Strings and Arrays

Computer Organization and Assembly Languages
Yung-Yu Chuang
2005/12/01

with slides by Kip Irvine

Overview

- Assembly is for efficient code. Loops are what you likely want to optimize. Loops are usually used to process strings (essentially 1D arrays) and arrays.
- Optimized string primitive instructions
- Some typical string procedures
- Two-dimensional arrays
- Searching and sorting integer arrays

String primitive instructions

- Move string data: **MOVSB, MOVSW, MOVSD**
- Compare strings: **CMPSB, CMPSW, CMPSD**
- Scan string: **SCASB, SCASW, SCASD**
- Store string data: **STOSB, STOSW, STOSD**
- Load ACC from string: **LODSB, LODSW, LODSD**

- Only use memory operands
- Use **ESI, EDI** or both to address memory

MOVSB, MOVSW, MOVSD

- The **MOVSB**, **MOVSW**, and **MOVSD** instructions copy data from the memory location pointed to by **ESI** to the memory location pointed to by **EDI**.

```
.data
source DWORD 0FFFFFFFFh
target DWORD ?
.code
mov esi,OFFSET source
mov edi,OFFSET target
movsd
```

MOVSB, MOVSW, MOVSD

- **ESI** and **EDI** are automatically incremented or decremented:
  - **MOVSB** increments/decrements by 1
  - **MOVSW** increments/decrements by 2
  - **MOVSD** increments/decrements by 4

Direction flag

- The direction flag controls the incrementing or decrementing of **ESI** and **EDI**.
  - **DF** = clear (0): increment **ESI** and **EDI**
  - **DF** = set (1): decrement **ESI** and **EDI**

The direction flag can be explicitly changed using the **CLD** and **STD** instructions:

```
CLD        ; clear Direction flag
STD        ; set Direction flag
```

Using a repeat prefix

- **REP** (a repeat prefix) can be inserted just before **MOVSB**, **MOVSW**, or **MOVSD**.
- **ECX** controls the number of repetitions
- Example: copy 20 doublewords from source to target

```
.data
source DWORD 20 DUP(?)
target DWORD 20 DUP(?)
.code
Cld                    ; direction = forward
mov ecx,LENGTHOF source  ; set REP counter
mov esi,OFFSET source
mov edi,OFFSET target
rep movsd         ; REP checks ECX=0 first
```

Using a repeat prefix

REP	Repeat while ECX>0
REPZ,REPE	Repeat while Zero=1 and ECX>0
REPNZ,REPNE	Repeat while Zero=0 and ECX>0

- Conditions are checked first before repeating the instruction

Your turn . . .

- Use **MOVSD** to delete the first element of the following doubleword array. All subsequent array values must be moved one position forward toward the beginning of the array:

  array DWORD 1,1,2,3,4,5,6,7,8,9,10

```
.data
array DWORD 1,1,2,3,4,5,6,7,8,9,10
.code
cld
mov ecx,(LENGTHOF array) - 1
mov esi,OFFSET array+4
mov edi,OFFSET array
rep movsd
```

CMPSB, CMPSW, CMPSD

- The **CMPSB**, **CMPSW**, and **CMPSD** instructions each compare a memory operand pointed to by **ESI** to a memory operand pointed to by **EDI**.
  - **CMPSB** compares bytes
  - **CMPSW** compares words
  - **CMPSD** compares doublewords
- Repeat prefix (**REP**) is often used

Comparing a pair of doublewords

If source > target, the code jumps to label L1; otherwise, it jumps to label L2

```
.data
source DWORD 1234h
target DWORD 5678h

.code
mov esi,OFFSET source
mov edi,OFFSET target
cmpsd        ; compare doublewords
ja L1        ; jump if source > target
jmp L2       ; jump if source <= target
```

Comparing arrays

Use a **REPE** (repeat while equal) prefix to compare corresponding elements of two arrays.

```
.data
source DWORD COUNT DUP(?)
target DWORD COUNT DUP(?)
.code
mov ecx,COUNT       ; repetition count
mov esi,OFFSET source
mov edi,OFFSET target
cld                 ; direction = forward
repe cmpsd          ; repeat while equal
```

Example: comparing two strings

This program compares two strings of equal lengths (source and destination). It displays a message indicating whether the lexical value of the source string is less than the destination string.

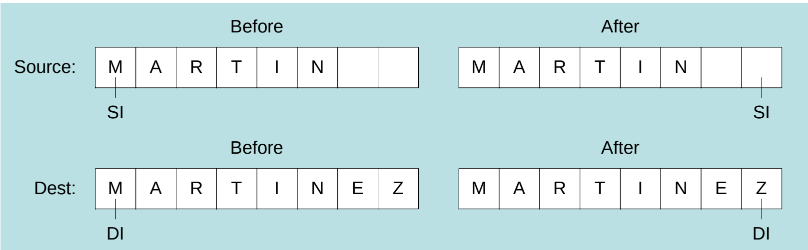
```
.data
source BYTE "MARTIN  "
dest BYTE   "MARTINEZ"
str1 BYTE "Source is smaller",0dh,0ah,0
str2 BYTE "Source is not smaller",0dh,0ah,0
```

Example: comparing two strings

```
.code
main PROC
  cld               ; direction = forward
  mov esi,OFFSET source
  mov edi,OFFSET dest
  mov ecx,LENGTHOF source
  repe cmpsb
  jb source_smaller
  mov edx,OFFSET str2 ;source is not smaller
  jmp done
source_smaller:
  mov edx,OFFSET str1 ;source is smaller
done:
  call WriteString
  exit
main ENDP
END main
```

Example: comparing two strings

- The following diagram shows the final values of **ESI** and **EDI** after comparing the strings:



SCASB, SCASW, SCASD

- The **SCASB**, **SCASW**, and **SCASD** instructions compare a value in **AL/AX/EAX** to a byte, word, or doubleword, respectively, addressed by **EDI**.
- Useful types of searches:
  - Search for a specific element in a long string or array.
  - Search for the first element that does not match a given value.

SCASB example

Search for the letter '**F**' in a string named str:

```
.data
str BYTE "ABCDEFGH",0
.code
mov edi,OFFSET str
mov al,'F'          ; search for 'F'
mov ecx,LENGTHOF str
cld
repne scasb         ; repeat while not equal
jnz quit
dec edi             ; EDI points to 'F'
```

What is the purpose of the **JNZ** instruction?

STOSB, STOSW, STOSD

- The **STOSB**, **STOSW**, and **STOSD** instructions store the contents of **AL/AX/EAX**, respectively, in memory at the offset pointed to by **EDI**.
- Example: fill an array with 0FFh (memset)

```
.data
Count = 100
str BYTE Count DUP(?)
.code
mov al,0FFh         ; value to be stored
mov edi,OFFSET str ; ES:DI points to target
mov ecx,Count      ; character count
cld                ; direction = forward
rep stosb          ; fill with contents of AL
```

LODSB, LODSW, LODSD

- The **LODSB**, **LODSW**, and **LODSD** instructions load a byte or word from memory at **ESI** into **AL/AX/EAX**, respectively.
- Rarely used with **REP**
- **LODSB** can be used to replace code

```
mov al,[esi]
inc esi
```

Example

- convert each decimal byte of an array into an its ASCII code.

```
.data
array 1,2,3,4,5,6,7,8,9
dest  9 DUP(?)
.code
  mov esi,OFFSET array
  mov edi,OFFSET dest
  mov ecx,LENGTHOF array
  cld
L1:
  lodsb
  or al,30h
  stosb
  loop L1
```

Array multiplication example

Multiply each element of a doubleword array by a constant value.

```
.data
array DWORD 1,2,3,4,5,6,7,8,9,10
multiplier DWORD 10
.code
    cld                      ; direction = up
    mov esi,OFFSET array    ; source index
    mov edi,esi        ; destination index
    mov ecx,LENGTHOF array ; loop counter
L1: lodsd           ; copy [ESI] into EAX
    mul multiplier  ; multiply by a value
    stosd            ; store EAX at [EDI]
    loop L1
```

Selected string procedures

The following string procedures may be found in the Irvine32 and Irvine16 libraries:

- **Str_length**
- **Str_copy**
- **Str_compare**
- **Str_ucase**
- **Str_trim**

Str_length procedure

- Calculates the length of a null-terminated string and returns the length in the **EAX** register.
- Prototype:

```
Str_length PROTO,
  pString:PTR BYTE  ; pointer to string
```

Example:

```
.data
myString BYTE "abcdefg",0
.code
  INVOKE Str_length, ADDR myString
; EAX = 7
```

Str_length source code

```
Str_length PROC USES edi,
   pString:PTR BYTE     ; pointer to string
   mov edi,pString
   mov eax,0            ; character count
L1:
   cmp byte ptr [edi],0 ; end of string?
   je  L2               ; yes: quit
   inc edi              ; no: point to next
   inc eax              ; add 1 to count
   jmp L1
L2: ret
Str_length ENDP
```

Str_copy Procedure

- Copies a null-terminated string from a source location to a target location.
- Prototype:

```
Str_copy PROTO,
  source:PTR BYTE,   ; pointer to string
  target:PTR BYTE    ; pointer to string
```

Str_copy Source Code

```
Str_copy PROC USES eax ecx esi edi,
  source:PTR BYTE,     ; source string
  target:PTR BYTE      ; target string

  INVOKE Str_length,source ; EAX = length
  mov ecx,eax          ; REP count
  inc ecx              ; add 1 for null byte
  mov esi,source
  mov edi,target
  cld                  ; direction = up
  rep movsb            ; copy the string
  ret
Str_copy ENDP
```

Str_compare procedure

- Compares *string1* to *string2*, setting the Carry and Zero flags accordingly
- Prototype:

```
Str_compare PROTO,
  string1:PTR BYTE,  ; pointer to string
  string2:PTR BYTE   ; pointer to string
```

relation	carry	zero	Branch if true
str1<str2	1	0	JB
str1==str2	0	1	JE
str1>str2	0	0	JA

Str_compare source code

```
Str_compare PROC USES eax edx esi edi,
     string1:PTR BYTE, string2:PTR BYTE
    mov  esi,string1
    mov  edi,string2
L1: mov  al,[esi]
    mov  dl,[edi]
    cmp  al,0       ; end of string1?
    jne  L2         ; no
    cmp  dl,0       ; yes: end of string2?
    jne  L2         ; no
    jmp  L3         ; yes, exit with ZF = 1
L2: inc  esi        ; point to next
    inc  edi
    cmp  al,dl      ; chars equal?
    je   L1         ; yes: continue loop
L3: ret
Str_compare ENDP
```

CMPSB is not used here

Str_ucase procedure

- converts a string to all uppercase characters. It returns no value.
- Prototype:

```
Str_ucase PROTO,
  pString:PTR BYTE   ; pointer to string
```

Example:

```
.data
myString BYTE "Hello",0
.code
   INVOKE Str_ucase, ADDR myString
```

Str_ucase source code

```
Str_ucase PROC USES eax esi,
   pString:PTR BYTE
   mov esi,pString
L1:mov al,[esi]          ; get char
   cmp al,0              ; end of string?
   je  L3                ; yes: quit
   cmp al,'a'            ; below "a"?
   jb  L2
   cmp al,'z'            ; above "z"?
   ja  L2
   and BYTE PTR [esi],11011111b ;conversion
L2:inc esi               ; next char
   jmp L1
L3:ret
Str_ucase ENDP
```

Str_trim Procedure

- removes all occurrences of a selected trailing character from a null-terminated string.
- Prototype:

```
Str_trim PROTO,
  pString:PTR BYTE, ; points to string
  char:BYTE         ; char to remove
```

Example:

```
.data
myString BYTE "Hello###",0
.code
   INVOKE Str_trim, ADDR myString, '#'
; myString = "Hello"
```

Str_trim Procedure

- **Str_trim** checks a number of possible cases (shown here with # as the trailing character):
  - The string is empty.
  - The string contains other characters followed by one or more trailing characters, as in "Hello##".
  - The string contains only one character, the trailing character, as in "#"
  - The string contains no trailing character, as in "Hello" or "H".
  - The string contains one or more trailing characters followed by one or more nontrailing characters, as in "#H" or "###Hello".

Str_trim source code

```
Str_trim PROC USES eax ecx edi,
   pString:PTR BYTE,          ; points to string
   char:BYTE                  ; char to remove
   mov  edi,pString
   INVOKE Str_length,edi      ; returns length in EAX
   cmp  eax,0                 ; zero-length string?
   je   L2                    ; yes: exit
   mov  ecx,eax               ; no: counter = string length
   dec  eax
   add  edi,eax               ; EDI points to last char
   mov  al,char               ; char to trim
   std                        ; direction = reverse
   repe scasb                 ; skip past trim character
   jne  L1                    ; removed first character?
   dec  edi                   ; adjust EDI: ZF=1 && ECX=0
L1:mov  BYTE PTR [edi+2],0    ; insert null byte
L2:ret
Str_trim ENDP
```

Two-dimensional arrays

- IA32 has two operand types which are suited to array applications: base-index operands and base-index displacement

Base-index operand

- A base-index operand adds the values of two registers (called base and index), producing an effective address. Any two 32-bit general-purpose registers may be used.

```
[ base + index ]
```

- Base-index operands are great for accessing arrays of structures. (A structure groups together data under a single name.)

Structure application

A common application of base-index addressing has to do with addressing arrays of structures (Chapter 10). The following defines a structure named COORD containing X and Y screen coordinates:

```
COORD STRUCT
  X WORD ?     ; offset 00
  Y WORD ?     ; offset 02
COORD ENDS
```

Then we can define an array of COORD objects:

```
.data
setOfCoordinates COORD 10 DUP(<>)
```

Structure application

The following code loops through the array and displays each Y-coordinate:

```
    mov   ebx,OFFSET setOfCoordinates
    mov   esi,2        ; offset of Y value
    mov   eax,0
L1:
    mov   ax,[ebx+esi]
    call  WriteDec
    add   ebx,SIZEOF COORD
    loop  L1
```

Two-dimensional table example

Imagine a table with 3 rows and 5 columns. The data can be arranged in any format on the page:

```
NumCols = 5
table   BYTE  10h,  20h,  30h,  40h,  50h
         BYTE  60h,  70h,  80h,  90h, 0A0h
         BYTE 0B0h, 0C0h, 0D0h, 0E0h, 0F0h
```

Alternative format:

```
table   BYTE  10h,20h,30h,40h,50h,60h,70h,
              80h,90h,0A0h,
              0B0h,0C0h,0D0h, 0E0h,0F0h
```

Physically, they are all 1D arrays in the memory. But, sometimes, we prefer to think as 2D array logically.

Two-dimensional table example

```
NumCols = 5
table   BYTE  10h,  20h,  30h,  40h,  50h
         BYTE  60h,  70h,  80h,  90h, 0A0h
         BYTE 0B0h, 0C0h, 0D0h, 0E0h, 0F0h
```

logically

10	20	30	40	50
60	70	80	90	A0
B0	C0	D0	E0	F0

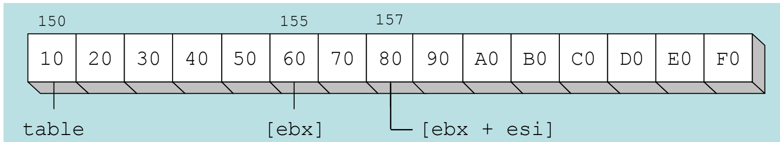
physically

10	20	30	40	50	60	70	80	90	A0	B0	C0	D0	E0	F0

Two-dimensional table example

The following code loads the table element stored in row 1, column 2:

```
RowNumber = 1
ColumnNumber = 2
mov ebx OFFSET table
add ebx, NumCols * RowNumber
mov esi, ColumnNumber
mov al,[ebx + esi]
```



Sum of row example

```
    mov ecx, NumCols
    mov ebx, OFFSET table
    mdd ebx, (NumCols*RowNumber)
    mov esi, 0
    mox ax, 0  ; sum = 0
    mov dx, 0  ; hold current element
L1: mov dl, [ebx+esi]
    add ax, dx
    inc esi
    loop L1
```

Base-index-displacement operand

- A base-index-displacement operand adds base and index registers to a constant, producing an effective address. Any two 32-bit general-purpose registers may be used.
- Common formats:

```
[ base + index + displacement ]
displacement [ base + index ]
```

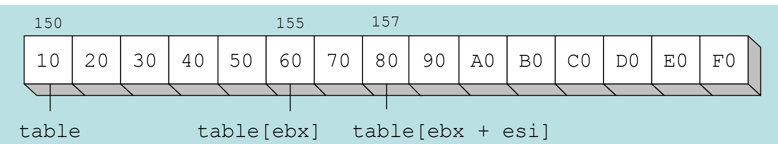
- **`base`** *and* **`index`** *can be any general-purpose 32-bit registers*
- **`displacement`** *can be the name of a variable or a constant expression*

Two-dimensional table example

The following code loads the table element stored in row 1, column 2:

```
RowNumber = 1
ColumnNumber = 2

mov ebx,NumCols * RowNumber
mov esi,ColumnNumber
mov al,table[ebx + esi]
```

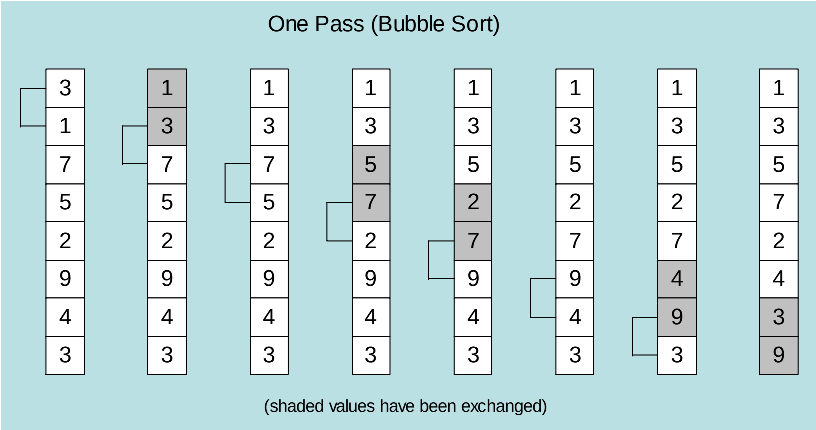


Searching and sorting integer arrays

- Bubble Sort
  - A simple sorting algorithm that works well for small arrays
- Binary Search
  - A simple searching algorithm that works well for large arrays of values that have been placed in either ascending or descending order
- Good examples for studying algorithms, Knuth used assembly for his book
- Good chance to use some of the addressing modes introduced today

Bubble sort

Each pair of adjacent values is compared, and exchanged if the values are not ordered correctly:



Bubble sort pseudocode

N = array size, cx1 = outer loop counter, cx2 = inner loop counter:

```
cx1 = N - 1
while( cx1 > 0 )
{
  esi = addr(array)
  cx2 = cx1
  while( cx2 > 0 )
  {
    if( array[esi] < array[esi+4] )
      exchange( array[esi], array[esi+4] )
    add esi,4
    dec cx2
  }
  dec cx1
}
```

Bubble sort implementation

```
BubbleSort PROC USES eax ecx esi,
   pArray:PTR DWORD, Count:DWORD
   mov  ecx,Count
   dec  ecx          ; decrement count by 1
L1:push ecx          ; save outer loop count
   mov  esi,pArray   ; point to first value
L2:mov  eax,[esi]    ; get array value
   cmp  [esi+4],eax  ; compare a pair
   jge  L3           ; if [esi]<=[esi+4],skip
   xchg eax,[esi+4]  ; else exchange the pair
   mov  [esi],eax
L3:add  esi,4   ; move both pointers forward
   loop L2      ; inner loop
   pop  ecx     ; retrieve outer loop count
   loop L1      ; else repeat outer loop
L4:ret
BubbleSort ENDP
```

Binary search

- Searching algorithm, well-suited to large ordered data sets
- Divide and conquer strategy
- Classified as an O(log n) algorithm:
  - As the number of array elements increases by a factor of *n*, the average search time increases by a factor of *log n*.

Array Size (n)	Maximum Number of Comparisons: $(\log_2 n) + 1$
64	7
1,024	11
65,536	17
1,048,576	21
4,294,967,296	33

Binary search pseudocode

```
int BinSearch( int values[], int count
               const int searchVal,)
{
   int first = 0;
   int last = count - 1;
   while( first <= last )
   {
      int mid = (last + first) / 2;
      if( values[mid] < searchVal )
        first = mid + 1;
      else if( values[mid] > searchVal )
        last = mid - 1;
      else
        return mid;  // success
   }
   return -1;        // not found
}
```

Binary search implementation

```
BinarySearch PROC uses ebx edx esi edi,
    pArray:PTR DWORD, ; pointer to array
    Count:DWORD,      ; array size
    searchVal:DWORD   ; search value

LOCAL first:DWORD,    ; first position
    last:DWORD,       ; last position
    mid:DWORD         ; midpoint
    mov  first,0      ; first = 0
    mov  eax,Count    ; last = (count - 1)
    dec  eax
    mov  last,eax
    mov  edi,searchVal; EDI = searchVal
    mov  ebx,pArray   ; EBX points to the array
L1:                   ; while first <= last
    mov  eax,first
    cmp  eax,last
    jg   L5           ; exit search
```

Binary search implementation

```
; mid = (last + first) / 2
    mov  eax,last
    add  eax,first
    shr  eax,1
    mov  mid,eax

; EDX = values[mid]
    mov  esi,mid
    shl  esi,2          ; scale mid value by 4
    mov  edx,[ebx+esi]  ; EDX = values[mid]

; if ( EDX < searchval(EDI) ) first = mid + 1;
    cmp  edx,edi
    jge  L2
    mov  eax,mid        ; first = mid + 1
    inc  eax
    mov  first,eax
    jmp  L4             ; continue the loop
```

base-index addressing

Binary search implementation

```
;else if( EDX > searchVal(EDI)) last = mid - 1;
L2: cmp  edx,edi       ; (could be removed)
    jle  L3
    mov  eax,mid       ; last = mid - 1
    dec  eax
    mov  last,eax
    jmp  L4            ; continue the loop

; else return mid
L3: mov  eax,mid       ; value found
    jmp  L9            ; return (mid)

L4: jmp  L1            ; continue the loop
L5: mov  eax,-1        ; search failed
L9: ret
BinarySearch ENDP
```