Procedures and the Stack

Chapter 4

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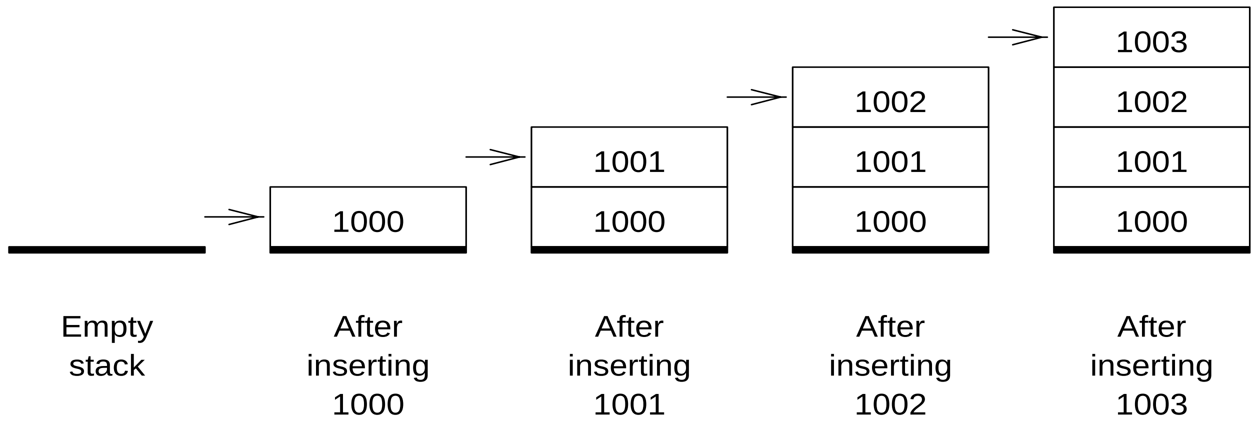
Outline

- What is stack?
- Pentium implementation of stack
- Pentium stack instructions
- Uses of stack
- Procedures
  - Assembler directives
  - Pentium instructions
- Parameter passing
  - Register method
  - Stack method
- Examples
  - Call-by-value
  - Call-by-reference
  - Bubble sort
- Procedures with variable number of parameters
- Local variables
- Multiple source program modules
- Performance: Procedure overheads

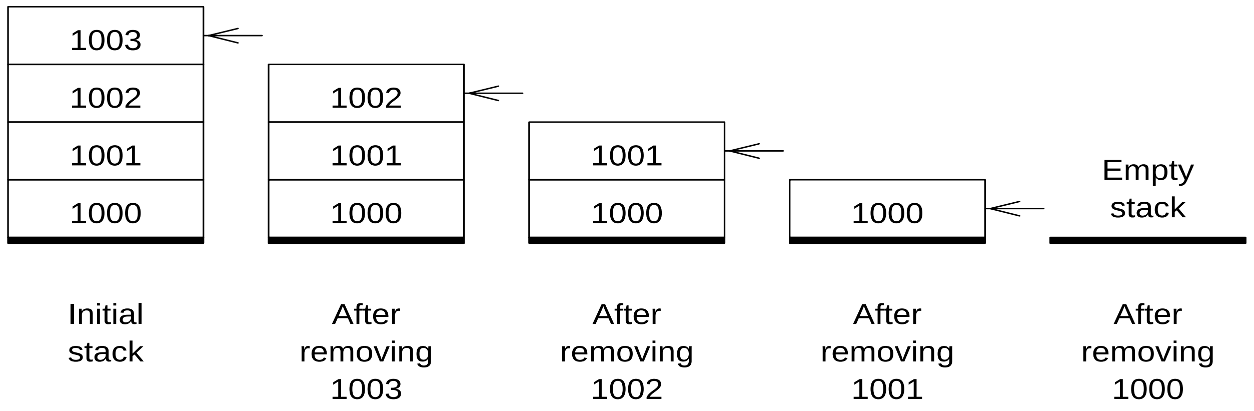
What is a Stack?

- Stack is a last-in-first-out (LIFO) data structure
- If we view the stack as a linear array of elements, both insertion and deletion operations are restricted to one end of the array
- Only the element at the top-of-stack (TOS) is directly accessible
- Two basic stack operations:
  - ∗ push (insertion)
  - ∗ pop (deletion)

Stack Example



Insertion of data items into the stack (arrow points to the top-of-stack)

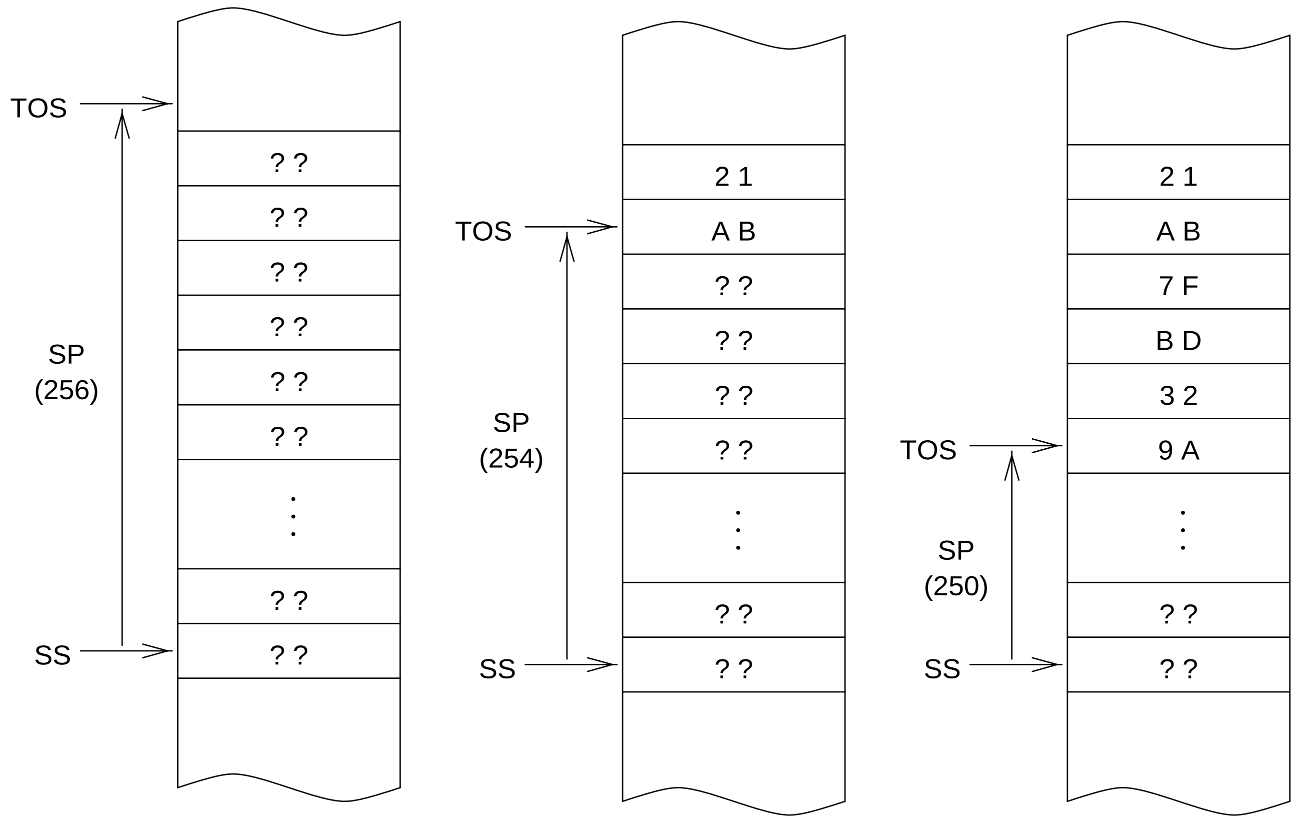


Deletion of data items from the stack (arrow points to the top-of-stack)

Pentium Implementation of the Stack

- Stack segment is used to implement the stack
  - ∗ Registers SS and (E)SP are used
  - ∗ SS:(E)SP represents the top-of-stack
- Pentium stack implementation characteristics are:
  - ∗ Only words (i.e., 16-bit data) or doublewords (i.e., 32-bit data) are saved on the stack, never a single byte
  - ∗ Stack grows toward lower memory addresses (i.e., stack grows "downward")
  - ∗ Top-of-stack (TOS) always points to the last data item placed on the stack

Pentium Stack Example - 1



Empty stack (256 bytes)

(a)

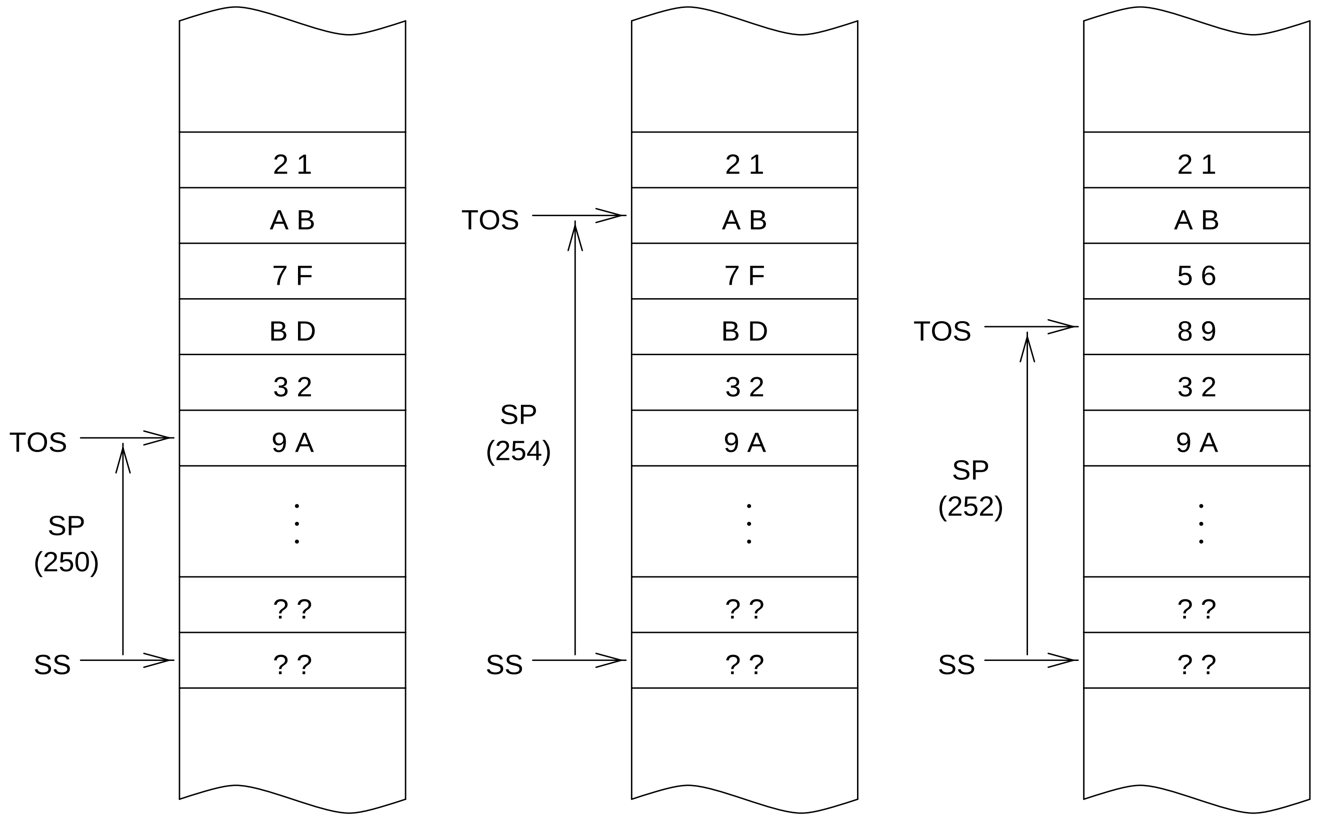
After pushing 21ABH

(b)

After pushing 7FBD329AH

(c)

Pentium Stack Example - 2



Initial stack (two data items)
(a)

After removing 7FBD329AH
(b)

After pushing 5689H
(c)

Pentium Stack Instructions

- Pentium provides two *basic* instructions:

```
push    source
pop     destination
```

- **`source`** and **`destination`** can be a
  - 16- or 32-bit general register
  - a segment register
  - a word or doubleword in memory
- **`source`** of **`push`** can also be an *immediate operand* of size 8, 16, or 32 bits

Pentium Stack Instructions: Examples

- On an empty stack created by

  ```
          .STACK 100H
  ```

  the following sequence of **push** instructions

  ```
          push    21ABH
          push    7FBD329AH
  ```

  results in the stack state shown in (a) in the last figure

- On this stack, executing

  ```
          pop     EBX
  ```

  results in the stack state shown in (b) in the last figure and the register EBX gets the value 7FBD329AH

Additional Pentium Stack Instructions

Stack Operations on Flags

- **`push`** and **`pop`** instructions cannot be used with the Flags register
- Two special instructions for this purpose are

```
pushf (push 16-bit flags)
popf  (pop 16-bit flags)
```

- No operands are required
- Use **`pushfd`** and **`popfd`** for 32-bit flags (EFLAGS)

Additional Pentium Stack Instructions (cont'd)

Stack Operations on 8 General-Purpose Registers

- **pusha** and **popa** instructions can be used to save and restore the eight general-purpose registers

  AX, CX, DX, BX, SP, BP, SI, and DI
- **pusha** pushes these eight registers in the above order (AX first and DI last)
- **popa** restores these registers except that SP value is not loaded into the SP register
- Use **pushad** and **popad** for saving and restoring 32-bit registers

Uses of the Stack

- Three main uses
  - » Temporary storage of data
  - » Transfer of control
  - » Parameter passing

Temporary Storage of Data

Example: Exchanging **`value1`** and **`value2`** can be done by using the stack to temporarily hold data

```
push    value1
push    value2
pop     value1
pop     value2
```

Uses of the Stack (cont’d)

- Often used to free a set of registers

```
;save EBX & ECX registers on the stack
     push    EBX
     push    ECX
     . . . . . .
     <<EBX and ECX can now be used>>
     . . . . . .
;restore EBX & ECX from the stack
     pop     ECX
     pop     EBX
```

Uses of the Stack (cont'd)

Transfer of Control

- In procedure calls and interrupts, the return address is stored on the stack
- Our discussion on procedure calls clarifies this particular use of the stack

Parameter Passing

- Stack is extensively used for parameter passing
- Our discussion later on parameter passing describes how the stack is used for this purpose

Assembler Directives for Procedures

- Assembler provides two directives to define procedures: PROC and ENDP
- To define a NEAR procedure, use

```
proc-name    PROC   NEAR
```

  - In a NEAR procedure, both calling and called procedures are in the same code segment
- A FAR procedure can be defined by

```
proc-name    PROC   FAR
```

  - Called and calling procedures are in two different segments in a FAR procedure

Assembler Directives for Procedures (cont’d)

- If FAR or NEAR is not specified, NEAR is assumed (i.e., NEAR is the default)
- We focus on NEAR procedures
- A typical NAER procedure definition

```
proc-name    PROC
   . . . . .
<procedure body>
   . . . . .
proc-name    ENDP
```

`proc-name` should match in PROC and ENDP

Pentium Instructions for Procedures

- Pentium provides two instructions: **`call`** and **`ret`**
- **`call`** instruction is used to invoke a procedure
- The format is

```
call    proc-name
```

`proc-name` is the procedure name

- Actions taken during a near procedure call:

```
SP := SP - 2                ; push return address
(SS:SP) := IP               ;       onto the stack
IP := IP + relative displacement    ; update IP
                            ; to point to the procedure
```

Pentium Instructions for Procedures (cont’d)

- **`ret`** instruction is used to transfer control back to the calling procedure
- How will the processor know where to return?
  - Uses the return address pushed onto the stack as part of executing the **`call`** instruction
  - Important that TOS points to this return address when **`ret`** instruction is executed
- Actions taken during the execution of **`ret`** are:

```
IP := (SS:SP)          ; pop return address
SP := SP + 2           ;        from the stack
```

Pentium Instructions for Procedures (cont'd)

- We can specify an optional integer in the **`ret`** instruction
  - ∗ The format is

```
        ret    optional-integer
```

  - ∗ Example:

```
        ret 6
```

- Actions taken on **`ret`** with optional-integer are:

```
IP := (SS:SP)
SP := SP + 2 + optional-integer
```

How Is Program Control Transferred?

```
Offset(hex) machine code(hex)
                        main    PROC
                        . . . . . .
cs:000A     E8000C      call    sum
cs:000D     8BD8        mov     BX,AX
                        . . . . . .
                        main    ENDP
------------------------------------------------
                        sum     PROC
cs:0019     55          push    BP
                        . . . . . .
                        sum     ENDP
------------------------------------------------
                        avg     PROC
                        . . . . . .
cs:0028     E8FFEE      call    sum
cs:002B     8BD0        mov     DX,AX
                        . . . . . .
                        avg     ENDP
```

Parameter Passing

- Parameter passing is different and complicated than in a high-level language
- In assembly language
  - » You should first place all required parameters in a mutually accessible storage area
  - » Then call the procedure
- Type of storage area used
  - » Registers (general-purpose registers are used)
  - » Memory (stack is used)
- Two common methods of parameter passing:
  - » Register method
  - » Stack method

Parameter Passing: Register Method

- Calling procedure places the necessary parameters in the general-purpose registers before invoking the procedure through the **`call`** instruction
- Examples:
  * **`PROCEX1.ASM`**
    » call-by-value using the register method
    » a simple sum procedure
  * **`PROCEX2.ASM`**
    » call-by-reference using the register method
    » string length procedure

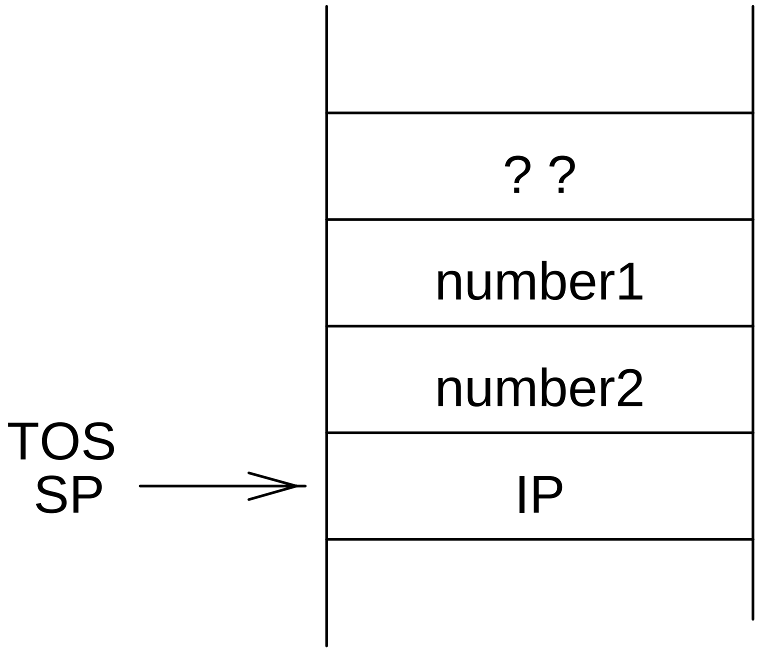
Pros and Cons of the Register Method

- Advantages
  - ∗ Convenient and easier
  - ∗ Faster
- Disadvantages
  - ∗ Only a few parameters can be passed using the register method
    - – Only a small number of registers are available
  - ∗ Often these registers are not free
    - – freeing them by pushing their values onto the stack negates the second advantage

Parameter Passing: Stack Method

- All parameter values are pushed onto the stack before calling the procedure
- Example:

```
push    number1
push    number2
call    sum
```



Accessing Parameters on the Stack

- Parameter values are buried inside the stack
- We cannot use

```
mov    BX,[SP+2]  ;illegal
```

to access **`number2`** in the previous example

- We can use

```
mov    BX,[ESP+2]  ;valid
```

Problem: The ESP value changes with **`push`** and **`pop`** operations

  » Relative offset depends of the stack operations performed

  » Not desirable

Accessing Parameters on the Stack (cont'd)

- We can also use

```
add    SP,2
mov    BX,[SP]     ;valid
```

Problem: cumbersome

» We have to remember to update SP to point to the return address on the stack before the end of the procedure

- Is there a better alternative?
  - ∗ Use the BP register to access parameters on the stack

Using BP Register to Access Parameters

- Preferred method of accessing parameters on the stack is

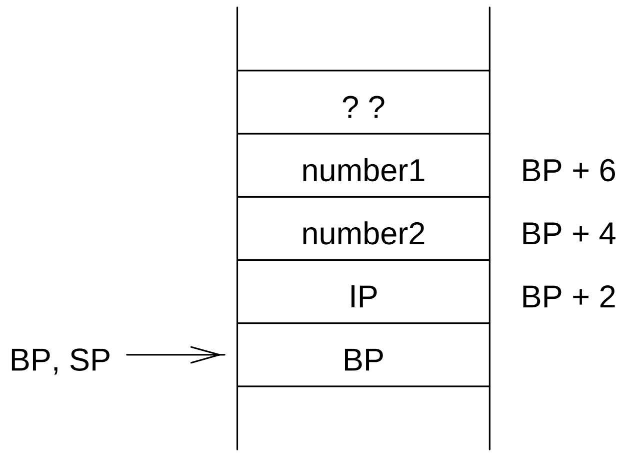
```
mov     BP,SP
mov     BX,[BP+2]
```

to access **`number2`** in the previous example

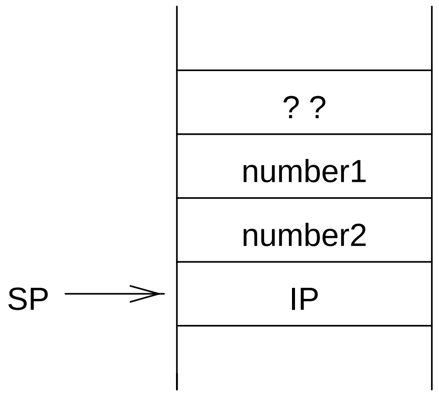
- Problem: BP contents are lost!
  - We have to preserve the contents of BP
  - Use the stack (caution: offset value changes)

```
push    BP
mov     BP,SP
```

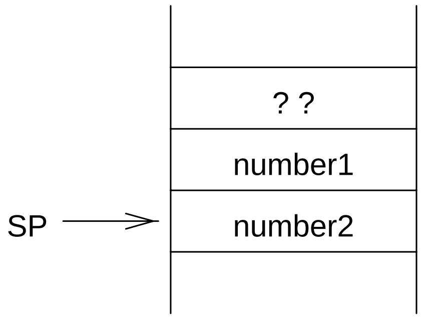
Clearing the Stack Parameters



Stack state after pushing BP



Stack state after pop BP



Stack state after executing **`ret`**

Clearing the Stack Parameters (cont'd)

- Two ways of clearing the unwanted parameters on the stack:
  - ∗ Use the optional-integer in the `ret` instruction
    - » Use

      ```
      ret    4
      ```

      in the previous example
  - ∗ Add the constant to SP in calling procedure (C uses this method)

    ```
    push    number1
    push    number2
    call    sum
    add    SP,4
    ```

Housekeeping Issues

- Who should clean up the stack of unwanted parameters?
  - ∗ Calling procedure
    - » Need to update SP with every procedure call
    - » Not really needed if procedures use fixed number of parameters
    - » C uses this method because C allows variable number of parameters
  - ∗ Called procedure
    - » Code becomes modular (parameter clearing is done in only one place)
    - » Cannot be used with variable number of parameters

Housekeeping Issues (cont'd)

- Need to preserve the state (contents of the registers) of the calling procedure across a procedure call.
    - » Stack is used for this purpose
- Which registers should be saved?
    - ∗ Save those registers that are used by the calling procedure but are modified by the called procedure
        - » Might cause problems as the set of registers used by the calling and called procedures changes over time
    - ∗ Save all registers (brute force method) by using **pusha**
        - » Increased overhead (**pusha** takes 5 clocks as opposed 1 to save a register)

Housekeeping Issues (cont’d)

- Who should preserve the state of the calling procedure?
  - ∗ Calling procedure
    - » Need to know the registers used by the called procedure
    - » Need to include instructions to save and restore registers with every procedure call
    - » Causes program maintenance problems
  - ∗ Called procedure
    - » Preferred method as the code becomes modular (state preservation is done only once and in one place)
    - » Avoids the program maintenance problems mentioned

A Typical Procedure Template

```
proc-name    PROC
             push    BP
             mov     BP,SP
               . . . . . .
             <procedure body>
               . . . . . .
             pop     BP
             ret     integer-value
proc-name    ENDP
```

Stack Parameter Passing: Examples

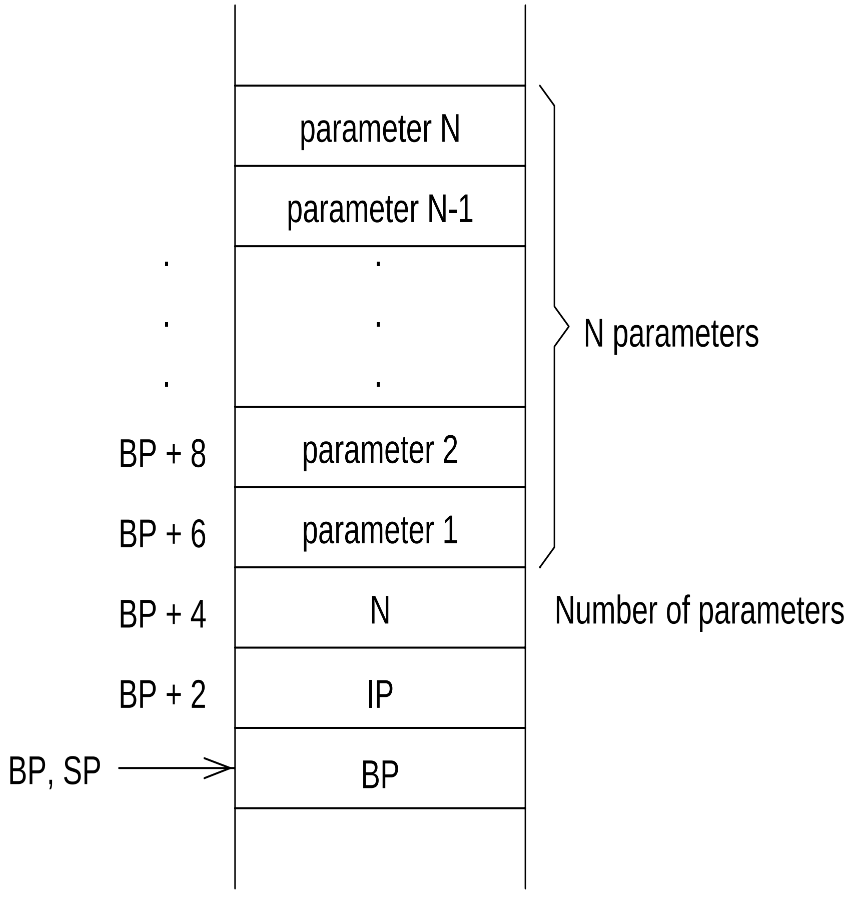
- **`PROCEX3.ASM`**
  - ∗ call-by-value using the stack method
  - ∗ a simple sum procedure
- **`PROCSWAP.ASM`**
  - ∗ call-by-reference using the stack method
  - ∗ first two characters of the input string are swapped
- **`BBLSORT.ASM`**
  - ∗ implements bubble sort algorithm
  - ∗ uses **`pusha`** and **`popa`** to save and restore registers

Variable Number of Parameters

- For most procedures, the number of parameters is fixed (i.e., every time the procedure is called, the same number of parameter values are passed)
- In procedures that can have variable number of parameters, with each procedure call, the number of parameter values passed can be different
- C supports procedures with variable number of parameters
- Easy to support variable number of parameters using the stack method

Variable Number of Parameters (cont'd)

- To implement variable number of parameter passing:
  - ∗ Parameter count should be one of the parameters passed onto the called procedure
  - ∗ This count should be the last parameter pushed onto the stack so that it is just below IP independent of the number of parameters passed



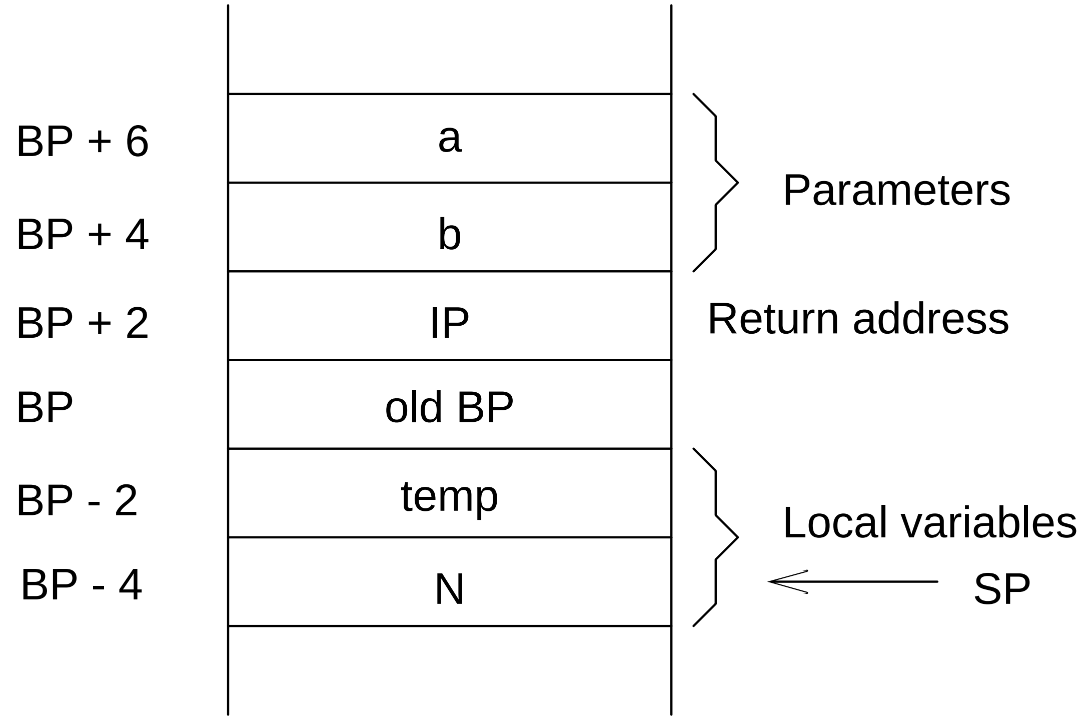
Local Variables

- Local variables are dynamic in nature
  - ∗ Local variables of a procedure come into existence when the procedure is invoked and disappear when the procedure terminates.
- Cannot reserve space for these variable in the data segment for two reasons:
  - » Such space allocation is static (remains active even when the procedure is not)
  - » It does not work with recursive procedures
- For these reasons, space for local variables is reserved on the stack

Local Variables (cont'd)

Example

- Assume that **N** and **temp** of two local variables, each requiring 16 bits of storage



Local Variables (cont'd)

- The information stored in the stack
  - » parameters
  - » returns address
  - » old BP value
  - » local variables

  is collectively called *stack frame*

- In high-level languages, stack frame is also referred to as the *activation record*
  - » Because each procedure activation requires all this information

- The BP value is referred to as the *frame pointer*
  - » Once the BP value is known, we can access all the data in the stack frame

Local Variables: Examples

- **`PROCFIB1.ASM`**
  - ∗ For simple procedures, registers can also be used for local variable storage
  - ∗ Uses registers for local variable storage
  - ∗ Outputs the largest Fibonacci number that is less than the given input number

- **`PROCFIB2.ASM`**
  - ∗ Uses the stack for local variable storage
  - ∗ Performance implications of using registers versus stack are discussed later

Multiple Module Programs

- In multi-module programs, a single program is split into multiple source files
- Advantages
    - » If a module is modified, only that module needs to be reassembled (not the whole program)
    - » Several programmers can share the work
    - » Making modifications is easier with several short files
    - » Unintended modifications can be avoided
- To facilitate separate assembly, two assembler directives are provided:
    - » PUBLIC and EXTRN

PUBLIC Assembler Directive

- The PUBLIC directive makes the associated labels public
  - » Makes these labels available for other modules of the program
- The format is

```
PUBLIC    label1, label2, . . .
```

- Almost any label can be made public including
  - » procedure names
  - » variable names
  - » equated labels
- In the PUBLIC statement, it is not necessary to specify the type of label

Example: PUBLIC Assembler Directive

```
                 . . . . .
PUBLIC    error_msg, total, sample
                 . . . . .
.DATA
error_msg    DB    “Out of range!”,0
total        DW    0
                 . . . . .
.CODE
                 . . . . .
sample    PROC
                 . . . . .
sample    ENDP
                 . . . . .
```

EXTRN Assembler Directive

- The EXTRN directive tells the assembler that certain labels are not defined in the current module
- The assembler leaves “holes” in the OBJ file for the linker to fill in later on
- The format is

```
    EXTRN    label:type
```

  where **`label`** is a label made public by a PUBLIC directive in some other module and **`type`** is the type of the label

EXTRN Assembler Directive (cont'd)

Type	**Description**
UNKNOWN	Undetermined or unknown type
BYTE	Data variable (size is 8 bits)
WORD	Data variable (size is 16 bits)
DWORD	Data variable (size is 32 bits)
QWORD	Data variable (size is 64 bits)
FWORD	Data variable (size is 6 bytes)
TBYTE	Data variable (size is 10 bytes)
PROC	A procedure name (NEAR or FAR according to .MODEL)
NAER	A near procedure name
FAR	A far procedure name

EXTRN Assembler Directive (cont’d)

Example

```
.MODEL   SMALL
         . . . .
EXTRN    error_msg:BYTE, total:WORD
EXTRN    sample:PROC
         . . . .
```

Note: EXTRN (not EXTERN)

Example

`module1.asm` (main procedure)

`module2.asm` (string length procedure)

Performance: Procedure Overheads

Stack versus Registers

- *AL-original* (AX is not preserved)

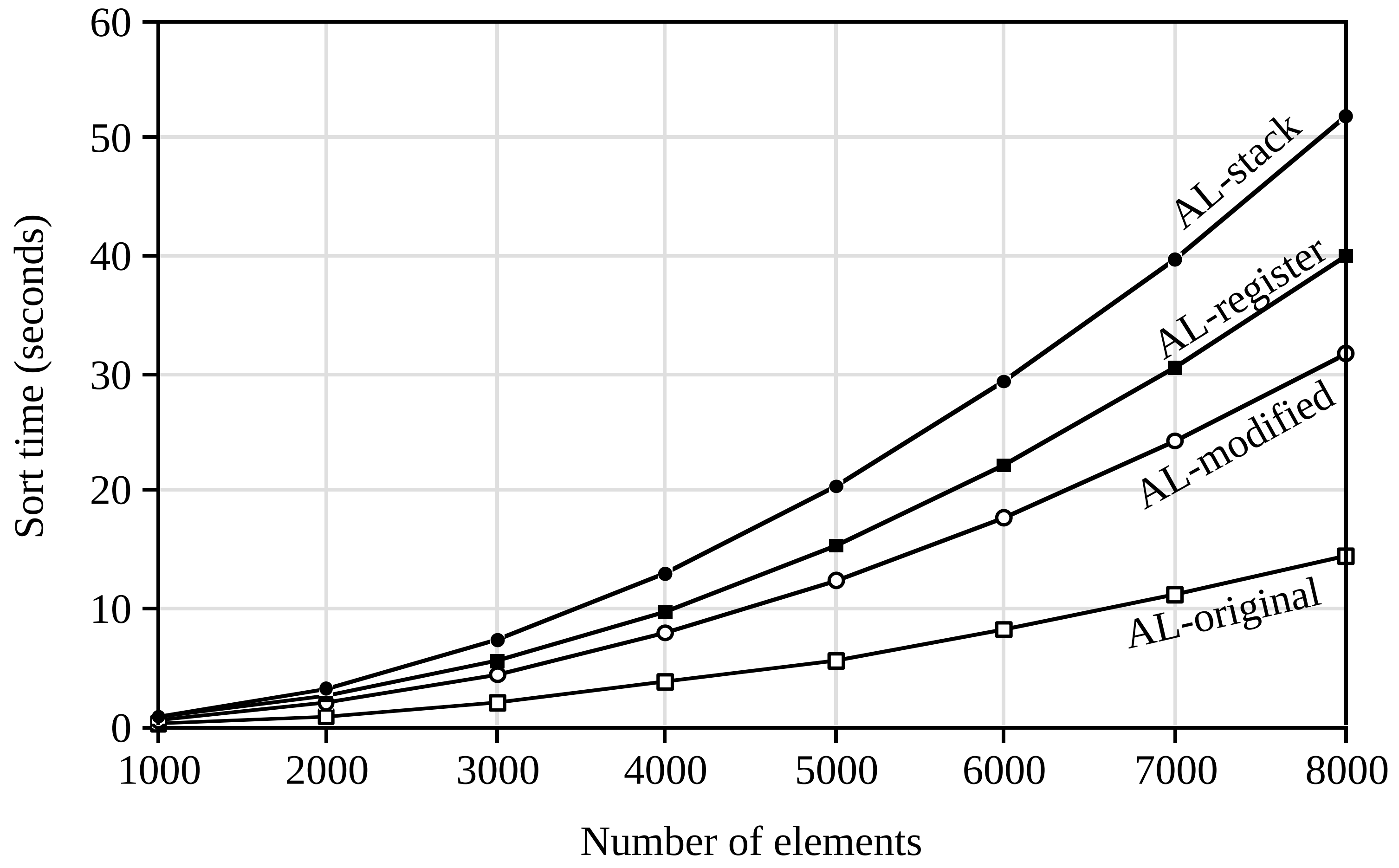
```
;AX contains the element pointed to by SI
xchg   AX,[SI+2]
mov    [SI],AX
```

- *AL-modified* (AX is preserved)

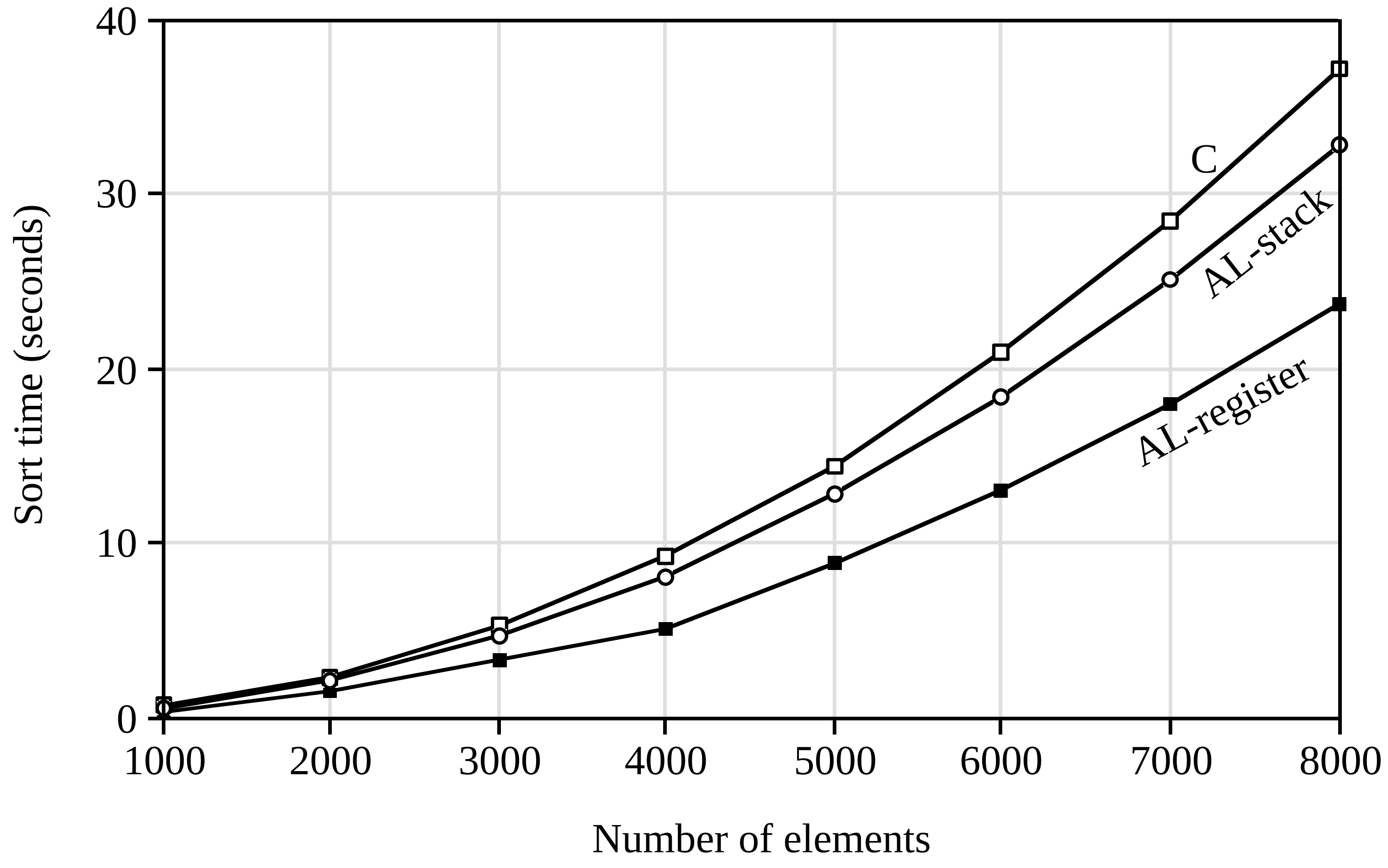
```
xchg   AX,[SI+2]
xchg   AX,[SI]
xchg   AX,[SI+2]
```

- Separate swap procedure
  - *AL-register* (register method of parameter passing)
  - *AL-stack* (stack method of parameter passing)

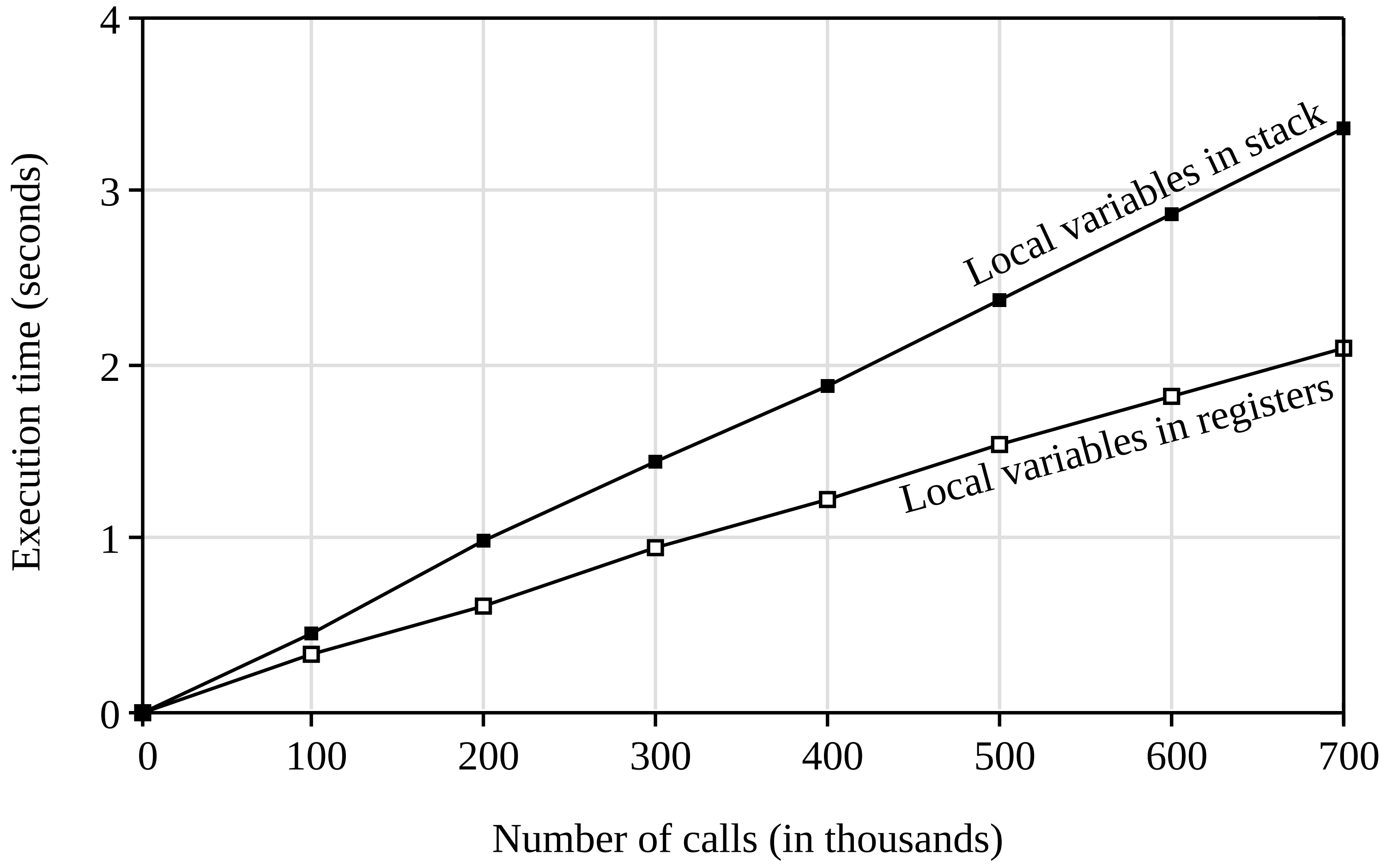
Performance: Procedure Overheads (cont’d)



Performance: C versus Assembly



Performance: Local Variable Overhead


Execution time (seconds)
Number of calls (in thousands)
Local variables in stack
Local variables in registers