Mixed C and Assembly (for Atmel XMEGA)

KEY WORDS

Compiler, Inline Assembly, GNU Assembler, GCC, AVR-GCC

RESOURCES

- GNU Assembler Resource - http://sourceware.org/binutils/docs-2.23.1/as/index.html
- AVR-LibC Inline ASM Cookbook - http://www.nongnu.org/avr-libc/user-manual/inline_asm.html
- Atmel APPNote AT1886 - http://www.atmel.com/images/doc42055.pdf
- Atmel APPNote AVR1000 - http://www.atmel.com/Images/doc8075.pdf

INTRODUCTION

Beyond standard assembly programming for a specific device, some devices allow the use of the C programming language to create code that will control the device. When a computer program is completed in a source language such as C, it must then be converted to a target language to control the desired device. To do this, a compiler is used to transform the source code into the desired object code (e.g., assembly language).

During the conversion process, the compiler attempts to "optimize" the order and use of object code. Given that a compiler tries to be quick, or simply may be poorly built, it is possible that the resulting object code may not be as fast or efficient as desired. A programmer who is familiar with assembly may want to take advantage of their skills to improve the resulting assembly code given by using assembly within the C program being generated. Specifically, a programmer may desired for a C program to call an Assembly function or vice versa. For Atmel, this happens in either two cases: the use of ".s" assembly files, or using "inline assembly" commands.

Note that for Atmel, the GCC (AVR-GCC) compiler is used to combine .c, .cpp, or .s files to create a project.

C ASSEMBLER

When creating a C project, if working with long and complex pieces of assembly code is required, it is more desirable to express the code in a dedicated assembler file. The portions of C code and Assembly code can be used to communicate between each other so nothing is lost, allowing that the programmer pays close attention to the use of registers. Typically, Assembler files are very useful in cases of optimizing large pieces of code such as communication with external devices or Interrupt Service Routines. Note that in C, the assembly language functions low and high are replaced with lo8 and hi8. Also note that in C, we do not need to shift pointers into Z, i.e., in Assembly, we had ldi ZL, low(VA << 1), but in C, we use ldi ZL, lo8(VA).

```
// Program Flash Data Section (in Code Memory Space)
.section .text
VA: .byte 1,2,3,4,5,6
VB: .byte 0xA0, 0xB0, 0xC0, 0xD0, 0xE0, 0xF0
VB: .byte 6
/******************************PRIMARY CODE***************************************/
.global MAIN_ASM // The assembly function must be declared as global

MAIN_ASM:
       ldi R18, N                 // Load the number of values
       ldi ZL, lo8(VA)            // Load the address of program memory for VA
       ldi ZH, hi8(VA)

       call VADD                  // Call the ASM function for vector addition
       ret                        // Return to call from C code
```

Figure 1: Assembler File .s example

INLINE ASSEMBLY

In cases where smaller pieces of assembly code are used, inline assembly commands directly embedded into the C code may be desirable. In these cases, instead of creating a separate Assembler file, the "asm" command may be used to wrap around and insert assembler commands into C.

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```
// Program Flash Data Section (in Code Memory Space)
asm(".section .text");
asm("VA: .byte 1,2,3,4,5,6");
asm("VB: .byte 0xA0, 0xB0, 0xC0, 0xD0, 0xE0, 0xF0");

/*******************************PRIMARY CODE****************************************/
void VADD();         // C Prototype for VADD

// Main function required in primary C file of project
int main(void)
{
       asm("ldi R18, N");          // Load the number of values
       asm("ldi R30, lo8(VA)");    // Load the address of program memory for VA
       asm("ldi R31, hi8(VA)");
       asm("ldi R26, lo8(VC)");    // Load the address of data memory storage for VC
                                   //   result
       asm("ldi R27, hi8(VC)");

    VADD();                        // Use C function call

       // DONE while loop once main program is complete
       while(1)
    {
    }
}
```

Figure 2: Inline Assembly example

C ASSEMBLER (.S) USAGE

REGISTERS

When using the GCC compiler in a C program, registers are used slightly differently from a standard assembly project. First, **r0** is defined as a temporary register which may be used by compiler generated code. Any assembly code that uses **r0** and calls a C function should save and restore the register. **r1** is assumed to always be zero by the compiler, so any assembly code that uses this should clear the register before calling compiler generated code. The rest of the registers are defined as being “call-saved” or “call-used”. “call-saved” registers are those that a called C function may leave unaltered, however, assembly functions called from C should save and restore the contents of the register (using the stack). “call-used” registers are available for any code to use, but if calling a C function, these registers should be saved since compiler generated code will not attempt to save them.

A table is give below to quickly define how each register is to be considered:

Table 1: Register Interfaces between C and Assembly

Register	Description	Assembly code called from C	Assembly code that calls C code
r0	Temporary	Save and restore if using	Save and restore if using
r1	Always Zero	Must clear before returning	Must clear before returning
r2-r17 **r28** **r29**	“call-saved”	Save and restore if using	Can freely use
r18-r27	“call-used”	Can freely use	Save and restore if using

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r30 **r31**			

COMMANDS AND CONSTRAINTS

All commands that are given through the instruction set are available in the mixed C/Assembly setup. Below is a subset of the instruction set, but are many of the primary commands that are given in various avr-gcc compiling guides. Notice the constraint descriptions are slightly different.

Table 2: Commands in AVR-GCC

Mnemonic	Constraint	Meaning
adc	r, r	Add without Carry
add	r, r	Add with Carry
adiw	w, I	Add Immediate to Word
and	r, r	Logical AND
andi	d, M	Logical AND with Immediate
asr	r	Arithmetic Shift Right
bclr	I	Flag Clear
bld	r, I	Bit load from T to Register
brbc	I, label	Branch if Status Flag Cleared
brbs	I, label	Branch if Status Flag Set
bset	I	Flag Set
bst	r, I	Bit Store from Register to T
cbi	I, I	Clear Bit(s) in I/O Register
cbr	d, I	Clear Bit(s) in Register
com	r	One’s Complement
cp	r, r	Compare
cpc	r, r	Compare with Carry
cpi	d, M	Compare with Immediate
cpse	r, r	Compare, Skip if Equal
dec	r	Decrement
elpm	t, z	Extended Load Program Memory
eor	r, r	Exclusive OR
in	r, I	In From I/O Location
inc	r	Increment
ld	r, e	Load Indirect
ld	r, e+	Load Indirect, post-increment
ld	r, -e	Load Indirect, pre-decrement
ldd	r, b + I	Load Indirect with Displacement
ldi	d, M	Load Immediate
lds	r, label	Load Direct from data space
lpm	t, z	Load Program Memory
lsl	r	Logical Shift Left
lsr	r	Logical Shift Right
mov	r, r	Copy Register
movw	r, r	Copy Register Pair
mul	r, r	Multiply Unsigned
muls	d, d	Multiply Signed
neg	r	Two’s Compliment
or	r, r	Logical OR
ori	d, M	Logical OR with Immediate
out	I, r	Out To I/O Location

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Mnemonic	Constraint	Meaning
pop	r	Pop Register from Stack
push	r	Push Register on Stack
rol	r	Rotate Left Through Carry
ror	r	Rotate Right Through Carry
sbc	r, r	Subtract with Carry
sbci	d, M	Subtract immediate with Carry
sbi	I, I	Set Bit in I/O Register
sbic	I, I	Skip if Bit in I/O Register Cleared
sbiw	w, I	Subtract Immediate from Word
sbr	d, M	Set Bit(s) in Register
sbrc	r, I	Skip if Bit in Register Cleared
sbrs	r, I	Skip if Bit in Register Set
ser	d	Set Register
st	e, r	Store Indirect
st	e+, r	Store Indirect, Post-Increment
st	-e, r	Store Indirect, Pre-Increment
std	b, r	Store Indirect with Displacement
sts	label, r	Store Direct to Data Space
sub	r, r	Subtract without Carry
subi	d, M	Subtract Immediate
swap	r	Swap Nibbles
xch	z, r	Exchange

Though the commands are like standard assembly commands, some of the constraints are described slightly differently. For instance, some commands that you could typically use register definitions such as XH or XL must now use their specific register declarations (r27 or r26). A description of the various constraints as well as operand definitions seen in other C Assembly structures is shown in Table 3.

Table 3: Command/Operand Constraints

Constraint	Type	Range of Values
a	Simple upper register	r16 … r23
b	Pointer Register	y, z
d	Upper Register	r16 … r31
i	Constant	
l	Lower Register	r0 … r15
m	Memory	
n	Value is known at compile	
q	Stack Pointer	SPH: SPL
r	Any Register	r0 to r31
s	Pointer Register	x, y, z
t	Scratch (Temp) Register	r0
w	Upper Register pairs	r24, r26, r28, r30
x	Pointer Register x	x (r27: r26)
y	Pointer Register y	y (r29: r28)
z	Pointer Register z	z (r31: r30)
G	Floating-point Constant	0.0
I	6-bit positive constant	0 to 63
J	6-bit negative constant	- 63 to 0
M	8-bit integer constant	0 to 255
0 … 9	Identical to the specified operand	

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Notice that the X register is r27:r26, Y register is r29:r28, and Z register is r31:r30.

SYNTAX

When working with Assembler files within C, there are small changes from what is expected in an assembly file.

- In code segments, .org is not needed since the compiler handles code placement.
- In data segments, .org directives are offset from the last location used by the compiler in placement.
- The .s extension is used for assembler files.
- Lines using preprocessor directives defined by # must use C/C++ style comments (semicolons will cause errors).
- Table 3 shows a comparison of the structures for assembly and C.

Table 4: Structure Comparisons

Atmel AVR	AVR-GCC
.include "xxx.inc"	#include <avr.io>
.dseg	.section .data
.cseg	.section .text
.db 1,2,3,4	.byte 1,2,3,4
.db "message"	.ascii "message"
.db "message", 0x00	.asciz "message"
.dw	.word
HIGH()	hi8()
LOW()	lo8()

EXAMPLES

.DSEG AND DATA MEMORY

When working with data memory the ".section .data" structure is used. The below example shows various methods of using Data Memory:

```
// SRAM Data Segment
.section .data              // This will start at address 0x2000 as default
Text: .asciz   "hello world"

Variable1:    .ds.b 4             // Define storage of bytes 4 long
Variable2:    .ds.w 2             // Define storage of words 2 long
Variable3:    .byte 5             // Define byte value of 5

.global __do_copy_data // Copy a defined variable in program memory to data memory
```

Figure 3: .DSEG and Data Memory example

The ***Text*** label uses "asciz" to define a null terminated string. Labels ***Variable1*** and ***Variable2*** are used to define storage spaces of either byte size or words size respectively. Label ***Variable3*** is used to define a specific value of 5 in a space of *byte* size.

Data memory is typically used for creating storage of variables such as defined by ***Variable1*** and ***Variable2***. In some cases, it is desired to not only create a space in memory, but also to define a value to be stored at that position on startup. ***Text*** and ***Variable3*** define a space in data memory as well as desired initial values. The initial value is initially stored in program memory, however, the special command ***.global __do_copy_data*** handles copying the data from program memory to the desired position for that information in data memory.

.CSEG AND PROGRAM MEMORY

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Like assembly, program memory is used to hold both program variables (constants) and the assembly code. The following example shows how the ".section .text" structure may be used:

```
// Program Flash Data Section (in Code Memory Space)
.section .text
VA: .byte 1,2,3,4,5,6
VB: .byte 0xA0, 0xB0, 0xC0, 0xD0, 0xE0, 0xF0

/******************************PRIMARY CODE***************************************/
.global MAIN_ASM // The assembly function must be declared as global

MAIN_ASM:
	ldi R18, N		// Load the number of values
	ldi ZL, lo8(VA)		// Load the address of program memory for Variable1
	ldi ZH, hi8(VA)

	call VADD		// Call the ASM function for vector addition
	ret				// Return to call from C code
```

Figure 4: .CSEG and Program Memory example

The ***Variable1*** and ***Variable2*** labels define a place in program memory that holds two sets of respective values. Following this declaration, the main body of the assembly program (various functions) may now be defined.

ASSEMBLY FUNCTION DEFINITIONS AND USE

Assembly functions are defined the same way they are in a standard assembly project using standard labels. The "ret" command is still used to return from a function call to an assembly function. Within the Assembler file (.s), calls between functions within the same file require no special consideration. However, when dealing with calls to assembler functions from C code, the function must be define a special way.

```
/********************************INITIALIZATIONS*********************************/
extern void MAIN_ASM(); // C Prototype that defines an externally defined function

// Main function required in primary C file of project
int main(void)
{
	MAIN_ASM();		// Single call to Vector Add Function
}
```

Figure 5: Assembly Function Use - .c File

```
/******************************PRIMARY CODE***************************************/
.global MAIN_ASM // The assembly function must be declared as global

MAIN_ASM:
	ret				// Return to call from C code
```

Figure 6: Assembly Function Use - .s File

The above two examples show both the .c file and the .s file descriptions for connection to an assembly function. In the .c file, a C Prototype is created for the assembly function. The use of the "extern" keyword shows that the function is externally defined. The assembly function is later called in the .c file. In the .s file, the assembly function is defined by the ".global" directive to make the function available to other partial programs that are linked within the project. Notice that within the assembly function the "ret" command is still used to return from the function when it is complete.

INLINE ASSEMBLY USAGE

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Many of the rules and usage defined within the C Assembler section are used when executing inline assembly commands. The following sections will detail the differences in Syntax usage as well as define the templates used when working with inline assembly.

SYNTAX

As described, inline assembly makes use of the ***asm()*** command (also defined as ***__asm*** or ***__asm__***). In special circumstances where it is important that the command should not be optimized away (i.e., not moved from the defined position in memory), the ***volatile*** modifier should be added (***asm volatile ()***). Notice that the volatile modifier does not need to be used at every ***asm*** call. The template for the ***asm*** call follows:

```
asm volatile ( asm-template  : output-operand-list  : list-input-operand  : clobber list )
```

The **asm-template** follows the standard assembly instruction structure defined in ***Table 2***: Commands in AVR-GCC. The assembly instructions are incased in quotes. The **asm-template** may use "%" expressions to define placeholders replaced by operands defined in the **output-operand-list** and **list-input-operand** sections. Below is a table of possible placeholders:

Table 5: ASM Template Placeholders

Placeholder	Replaced by
% n	By argument in operands where n = 0 to 9 for argument
A% n	The first register of the argument n (bits 0 to 7)
% B n	The second register of the argument n (bits 8 to 15)
% C n	The third register of the argument n (bits 16 to 23)
% D n	The fourth register of the argument n (bits 24 to 31)
% A n	The Address register X, Y, or Z
% %	The % symbol when needed
\ \	The \ symbol when needed
\ N	A newline to separate multiple asm commands
\ T	A tab used in generated asm

The **output-operand-list** and **list-input-operand** follows the definitions given in ***Table 3:*** Command/Operand Constraints. The various operands may be used with various modifiers as defined in the following:

Table 6: Operand Modifiers

Modifier	Meaning
=	Output operand
=&	Not used as input but only an output
+	Input and Output Operand

Operands are used by placing an operand (and modifier) in quotes, while placing the true variable, register, or memory position in parenthesis. Any C expression may be used within the parenthesis.

EXAMPLES

SIMPLE INLINE ASSEMBLY COMMANDS

When using simple inline assembly commands, there is little difference from the look in a C Assembler (.s) file other than the required **asm(" ")** function call surrounding the assembly command.

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```
void VADD()
{
    asm("nop");
    asm("VADD_ASM: push R18");// Push the number of values onto the stack for later use
    asm("movw R28,R26");      // movw Y, X
    asm("mov  R19, R18");     // Copy count of values in vector to counter register

    // Work with first vector
    asm("LOOP:");
    asm("lpm  R21, Z+");    // Load values of first vector pointed to by Z
    asm("st   Y+, R21");    // Store currently loaded value into data memory pointed by Y
    asm("dec  R19");        // Decrement counter
    asm("brne LOOP");       // Loop until counter = 0
    asm("pop  R19");        // Restore the count of values in vector to counter register
```

Figure 7: Simple Inline Assembly example

INLINE ASSEMBLY COMMANDS USING OPERANDS

In circumstances where defined PORT names, Control Registers, or Memory locations are used, the more advanced ***asm()*** template with operands must be used. In some of these situations, it is also important to insure that the assembly command used is not moved during the compiler process, requiring the ***volatile*** modifier to be used.

```
    asm("LDI R18, 0xFF");
    asm volatile ("STS %0,r18" : "=m" (PORTK_DIRSET));

    asm("LDI R18, 0x01");
    asm volatile ("STS %0,r18" : "=m" (EBI_CTRL));

    asm volatile("LDI R31, hi8(%0)" :: "i" (&EBI_CS0_BASEADDR));
    asm volatile("LDI R30, lo8(%0)" :: "i" (&EBI_CS0_BASEADDR));

    asm("LDI R18, (IOPORT>>8)");
    asm("ST Z+, R18");
```

Figure 8: Inline Assembly with Operands example

In the example, the **STS** command used to define **PORTK_DIRSET** uses a simple placeholder operand (**%0**) showing that the defined operand will come later in the template. Then, in the output operand section, **PORTK_DIRSET** is defined as an output only memory ("=m") location address.

Later in the example, the **LDI** command used to define **EBI_CS0_BASEADDR** uses another simple placeholder operand (%0). The operand is later shown to be an input operand defined as a constant (" i "). The constant is defined by using the C Pointer "**&**" modifier on **EBI_CS0_BASEADDR**. The "**&**" designated for C to return the address of **EBI_CS0_BASEADDR.**

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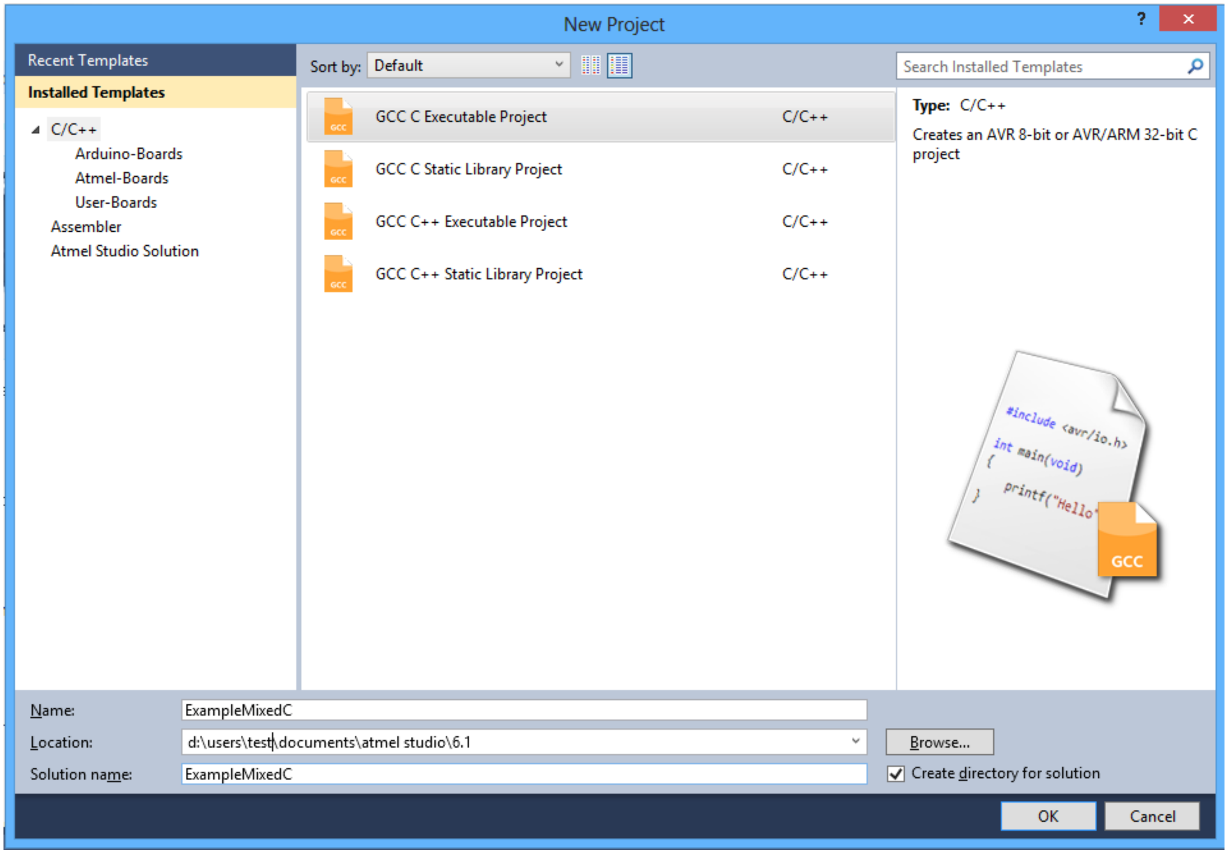
STARTING A C PROJECT

To begin, a C Project must be first started within Atmel Studio. After opening Atmel Studio, choose New Project and make sure to choose the "GCC C Executable Project" option.



Once the project is open, the standard ".c" file will be opened with the template "main" function. C code may be written using the "main" function as the starting point. Assembly may be used in a new ".s" file added to the project or directly inserted using inline assembly commands within the ".c" file.

TO CREATE ".S" ASSEMBLY FILE

All files for the project are displayed in the Solution Explorer. Right click on the project name in the Solution Explorer (highlighted in figure) and choose "Add -> New Item" in context menu. In the new "Add New Item" window, choose to create an Assembly File. This new file will then be displayed in the Solution Explorer.

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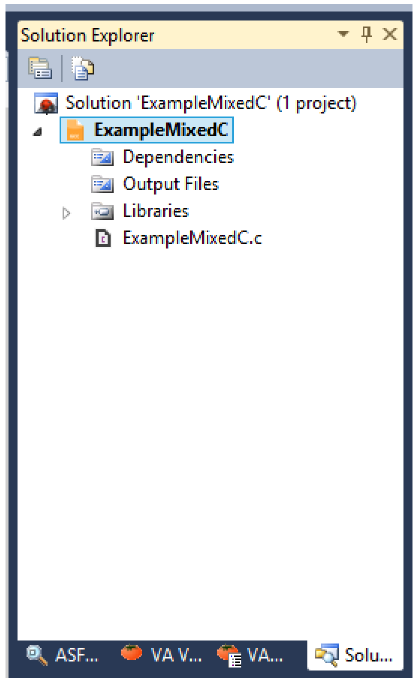

Figure 9: Project Solution Explorer Window

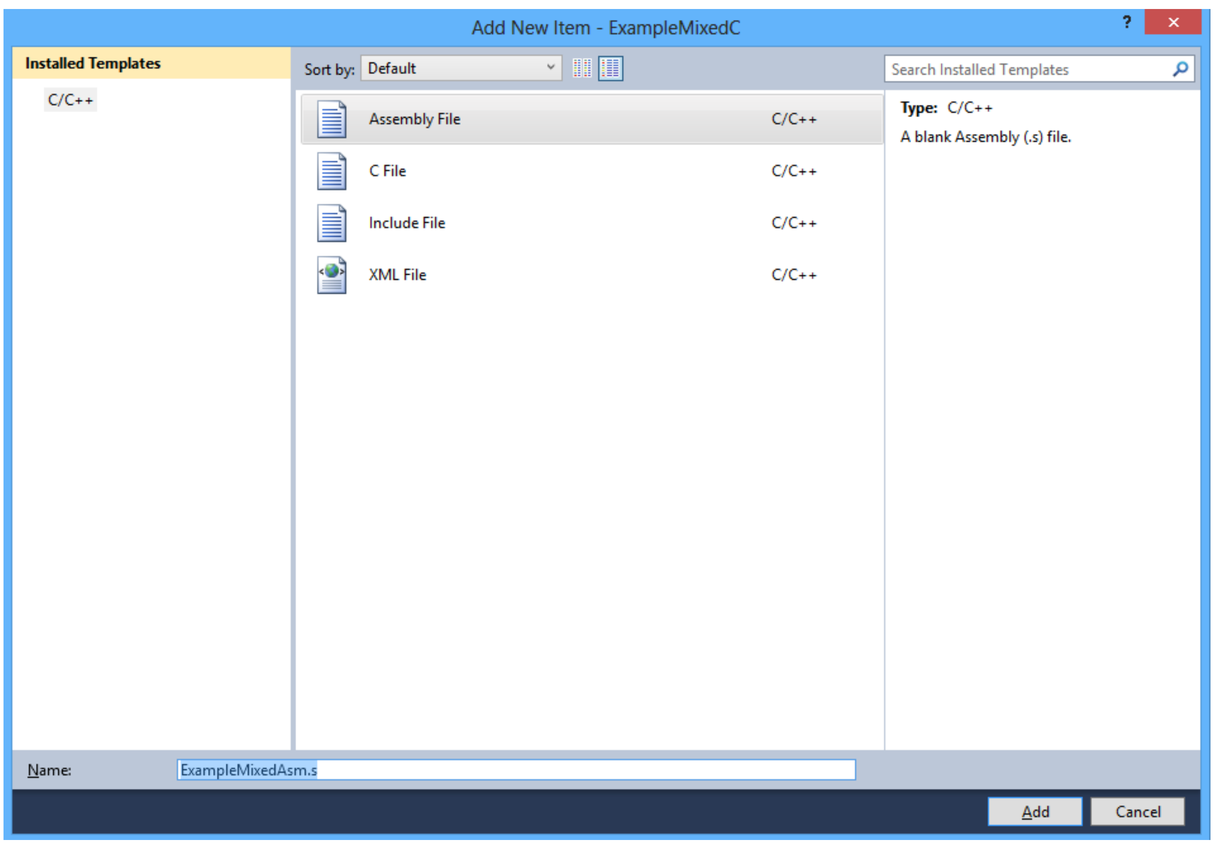

Figure 10: Add New Item Window

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TROUBLESHOOTING

GARBAGE AT END OF LINE

If you receive an error with the following comments

- ;' required
- constant value required
- garbage at end of line

Check any lines with preprocessor directives that begin with # (e.g., **#include, #define**). If comments follow the directive, they must be in the form of C/C++ style comments. Any comments using assembler structure with a semicolon will result in an error.

DEFINING A VARIABLE WITH INLINE ASM DOES NOT WORK

Using the standard method of a #define will not connect correctly when used within an asm command:

asm("#define test r18")

To define the register correctly you can use the command:

```
register unsigned char CTR asm("r18");
```

Notice you will get a warning "call-clobbered register used for global register variable [enabled by default]" depending on the register you use.