Data Structures for 8-Bit Microcontrollers

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Introduction

A data structure describes how information is organized and stored in a computer system. Although data structures are usually presented in the context of large computers, the same principles can be applied to embedded 8-bit processors. The efficient use of appropriate data structures can improve both the dynamic (time-based) and static (storage-based) performance of microcontroller software.

This application note presents data structures which are useful in the development of microcontroller software. The applications presented here are by no means absolute. One can find an infinite variety of ways to apply these basic data structures in a microcontroller application.

Strings

A string is a sequence of elements accessed in sequential order. The string data structure usually refers to a sequence of characters. For example, a message which is to be output to a display is stored as a string of ASCII character bytes in memory.
Storing Strings

A string of elements must be identified by a starting and ending address. A starting address for a string can be defined using an absolute address label or by using a base address of a group of strings and identifying particular strings with an offset into the group.

There are several methods of terminating string information. One common way of terminating a string is by using a special character to mark the end of the string. One terminating character to use is the value $04, an ASCII EOT (end-of-transmission) byte.

Figure 1 shows an example of string data.

```
MESSAGE POINTER $50
$51
$52
$53
$54
$55
'O'
'H'
'E'
'L'
'\'
\$04
```

**Figure 1. String Data Structure**

Another method of terminating a string is to identify its length. Its length can then be used as a counter value, eliminating the need for an extra byte of storage for the end of the string.

A string of ASCII characters can be terminated without using an extra byte of storage by using the sign bit (most significant bit) as an indicator of the last byte of the string. Because ASCII character data is only seven bits long, the last byte of a string can be indicated by a 1 in its most significant bit location. When using this method, the programmer must be careful to strip off the sign bit before using the ASCII character value.
Accessing Strings

An efficient way of accessing a string is with the indexed addressing mode and the INCX or DECX instruction. Listing 1. String Storage Example and Listing 2. String Access Example illustrate this string storage scheme and how to use it.

Listing 1. String Storage Example

*-----------------------------------------------------------------------------------
* Absolute string addresses
* One way of specifying string data
*-----------------------------------------------------------------------------------
Message1 FCB ‘This is a string’
FCB $04
Message2 FCB ‘This is another string’
FCB $04

*-----------------------------------------------------------------------------------
* Indexed string addressing
* Another way of specifying string data
*-----------------------------------------------------------------------------------
Msgs EQU *
Message3 EQU *-msgs
FCB ‘This is a string’
FCB $04
Message4 EQU *-msgs
FCB ‘This is another string’
FCB $04

Listing 2. String Access Example

*-----------------------------------------------------------------------------------
* String display code
* A generic method of displaying an entire string.
*-----------------------------------------------------------------------------------
LoadMsg LDX #Message1 ;Offset into X
Loop LDA Messages,X ;Load character
CMP #$04 ;Check for EOT
BEQ StringDone ;End of string
JSR ShowByte ;Show character
INCX ;Point to next
BRA Loop

*-----------------------------------------------------------------------------------
* String storage code
*-----------------------------------------------------------------------------------
Messages EQU *
Message1 EQU *-Messages
FCB ‘This is a string’
FCB $04
String Applications

Practical applications of strings include storing predefined "canned" messages. This is useful for applications which require output to text displays, giving users information or prompting users for input.

Strings are also effective for storing initialization strings for hardware such as modems. Strings may also store predefined command and data sequences to communicate with other devices.

Stacks

A stack is a series of data elements which can be accessed only at one end. An analogy for this data structure is a stack of dinner plates; the first plate placed on the stack is the last plate taken from the stack. For this reason, the stack is considered a LIFO (last in, first out) structure. The stack is useful when the latest data is desired. A stack will typically have a predefined maximum size.

shows a representation of a stack.

Figure 2. Stack Data Structure
Just like a physical stack of items, the software stack has a bottom and a top. Software should keep track of the location of the top of the stack. This address can either point to the first piece of valid data or it can point to the next available location. For the following examples it will be pointing to the next available location.

Stack Reading and Writing

The read operation of a stack is called "pulling" (or "popping"), and the write operation of a stack is called "pushing." When one pulls data from the stack, the data is removed from the stack and the stack pointer is adjusted. When data is pushed onto the stack, the stack pointer is adjusted and the data is added to the stack.

So, in the implementation of Figure 2, a push operation would first decrement the stack pointer and then store the data to the address pointed to by (stack pointer) +1. A pull operation would retrieve the data at (stack pointer) +1 and then increment the stack pointer.

Two error conditions are intrinsic to this data structure; underflow and overflow. A stack underflow occurs when a user attempts to pull information off an empty stack. A stack overflow occurs when a user attempts to push information onto a stack which is full. When using this data structure, these conditions should be attended to. An underflow condition should return an error. On an overflow, one can either reject the data and return an error, or the stack can "wrap" around to the bottom, destroying the data at the bottom of the stack.

MCU Hardware Stack

Freescale MCUs utilize a stack structure for saving program context before transferring program control. This interaction may be the result of a jump or interrupt. As a result of an interrupt, the stack is used to push the values in the X, A, and CCR (condition code register) registers, as well as the 16-bit PC (program counter) value. When a jump instruction is encountered, the PC value is pushed on to the stack. On returning from an interrupt (RTI instruction) the program context (registers and PC) are pulled from the stack. When returning from a jump (RTS instruction) the PC is pulled from the stack.
HC05 Stack

The HC05 Family of MCUs have limited stack access. The only operation that can be performed with the MCU’s stack pointer is to reset it. The RSP instruction will reset the stack pointer to $FF. The HC05 stack pointer also has a limited size of 64 bytes. When the stack pointer grows beyond address $C0, the stack pointer wraps around to $FF, destroying any existing data at that address.

HC08 Stack

The HC08 Family of MCUs has a more flexible stack structure. The stack pointer can be set to any address. The HC08 MCUs also have an added addressing mode which is indexed by the stack pointer. In this way, a user can pass parameters to subroutines using the hardware stack, accessing the parameters using stack pointer indexed addressing.

Other HC08 Family instructions allow data to pushed on and pulled off the stack. The stack pointer can also be transferred to the X index register and vice-versa. With the addition of these instructions and addressing modes, a user has good control over the stack in the HC08 MCU.

Stack Applications

A stack is useful for dynamically allocating memory or passing parameters to and from subroutines. Typically, MCU RAM variables are statically allocated at assembly time.

For example:

```assembly
; Statically allocated RAM variables
ORG RAMSPACE
MyVar1 RMB 1
MyVar2 RMB 1
MyVar3 RMB 2
; Another method to statically allocate variable
MyVar4 EQU RAMSPACE+4
MyVar5 EQU RAMSPACE+5
```

This is appropriate for global variables, which need to be available throughout the program flow. However, for local variables which are only used in specific subroutines, this method is not the most efficient. The RAM space these variables use can be dynamically allocated using a software stack or MCU stack, freeing up RAM memory. The same
method can be applied to subroutine input and output parameters, passing them on the stack instead of in the A or X register.

Listing 3. Software Stack shows a software implementation of a stack, which would be appropriate for the HC05 Family of microcontrollers.
Listing 3. Software Stack

* STACK.ASM
* A simple software stack implementation Simply shows the PUSH and PULL operations on
* a stack; not intended to be a complete application.
* StackPtr points to next (empty) available location
* Written for the MC68HC705P6A MCU

* Memory map equates

RAMSPACE     EQU       $50
ROMSPACE     EQU       $100
RESETVEC EQU   $1FFE

* Stack equates

STACKSIZE EQU       $08
STACKBOT  EQU       $70 ;Bottom of software stack
STACKMAX EQU   (STACKBOT-STACKSIZE+1) ;Maximum address of stack

* RAM variables

ORG RAMSPACE ;First address of RAM
StackPtr RMB 1 ;Pointer to next stack byte

* Start of program code

Init LDA      #STACKBOT         ;Initialize the stack pointer
       STA      StackPtr

* Some simple read and write operations
* For illustration only

LDA      #$01
Jsr      PushA                ;Write to stack
Bcs      FullErr
Jsr      PushA                ;Write to stack
Bcs      FullErr
Jsr      PushA                ;Write to stack
Bcs      FullErr
Jsr      PushA                ;Write to stack
Bcs      FullErr
Jsr      PushA                ;Write to stack
Bcs      FullErr
Jsr      PushA                ;Write to stack
Bcs      FullErr
Jsr      PushA                ;Write to stack

BCS  FullErr
JSR  PushA               ;Write to FULL stack
BCS  FullErr
JSR  PushA               ;Write to FULL stack
BCS  FullErr
JSR  PullA                ;Read from stack
BCS  EmptyErr
JSR  PullA                ;Read from stack
BCS  EmptyErr
JSR  PullA                ;Read from stack
BCS  EmptyErr

Loop  BRA  *                ;Your code here
EmptyErr  BRA  *           ;Your code here
FullErr  BRA  *            ;Your code here

*------------------------------------------------------------------
* Subroutines - The code to access the data structure
*------------------------------------------------------------------
* PUSH subroutine
* Push the contents of the accumulator onto stack
* Use C bit of CCR to indicate full error
*------------------------------------------------------------------
PushA  LDX  StackPtr         ;Get stack pointer
       CPX  #STACKMAX           ;Check for full stack
       BLO  Full               ;Decrement stack pointer
       DECX                      ;Store data
       STA  1,X                ;Record new stack pointer
       CLC                        ;Clear carry bit
       RTS                        ;Return
Full  SEC                        ;Set carry bit for error
       RTS                        ;Return

*------------------------------------------------------------------
* PULL subroutine
* PULL a byte off the stack into accumulator
* Use C bit of CCR to indicate empty stack error
*------------------------------------------------------------------
PullA  LDX  StackPtr         ;Get stack pointer
       CPX  #STACKBOT           ;Check for empty stack
       BEQ  Empty               ;Get data
       INCX                      ;Increment stack pointer
       STX  StackPtr            ;Record stack pointer
       CLC                        ;Clear carry bit
       RTS                        ;Return
Empty  SEC                        ;Set carry bit
       RTS                        ;Return

*------------------------------------------------------------------
* Vector definitions
*------------------------------------------------------------------
ORG  RESETVEC
FDB  Init

AN1752 — REV 1
Using the software stack, a subroutine can allocate variables by pushing (allocating) bytes on the stack, accessing them with indexed addressing (relative to the stack pointer variable) and pulling them (deallocating) before returning. In this way, the same RAM space can be used by multiple subroutines.

Parameters can be passed to and from subroutines as well. An input parameter can be pushed on the stack. When a subroutine is entered, it can access the input parameter relative to the stack pointer. By the same token, a subroutine can push an output parameter onto the stack to be passed back to the calling routine.

The MCU hardware stack and stack pointer can also be used for these purposes. Because of the expanded instruction set, the use of the MCU stack is easily exploited in the HC08 Family of microcontrollers.

**Listing 4. Using the HC08 Stack Operations** shows an example of using the HC08 MCU stack to pass parameters and allocate local variables.

**Listing 4. Using the HC08 Stack Operations**

Using the stack to pass parameters and allocate variables optimizes memory usage.

*-----------------------------------------------------------------------------------------------
* Code segment example of using the HC08 stack to pass parameters and allocate local variables.
* Not intended to be a complete application.
*-----------------------------------------------------------------------------------------------

LDA #$AA ;Load some data to be passed
PSHA ;Push parameter for subroutine
PSHA ;Push parameter for subroutine
JSR Sub ;Call subroutine
PULA ;Parameter passed back
STA Result2 ;Parameter passed back
PULA
STA Result1
Loop BRA * ;Your code here
* Subroutine which uses the stack for variable access

*---------
* SP--->Empty
*---------
* LOCAL2
*---------
* LOCAL1
*---------
* PCH
*---------
* PCL
*---------
* PARAM2
*---------
* PARAM1

PARAM1 EQU 6 ;Parameters passed in
PARAM2 EQU 5
LOCAL1 EQU 2 ;Local variables
LOCAL2 EQU 1

Sub
PSHA ;Allocate local variable
PSHA ;Allocate local variable
LDA PARAM1,SP ;Load the parameter passed in
ROLA ;Do something to it
STA LOCAL1,SP ;Store in a local variable
LDA PARAM2,SP ;Load the parameter passed in
ROLA
STA LOCAL2,SP ;Store in a local variable
LDA LOCAL1,SP
STA PARAM1,SP ;Store value to be passed back
LDA LOCAL2,SP
STA PARAM2,SP ;Store value to be passed back
PULA ;Deallocate local variable memory
PULA ;Deallocate local variable memory
RTS ;Return
Queues

A queue is a series of elements which accepts data from one end and extracts data from the other end. An analogy for this data structure would be a checkout line at the supermarket. The first people in are the first people out. For this reason, it is considered a FIFO (first in, first out) structure. This is useful when accessing data in the order it is received. A queue will usually have a predefined maximum size.

Figure 3 illustrates a queue.

![Queue Diagram]

**Figure 3. Queue**

Reading and Writing

The read operation of a queue is called "dequeue," and the write operation is "enqueue." Two pointers are necessary for a queue, one for the head of the line, and one for the tail. For an enqueue operation, after checking the size of the queue, the data is stored at the location pointed to by the "put" pointer, and the put pointer is adjusted. For a dequeue operation, the data is read from the "get" pointer location, and the pointer is adjusted.

Queues usually have a fixed size, so it is important to keep track of the number of items in the queue. This can be done with a variable containing the size of the queue or with pointer arithmetic.
Queue Errors

As with the stack structure, a queue can be subject to underflow and overflow errors. The write, or "enqueue" operation, should be non-destructive and should error if the queue is full. The read, or "dequeue" operation, should be destructive (remove the data element) and should error if the queue is empty.

Queue Applications

A practical application of a FIFO queue is for a data buffer. Queues can be used as buffers for transmitted or received data and for use with printers or serial communication devices.

Listing 5. Queue Example shows an example of queue software. A good application for this would be to store data received from the SIOP (serial input/output port) for processing later.

Listing 5. Queue Example

*-----------------------------------------------------------------------------------
* Illustrates an implementation of a queue For the 705P6A
*-----------------------------------------------------------------------------------
* Register definitions

* Memory map definitions
RAMSPACE EQU $50
ROMSPACE EQU $100
RESETVEC EQU $1FFE

* Queue data structure definitions
* These three equates defines the data structure
* To change the queue, change the data structure,
* and not the code.
QMAX EQU 4 ;Maximum Q size
QTOP EQU $A0 ;Top of Q array
QBOT EQU QTOP+QMAX-1 ;Bottom of Q array

* RAM variables

ORG RAMSPACE
TempA RMB 1
TempX RMB 1
GetPtr RMB 1 ;8-bit pointer
PutPtr RMB 1 ;8-bit pointer
QCount RMB 1 ;Counter for Q size
* Start of program code

ORG    ROMSPACE
Start   EQU      *
InitQ   LDA      #QTOP   ;Initialize Q pointers and variables
STA     GetPtr
STA     PutPtr
CLR     QCount

* Write and read from the Q
* A good application of this is to place bytes received
* from the SCI into the queue, and retrieve them later

JSR    DeQ
LDA    #$FF
JSR    EnQ
SR     EnQ
JSR    EnQ
JSR    EnQ
JSR    EnQ
JSR    DeQ
SR     DeQ
LDA    #$55
JSR    EnQ
JSR    EnQ

Loop   BRA      *

* Subroutines

* EnQ - enqueues a data byte passed in accumulator A
* Checks for a full Q, and returns a set carry bit if full.
* Otherwise returns a cleared carry bit on successful enqueue.

EnQ     STX      TempX   Save X register contents
       LDX      QCount   ;Check for a full Q
       CMPX     #QMAX
       BEQ      QFull   ;Q full error
       LDX      PutPtr
       STA      0,X     ;Store the data in A
       CMPX     #QBOT
       BEQ      WrapPut ;Wrap the put pointer
       INCX              ;Adjust the put pointer
       BRA      EnQDone
WrapPut LDX      #QTOP   ;Successful enqueue

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EnQDone STX PutPtr ;Store new put pointer
LDX TempX ;Restore X register
INC QCount ;Increment count variable
CLC ;Clear carry bit
RTS ;Return

;Unsuccessful enqueue
QFull LDX TempX ;Restore X register
SEC ;Set carry bit
RTS ;Return

*-----------------------------------------------------------------------------------
* DeQ - Dequeue a byte from the queue, and return the byte in the accumulator A.
* If the queue is empty,
  * return a set carry bit to indicate an error. Otherwise,
  * return a clear carry bit and the data in A.
*-----------------------------------------------------------------------------------
DeQ STX TempX ;Save X register contents
LDX QCount ;Check for empty Q
CMPX #$00 ;Check for empty Q
BEQ QEmpty ;Check for empty Q
LDX GetPtr
LDA 0,X
CMPX #QBOT ;Check for wrap condition
BEQ WrapGet ;Check for wrap condition
INCX ;Check for wrap condition
BRA DeQDone
WrapGet LDX #QTOP
 ;Successful dequeue
DeQDone STX GetPtr ;Record new get pointer
LDX TempX ;Restore X register
DEC QCount ;Decrement Q counter
CLC ;Clear carry bit
RTS ;Return

QEmpty LDX TempX ;Restore X register
SEC ;Set carry bit
RTS ;Return

*-----------------------------------------------------------------------------------------------------------------------
* Vector definitions
*-----------------------------------------------------------------------------------------------------------------------
ORG RESETVEC
FDB Start
MACQ (Multiple Access Circular Queue)

A multiple access circular queue (or circular buffer) is a modified version of the queue data structure. It is a fixed-length, order-preserving data structure, and always contains the most recent entries. It is useful for data flow problems, when only the latest data is of interest. Once initialized it is always full, and a write operation always discards the oldest data.

Figure 4 depicts a MACQ.

Reading and Writing

After being initially filled, a write operation will place new data at the top of the MACQ, and shift existing data downward. The last byte will be discarded, so the result is the latest data existing in the buffer.

A read operation is non-destructive and can return any number of data bytes desired from the MACQ.

Figure 4. Result of a MACQ Write
Applications

A MACQ is useful for data streams which require the latest data and can afford to have a destructive write operation. For example, to predict the weather a forecaster might use temperature readings from the last five days to predict the next day’s temperature. Daily temperature readings can be recorded in a MACQ, so the latest data is available.

MACQs are also useful for digital filters. For example, they can be used to calculate a second derivative, running average, etc.

Example

Listing 6. MACQ illustrates the implementation of a MACQ or circular buffer. This could be effectively used for storing A/D converter readings. In this way, the latest A/D conversion results would be accessible through the circular buffer.

Listing 6. MACQ

*-----------------------------------------------------------------------------------
* Illustrates an implementation of a multiple-access circular queue. (MACQ)
* The MACQ is a fixed-length, order-preserving, indexable data structure.
* Once initialized, the MACQ is always full.
* A write to the MACQ is destructive, discarding the oldest data.
* A read from the MACQ is non-destructive. For the 705P6A
*-----------------------------------------------------------------------------------
* Register definitions
* Memory map definitions
RAMSPACE EQU $50
ROMSPACE EQU $100
RESETVEC EQU $1FFE

* MACQueue data structure definitions
* These three equates defines the data structure
* To change the queue, change the data structure, and not the code.
QSIZE EQU 8 ; Maximum Q size
QTOP EQU $A0 ; Top of Q array
QBOT EQU QTOP+QSIZE-1 ; Bottom of Q array

* RAM variables
  ORG RAMSPACE
TempA RMB 1
TempX RMB 1
TempData RMB 1
QPtr RMB 1 ; 8-bit pointer
* Start of program code

ORG     ROMSPACE
Start    EQU     *
InitQ    LDA      #QBOT    ;Initialize Q pointer
           STA      QPtr

* Write and read from the MACQ
* A useful application of this would be to store A/D converter readings, so the latest
* n readings are available.

LDA     #$55
JSR      WriteQ
LDA      #$56
JSR      WriteQ
LDA      #$57
JSR      WriteQ
LDA      #$58
JSR      WriteQ
LDA      #$AA
JSR      WriteQ
LDA      #$AB
JSR      WriteQ
LDA      #$AC
JSR      WriteQ
LDA      #$AD
JSR      WriteQ
LDA      #0
JSR      ReadQ
LDA      #1
JSR      ReadQ
LDA      #2
JSR      ReadQ
Loop     BRA      *

* Subroutines

* WriteQ, A contains data to be written write is destructive on full Q, once
* initialized Q is always full.

WriteQ   STX      TempX    ;Store X register value
          LDX      QPtr     ;Load Q pointer
          CMPX     #QTOP-1  ;See if Q is full
          BEQ      QFull
          STA      0,X      ;Store data to Q
**Tables**

A table can be viewed as a vector of identically structured lists. A table is a common way of storing "lookup" data, such as display data or vector bytes.

*Figure 5* shows an example of a table.
A table is commonly used to look up information. Table entries can be accessed with an offset from the base address of the table. Therefore, a read from a table is typically done by computing the offset of the desired data and accessing it using an indexed addressing mode.

Table Applications

The table data structure is common in MCU applications. One way of using tables is to perform character conversions. For example, a table can be used to convert binary numbers to BCD equivalents. For LCD (liquid crystal display) displays, an ASCII character byte may need to be converted to segment bitmaps for the display. A table could be used for this purpose.

Another application of a table is a "jump" table. This is a table of vector values which are addresses to be loaded and vectored to. Some program parameter can be converted to an offset into a jump table, so the appropriate vector is fetched for a certain input.

For example, in their memory maps Freescale MCUs have a built-in vector table, used for interrupt and exception processing. These vector tables allow preprogrammed addresses to be defined for certain MCU exceptions. When an exception occurs, a new program counter value is fetched from the appropriate table entry.
Another way of utilizing the table data structure is to store predefined values for lookup. An example of this is storing interpolation data in a table, to perform mathematical functions. This use of a table is documented in the application note, *M68HC08 Integer Math Routines*, Freescale document order number AN1219.

Another example involves using a table of sinusoidal values to produce sine wave output as in the application note *Arithmetic Waveform Synthesis with the HC05/08 MCUs*, Freescale document order number AN1222. If an equation to calculate data is CPU-intensive and can be approximated with discrete values, these values can be precalculated and stored in a table. In this way, a value can be quickly fetched, saving CPU time.

**Table Example**

Listing 7. Table is an example of the use of tables to convert ASCII data to LCD segment values.

**Listing 7. Table**

```
*-----------------------------------------------------------------------------------
* Code segment example of using a table to store LCD segment values
* Could be used when 2 data registers define the segment values for a display position.
* Takes in an ASCII character, converts it to an offset into the table of segment
* values, and uses the offset to access the segment bitmap values.
*-----------------------------------------------------------------------------------
Loop       LDA        Character  ;Load an ASCII character
JSR        Convert    ;Convert the character
TAX                   ;Offset into table is in A
LDA        0,X        ;Load the first byte
STA        LCD1       ;Store to data register
LDA        1,X        ;Load the second byte
STA        LCD2       ;Store to data register
BRA        Loop       ;Repeat

*-----------------------------------------------------------------------------------
* Convert ASCII character byte in A to an offset value into the table of LCD segment
* values. Valid ASCII values are (decimal): 32-47, 48-57, 65-90
*-----------------------------------------------------------------------------------
Convert    CMP        #!48       ;Check for "special" character
          BLO        Special
          CMP        #!65       ;Check for numeric character
          BLO        Numeric
Alpha     CMP        #!90       ;Check for invalid value
          BHI        ConvError
```
SUB    #39 ;Convert to table offset
BRA    ConvDone

Special
CMP    #32 ;Check for invalid value
BLO    ConvError
SUB    #32 ;Convert to table offset
BRA    ConvDone

Numeric
CMP    #57 ;Check for invalid value
BHI    ConvError
SUB    #32 ;Convert to table offset
RA    ConvDone

ConvError
CLRA                  ;Invalid value shows as blank
ConvDone
ROLA                  ;Multiply offset by 2
RTS                   ;2 bytes data per LCD position

* Lookup table of LCD segment values for ASCII character values
* Some characters can not be displayed on 15-segment LCD, so they are marked as
* invalid, and will be displayed as a blank space.

Table
FDB     $0000     ;' '  
FDB     $0000     ;'!' INVALID  
FDB     $0000     ;'"'  
FDB     $0000     ;'#' INVALID  
FDB     $A5A5     ;'$'  
FDB     $0000     ;'%' INVALID  
FDB     $0000     ;'&' INVALID  
FDB     $0001     ;'('  
FDB     $5000     ;')'  
FDB     $F00F     ;'*'  
FDB     $A005     ;'+'  
FDB     $0000     ;',' INVALID  
FDB     $2004     ;'-.'  
FDB     $0800     ;'.,'  
FDB     $4002     ;'/'  
FDB     $47E2     ;'0'  
FDB     $0602     ;'1'  
FDB     $23C4     ;'2'  
FDB     $2784     ;'3'  
FDB     $2624     ;'4'  
FDB     $21A8     ;'5'  
FDB     $25E4     ;'6'  
FDB     $0700     ;'7'  
FDB     $27E4     ;'8'  
FDB     $27A4     ;'9'  
FDB     $2764     ;'A'  
FDB     $8785     ;'B'  
FDB     $01E0     ;'C'  
FDB     $8781     ;'D'  
FDB     $21E4     ;'E'  
FDB     $2164     ;'F'  

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A list is a data structure whose elements may vary in precision. For example, a record containing a person’s name, address, and phone number could be considered a list. A linked list is a group of lists, each of which contains a pointer to another list.

**Figure 6** represents a linked list.

### Linked Lists

<table>
<thead>
<tr>
<th>FDB</th>
<th>Address</th>
<th>Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>$05E4</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>$2664</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>$8181</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>$06C0</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>$206A</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>$00E0</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>$1662</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>$1668</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>$07E0</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>$2364</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>$07E8</td>
<td>Q</td>
<td></td>
</tr>
<tr>
<td>$236C</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>$25A4</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>$8101</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>$06E0</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>$4062</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$4668</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>$500A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$9002</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>$4182</td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>

EndTable EQU *-Table ; End of table label
Each list in the structure contains the same type of information, including a link to the next item in the list. The link might be an absolute address or an offset from some base address. In a doubly linked list, pointers are kept to both the next and the previous item in the list. A linked list can be traversed easily by simply following the pointers from one list to the next.

A linked list is used traditionally to define a dynamically allocated database, in which the elements can be ordered or resorted by adjusting the links. However, in a small microcontroller, there are more appropriate applications of linked lists.

A linked list can be used as a structure for a command interpreter. Each command could contain the string of characters, an address of a subroutine to call on that command, and a link to the next command in the linked list. In this way, a command string could be input, searched for in a linked list, and appropriate action taken when the string is found.

Another useful application of a linked list is to define a state machine. A state machine can be represented by a discrete number of states, each of which has an output and pointers to the next state(s). See Figure 7.

Figure 6. Linked List
A state machine can be considered a Mealy or a Moore machine. A Mealy machine’s output is a function of both its inputs and its current state. A Moore machine has an output dependent only on its current state.

This state machine model can be useful for controlling sequential devices such as vending machines, stepper motors, or robotics. These machines have a current internal state, receive input, produce output, and advance to the next state.

One can first model a process as a sequential machine, then convert this behavior to a linked-list structure and write an interpreter for it. An important goal is to be able to make modifications to the state machine by changing the data structure (linked list) and not the code.

**State Machine Example**

As an example, consider a traffic light controller which determines the light patterns for an intersection. Two light patterns are needed, one for the north/south directions and one for the east/west directions. Consider that the bulk of traffic travels on the north/south road, but sensors are placed at the east/west road intersection to determine when traffic needs to cross. See Figure 8.
This example can be modeled as a Moore state machine, with its output a function of its current state. The next state is a function of the current state and the state of the input. Figure 9 shows a state graph for this example. The initial state will be a green light in the north/south direction and a red light in the east/west direction. The controller remains in this state, until input is seen in the east/west direction. The flow continues as shown in the diagram. The output shown in the diagram is a pattern for the light array to activate the lights for the state.
Simulation

This example can be simulated using LEDs and a 68HC705P6A MCU. A pushbutton switch can be used to simulate the input sensor. Figure 10 illustrates the simulation circuit. Using six bits of an output port, a pattern can be generated to display the appropriate north/south and east/west lights (LEDs). Table 1 shows the bitmap in this application.
Figure 10. Circuit Simulation of Traffic-Light Controller

Table 1. Traffic Light Bitmap for Port A

<table>
<thead>
<tr>
<th>Bit Position</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meaning</td>
<td>Not used</td>
<td>North/South Signal</td>
<td>East/West Signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>G</td>
<td>Y</td>
<td>R</td>
<td>G</td>
<td>Y</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

With the hardware in place, all that is left is to define the state machine in software. This can be done by implementing a linked-list data structure and the code to access and interpret the machine.

For this particular example, each list in the data structure defines the current state of the traffic light. Each list contains:

1. The byte which is the bitmap for the lights.
2. A delay value; the time the controller remains in the state
3. The next state pointer for an input of 0
4. The next state pointer for an input of 1
The main loop of the program should execute the program flow charted in Figure 11. The software for this simulated traffic light controller is documented in Listing 8. Traffic Controller State Machine.

![Figure 11. State Machine Program Flow](image_url)

**Listing 8. Traffic Controller State Machine**

*------------------------------------------------------------------*
* Traffic light controller example Illustrates a linked list implementation of a state machine For the 705P6A *
*------------------------------------------------------------------*

* Register definitions

<table>
<thead>
<tr>
<th>Register</th>
<th>EQU</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PORTA</td>
<td>EQU</td>
<td>$00</td>
</tr>
<tr>
<td>PORTD</td>
<td>EQU</td>
<td>$03</td>
</tr>
<tr>
<td>DDRA</td>
<td>EQU</td>
<td>$04</td>
</tr>
<tr>
<td>DDRD</td>
<td>EQU</td>
<td>$07</td>
</tr>
</tbody>
</table>

* Memory map definitions

<table>
<thead>
<tr>
<th>Map Definition</th>
<th>EQU</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMSPACE</td>
<td>EQU</td>
<td>$50</td>
</tr>
<tr>
<td>ROMSPACE</td>
<td>EQU</td>
<td>$100</td>
</tr>
<tr>
<td>RESETVEC</td>
<td>EQU</td>
<td>$1FFE</td>
</tr>
</tbody>
</table>

* RAM variables

ORG RAMSPACE
TempA RMB 1
TempX RMB 1

*------------------------------------------------------------------------*
* Start of program code                                                 *
*------------------------------------------------------------------------*
ORG ROMSPACE

Start
LDA #$00             ;Predefine output levels
STA PORTA
LDA #$FF
STA DDRA             ;Make Port A all outputs
BCLR 7,PORTD        ;Make Port D pin 0 an input
LDX #INITST         ;Index initial state

Loop
LDA STATES+LIGHTS,X ;Get light pattern
STA PORTA          ;Output light pattern
LDA STATES+DELAY,X ;Get delay in seconds
JSR SecDelay       ; Cause delay
BRCLR 7,PORTD,In0  ; Check for input of 0

In1
LDX STATES+NEXT0,X ; Get next state offset
BRA Loop           ; (input = 1)

In0
LDX STATES+NEXT1,X ; Get next state offset
BRA Loop           ; (input = 0)

*------------------------------------------------------------------------*
* DATA STRUCTURE FOR STATE MACHINE LINKED LIST (05)                    *
* Offsets and base address scheme is adequate for a small table (<255 bytes)  *
*------------------------------------------------------------------------*

LIGHTS EQU 0          ; Offset for light pattern
DELAY  EQU 1           ; Offset for time delay
NEXT0  EQU 2           ; Offset for pointer 0
NEXT1  EQU 3           ; Offset for pointer 1
STATES EQU *          ; Base address of states
INITST EQU *-STATES   ; Initial state offset

* North/South green light, East/West red light
NSG    EQU *-STATES    ; Offset into STATES
       FCB %11011110    ; Output for state
       FCB !10         ; Delay for state
       FCB NSG         ; Next state for input of 0
       FCB NSY         ; Next state for input of 1

* N/S yellow light, E/W red light
NSY    EQU *-STATES    ; Offset into STATES
       FCB %11101110    ; Output for state
       FCB !5          ; Delay for state
       FCB NSR
       FCB NSR

* N/S red light, E/W green light
NSR    EQU *-STATES    ; Offset into STATES
       FCB %11110011    ; Delay for state
       FCB !5
       FCB EWY
FCB        EWY
* E/W yellow light, N/S red light
EWY        EQU  *-STATES
FCB        %11110101
FCB        !5               ;Delay for state
FCB        NSG
FCB        NSG

* Delay subroutines

* Cause a delay of ~(1 second * Accumulator value) @ fop = 1MHz

SecDelay   CMP      #$00
           BEQ      SecDone
           JSR      Delay0
           JSR      Delay0
           DECA
           BRA      SecDelay
SecDone    RTS

* Cause a delay of ~1/2 of a second

Delay0     STX      TempX
           LDX      #$B2
DLoop0     CMPX     #$00
           BEQ      DDone0
           JSR      Delay1
           DECX
           BRA      DLoop0
DDone0     LDX     TempX
           RTS

* Cause about 2.8msec delay @ fop of 1MHz

Delay1     STA      TempA
           LDA      #$FF
DLoop1     CMP      #$00
           BEQ      DDone1
           DECA
           BRA      DLoop1
DDone1     LDA      TempA
           RTS

* Vector definitions

ORG  RESETVEC
FDB  Start
Conclusion

The use of data structures is not necessarily limited to large, complicated computers. Although the data structure is a powerful concept in such a context, the same principles can be applied to smaller processors such as 8-bit microcontrollers.

The code to implement these data structures does not necessarily have to be complex or confusing. The goal of programming should be to modularize commonly used functions, so that they may be reused in other applications with a minimal amount of modification.

The appropriate use of data structure concepts can improve the static and dynamic performance of an MCU application, without affecting its portability or legibility.