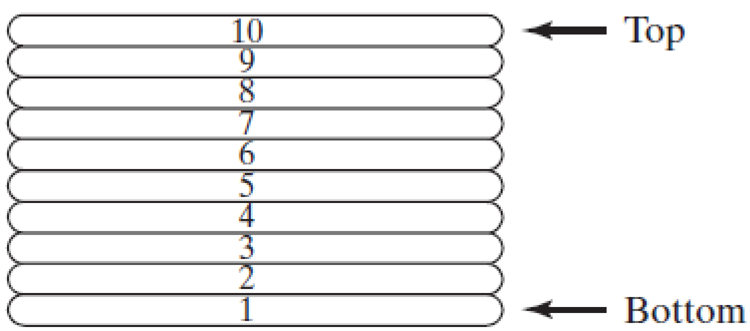
Lab 6 - Stack and Procedures

6.1 Stack

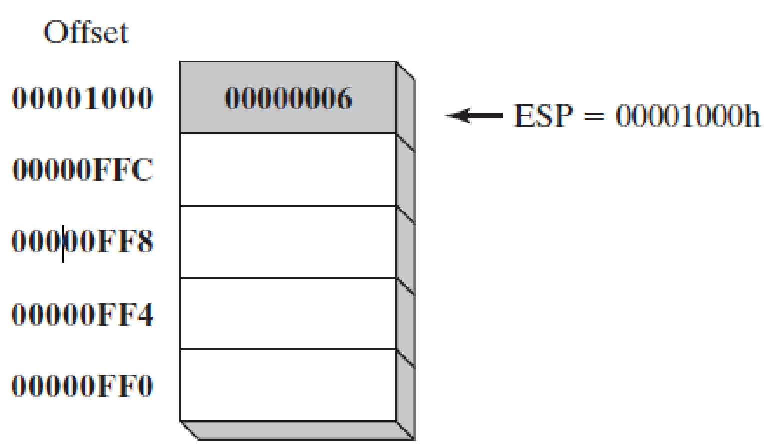
A *stack* is also called a LIFO structure (Last-In, First-Out) because the last value put into the stack is always the first value taken out. New values are added to the top of the stack, and existing values are removed from the top. In this Lab, we concentrate specifically on the *runtime stack*. It is supported directly by hardware in the CPU, and it is an essential part of the mechanism for calling and returning from procedures. Most of the time, we just call it the *stack*.



6.2 Runtime Stack (32-Bit Mode)

The *runtime stack* is a memory array managed directly by the CPU, using the ESP (extended stack pointer) register, known as the *stack pointer register*. In 32-bit mode, ESP register holds a 32-bit offset into some location on the stack. We rarely manipulate ESP directly; instead, it is indirectly modified by instructions such as CALL, RET, PUSH, and POP.

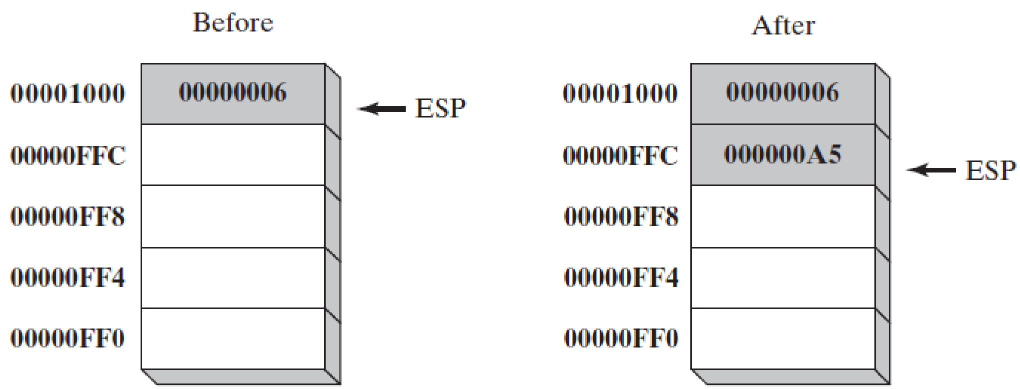
ESP register always points to the last value to be added to, or pushed on, the top of stack. To demonstrate, let's begin with a stack containing one value. In below figure, the ESP contains hexadecimal 00001000, the offset of the most recently pushed value (00000006). In diagrams, the top of the stack moves downward when the stack pointer decreases in value:



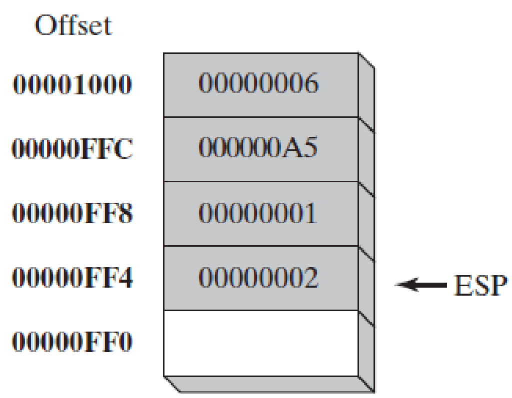
Each stack location in this figure contains 32 bits, which is the case when a program is running in 32-bit mode.

6.2.1 Push Operation

A 32-bit push operation decrements the stack pointer by 4 and copies a value into the location in the stack pointed to by the stack pointer. The below figure shows the effect of pushing 000000A5 on a stack that already contains one value (00000006). Notice that the ESP register always points to the last item pushed on the stack. The figure shows the stack ordering opposite to that of the diagram of stack we saw earlier in start of Lab, because the runtime stack grows downward in memory, from higher addresses to lower addresses. Before the push, ESP = 00001000h; after the push, ESP = 00000FFCh.

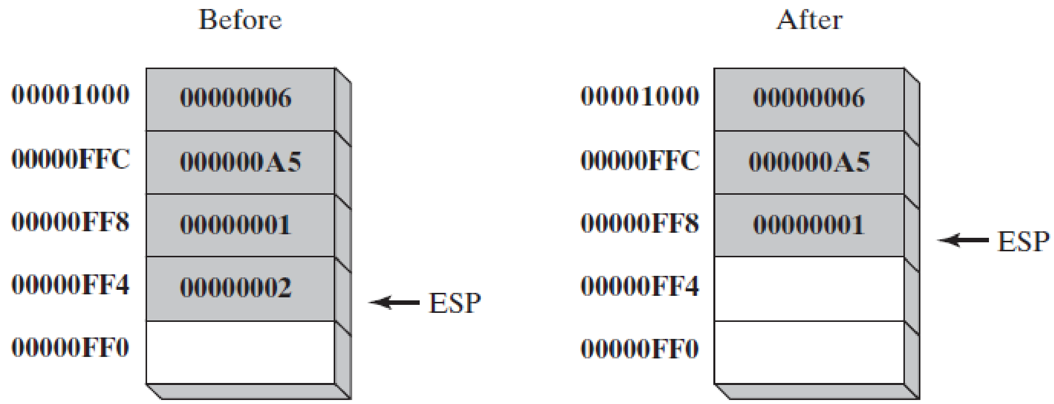


The below figure shows the same stack after pushing a total of four integers.



6.2.2 Pop Operation

A pop operation removes a value from the stack. After the value is popped from the stack, the stack pointer is incremented (by the stack element size) to point to the next-highest location in the stack. The below figure shows the stack before and after the value 00000002 is popped.



6.2.3 Stack Applications

- A stack makes a convenient temporary save area for registers when they are used for more than one purpose. After they are modified, they can be restored to their original values.
- When the CALL instruction executes, the CPU saves the current subroutine's return address on the stack.
- When calling a subroutine, you pass input values called *arguments* by pushing them on the stack.
- The stack provides temporary storage for local variables inside subroutines.

6.3 PUSH and POP Instructions

6.3.1 PUSH Instruction

The PUSH instruction first decrements ESP and then copies a source operand into the stack. A 16-bit operand causes ESP to be decremented by 2. A 32-bit operand causes ESP to be decremented by 4. There are three instruction formats:

```
PUSH reg/mem16
PUSH reg/mem32
PUSH imm32
```

6.3.2 POP Instruction

The POP instruction first copies the contents of the stack element pointed to by ESP into a 16- or 32-bit destination operand and then increments ESP. If the operand is 16 bits, ESP is incremented by 2; if the operand is 32 bits, ESP is incremented by 4:

```
POP reg/mem16
POP reg/mem32
```

6.3.3 PUSHFD and POPFD Instructions

The PUSHFD instruction pushes the 32-bit EFLAGS register on the stack, and POPFD pops the stack into EFLAGS:

```
pushfd
popfd
```

The MOV instruction cannot be used to copy the flags to a variable, so PUSHFD may be the best way to save the flags:

```
pushfd              ;save the flags
popfd               ;restore the flags
```

Note: When using pushes and pops of this type, be sure the program's execution path does not skip over the POPFD instruction.

A less error-prone way to save and restore the flags is to push them on the stack and immediately pop them into a variable:

```
.data
      saveFlags DWORD ?
.code
      pushfd                    ;push flags on stack
      pop saveFlags             ;copy into a variable
```

The following statements restore the flags from the same variable:

```
push saveFlags             ;push saved flag values
popfd                      ;copy into the flags
```

6.3.4 PUSHA and POPA Instructions

PUSHA instruction pushes the 16-bit general-purpose registers (AX, CX, DX, BX, SP, BP, SI, DI) on the stack in the order listed. The POPA instruction pops the same registers in reverse. You should only use PUSHA and POPA when programming in 16-bit mode.

6.3.5 PUSHAD and POPAD Instructions

The PUSHAD instruction pushes all of the 32-bit general-purpose registers on the stack in the following order:

- EAX
- ECX
- EDX
- EBX
- ESP
- EBP
- ESI
- EDI

The POPAD instruction pops the same registers off the stack in reverse order.

If you write a procedure that modifies a number of 32-bit registers, use PUSHAD at the beginning of the procedure and POPAD at the end to save and restore the registers. The following code fragment is an example:

```
MySub PROC
pushad              ;save general-purpose registers
.
.
mov eax,...
mov edx,...
mov ecx,...
.
.
popad               ;restore general-purpose registers
ret                 ;return from procedure
MySub ENDP
```

Note: Procedures returning results in one or more registers should not use PUSHA and PUSHAD. Suppose the following **ReadValue** procedure returns an integer in EAX; the call to POPAD overwrites the return value from EAX:

```
ReadValue PROC
pushad              ;save general-purpose registers
.
.
mov eax,return_value
.
.
popad               ;overwrites EAX!
ret
ReadValue ENDP
```

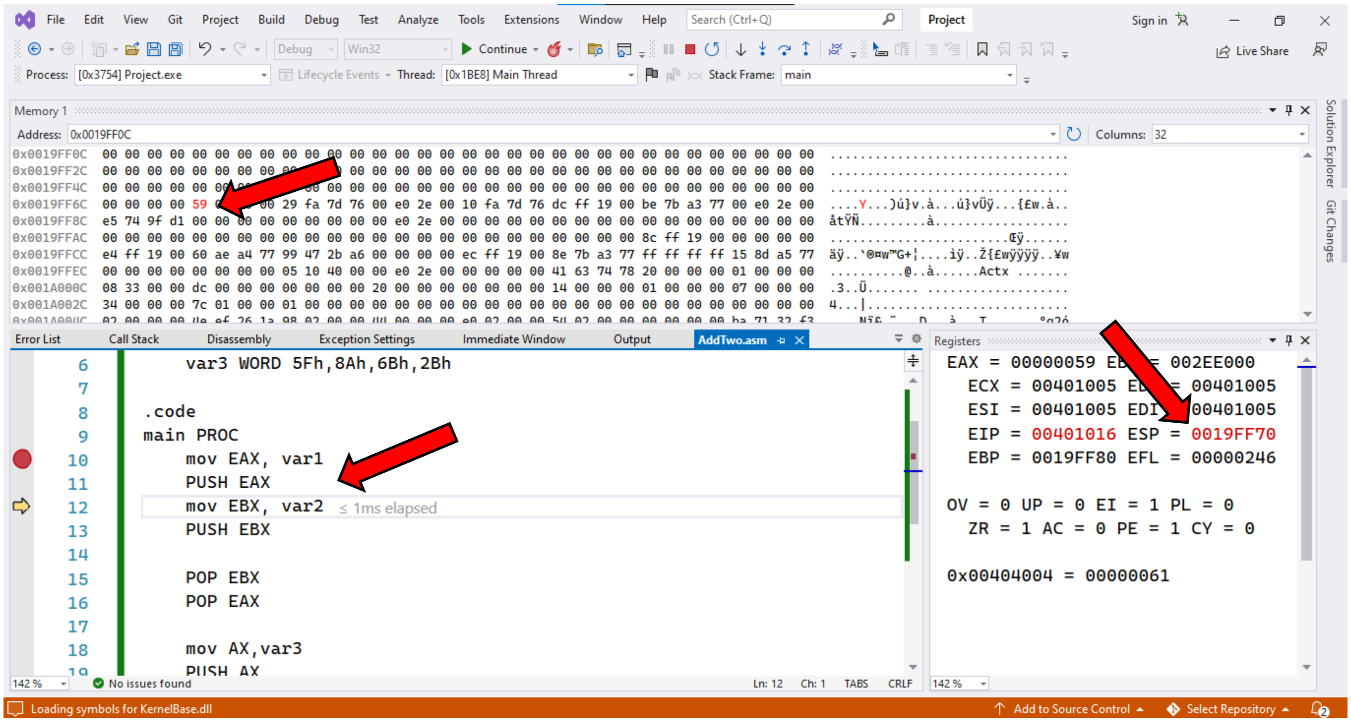
6.3.6 Show Run-Time Stack in Visual Studio

Debug the following code in Visual Studio:

```
Include Irvine32.inc

.data
      var1 DWORD 59h
      var2 DWORD 61h
      var3 WORD 5Fh,8Ah,6Bh,2Bh

.code
main PROC
      mov   EAX, var1
      PUSH EAX
      mov EBX, var2
      PUSH EBX

      POP EBX
      POP EAX

      mov AX,var3
      PUSH AX

      exit
main ENDP
END main
```

Start program in debugging and go to Memory window.

After pushing the value to stack. Copy the ESP value to Memory Window Address box.



The Memory window shows the stack data in Memory window.

6.3.7 Example: Reversing a String

```
Include Irvine32.inc

.data
        aName BYTE "Hello World",0
        nameSize = ($ - aName) - 1
.code
main PROC
        ;Push the name on the stack.
        mov ecx,nameSize
        mov esi,0
        L1: movzx eax,aName[esi]        ; get character
        push eax                        ; push on stack
        inc esi
        loop L1

        ; Pop the name from the stack, in reverse order
        mov ecx,nameSize
        mov esi,0
        L2: pop eax                     ; get character
        mov aName[esi],al               ; store in string
        inc esi
        loop L2

        mov EDX,OFFSET aName
        call WriteString

        INVOKE ExitProcess,0
main ENDP
END main
```

6.4 Procedures

We can divide programs into *subroutines*. A complicated problem is usually divided into separate tasks before it can be understood, implemented, and tested effectively.

6.4.1 PROC Directive

A procedure is declared using the PROC and ENDP directives. It must be assigned a name (a valid identifier). Each program we've written so far contains a procedure named main.

```
main PROC
.
.
main ENDP
```

When you create a procedure other than your program's startup procedure, end it with a RET instruction. RET forces the CPU to return to the location from where the procedure was called:

```
sample PROC
.
.
ret
sample ENDP
```

6.4.2 Labels in Procedures

By default, labels are visible only within the procedure in which they are declared. This rule often affects jump and loop instructions. In the following example, the label named Destination must be located in the same procedure as the JMP instruction:

```
jmp Destination
```

It is possible to work around this limitation by declaring a global label, identified by a double colon (::) after its name:

```
Destination::
```

Note: It is not a good idea to jump or loop outside of the current procedure. Procedures have an automated way of returning and adjusting the runtime stack. If you directly transfer out of a procedure, the runtime stack can easily become corrupted.

6.4.3 Documenting Procedures

- A description of all tasks accomplished by the procedure.
- A list of input parameters and their usage, labeled by a word such as **Receives**. If any input parameters have specific requirements for their input values, list them here.
- A description of any values returned by the procedure, labeled by a word such as **Returns**.
- A list of any special requirements, called preconditions, that must be satisfied before the procedure is called. These can be labeled by the word **Requires**. For example, for a procedure that draws a graphics line, a useful precondition would be that the video display adapter must already be in graphics mode.

For example:

```
;-------------------------------------------------------
; sumof
;
; Calculates and returns the sum of three 32-bit integers.
; Receives: EAX, EBX, ECX, the three integers. May be
; signed or unsigned.
; Returns: EAX = sum
--------------------------------------------------------
SumOf PROC
   add eax,ebx
   add eax,ecx
   ret
SumOf ENDP
```

6.4.4 CALL and RET Instructions

The CALL instruction calls a procedure by directing the processor to begin execution at a new memory location. The procedure uses a RET (return from procedure) instruction to bring the processor back to the point in the program where the procedure was called.

The CALL instruction pushes its return address on the stack and copies the called procedure's address into the instruction pointer. When the procedure is ready to return, its RET instruction pops the return address from the stack into the instruction pointer. In 32-bit mode, the CPU executes the instruction in memory pointed to by EIP (instruction pointer register). In 16-bit mode, IP points to the instruction.

Suppose that in **main**, a CALL statement is located at offset 00000020. Typically, this instruction requires 5 bytes of machine code, so the next statement (a MOV in this case) is located at offset 00000025:

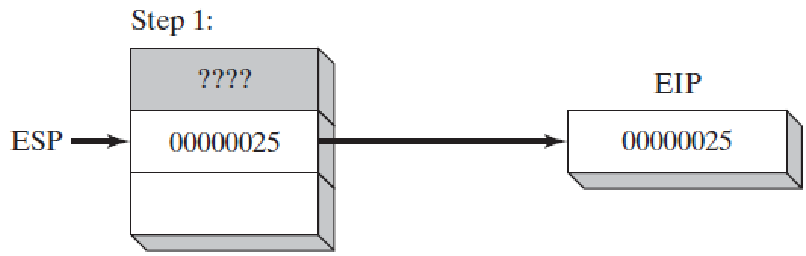
```
                    main PROC
00000020                  call MySub
00000025                  mov eax,ebx
```

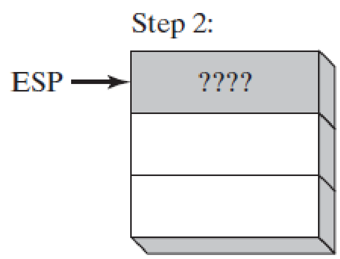
Next, suppose that the first executable instruction in **MySub** is located at offset 00000040:

```
                    MySub PROC
00000040                  mov eax,edx
                          .
                          .
                          ret
                    MySub ENDP
```

When the CALL instruction executes, the address following the call (00000025) is pushed on the stack and the address of **MySub** is loaded into EIP. All instructions in **MySub** execute up to its RET instruction.

When the RET instruction executes, in Step 1, the value in the stack pointed to by ESP is popped into EIP. In step 2, ESP is incremented so it points to the previous value on the stack.





6.4.5 Passing Register Arguments to Procedures

While using procedures, it is not a good idea to include references to specific variable names inside the procedure. If you did, the procedure could only be used with one array. A better approach is to pass the offset of an array to the procedure and pass an integer specifying the number of array elements. We call these *arguments* (or *input parameters*). In assembly language, it is common to pass arguments inside general-purpose registers.

In the below example we created a simple procedure named **SumOf** that added the integers in the EAX, EBX, and ECX registers. In main, before calling **SumOf**, we assign values to EAX, EBX, and ECX:

```
.data
      theSum DWORD ?
.code
main PROC
      mov eax,10000h      ; argument
      mov ebx,20000h      ; argument
      mov ecx,30000h      ; argument
      call Sumof          ; EAX = (EAX + EBX + ECX)
      mov theSum,eax      ; save the sum
main ENDP

SumOf PROC
      add eax,ebx
      add eax,ecx
      ret
SumOf ENDP
```

After the CALL statement, we have the option of copying the sum in EAX to a variable.

6.4.6 Example: Summing an Integer Array

```
Include Irvine32.inc
.data
      array DWORD 10000h,20000h,30000h,40000h,50000h
      theSum DWORD ?
.code
main PROC
      mov esi,OFFSET array            ;ESI points to array
      mov ecx,LENGTHOF array          ;ECX = array count
      call ArraySum                   ;calculate the sum
      mov theSum,eax                  ;returned in EAX
      INVOKE ExitProcess,0
main ENDP
;-----------------------------------------------------
; ArraySum
;
; Calculates the sum of an array of 32-bit integers.
; Receives: ESI = the array offset
; ECX = number of elements in the array
; Returns: EAX = sum of the array elements
;-----------------------------------------------------
ArraySum PROC
      push esi                  ;save ESI, ECX
      push ecx
      mov eax,0                 ;set the sum to zero
      L1:
      add eax,[esi]             ;add each integer to sum
      add esi,TYPE DWORD        ;point to next integer
      loop L1                   ;repeat for array size
      pop ecx                   ;restore ECX, ESI
      pop esi
      ret                       ;sum is in EAX
ArraySum ENDP
```

6.4.7 USES Operator

The USES operator is used with the PROC directive. It lets you list the names of all registers modified within a procedure. USES tells the assembler to do two things:

- First, generate PUSH instructions that save the registers on the stack at the beginning of the procedure.
- Second, generate POP instructions that restore the register values at the end of the procedure.

The USES operator immediately follows PROC and is itself followed by a list of registers on the same line separated by spaces or tabs (not commas). The **ArraySum** procedure from above example used PUSH and POP instructions to save and restore ESI and ECX. The USES operator can more easily do the same:

```
ArraySum PROC USES esi ecx
      mov eax,0                 ;set the sum to zero
      L1:
      add eax,[esi]             ;add each integer to sum
      add esi,TYPE DWORD        ;point to next integer
      loop L1                   ;repeat for array size
      ret                       ;sum is in EAX
ArraySum ENDP
```

6.5 Linking to an External Library

This section shows how to call procedures from the book's link libraries, named **Irvine32.lib** and **Irvine64.obj**. The complete library source code is available at the author's web site (asmirvine.com). It should be installed on your computer in the *Examples\Lib32* subfolder of the book's install file (usually named *C:\Irvine*).

The Irvine32 library can only be used by programs running in 32-bit mode. It contains procedures that link to the MS-Windows API when they generate input–output. The Irvine64 library is a more limited library for 64-bit applications that is limited to essential display and string operations.

A *link library* is a file containing procedures (subroutines) that have been assembled into machine code. A link library begins as one or more source files, which are assembled into object files. The object files are inserted into a specially formatted file recognized by the linker utility. Suppose a program displays a string in the console window by calling a procedure named **WriteString**. The program source must contain a PROTO directive identifying the **WriteString** procedure:

```
WriteString proto
```

Next, a CALL instruction executes WriteString:

```
call WriteString
```

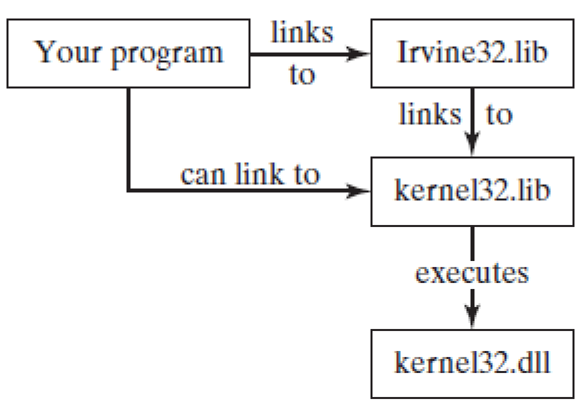
When the program is assembled, the assembler leaves the target address of the CALL instruction blank, knowing that it will be filled in by the linker. The linker looks for **WriteString** in the link library and copies the appropriate machine instructions from the library into the program's executable file. In addition, it inserts **WriteString's** address into the CALL instruction. If a procedure you're calling is not in the link library, the linker issues an error message and does not generate an executable file.

6.5.1 Linker Command

The linker utility combines a program's object file with one or more object files and link libraries. The following command, for example, links hello.obj to the irvine32.lib and kernel32.lib libraries:

```
link hello.obj irvine32.lib kernel32.lib
```

The kernel32.lib file, part of the Microsoft Windows Platform Software Development Kit, contains linking information for system functions located in a file named kernel32.dll. The latter is a fundamental part of MS-Windows and is called a *dynamic link library*. It contains executable functions that perform character-based input–output. The figure below shows how kernel32.lib is a bridge to kernel32.dll.



6.6 The Irvine32 Library

- There is no Microsoft-approved standard library for assembly language programming.
- To display an integer on the console, you had to write a complicated procedure that converts the internal binary representation of integers to a sequence of ASCII characters and display the integer on the screen.
- Professional programmers often prefer to build their own libraries.
- The Irvine32 library is designed to provide a simple interface for input-output for beginners.

6.6.1 Procedures in the Irvine32 Library

The table below contains a complete list of procedures in the Irvine32 library.

Procedure	Description
CloseFile	Closes a disk file that was previously opened.
Clrscr	Clears the console window and locates the cursor at the upper left corner.
CreateOutputFile	Creates a new disk file for writing in output mode.
Crlf	Writes an end-of-line sequence to the console window.
Delay	Pauses the program execution for a specified n-millisecond interval.
DumpMem	Writes a block of memory to the console window in hexadecimal.
DumpRegs	Displays the EAX, EBX, ECX, EDX, ESI, EDI, EBP, ESP, EFLAGS, and EIP registers in hexadecimal. Also displays the most common CPU status flags.
GetCommandTail	Copies the program's command-line arguments (called the command tail) into an array of bytes.
GetDateTime	Gets the current date and time from the system.
GetMaxXY	Gets the number of columns and rows in the console window's buffer.
GetMseconds	Returns the number of milliseconds elapsed since midnight.
GetTextColor	Returns the active foreground and background text colors in the console window.
Gotoxy	Locates the cursor at a specific row and column in the console window.
IsDigit	Sets the Zero flag if the AL register contains the ASCII code for a decimal digit (0 9).
MsgBox	Displays a popup message box.
MsgBoxAsk	Display a yes/no question in a popup message box.
OpenInputFile	Opens an existing disk file for input.
ParseDecimal32	Converts an unsigned decimal integer string to 32-bit binary.
ParseInteger32	Converts a signed decimal integer string to 32-bit binary.
Random32	Generates a 32-bit pseudorandom integer in the range 0 to FFFFFFFFh.
Randomize	Seeds the random number generator with a unique value.
RandomRange	Generates a pseudorandom integer within a specified range.
ReadChar	Waits for a single character to be typed at the keyboard and returns the character.
ReadDec	Reads an unsigned 32-bit decimal integer from the keyboard, terminated by the Enter key.
ReadFromFile	Reads an input disk file into a buffer.
ReadHex	Reads a 32-bit hexadecimal integer from the keyboard, terminated by the Enter key.
ReadInt	Reads a 32-bit signed decimal integer from the keyboard, terminated by the Enter key.
ReadKey	Reads a character from the keyboard's input buffer without waiting for input.
ReadString	Reads a string from the keyboard, terminated by the Enter key.
SetTextColor	Sets the foreground and background colors of all subsequent text output to the console.
Str_compare	Compares two strings.

Str_copy	Copies a source string to a destination string.
Str_length	Returns the length of a string in EAX.
Str_trim	Removes unwanted characters from a string.
Str_ucase	Converts a string to uppercase letters.
WaitMsg	Displays a message and waits for a key to be pressed.
WriteBin	Writes an unsigned 32-bit integer to the console window in ASCII binary format.
WriteBinB	Writes a binary integer to the console window in byte, word, or doubleword format.
WriteChar	Writes a single character to the console window.
WriteDec	Writes an unsigned 32-bit integer to the console window in decimal format.
WriteHex	Writes a 32-bit integer to the console window in hexadecimal format.
WriteHexB	Writes a byte, word, or doubleword integer to the console window in hexadecimal format.
WriteInt	Writes a signed 32-bit integer to the console window in decimal format.
WriteStackFrame	Writes the current procedure's stack frame to the console.
WriteStackFrameName	Writes the current procedure's name and stack frame to the console.
WriteString	Writes a null-terminated string to the console window.
WriteToFile	Writes a buffer to an output file.
WriteWindowsMsg	Displays a string containing the most recent error generated by MS-Windows.

6.7 Irvine32 Library Procedures Examples

6.7.1 Testing Colors

```
; Testing SetTextColor and GetTextColor.
INCLUDE Irvine32.inc

.data
str1 BYTE "Sample string, in color",0dh,0ah,0

.code
main PROC

      mov    ax,yellow + (blue * 16)
      call   SetTextColor

      mov    edx,OFFSET str1
      call   WriteString

      call   GetTextColor
      call   DumpRegs

      exit
main ENDP
END main
```

For more details about "SetTextColor" procedure read Book's page number 167.

6.7.2 Testing the Clrscr, Crlf, DumpMem, ReadInt, SetTextColor, WaitMsg, WriteBin, WriteHex, and WriteString procedures.

```
; Tests the Clrscr, Crlf, DumpMem, ReadInt, SetTextColor,
; WaitMsg, WriteBin, WriteHex, and WriteString procedures.

INCLUDE Irvine32.inc

.data
      COUNT = 4
      BlueTextOnGray = blue + (lightGray * 16)
      DefaultColor = lightGray + (black * 16)
      arrayD SDWORD 12345678h,1A4B2000h,3434h,7AB9h
      prompt BYTE "Enter a 32-bit signed integer: ",0

.code
main PROC

      ; Set text color to blue text on a light gray background
      mov   eax,BlueTextOnGray
      call  SetTextColor
      call  Clrscr                    ; clear the screen

      ; Display an array using DumpMem.
      mov    esi,OFFSET arrayD        ; starting OFFSET
      mov    ebx,TYPE arrayD          ; doubleword = 4 bytes
      mov    ecx,LENGTHOF arrayD      ; number of units in arrayD
      call   DumpMem                  ; display memory

    ; Ask the user to input a sequence of signed integers
      call    Crlf                    ; new line
   mov    ecx,COUNT

L1: mov   edx,OFFSET prompt
    call  WriteString
    call  ReadInt               ; input integer into EAX
    call  Crlf                        ; new line

      call    WriteInt                ; display in signed decimal
      call    Crlf
      call    WriteHex                ; display in hexadecimal
      call    Crlf
      call    WriteBin                ; display in binary
      call    Crlf
      call    Crlf

Loop  L1

      ; Return console window to default colors.
      call    WaitMsg                 ; "Press any key..."
      mov     eax,DefaultColor
      call    SetTextColor
      call    Clrscr

      exit
main ENDP
END main
```

6.7.3 Message Boxes

```
INCLUDE Irvine32.inc

.data
caption db "Dialog Title", 0

HelloMsg BYTE "This is a pop-up message box.", 0dh,0ah
               BYTE "Click OK to continue...", 0

.code
main PROC

      mov    ebx,0                           ; no caption
      mov    edx,OFFSET HelloMsg             ; contents
      call   MsgBox

      mov    ebx,OFFSET caption              ; caption
      mov    edx,OFFSET HelloMsg             ; contents
      call   MsgBox

      exit
main ENDP
END main
```

Another example:

```
Include Irvine32.inc

.data
      caption BYTE "LAB-6 Completed",0
      question BYTE "Did you complete your LAb Tasks?."
      BYTE 0dh,0ah
      BYTE "Would you like to receive the Graded?",0
      results BYTE "The results will be uploaded on LMS.",0dh,0ah,0

.code
main PROC

      mov ebx,OFFSET caption
      mov edx,OFFSET question
      call MsgBoxAsk
      ;(check return value in EAX)

      exit
main ENDP
END main
```

6.7.4 Random Number Generation

```
INCLUDE Irvine32.inc

TAB = 9                         ; ASCII code for Tab

.code
main PROC
      call   Randomize          ; init random generator
      call   Rand1
      call   Rand2
      exit
main ENDP

Rand1 PROC
; Generate ten pseudo-random integers.
      mov    ecx,10             ; loop 10 times

L1:   call   Random32           ; generate random int
      call   WriteDec           ; write in unsigned decimal
      mov    al,TAB             ; horizontal tab
      call   WriteChar          ; write the tab
      loop   L1

      call   Crlf
      ret
Rand1 ENDP

Rand2 PROC
; Generate ten pseudo-random integers between -50 and +49
      mov    ecx,10             ; loop 10 times

L1:   mov    eax,100            ; values 0-99
      call   RandomRange        ; generate random int
      sub    eax,50             ; vaues -50 to +49
      call   WriteInt           ; write signed decimal
      mov    al,TAB             ; horizontal tab
      call   WriteChar          ; write the tab
      loop   L1

      call   Crlf
      ret
Rand2 ENDP
END main
```

6.7.5 Calculation of the Elapsed Execution Time of a Nested Loop

```
Include Irvine32.inc
.data
      OUTER_LOOP_COUNT = 3
      startTime DWORD ?
      msg1 BYTE "Please wait...",0dh,0ah,0
      msg2 BYTE "Elapsed milliseconds: ",0

.code
main PROC
      mov   edx,OFFSET msg1                 ; "Please wait..."
      call WriteString

      ; Save the starting time
      call GetMSeconds
      mov   startTime,eax

      ; Start the outer loop
      mov   ecx,OUTER_LOOP_COUNT

L1:   call innerLoop
      loop L1

      ; Calculate the elapsed time
      call GetMSeconds
      sub   eax,startTime

      ; Display the elapsed time
      mov   edx,OFFSET msg2                 ; "Elapsed milliseconds: "
      call WriteString
      call WriteDec                         ; write the milliseconds
      call Crlf

      exit
main ENDP

innerLoop PROC
      push  ecx                             ; save current ECX value
      mov   ecx,0FFFFFFFFh                  ; set the loop counter
L1:   mul  eax                              ; eat up some cylces
      mul  eax
    mul  eax
      loop L1                               ; repeat the inner loop

      pop   ecx                             ; restore ECX's saved value
      ret
innerLoop ENDP

END main
```