
AVR035: Efficient C Coding for AVR

Features

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Introduction

The C High-level Language (HLL) has become increasingly popular for programming microcontrollers. The advantages of using C compared to Assembler are numerous: Reduced development time, easier maintainability and portability, and easier to reuse code. The penalty can be larger code size and as a result of that often reduced speed. To reduce these penalties the AVR architecture is tuned to efficiently decode and execute instructions that are typically generated by C compilers.

The C Compiler development was done by IAR systems before the AVR architecture and instruction set specifications were completed. The result of the co-operation between the compiler development team and the AVR development team is a microcontroller for which highly efficient, high performance code is generated.

This application note describes how to utilize the advantages of the AVR architecture and the development tools to achieve more efficient C code than for any other microcontroller.

Architecture Tuned for C Code

The 32 working registers is one of the keys to efficient C coding. These registers have the same function as the traditional accumulator, except that there are 32 of them. In one clock cycle, AVR can feed two arbitrary registers from the Register File to the ALU, perform an operation, and write back the result to the Register File.

When data are stored in the 32 working registers there are no need to move the data to and from memory between each arithmetic instruction. Some of the registers can be combined to 16-bits pointers that efficiently access data in the data and program memories. For large memory sizes the memory pointers can be combined with a third 8-bit register to form 24-bits pointers that can access 16M bytes of data, with no paging.



8-bit **AVR**[®]
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Addressing Modes

The AVR architecture has four memory pointers that are used to access data and Program memory. The Stack Pointer (SP) is dedicated for storing the return address after return from a function. The C compiler allocates one pointer as parameter Stack. The two remaining pointers are general purpose pointers used by the C Compiler to load and store data. The example below shows how efficiently the pointers are used for typical pointer operations in C.

```
char *pointer1 = &table[0];
char *pointer2 = &table[49];

*pointer1++ = *--pointer2;
```

This generates the following Assembly code:

```
LD R16,-Z      ; Pre-decrement Z pointer and load data
ST X+,R16     ; Store data and post increment
```

The four pointer addressing modes and examples are shown below. All pointer operations are single-word instructions that execute in two clock cycles.

1. Indirect addressing: For addressing of arrays and pointer variables:

```
*pointer = 0x00;
```

2. Indirect addressing with displacement: Allows accesses to all elements in a structure by pointing to the first element and add displacement without having to change the pointer value. Also used for accessing variables on the software stack and array accesses.
3. Indirect addressing with post-increment: For efficient addressing of arrays and pointer variables with increment after access:

```
*pointer++ = 0xFF;
```

4. Indirect addressing with pre-decrement: For efficient addressing of arrays and pointer variables with decrement before access:

```
*--pointer = 0xFF
```

The pointers are also used to access the Flash Program memory. In addition to indirect addressing with pointers, the data memory can also be accessed by direct addressing. This gives access to the entire data memory in a two-word instruction.

Support for 16-/32-bit Variables

The AVR instruction set includes special instructions for handling 16-bit numbers. This includes Add/Subtract Immediate Values to Word (ADIW, SBIW). Arithmetic operations and comparison of 16-bit numbers are completed with two instructions in two clock cycles. 32-bit arithmetic operations and comparison are ready in four instructions and four cycles. This is more efficient than most 16-bit processors.

C Code for AVR

Initializing the Stack Pointer

After Power-up or RESET the Stack Pointer needs to be set up before any function is called. The linker command file determines the placement and size of the Stack Pointer. The configuration of memory sizes and Stack Pointer setup is explained in application note “AVR032: Modifying Linker Command Files”.

Accessing I/O Memory Locations

The AVR I/O Memory is easily accessed in C. All registers in the I/O Memory are declared in a header file usually named “ioxxx.h”, where xxxx is the AVR part number. The code below shows examples of accessing I/O location. The assembly code generated for each line is shown below each C code line.

```
#include <io8515.h>           /* Include header file with symbolic names */

__C_task void main(void)
{
    char temp;                /* Declare a temporary variable*/

    /*To read and write to an I/O register*/
    temp = PIND;              /* Read PIND into a variable*/
    //      IN      R16,LOW(16) ; Read I/O memory

    TCCR0 = 0x4F;             /* Write a value to an I/O location*/
    //      LDI     R17,79      ; Load value
    //      OUT     LOW(51),R17 ; Write I/O memory

    /*Set and clear a single bit */
    PORTB |= (1<<PIND2);      /* PIND2 is pin number(0..7)in port */
    //      SBI     LOW(24),LOW(2) ; Set bit in I/O

    ADCSR &= ~(1<<ADEN);      /* Clear ADEN bit in ADCSR register */
    //      CBI     LOW(6),LOW(7) ; Clear bit in I/O
    /* Set and clear a bitmask*/
    DDRD |= 0x0C;             /* Set bit 2 and 3 in DDRD register*/
    //      IN      R17,LOW(17) ; Read I/O memory
    //      ORI     R17,LOW(12) ; Modify
    //      OUT     LOW(17),R17 ; Write I/O memory

    ACSR &= ~(0x0C);          /* Clear bit 2 and 3 in ACSR register*/
    //      IN      R17,LOW(8)  ; Read I/O memory
    //      ANDI    R17,LOW(243) ; Modify
    //      OUT     LOW(8),R17  ; Write I/O memory

    /* Test if a single bit is set or cleared */
    if(USR & (1<<TXC))        /* Check if UART Tx flag is set*/
    {
        PORTB |= (1<<PB0);

        //      SBIC   LOW(11),LOW(6) ; Test direct on I/O
        //      SBI    LOW(24),LOW(0)
    }
}
```

```

while(!(SPSR & (1<<WCOL))) /* Wait for WCOL flag to be set */
//      ?0003:SBIS      LOW(14),LOW(6); Test direct on I/O
//      RJMP      ?0003

/* Test if an I/O register equals a bitmask */
if(UDR & 0xF3) /* Check if UDR register "and" 0xF3 is non-zero
{
}
//      IN      R16,LOW(12) ; Read I/O memory
//      ANDI     R16,LOW(243) ; "And" value
//      BREQ     ?0008 ; Branch if equal

//?0008:
}
/* Set and clear bits in I/O registers can also be declared as macros */

#define SETBIT(ADDRESS,BIT) (ADDRESS |= (1<<BIT))
#define CLEARBIT(ADDRESS,BIT) (ADDRESS &= ~(1<<BIT))

/* Macro for testing of a single bit in an I/O location*/
#define CHECKBIT(ADDRESS,BIT) (ADDRESS & (1<<BIT))

/* Example of usage*/
if(CHECKBIT(PORTD,PIND1)) /* Test if PIN 1 is set*/
{
    CLEARBIT(PORTD,PIND1); /* Clear PIN 1 on PORTD*/
}
if(!(CHECKBIT(PORTD,PIND1))) /* Test if PIN 1 is cleared*/
{
    SETBIT(PORTD,PIND1); /* Set PIN 1 on PORTD*/
}

```

Accessing Memory Mapped I/O

Some AVR devices include an external Data memory interface. This interface can be used to access external RAM, EEPROM, or it can be used to access memory mapped I/O. The following examples show how to declare, write and read memory mapped I/O:

```
#include <io8515.h>

#define reg (* (char *) 0x8004)/* Declare a memory mapped I/O address*/

__C_task void main(void)
{
    char temp;                /* Local temp variable */

    reg = 0x05;               /* Write a value to the memory mapped address*/
    temp = reg;               /* Read the memory mapped I/O address */
}
```

If consecutive memory mapped addresses are accessed, the most efficient way to access them is to declare a constant pointer and add an displacement value to this offset. The example below shows how to access memory mapped I/O this way. The generated assembly code for each instruction is shown in italic.

```
/* Define the memory mapped addresses */
#define data          0x0003
#define address_high  0x0002
#define address_low   0x0001

__C_task void main(void)
{
    /* Start address for memory map */
    unsigned char *pointer = (unsigned char *) 0x0800;
//    LDI    R30,LOW(0)    ; Init Z-pointer
//    LDI    R31,8

    *(pointer+address_low) |= 0x40;    /* Read and modify one address*/
//    LDD    R18,Z+1      ; Load variable
//    ORI    R18,LOW(64)  ; Modify
//    STD    Z+1,R18     ; Store Back

    *(pointer+address_high) = 0x00;    /* Write an address*/
//    STD    Z+2,R30     ; Store zero

    PORTC = *(pointer+data);           /* Read an address*/
//    LDD    R16,Z+3     ; Load variable
//    OUT    LOW(21),R16 ; Output to port
}
```

Note that the Z-pointer is initialized before the memory is accessed, and the LDD and STD (Load and Store with Displacement) instructions are used to access the data. LDD and STD are one-word instructions that execute in two cycles. The pointer is only loaded once. Memory mapped I/O locations can be declared as *volatile*, this indicates that the variable locations may be modified by hardware and the access will not be removed by optimization.



Accessing Data in EEPROM

The internal EEPROM in the AVR can be read and written during normal operation. For the IAR compiler macros to read and write the EEPROM are included in the file `ina90.h`. The following macros are normally defined to read and write the EEPROM:

```
#define _EEGET(VAR,ADR)/* Read data in EEPROM address ADR into variable VAR
*/ \
{ \
    while(EECR & 0x02); /* Check if EEPROM is ready*/ \
    EEAR = (ADR); /* Write EEPROM address register*/ \
    EECR |= 0x01; /* Set the read strobe*/ \
    (VAR) = EEDR; /* Read the data into variable in the next cycle */ \
}

#define _EEPWRITE(ADR,VAL) /* Write data in VAL into EEPROM address ADR*/\
{\
    while(EECR&0x02); /* Check if EEPROM is ready*/ \
    EEAR = (ADR); /* Write EEPROM address register*/ \
    EEDR = (VAL); /* Write EEPROM data register*/ \
    EECR |= 0x04; /* Set master write enable signal*/ \
    EECR |= 0x02; /* Set write strobe*/ \
}
```

Example code for reading and writing to EEPROM using predefined macros:

```
#include <io8515.h>
#include <ina90.h>

#define EE_ADDRESS 0x010 /* Define address constant for EEPROM data*/

__C_task void main(void)
{
    char temp; /* Local variable for temporary storage */

    _EEGET(temp,EE_ADDRESS); /* Read data from EEPROM*/
    temp += UDR; /* Add UART data to temp variable */
    _EEPWRITE(EE_ADDRESS,temp); /* Write data to EEPROM*/
}
```

Note that if interrupts are enabled, they need to be disabled while the EEPROM write is in progress to avoid a time-out for the Master Write Enable (EEMWE) bit. If the program includes access to the EEPROM inside interrupt routines, interrupts should be disabled also before reading the EEPROM to avoid corruption of the EEPROM Address Register.

Creating EEPROM Data Files(IAR v2)

Access of variables in EEPROM is greatly improved in version 2 of the IAR compiler. This chapter explains use of EEPROM variables. For use of EEPROM variables in older versions of the IAR compiler, please see next chapter.

To use the method described below, the “Use inbuilt EEPROM” option must be enabled, and the size must be specified in the compiler options setup. The segment EEPROM_I must be defined in the linker file

EEPROM variables should be declared as global variables.

Example: To declare a EEPROM variable:

```
__eeprom volatile unsigned char ee_var = 0xff;
```

To access this variable in the code, simply read or write the variable like any other variable:

```
__C_task void main(void)
{
    unsigned char temp;
    temp = ee_var;

    //      LDI      R20,LOW(ee_var)
    //      LDI      R21,(ee_var) >> 8
    //      CALL     __eeget8_16

    PORTB = temp;
    //      OUT      0x18,R16

    ee_var = TCNT0;
    //      IN       R16,0x32
    //      LDI      R20,LOW(ee_var)
    //      LDI      R21,(ee_var) >> 8
    //      CALL     __eeput8_16
}
```

When EEPROM variables are declared with initial values, these values can be extracted into a separate hex file for programming into the EEPROM using any AVR programmer.

A special program is provided with the IAR compiler to make the separate file. It is called “postlink.exe” and is located in the “\bin” directory under the IAR installation. Run the program without argument for explanation how to use it.

To use the postlink.exe program, the XLINK output format must be set to generate **simple** format. This is controlled from the XLINK options setup.



Creating EEPROM Data Files(IAR v1)

For access of EEPROM using IAR compiler v2, please see previous chapter. The method in this chapter describes methods for accessing EEPROM efficiently using IAR compiler v1.

In some cases it may be convenient to place initial data in the EEPROM and access them from the C code. The IAR tools can be used for generating initial data for the EEPROM. By using header files for defining the structures, it can be assured that the structures are addressable from the C program itself.

The EEPROM data and the program code are two separate projects that must be compiled and linked separately. A header file describing the structure of the EEPROM memory is used by both projects to ensure that the data in the EEPROM memory can be referenced by their symbolic names.

Example

The feature will be illustrated through an example. In this example, assume the following setup of the EEPROM:

1. A character array (100 bytes).
2. An integer (two bytes).
3. Two unsigned characters (two bytes each).

The EEPROM Header File

The EEPROM header file is included both by the program defining the contents of the EEPROM data and the C program accessing the EEPROM. The EEPROM header file is defined as follows:

```
#define EEPROMADR(x) (unsigned int) (&((TypeEEPROMStruct *)0x0000)->x)

typedef struct
{
    char cArray[100];           /* The character array */
    int iNumber;               /* The integer */
    unsigned char uMinorVersion; /* The first unsigned character */
    unsigned char uMajorVersion; /* The second unsigned character */
} TypeEEPROMStruct;          /* Just a type name */
```

The *#define* directive contains a macro to be used in the C program to get the addresses of the structure variables. It contains a constant pointer (0x0000). In order to displace the EEPROM data contents, this pointer, needs to be changed (this will also require a change in the EEPROM linker file, see below).

The EEPROM Program File

The EEPROM Program File (eeprom.c) contains the initialization of the structure defined in the EEPROM Header File.

```
#include "eeprom.h"           /* Include the structure type definition */
#pragma memory=constseg(EEPROM) /* Make it a named segment */

const TypeEEPROMStruct __EEPROMInitializationData =
    { "Testing  ",           /* Initialize cArray */
      0x100,                 /* Initialize iNumber */
      0x10,                 /* Initialize uMinorVersion */
      0xFF };               /* Initialize uMajorVersion */
```


The EEPROM Linker File A very simple Linker File (eeprom.xcl) is required for the EEPROM Program File:

```
-ca90                -! Define CPU (AVR)                -!  
-Z(CODE)EEPROM=0-1FF -! EEPROM address space(internal EEPROM memory-!
```

The address range is here set to 0-1FF (e.g. AT90S8515) and must be changed to the match the range of the microcontroller being used. The name of the segment is EEPROM and that matches the *#pragma memory=constseg(EEPROM)* line in the “eeprom.c” sourcefile.

In order to displace the contents of the EEPROM, the start address in the EEPROM segment must be changed (see also the comment in the EEPROM header file section).

Building the EEPROM Intel-Hex Data File

In order to generate an Intel-Hex file with this content, the following commands are required:

```
icca90 eeprom.c      (note that -v1 -ms etc. are of no importance)  
xlink -f eeprom.xcl -B -Fintel-standard eeprom.r90 -o eeprom.hex
```

During linking, the following error message is generated:

```
Error[46]: Undefined external ?CL0T_1_41_L08 referred in eeprom ( eeprom.r90  
)
```

The C program references an external dummy symbol to make sure that a compiled program is linked with the correct version of the library. Since we do not have any library to link with, we can ignore this error, and the -B option ensures that the “eeprom.hex” file is generated even if we do have an error. Alternatively, the file can be linked with the following options:

```
xlink -f eeprom.xcl -D?CL0T_1_41_L08=0 -Fintel-standard eeprom.r90 -o  
eeprom.hex
```

The defined symbol is dependent on the processor version (-v0, -v1 etc), the memory model (-mt, -ms, etc) and the compiler version, so the symbol can vary from installation to installation (just try to link it, check which undefined symbol it reports and use -D=0). The generated “eeprom intel-hex” file looks like this (eeprom.h):

```
:1000000054657374696E67202000000000000000D2  
:10001000000000000000000000000000000000E0  
:10002000000000000000000000000000000000D0  
:10003000000000000000000000000000000000C0  
:10004000000000000000000000000000000000B0  
:10005000000000000000000000000000000000A0  
:0800600000000000000000110FF88  
:00000001FF
```



Accessing the EEPROM Data Structure from a C Program

The following program uses the defined EEPROM structure to access the EEPROM (main.c):

```
#include "eeprom.h"           /* We use the structure and macro */
#include <io8515.h>           /* Defines the EEPROM locations */

void error(void)             /* An error routine to catch errors */
{
    for(;;)                  /* Do nothing */
        ;
}

void C_task main(void)
{
    int i;                   /* Used for readback of integer */

    EEAR = EEPROMADR(cArray); /* Set up address to 1st element */
    EECR |=1;                /* Start EEPROM Read */
    if(EEDR != 'T')          /* Check towards initialization */
        error();             /* If not as expected -> error */
    EEAR = EEPROMADR(iNumber); /* Set up address to 2nd element */
    EECR |=1;                /* Start EEPROM Read */
    i = EEDR ;               /* Set low byte of integer */
    EEAR = EEPROMADR(iNumber)+1; /* Set up address to second byte */
    EECR |=1;                /* Start EEPROM Read */
    i |= EEDR<<8;            /* Set high byte of integer */
    if(i!=0x100)             /* Check towards initialization */
        error();             /* If not as expected -> error */
    EEAR = EEPROMADR(uMinorVersion); /* Set up address to 4th element */
    EECR |=1;                /* Start EEPROM Read */
    if(EEDR != 0x10)         /* Check towards initialization */
        error();             /* If not as expected -> error */
    EEAR = EEPROMADR(uMajorVersion); /* Set up address to 3rd element */
    EECR |=1;                /* Start EEPROM Read */
    if(EEDR != 0xFF)         /* Check towards initialization */
        error();             /* If not as expected -> error */
    for ( ;; )
        ;                    /* Do nothing (success) */
}
```

The program can be compiled and executed in AVR Studio®. The “eeprom.hex” file must be loaded into the EEPROM memory before the program is executed or it will go right into the error() routine. The EEPROM is loaded with a hex file by using the File->Up/Download memories function after the program has been loaded.

Variables and Data Types

Data Types

As the AVR is an 8-bit microcontroller, use of 16- and 32-bit variables should be limited to where it is absolutely necessary. The following example shows the code size for a loop counter for an 8-bit and 16-bit local variable:

8-bit Counter

```
unsigned char count8 = 5; /* Declare a variable, assign a value */
// LDI R16,5 ;Init variable

do /* Start a loop */
{
}while(--count8); /* Decrement loop counter and check for zero */
// ?0004:DEC R16 ; Decrement
// BRNE ?0004 ; Branch if not equal
```

16-bit Counter

```
unsigned int count16 = 6; /* Declare a variable, assign a value */
// LDI R24,LOW(6) ;Init variable, low byte
// LDI R25,0 ;Init variable, high byte

do /* Start a loop */
{
}while(--count16); /* Decrement loop counter and check for zero */
// ?0004:SBIW R24,LWRD(1) ; Subtract 16-bit value
// BRNE ?0004 ; Branch if not equal
```

Table 1. Variable and Code Size⁽¹⁾

Variable	Code Size (Bytes)
8-bit	6
16-bit	8

Note: 1. Always use the smallest applicable variable type. This is especially important for global variables.

Efficient Use of Variables

A C program is divided into many functions that execute small or big tasks. The functions receive data through parameters and may also return data. Variables declared inside a function are called local variables. Variables declared outside a function are called global variables. Variables that are local, but must be preserved between each time the function is called, must be declared as static local variables.

Global variables that are declared outside a function are assigned to an SRAM memory location. The SRAM location is reserved for the global variable and can not be used for other purposes, this is considered to be waste of valuable SRAM space. Too many global variables make the code less readable and hard to modify.

Local variables are preferably assigned to a register when they are declared. The local variable is kept in the same register until the end of the function, or until it is not referenced further. Global variables must be loaded from the SRAM into the working registers before they are accessed.

The following example illustrates the difference in code size and execution speed for local variables compared to global variables.

```

char global;                                /* This is a global variable */

__C_task void main(void)
{
    char local;                              /* This is a local variable*/

    global -= 45;                             /* Subtraction with global variable*/
    //     LDS     R16,LWRD(global)           ; Load variable from SRAM to register R16
    //     SUBI    R16,LOW(45)                ; Perform subtraction
    //     STS     LWRD(global),R16           ; Store data back in SRAM

    local -= 34;                              /* Subtraction with local variable*/
    //     SUBI    R16,LOW(34)                ; Perform subtraction directly on local
    //                                           : variable in register R16

}

```

Note that the LDS and STS (Load and Store Direct from/to SRAM) are used to access the variables in SRAM. These are two-word instructions that execute in two cycles.

Table 2. Code Size and Execution Time for Variables

Variable	Code Size (Bytes)	Execution Time (Cycles)
Global	10	5
Local	2	1

A local static variable is loaded into a working register at the start of the function and stored back to its SRAM location at the end of the function. Static variables will therefore give more efficient code than global variables if the variable is accessed more than once inside the function.

To limit the use of global variables, functions can be called with parameters and return a value which are commonly used in C. Up to two parameters of simple data types (char, int, long, float, double) are passed between functions in the registers R16 - R23. More than two parameters and complex data types (arrays, structs) are either placed on the software stack or passed between functions as pointers to SRAM locations.

When global variables are required they should be collected in structures whenever appropriate. This makes it possible for the C compiler to address them indirectly. The following example shows the code generation for global variable versus global structures.

```

typedef struct
{
    char sec;
}t;
t global /* Declare a global structure*/

char min;

__C_task void main(void)
{
    t *time = &global;
    //    LDI    R30,LOW(global)    ; Init Z pointer
    //    LDI    R31,(global >> 8) ; Init Z high byte

    if (++time->sec == 60)
    {
        //    LDD    R16,Z+2        ; Load with displacement
        //    INC    R16; Increment
        //    STD    Z+2,R16        ; Store with displacement
        //    CPI    R16,LOW(60)    ; Compare
        //    BRNE  ?0005          ; Branch if not equal
    }
    if ( ++min == 60)
    {
        //    LDS    R16,LWRD(min)   ; Load direct from SRAM
        //    INC    R16             ; Increment
        //    STS    LWRD(min),R16   ; Store direct to SRAM
        //    CPI    R16,LOW(60)    ; Compare
        //    BRNE  ?0005          ; Branch if not equal
    }
}

```

When accessing the global variables as structures the compiler is using the Z-pointer and the LDD and STD (Load/store with displacement) instructions to access the data. When the global variables are accessed without structures the compiler use LDS and STS (Load/store direct to SRAM). The difference in code size and will be:

Table 3. Code Size for Global Variables

Variable	Code Size (Bytes)
Structure	10
Non-structure	14

This does not include initialization of the Z-pointer (four bytes) for the global structure. To access one byte the code size will be the same, but if the structure consists of two bytes or more it will be more efficient to access the global variables in a structure.



Optimizing Global Flags

Most applications requires some global flags to control the program flow. Placing these in global variables in inefficient in AVR because the variable must be loaded into the register before the flag is tested. To optimize the flag testing the flag can either be placed in a dedicated register, or it can be placed in an unused I/O location.

Note: To place a global variable in a dedicated register requires that the register is allocated in the compiler options setup. This can only be done with IAR Compiler v2.

Unused locations in the I/O Memory can be utilized for storing global variables when certain peripherals are not used. As example, If the UART is not used the UART Baud Rate Register (UBRR) is available, and if the EEPROM is not used both the EEPROM Data Register (EEDR) and the EEPROM Address Register (EEAR) will be available to store global variables.

The I/O Memory is accessed very efficiently, and locations below 0x1F in the I/O Memory are especially suited since they are bit-accessible. I/O locations above 0x1F is less efficient, but still better than global SRAM variables.

The following examples shows the differenc in code size for using SRAM variables, I/O area or a dedicated register for Global Flags:

```
typedef struct bitfield{// Bitfield structure
    unsigned char bit0:1;
    unsigned char bit1:1;
    unsigned char bit2:1;
}bitfield;
```

Global Flags in RAM:

```
bitfield global_flag;           // Bitfield in a global variable
...
global_flag.bit1 = 1;

//      LDI      R30,LOW(global_flag)
//      LDI      R31,(global_flag) >> 8
//      LD       R16,Z
//      ORI      R16,0x02
//      ST       Z,R16
```

Code Size: 10 bytes

Global Flags in Register R15

Note that bitfields are not allowed as register variables.

```
__no_init __regvar unsigned char reg_flag@ 15;
//Global register R15
...
reg_flag |= 0x01;

//      SET
//      BLD     R15,0
```

Code size: 4 bytes

Global Flags in Free I/O Registers Above 0x1F

```

__no_init volatile bitfield high_io_flag@0x55;
// Bitfield in I/O above 0x1F, note that 0x30 offset is added to address
...
high_io_flag.bit2 = 1;

//      IN      R16,0x35
//      ORI      R16,0x04
//      OUT      0x35,R16
    
```

Code size: 6 bytes

Global Flags in Free I/O Register Below 0x1F

```

__no_init volatile bitfield low_io_flag@0x35;
// Bitfield in I/O location below 0x1F
...
low_io_flag.bit1 = 1;
//      SBI      0x15,0x01
    
```

Code size: 2 bytes

GPIO registers

The advantages of free I/O registers are increased in all new AVR devices. From ATmega169, ATmega48/88/168 and ATtiny2313, all AVR devices includes a number of General Purpose I/O registers, both below and above the 0x1F address limit. These registers are used as any other free I/O register, and could potentially increase performance and reduce code size for your design.

Table 4. Code Size (Bytes) for some Common Operations

Action	Data in SRAM	Data in I/O Above 0x1F	Data in Register File	Data in I/O Below 0x1F
Set/clear single bit	10	6	4	2
Test single bit	6	4	2	2
Set/clear multiple bits	10	6	4	6
Compare with immediate value	6	4	4	4

The examples shows using free I/O locations are very efficient for flag variables that operates on single bits, while using dedicated registers are efficient for frequently accessed variables. Note that locking registers for global variables limits the compilers ability to optimize the code. For complex programs it may increase the code size when dedicating registers for global variables.

Bit-field vs. Bit-mask

To save valuable bytes of data storage it may be necessary to save several single bit flags into one byte. A common use of this is bit flags that are packed in a status byte. This can either be defined as bit-mask or bit-field. Below is an example of use of bit-mask and bit-field to declare a status byte:

```

/* Use of bit-mask for status bits*/

/* Define bit macros, note that they are similar to the I/O macros*/

#define SETBIT(x,y) (x |= (y))      /* Set bit y in byte x*/
#define CLEARBIT(x,y) (x &= (~y)) /* Clear bit y in byte x*/
#define CHECKBIT(x,y) (x & (y))    /* Check bit y in byte x*/

/* Define Status bit mask constants */

#define RETRANS  0x01              /* bit 0 : Retransmit Flag*/
#define WRITEFLAG 0x02            /* bit 1 : Flag set when write is due*/
#define EMPTY    0x04            /* bit 2 : Empty buffer flag*/
#define FULL     0x08            /* bit 3 : Full buffer flag*/

__C_task void main(void)
{
    char status;                  /* Declare a status byte*/

    CLEARBIT(status,RETRANS);     /* Clear RETRANS and WRITEFLAG*/
    CLEARBIT(status,WRITEFLAG);

    /*Check if RETRANS flag is cleared */
    if (!(CHECKBIT(status, RETRANS)))
    {
        SETBIT(status,WRITEFLAG);
    }
}

```

Bit-masks are handled very efficient by the C compiler if the status variable is declared as local variable within the function it is used. Alternatively, use unused I/O locations with bit mask or bitfields.

Bitfields can be defined in SRAM and I/O locations. Global variables in registers only allows simple variables. To use bit instructions on the global variables in registers, use bit-masks.

The ANSI standard does not define how bitfields are packed into the byte, i.e., a bitfield placed in the MSB (Most Significant Bit) with one compiler can be placed in the LSB (Least Significant Bit) in another compiler. With bitmasks the user has complete control of the bit placement inside the variables.

Initialization of Global Variables

The startup initialization code executed after reset initializes all global variables. Global variables without initial value are always initialized to 0.

Example:

```
unsigned char global_counter = 100;
unsigned int global_flags ;// All global variables are initialized to 0
```

Normally there is no need to initialize global variables in initialization routines.

For best code density all global variable should be initialized at declaration. Alternatively, all variables can be initialized in a separate routine and the initialization code at startup can be removed.

Accessing Flash Memory

A common way to define a constant is:

```
const char max = 127;
```

This constant is copied from flash memory to SRAM at startup and remains in the SRAM for the rest of the program execution. This is considered to be waste of SRAM. To save SRAM space the constant can be saved in flash and loaded when it is needed:

```
flash char max = 127;
flash char string[] = "This string is stored in flash";

__C_task void main(void)
{
    char flash *flashpointer;           ; Declare flash pointer

    flashpointer = &string[0];         ; Assign pointer to flash location
    UDR = *flashpointer;                ; Read data from flash and write to UART
}
```

Note: IAR Compiler v2 uses **__flash** instead of **flash**.

When strings are stored in Flash like in the latter example they can be accessed directly or through pointers to the Flash Program memory. For the IAR C compiler, special library routines exist for string handling, see the "IAR Compiler Users Manual" for details.

Interrupt Routines

When entering an interrupt routine all registers used in the interrupt routine are pushed on the Stack. To reduce code size and optimize speed the interrupt routines should be small and preferably without calls to other functions. The reason is that when the routine calls an external function, the compiler pushes all registers on the Stack.



Functions Returning Several Values

In some cases global variables are used because several values must be returned from a function. With AVR, up to four bytes can be returned from a function by returning a value in the scratch registers. Some tricks can be used to combine several variables in one return value.

Example

```
unsigned int read_io(void)
{
    return (PIND<<8 | TCNT0); // Function is returning 2 values
}
//      IN      R17,0x10 // First value is shifted 8 bytes
//      IN      R16,0x32 // Second values read into register
//      RET
```

From the calling function

```
__C_task void main(void)
{
    unsigned int temp; // Declare a temporary variable

    temp = sum(); // Read value from function
    PORTB = temp>>8; // Use only high byte
    TCNT0 = temp&0x00FF; // Use only low byte
}

//      CALL    sum // Call the function
//      OUT     0x18,R17 // Use high byte
//      OUT     0x32,R16 // Use low byte
```

Memory Model

For the smallest AVR devices with less than 256 bytes of SRAM the tiny memory model can be used in many cases. When using tiny memory model, all variables in SRAM are accessed with 8-bit pointers instead of 16-bit pointers. This reduces the code size for loading pointer values. Note that 8-bit pointers can address 160 bytes of RAM + Register File and I/O memory. To make sure the compiler utilize all of the addressing range, make sure the linker file is configured to place the RSTACK and CSTACK at the top of SRAM.

Control Flow

The Main Function

The main function usually contains the main loop of the program. In most cases no functions are calling the main function, and there are no need to preserve any registers when entering it. The main function can therefore be declared as `C_task`. This saves stack space and code size:

```
__C_task void main(void)          /* Declare main() as C_task*/
{
}

```

Note: IAR Compiler v2 uses `__C_tast` instead of `C_task`.

Loops

Eternal loops are most efficiently constructed using `for(; ;) { }`:

```
for( ; ; )
{
    /* This is an eternal loop*/
}
//    ?0001:RJMP ?0001          ; Jump to label

```

`do{ }while(expression)` loops generally generates more efficient code than `while{ }` and `for{expr1; expr2; expr3}`. The following example shows the code generated for a `do{ }while` loop:

```
char counter = 100;                /* Declare loop counter variable*/
//    LDI    R16,100                ; Init variable
do
{
} while(--counter);                /* Decrement counter and test for zero*/
    ?0004:DEC    R16                ; Decrement
//    BRNE  ?0004                ; Branch if not equal

```

Pre-decrement variables as Loop Counter gives usually the most efficient code. Pre-decrement and post-increment is more efficient because branches are depending on the flags after decrement.

Macros vs. Functions

Functions that assemble into 3 - 4 lines of assembly code or less can in some cases be handled more efficiently as macros. When using macros the macro name will be replaced by the actual code inside the macro at compile time. For very small functions the compiler generates less code and gives higher speed to use macros than to call a function.

The example below shows how a task can be executed in a function and as a macro.

```

/* Main function to call the task*/
__C_task void main(void)
{
    UDR = read_and_convert();      /* Read value and write to UART*/
}

/* Function to read pin value and convert it to ASCII*/
char read_and_convert(void)
{
    return (PINB + 0x48);          /* Return the value as ASCII character */
}

/* A macro to do the same task*/
#define read_and_convert (PINB + 0x48)

```

The code with function assemble into the following code:

```

main:
//      RCALL   read_and_convert ; Call function
//      OUT    LOW(12),R16      ; Write to I/O memory

read_and_convert:
//      IN     R16,LOW(22)      ; Read I/O memory
//      SUBI   R16,LOW(184)     ; Add 48 to value
//      RET    ; Return

```

The code with macro assemble into this code:

```

main:
//      IN     R16,LOW(22)      ; Read I/O memory
//      SUBI   R16,LOW(184)     ; Add 48 to value
//      OUT    LOW(12),R16      ; Write I/O memory

```

Table 5. Code Size and Execution Time for Macros and Functions

Variable	Code Size (Bytes)	Execution Time (Cycles)
Function	10	10
Macro	6	3

Eighteen Hints to Reduce Code Size

1. Compile with full size optimization.
2. Use local variables whenever possible.
3. Use the smallest applicable data type. Use unsigned if applicable.
4. If a non-local variable is only referenced within one function, it should be declared static.
5. Collect non-local data in structures whenever natural. This increases the possibility of indirect addressing without pointer reload.
6. Use pointers with offset or declare structures to access memory mapped I/O.
7. Use `for(;;) { }` for eternal loops.
8. Use `do { } while(expression)` if applicable.
9. Use descending loop counters and pre-decrement if applicable.
10. Access I/O memory directly (i.e., do not use pointers).
11. Declare `main` as `C_task` if not called from anywhere in the program.
12. Use macros instead of functions for tasks that generates less than 2-3 lines assembly code.
13. Reduce the size of the Interrupt Vector segment (INTVEC) to what is actually needed by the application. Alternatively, concatenate all the CODE segments into one declaration and it will be done automatically.
14. Code reuse is intra-modular. Collect several functions in one module (i.e., in one file) to increase code reuse factor.
15. In some cases, full speed optimization results in lower code size than full size optimization. Compile on a module by module basis to investigate what gives the best result.
16. Optimize `C_startup` to not initialize unused segments (i.e., `IDATA0` or `IDATA1` if all variables are *tiny* or *small*).
17. If possible, avoid calling functions from inside the interrupt routine.
18. Use the smallest possible memory model.

Five Hints to Reduce RAM Requirements

1. All constants and literals should be placed in Flash by using the `Flash` keyword.
2. Avoid using global variables if the variables are local in nature. This also saves code space. Local variables are allocated from the stack dynamically and are removed when the function goes out of scope.
3. If using large functions with variables with a limited lifetime within the function, the use of subscopes can be beneficial.
4. Get good estimates of the sizes of the software Stack and return Stack (Linker File).
5. Do not waste space for the `IDATA0` and `UDATA0` segments unless you are using tiny variables (Linker File).

Checklist for Debugging Programs

1. Ensure that the `CSTACK` segment is sufficiently large.
2. Ensure that the `RSTACK` segment is sufficiently large.
3. Ensure that the external memory interface is enabled if it should be enabled and disabled if it should be disabled.
4. If a regular function and an interrupt routine are communicating through a global variable, make sure this variable is declared volatile to ensure that it is reread from RAM each time it is checked.





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