Procedure

Computer Organization and Assembly Languages
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with slides by Kip Irvine

Overview

- Stack Operations
- Defining and Using Procedures
- Stack frames, parameters and local variables
- Recursion
- Related directives

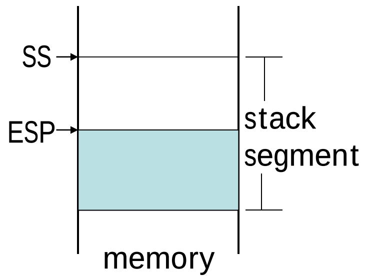
Stack operations

Stacks

- LIFO (Last-In, First-Out) data structure.
- push/pop operations
- You probably have had experiences on implementing it in high-level languages.
- Here, we concentrate on *runtime stack*, directly supported by hardware in the CPU. It is essential for calling and returning from procedures.

Runtime stack

- Managed by the CPU, using two registers
  - SS (stack segment)
  - ESP (stack pointer) * : point to the top of the stack
    usually modified by **CALL, RET, PUSH** and **POP**



ESP is modified by CALL , RET , PUSH and POP instructions

EBP is not modified

* SP in Real-address mode

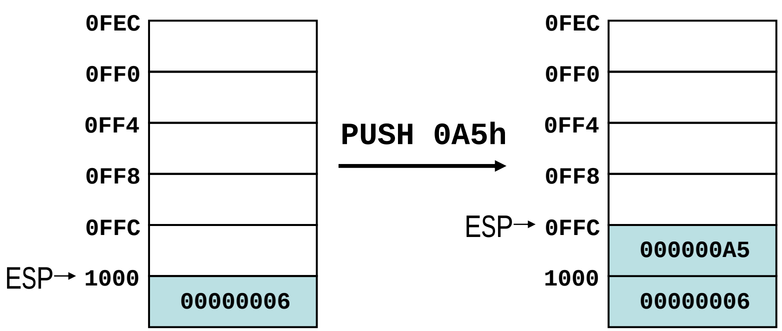
PUSH and POP instructions

- **PUSH** syntax:
  - **PUSH** ***r/m16***
  - **PUSH** ***r/m32***
  - **PUSH** ***imm32***
- **POP** syntax:
  - **POP** ***r/m16***
  - **POP** ***r/m32***

assembly syntax

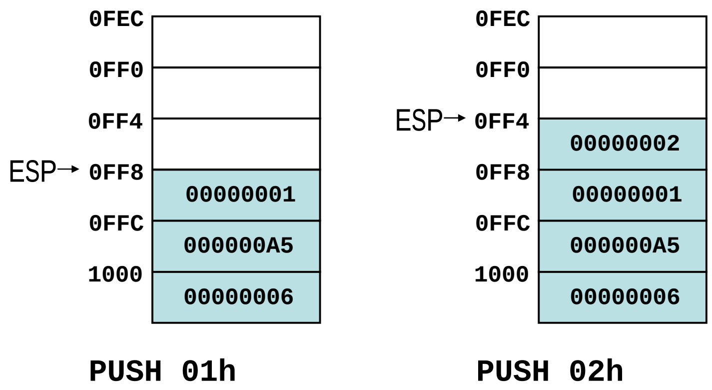
PUSH operation (1 of 2)

- A **push** operation decrements the stack pointer by 2 or 4 (depending on operands) and copies a value into the location pointed to by the stack pointer.



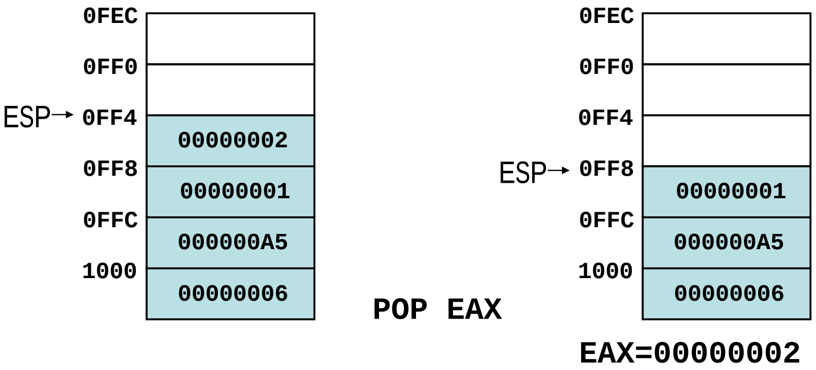
PUSH operation (2 of 2)

- The same stack after pushing two more integers:



POP operation

- Copies value at stack[ESP] into a register or variable.
- Adds *n* to ESP, where *n* is either 2 or 4, depending on the attribute of the operand receiving the data



When to use stacks

- Temporary save area for registers
- To save return address for CALL
- To pass arguments
- Local variables
- Applications which have LIFO nature, such as reversing a string

Example of using stacks

Save and restore registers when they contain important values. Note that the **PUSH** and **POP** instructions are in the opposite order:

```
push esi                ; push registers
push ecx
push ebx

mov esi,OFFSET dwordVal  ; starting OFFSET
mov ecx,LENGTHOF dwordVal; number of units
mov ebx,TYPE dwordVal ;size of a doubleword
call DumpMem            ; display memory

pop ebx                 ; opposite order
pop ecx
pop esi
```


Example: Nested Loop

When creating a nested loop, push the outer loop counter before entering the inner loop:

```
   mov ecx,100      ; set outer loop count
L1:                 ; begin the outer loop
   push ecx         ; save outer loop count

   mov ecx,20       ; set inner loop count
L2:                 ; begin the inner loop
   ;
   ;
   loop L2          ; repeat the inner loop

   pop ecx          ; restore outer loop count
   loop L1          ; repeat the outer loop
```

Example: reversing a string

```
.data
aName BYTE "Abraham Lincoln",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
```

moving string to stack - L1 function

Example: reversing a string

```
; Pop the name from the stack, in reverse,
; and store in the aName array.
  mov ecx,nameSize
  mov esi,0
L2:
  pop eax             ; get character
  mov aName[esi],al ; store in string
  inc esi
  Loop L2

  exit
main ENDP
END main
```

moving string from stack to aName . it reverses the string

Related instructions

- **PUSHFD** and **POPFD**
  - push and pop the EFLAGS register
  - **LAHF**, **SAHF** are other ways to save flags
- **PUSHAD** pushes the 32-bit general-purpose registers on the stack in the following order
  - **EAX, ECX, EDX, EBX, ESP, EBP, ESI, EDI**
- **POPAD** pops the same registers off the stack in reverse order
  - **PUSHA** and **POPA** do the same for 16-bit registers

Example

```
MySub PROC
     pushad
     ...
     ; modify some register
     ...
     popad
     ret
MySub ENDP
```

Do not use this if your procedure uses registers for return values

Defining and using procedures

Creating Procedures

- Large problems can be divided into smaller tasks to make them more manageable
- A procedure is the ASM equivalent of a Java or C++ function
- Following is an assembly language procedure named sample:

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

A named block of statements that ends with a return.

Documenting procedures

Suggested documentation for each procedure:

- A description of all tasks accomplished by the procedure.
- Receives: A list of input parameters; state their usage and requirements.
- Returns: A description of values returned by the procedure.
- Requires: Optional list of requirements called preconditions that must be satisfied before the procedure is called.

For example, a procedure of drawing lines could assume that display adapter is already in graphics mode.

Example: SumOf procedure

```
;------------------------------------------------
SumOf PROC
;
; 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, and the status flags
;          (Carry, Overflow, etc.) are changed.
; Requires: nothing
;------------------------------------------------
   add eax,ebx
   add eax,ecx
   ret
SumOf ENDP
```

CALL and RET instructions

- The **CALL** instruction calls a procedure
  - pushes offset of next instruction on the stack
  - copies the address of the called procedure into **EIP**
- The **RET** instruction returns from a procedure
  - pops top of stack into **EIP**
- We used **jl** and **jr** in our toy computer for **CALL** and **RET**, **BL** and **MOV PC, LR** in ARM.

CALL-RET example (1 of 2)

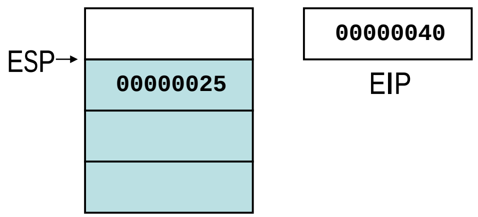
0000025 is the offset of the instruction immediately following the CALL instruction

00000040 is the offset of the first instruction inside MySub

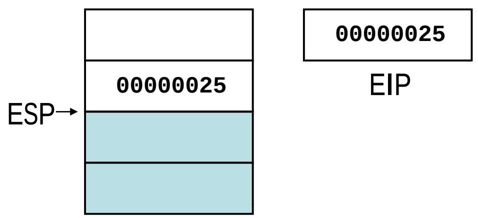
```
main PROC
   00000020 call MySub
   00000025 mov eax,ebx
   .
   .
main ENDP

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


CALL-RET example (2 of 2)

The CALL instruction pushes 00000025 onto the stack, and loads 00000040 into EIP

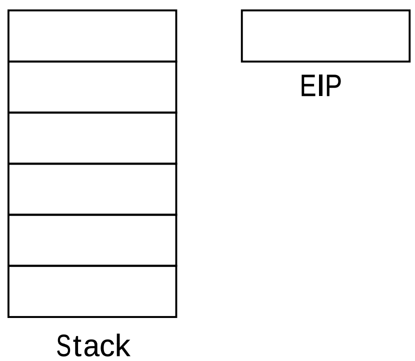


The RET instruction pops 00000025 from the stack into EIP



Nested procedure calls

```
     main PROC
        .
        .
        call Sub1
0050    exit
     main ENDP
0100 Sub1 PROC
        .
        .
        call Sub2
0150    ret
     Sub1 ENDP
0200 Sub2 PROC
        .
        .
        call Sub3
0250    ret
     Sub2 ENDP
0300 Sub3 PROC
        .
        .
        ret
     Sub3 ENDP
```



Local and global labels

A local label is visible only to statements inside the same procedure. A global label is visible everywhere.

```
main PROC
   jmp L2              ; error!
L1::                   ; global label
   exit
main ENDP

sub2 PROC
L2:                    ; local label
   jmp L1              ; ok
   ret
sub2 ENDP
```


Procedure parameters (1 of 3)

- A good procedure might be usable in many different programs
- Parameters help to make procedures flexible because parameter values can change at runtime
- General registers can be used to pass parameters

Procedure parameters (2 of 3)

The ArraySum procedure calculates the sum of an array. It makes two references to specific variable names:

```
ArraySum PROC
   mov esi,0             ; array index
   mov eax,0             ; set the sum to zero

L1:
   add eax,myArray[esi] ; add each integer to sum
   add esi,4             ; point to next integer
   loop L1               ; repeat for array size

   mov theSum,eax        ; store the sum
   ret
ArraySum ENDP
```


Procedure parameters (3 of 3)

This version returns the sum of any doubleword array whose address is in ESI. The sum is returned in EAX:

```
ArraySum PROC
; Recevies: ESI points to an array of doublewords,
;           ECX = number of array elements.
; Returns:  EAX = sum
;-------------------------------------------------
    push esi
    push ecx
    mov eax,0           ; set the sum to zero
L1: add eax,[esi]       ; add each integer to sum
    add esi,4           ; point to next integer
    loop L1             ; repeat for array size
    pop ecx
    pop esi
    ret
ArraySum ENDP
```

Calling ArraySum

```
.data
array DWORD 10000h, 20000h, 30000h, 40000h
theSum DWORD ?
.code
main PROC
  mov     esi, OFFSET array
  mov     ecx, LENGTHOF array
  call    ArraySum
  mov     theSum, eax
```


USES operator

- Lists the registers that will be saved (to avoid side effects) (return register shouldn't be saved)

```
ArraySum PROC USES esi ecx
   mov eax,0  ; set the sum to zero
   ...
```

MASM generates the following code:

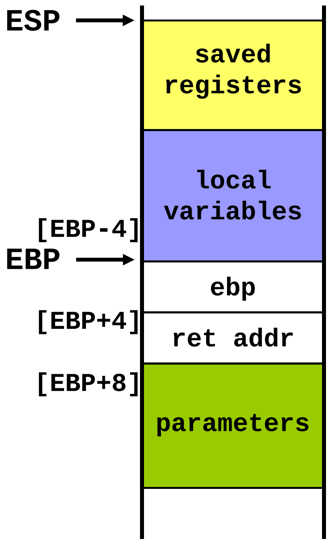
```
ArraySum PROC
   push esi
   push ecx
   .
   .
   pop ecx
   pop esi
   ret
ArraySum ENDP
```

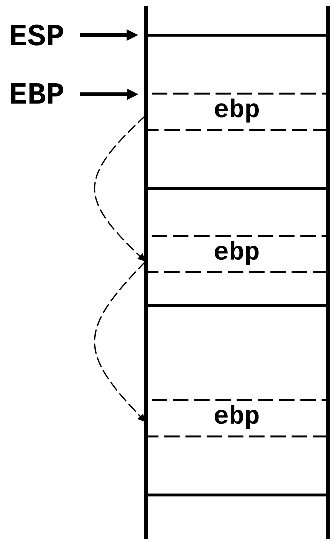

Stack frames, parameters and local variables

Stack frame

- Also known as an activation record
- Area of the stack set aside for a procedure's return address, passed parameters, saved registers, and local variables
- Created by the following steps:
  - Calling procedure pushes *arguments* on the stack and calls the procedure.
  - The subroutine is called, causing the *return address* to be pushed on the stack.
  - The called procedure pushes *EBP* on the stack, and *sets EBP to ESP*.
  - If *local variables* are needed, a constant is subtracted from ESP to make room on the stack.
  - The *registers needed to be saved* are pushed.

Stack frame





Explicit access to stack parameters

- A procedure can explicitly access stack parameters using constant offsets from **EBP**.
  - Example: **`[ebp + 8]`**
- **EBP** is often called the base pointer or frame pointer because it holds the base address of the stack frame.
- **EBP** does not change value during the procedure.
- **EBP** must be restored to its original value when a procedure returns.

Parameters

- Two types: register parameters and stack parameters.
- Stack parameters are more convenient than register parameters.

```
pushad
mov esi,OFFSET array
mov ecx,LENGTHOF array
mov ebx,TYPE array
call DumpMem
popad
```

register parameters

```
push TYPE array
push LENGTHOF array
push OFFSET array
call DumpMem
```

stack parameters

Parameters

call by value

```
int sum=AddTwo(a, b);
```

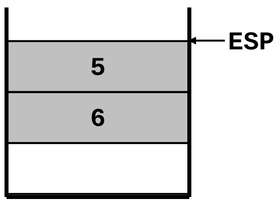
call by reference

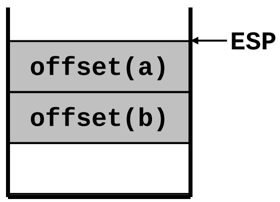
```
int sum=AddTwo(&a, &b);
```

```
.date
a   DWORD   5
b   DWORD   6
```

```
push b
push a
call AddTwo
```

```
push OFFSET b
push OFFSET a
call AddTwo
```

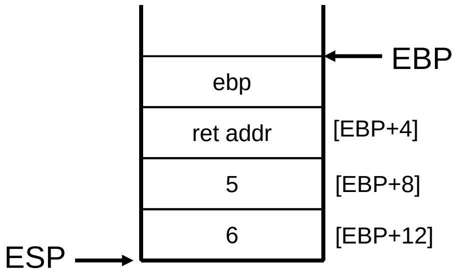




Stack frame example

```
.data
sum DWORD ?
.code
   push 6            ; second argument
   push 5            ; first argument
   call AddTwo       ; EAX = sum
   mov  sum,eax      ; save the sum
```

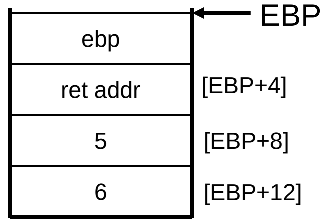
```
AddTwo PROC
   push ebp
   mov  ebp,esp
   .
   .
```



Stack frame example

```
AddTwo PROC
   push ebp
   mov ebp,esp          ; base of stack frame
   mov eax,[ebp + 12]   ; second argument (6)
   add eax,[ebp + 8]    ; first argument (5)
   pop ebp
   ret 8                ; clean up the stack
AddTwo ENDP             ; EAX contains the sum
```

Who should be responsible to remove arguments? It depends on the language model.



RET Instruction

- *Return from subroutine*
- Pops stack into the instruction pointer (EIP or IP). Control transfers to the target address.
- Syntax:
  - **RET**
  - **RET** *n*
- Optional operand *n* causes *n* bytes to be added to the stack pointer after EIP (or IP) is assigned a value.

Passing arguments by reference

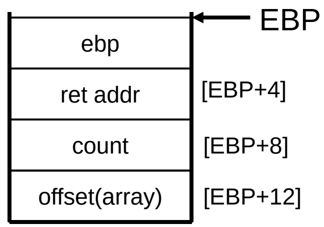
- The **ArrayFill** procedure fills an array with 16-bit random integers
- The calling program passes the address of the array, along with a count of the number of array elements:

```
.data
count = 100
array WORD count DUP(?)
.code
   push OFFSET array
   push COUNT
   call ArrayFill
```

Passing arguments by reference

`ArrayFill` can reference an array without knowing the array's name:

```
ArrayFill PROC
   push ebp
   mov  ebp,esp
   pushad
   mov  esi,[ebp+12]
   mov  ecx,[ebp+8]
   .
   .
```



Passing 8-bit and 16-bit arguments

- When passing stack arguments, it is best to push 32-bit operands to keep ESP aligned on a doubleword boundary.

```
Uppercase PROC
    push ebp
    mov  ebp, esp
    mov  al, [ebp+8]
    cmp  al, 'a'
    jb   L1
    cmp  al, 'z'
    ja   L1
    sub  al, 32
L1: pop  ebp
    ret  4
Uppercase ENDP
```

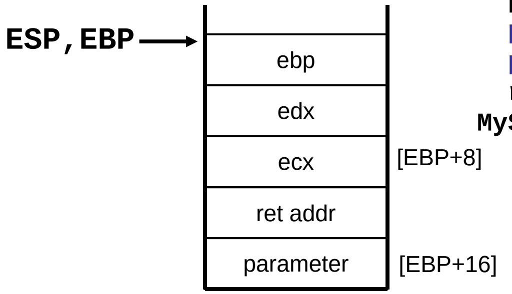
```
push  'x'   ; error
Call  Uppercase
```

```
.data
charVal  BYTE  'x'
.code
movzx eax, charVal
push  eax
Call  Uppercase
```


Saving and restoring registers

- When using stack parameters, avoid **USES**.

```
MySub2 PROC USES ecx, edx
  push ebp
  mov  ebp, esp
  mov  eax, [ebp+8]
  pop  ebp
  ret  4
MySub2 ENDP
```




```
MySub2 PROC
   push ecx
   push edx
   push ebp
   mov  ebp, esp
   mov  eax, [ebp+8]
   pop  ebp
   pop  edx
   pop  ecx
   ret  4
MySub2 ENDP
```


Local variables

- The variables defined in the data segment can be taken as *static global variables*.

  visibility=the whole program

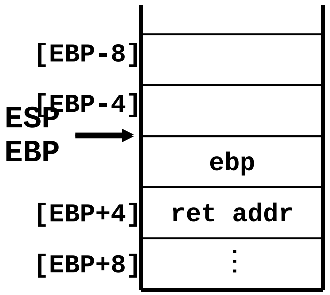
  lifetime=program duration

- A local variable is created, used, and destroyed within a single procedure (block)
- Advantages of local variables:
  - Restricted access: easy to debug, less error prone
  - Efficient memory usage
  - Same names can be used in two different procedures
  - Essential for recursion

Creating local variables

- Local variables are created on the runtime stack, usually above EBP.
- To explicitly create local variables, subtract their total size from ESP.

```
MySub PROC
    push ebp
    mov  ebp,esp
    sub  esp,8
    mov  [ebp-4],123456h
    mov  [ebp-8],0
    .
    .
```

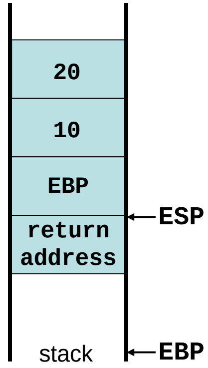


Local variables

- They can't be initialized at assembly time but can be assigned to default values at runtime.

```
void MySub()
{
  int X=10;
  int Y=20;
  ...
}
```

```
MySub PROC
    push ebp
    mov  ebp, esp
    sub  esp, 8
    mov  DWORD PTR [ebp-4], 10
    mov  DWORD PTR [ebp-8], 20
    ...
    mov  esp, ebp
    pop  ebp
    ret
MySub ENDP
```



Local variables

```
X_local EQU DWORD PTR [ebp-4]
Y_local EQU DWORD PTR [ebp-8]

MySub PROC
  push ebp
  mov  ebp, esp
  sub  esp, 8
  mov  X_local, 10
  mov  Y_local, 20
  ...
  mov  esp, ebp
  pop  ebp
  ret
MySub ENDP
```


LEA instruction (load effective address)

- The **LEA** instruction returns offsets of both direct and indirect operands at run time.
  - **OFFSET** only returns constant offsets (assemble time).
- **LEA** is required when obtaining the offset of a stack parameter or local variable. For example:

```
CopyString PROC,
    count:DWORD
    LOCAL temp[20]:BYTE

    mov edi,OFFSET count; invalid operand
    mov esi,OFFSET temp ; invalid operand
    lea edi,count       ; ok
    lea esi,temp        ; ok
```

LEA example

```
void makeArray()
{
  char myString[30];
  for (int i=0; i<30; i++)
    myString[i]='*';
}
```

```
makeArray PROC
    push ebp
    mov  ebp, esp
    sub  esp, 32
    lea  esi, [ebp-30]
    mov  ecx, 30
L1: mov  BYTE PTR [esi], '*'
    inc  esi
    loop L1
    add  esp 32
    pop  ebp
    ret
makeArray ENDP
```


ENTER and LEAVE

- **ENTER** instruction creates stack frame for a called procedure
  - pushes EBP on the stack **push ebp**
  - set EBP to the base of stack frame **mov ebp, esp**
  - reserves space for local variables **sub esp, n**
- **ENTER nbytes, nestinglevel**
  - **nbytes** (for local variables) is rounded up to a multiple of 4 to keep ESP on a doubleword boundary
  - **nestinglevel**: 0 for now

```
MySub PROC
  enter 8,0
```

```
MySub PROC
  push ebp
  mov ebp,esp
  sub esp,8
```


ENTER and LEAVE

- **LEAVE** reverses the action of a previous **ENTER** instruction.

```
MySub PROC
  enter 8, 0
  .
  .
  .
  .
  leave
  ret
MySub ENDP
```

```
MySub PROC
  push ebp
  mov  ebp, esp
  sub  esp, 8
  .
  .
  mov  esp, ebp
  pop  ebp
  ret
MySub ENDP
```

clearing the stack [local varaibles]

LOCAL directive

- The **LOCAL** directive declares a list of local variables
  - immediately follows the **PROC** directive
  - each variable is assigned a type
- Syntax:

  LOCAL *varlist*

Example:

```
MySub PROC
  LOCAL var1:BYTE, var2:WORD, var3:SDWORD
```

MASM-generated code

```
BubbleSort PROC
   LOCAL temp:DWORD, SwapFlag:BYTE
   . . .
   ret
BubbleSort ENDP
```

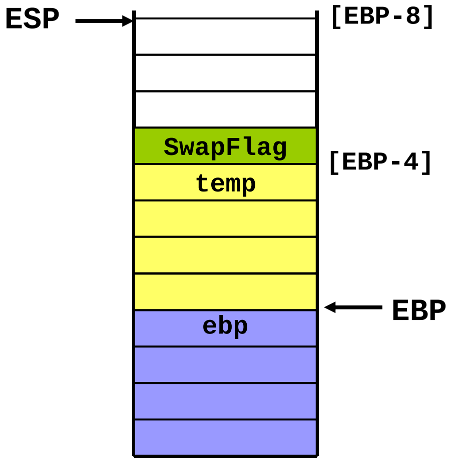
MASM generates the following code:

```
BubbleSort PROC
   push ebp
   mov  ebp,esp
   add  esp,0FFFFFFF8h ; add -8 to ESP
   . . .
   mov  esp,ebp
   pop  ebp
   ret
BubbleSort ENDP
```


Non-Doubleword Local Variables

- Local variables can be different sizes
- How are they created in the stack by **LOCAL** directive:
  - 8-bit: assigned to next available byte
  - 16-bit: assigned to next even (word) boundary
  - 32-bit: assigned to next doubleword boundary

MASM-generated code




```
mov   eax, temp           →    mov   eax, [ebp-4]
mov   bl, SwapFlag             mov   bl, [ebp-5]
```


Reserving stack space

- **.STACK 4096**
- **Sub1** calls **Sub2**, **Sub2** calls **Sub3,** how many bytes will you need in the stack?

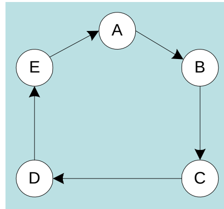
```
Sub1 PROC
  LOCAL array1[50]:DWORD ; 200 bytes

Sub2 PROC
  LOCAL array2[80]:WORD  ; 160 bytes

Sub3 PROC
  LOCAL array3[300]:WORD ; 300 bytes
```

660+8(ret addr)+saved registers…

Recursion

Recursion

- The process created when . . .
  - A procedure calls itself
  - Procedure A calls procedure B, which in turn calls procedure A
- Using a graph in which each node is a procedure and each edge is a procedure call, recursion forms a cycle:

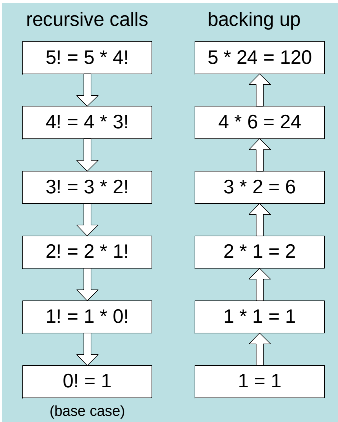


Calculating a factorial

This function calculates the factorial of integer *n*. A new value of *n* is saved in each stack frame:

```
int factorial(int n)
{
  if (n == 0)
    return 1;
  else
    return n*factorial(n-1);
}
```

```
factorial(5);
```



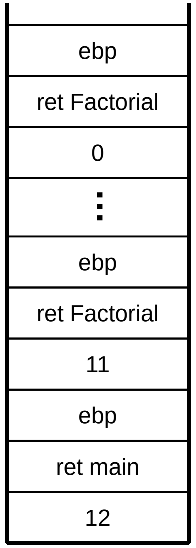
Calculating a factorial

```
Factorial PROC
   push ebp
   mov  ebp,esp
   mov  eax,[ebp+8]     ; get n
   cmp  eax,0           ; n > 0?
   ja   L1              ; yes: continue
   mov  eax,1           ; no: return 1
   jmp  L2
L1:dec  eax
   push eax             ; Factorial(n-1)
   call Factorial

ReturnFact:
   mov  ebx,[ebp+8]       ; get n
   mul  ebx               ; edx:eax=eax*ebx

L2:pop  ebp             ; return EAX
   ret  4               ; clean up stack
Factorial ENDP
```

Calculating a factorial

```
push 12
call Factorial
```

```
Factorial PROC
   push ebp
   mov  ebp,esp
   mov  eax,[ebp+8]
   cmp  eax,0
   ja   L1
   mov  eax,1
   jmp  L2
L1:dec  eax
   push eax
   call Factorial

ReturnFact:
   mov  ebx,[ebp+8]
   mul  ebx

L2:pop  ebp
   ret  4
Factorial ENDP
```



Related directives

.MODEL directive

- **.MODEL** directive specifies a program's memory model and model options (language-specifier).
- Syntax:

  .MODEL *memorymodel* [,*modeloptions*]
- ***memorymodel*** can be one of the following:
  - tiny, small, medium, compact, large, huge, or flat
- ***modeloptions*** includes the language specifier:
  - procedure naming scheme
  - parameter passing conventions
- **.MODEL flat, STDCALL**

Memory models

- A program's memory model determines the number and sizes of code and data segments.
- Real-address mode supports tiny, small, medium, compact, large, and huge models.
- Protected mode supports only the flat model.

Small model: code < 64 KB, data (including stack) < 64 KB. All offsets are 16 bits.

Flat model: single segment for code and data, up to 4 GB. All offsets are 32 bits.

Language specifiers

- STDCALL (used when calling Windows functions)
  - procedure arguments pushed on stack in reverse order (right to left)
  - called procedure cleans up the stack
  - **_name@nn** (for example, **_AddTwo@8**)
- C
  - procedure arguments pushed on stack in reverse order (right to left)
  - calling program cleans up the stack (variable number of parameters such as **printf**)
  - _name (for example, **_AddTwo**)
- PASCAL
  - arguments pushed in forward order (left to right)
  - called procedure cleans up the stack
- BASIC, FORTRAN, SYSCALL

INVOKE directive

- The **INVOKE** directive is a powerful replacement for Intel's **CALL** instruction that lets you pass multiple arguments
- Syntax:

  INVOKE *procedureName* [, *argumentList*]
- ***ArgumentList*** is an optional comma-delimited list of procedure arguments
- Arguments can be:
  - immediate values and integer expressions
  - variable names
  - address and ADDR expressions
  - register names

INVOKE examples

```
.data
byteVal BYTE 10
wordVal WORD 1000h
.code
   ; direct operands:
   INVOKE Sub1,byteVal,wordVal

   ; address of variable:
   INVOKE Sub2,ADDR byteVal

   ; register name, integer expression:
   INVOKE Sub3,eax,(10 * 20)

   ; address expression (indirect operand):
   INVOKE Sub4,[ebx]
```


INVOKE example

```
.data
val1 DWORD 12345h
val2 DWORD 23456h
.code
  INVOKE AddTwo, val1, val2

push val1
push val2
call AddTwo
```

ADDR operator

- Returns a near or far pointer to a variable, depending on which memory model your program uses:
  - Small model: returns 16-bit offset
  - Large model: returns 32-bit segment/offset
  - Flat model: returns 32-bit offset
- Simple example:

```
.data
myWord WORD ?
.code
INVOKE mySub,ADDR myWord
```


ADDR example

```
.data
Array DWORD 20 DUP(?)
.code
...
INVOKE Swap, ADDR Array, ADDR [Array+4]
```

```
push OFFSET Array+4
push OFFSET Array
Call Swap
```


PROC directive

- The **PROC** directive declares a procedure with an optional list of named parameters.
- Syntax:

  label **PROC [attributes] [USES] paramList**
- ***paramList*** is a list of parameters separated by commas. Each parameter has the following syntax:

  paramName:*type*

  type must either be one of the standard ASM types (BYTE, SBYTE, WORD, etc.), or it can be a pointer to one of these types.
- Example: **foo PROC C USES eax, param1:DWORD**

PROC example

- The AddTwo procedure receives two integers and returns their sum in EAX.
- C++ programs typically return 32-bit integers from functions in EAX.

```
AddTwo PROC,
 val1:DWORD,
 val2:DWORD

 mov eax,val1
 add eax,val2
 ret
AddTwo ENDP
```

```
AddTwo PROC,
 push ebp
 mov  ebp, esp
 mov  eax, dword ptr [ebp+8]
 add  eax, dword ptr [ebp+0Ch]
 leave
 ret 8
AddTwo ENDP
```

PROC example

```
Read_File PROC USES eax, ebx,
  pBuffer:PTR BYTE
  LOCAL fileHandle:DWORD

  mov  esi, pBuffer
  mov  fileHandle, eax
  .
  .
  ret
Read_File ENDP
```

```
Read_File PROC
  push ebp
  mov  ebp, esp
  add  esp, 0FFFFFFFCh
  push eax
  push ebx
  mov  esi, dword ptr [ebp+8]
  mov  dword ptr [ebp-4], eax
  .
  .
  pop  ebx
  pop  eax
  ret
Read_File ENDP
```


PROTO directive

- Creates a procedure prototype
- Syntax:
  - ***label*** **PROTO** ***paramList***
- Every procedure called by the **INVOKE** directive must have a prototype
- A complete procedure definition can also serve as its own prototype

PROTO directive

- Standard configuration: **PROTO** appears at top of the program listing, INVOKE appears in the code segment, and the procedure implementation occurs later in the program:

```
MySub PROTO    ; procedure prototype

.code
INVOKE MySub   ; procedure call


MySub PROC     ; procedure implementation
   .
   .
MySub ENDP
```


PROTO example

- Prototype for the ArraySum procedure, showing its parameter list:

```
ArraySum PROTO,
  ptrArray:PTR DWORD, ; points to the array
  szArray:DWORD       ; array size
```

```
ArraySum PROC USES esi, ecx,
  ptrArray:PTR DWORD, ; points to the array
  szArray:DWORD       ; array size
```

Multimodule programs

Multimodule programs

- A multimodule program is a program whose source code has been divided up into separate ASM files.
- Each ASM file (module) is assembled into a separate OBJ file.
- All OBJ files belonging to the same program are linked using the link utility into a single EXE file.
  - This process is called static linking

Advantages

- Large programs are easier to write, maintain, and debug when divided into separate source code modules.
- When changing a line of code, only its enclosing module needs to be assembled again. Linking assembled modules requires little time.
- A module can be a container for logically related code and data
  - encapsulation: procedures and variables are automatically hidden in a module unless you declare them public

Creating a multimodule program

- Here are some basic steps to follow when creating a multimodule program:
  - Create the main module
  - Create a separate source code module for each procedure or set of related procedures
  - Create an include file that contains procedure prototypes for external procedures (ones that are called between modules)
  - Use the INCLUDE directive to make your procedure prototypes available to each module

Multimodule programs

- **`MySub PROC PRIVATE`**
  `sub1 PROC PUBLIC`
- **`EXTERN sub1@0:PROC`**
- **`PUBLIC count, SYM1`**
  `SYM1=10`
  `.data`
  `count DWORD 0`
- **`EXTERN name:type`**

INCLUDE file

The sum.inc file contains prototypes for external functions that are not in the Irvine32 library:

```
INCLUDE Irvine32.inc

PromptForIntegers PROTO,
   ptrPrompt:PTR BYTE,       ; prompt string
   ptrArray:PTR DWORD,       ; points to the array
   arraySize:DWORD           ; size of the array

ArraySum PROTO,
   ptrArray:PTR DWORD,       ; points to the array
   count:DWORD               ; size of the array

DisplaySum PROTO,
   ptrPrompt:PTR BYTE,       ; prompt string
   theSum:DWORD              ; sum of the array
```


Main.asm

```
TITLE Integer Summation Program

INCLUDE sum.inc

.code
main PROC
   call Clrscr

   INVOKE PromptForIntegers,
      ADDR prompt1,
      ADDR array,
      Count

      ...
      call Crlf
      INVOKE ExitProcess,0
main ENDP
END main
```