

Embedded Software Fundamentals

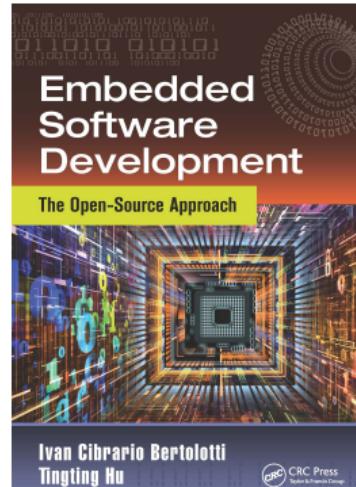
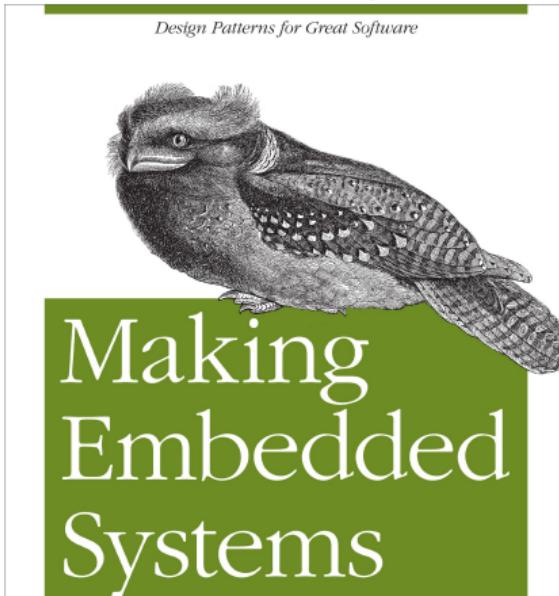
How does code get converted into ones and zeroes?

Kizito NKURIKIYEZU, Ph.D.

Reading material

Read the following resources available on the course platforms

- 1 Chapter 1 of White, E. (2011). *Making Embedded Systems: Design Patterns for Great Software.* " O'Reilly Media, Inc.".
- 2 Chapter 3 of Bertolotti, I. C., & Hu, T. (2017). *Embedded Software Development.* Amsterdam University Press.



Components of embedded software development

- Host Machine
- Development Environments
- Compiler Toolchain
- Debuggers
- Development Kits
- Version Control

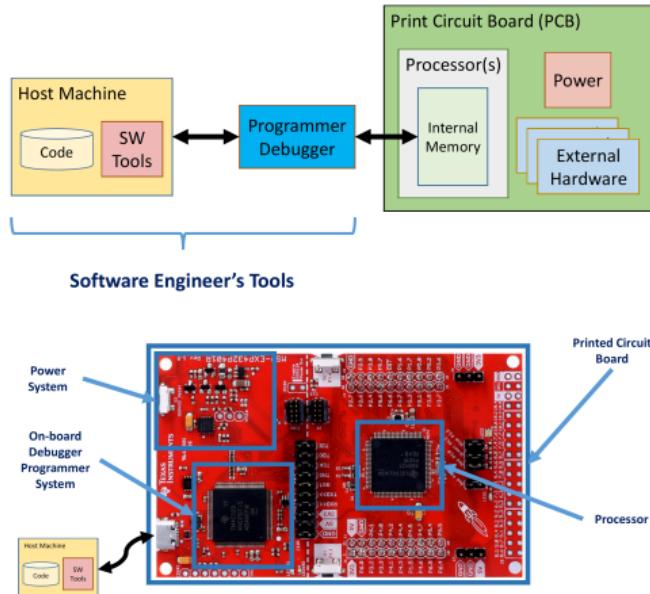


FIG 1. Components of an embedded development

Modules of a typical embedded software

- The software is organized in layers
- Each layer assumes specific functionality
- Modules are described in C-files (.c)
- Definitions are described in header files (.h)
- Functions interact with other modules
- Eventually interact with Hardware

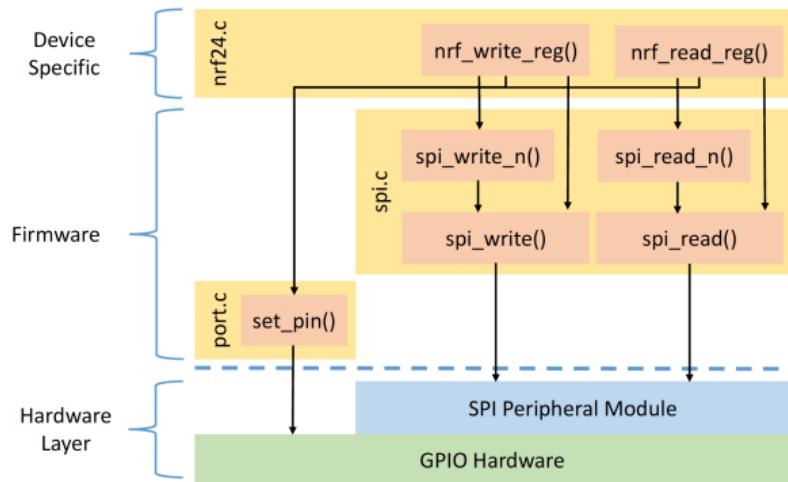
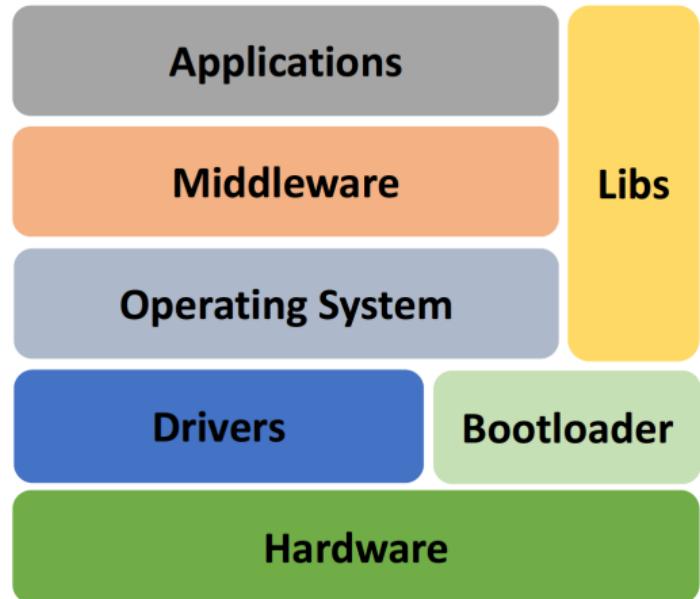


FIG 2. Layers of an embedded system software

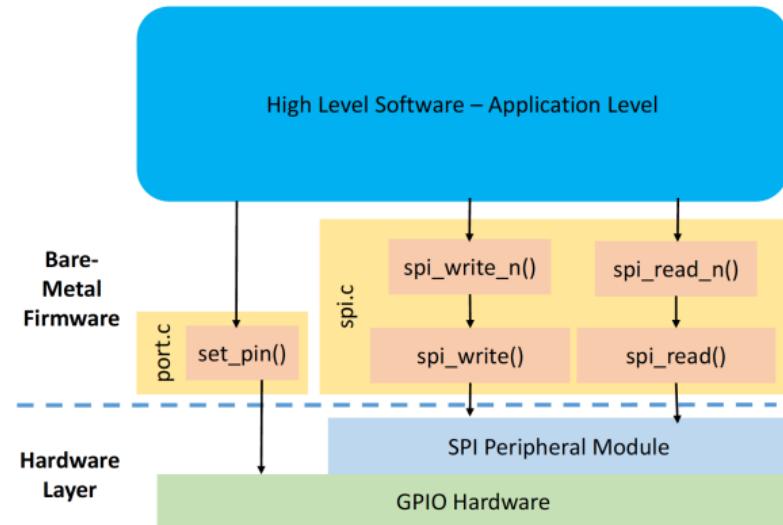
Embedded system software in layers

- Device Drivers
 - Interface to hardware layers
 - Hardware Abstraction Layer (HAL)
- Code Booting
- Real-time operation system (RTOS)
 - Abstracts High from Low levels
 - Scheduling
 - Resource management
- Libraries for shared code



Hardware Abstraction

- Low level and bare-Metal Firmware
- Hardware Abstraction Layer
- Platform Independence
- High quality and portable software
 - Maintainable
 - Testable
 - Portable
 - Robust
 - Efficient
 - Consistent



Embedded programming languages

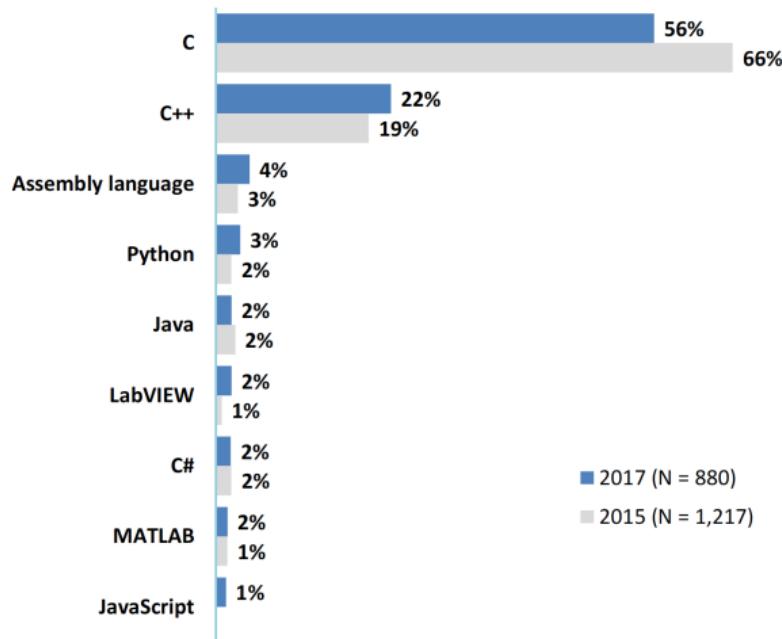


FIG 3. Top embedded programming languages

ASPENCORE. (2017). 2017 Embedded Markets Study Integrating IoT and Advanced Technology Designs, Application Development & Processing Environments. April, 1–102.

Why C?

- Availability of compilers for almost any MCU
- Small executable
- Deterministic resource use (e.g., no dynamic memory allocation)
- Efficient Memory Management
- Timing-centric operations
- Direction Hardware/IO Control
- Optimized execution
- **Note:** Modern C++ is as efficient as C and I believe it will slowly replace C in the future.

For details see **Kormanyos, C. (2018).**

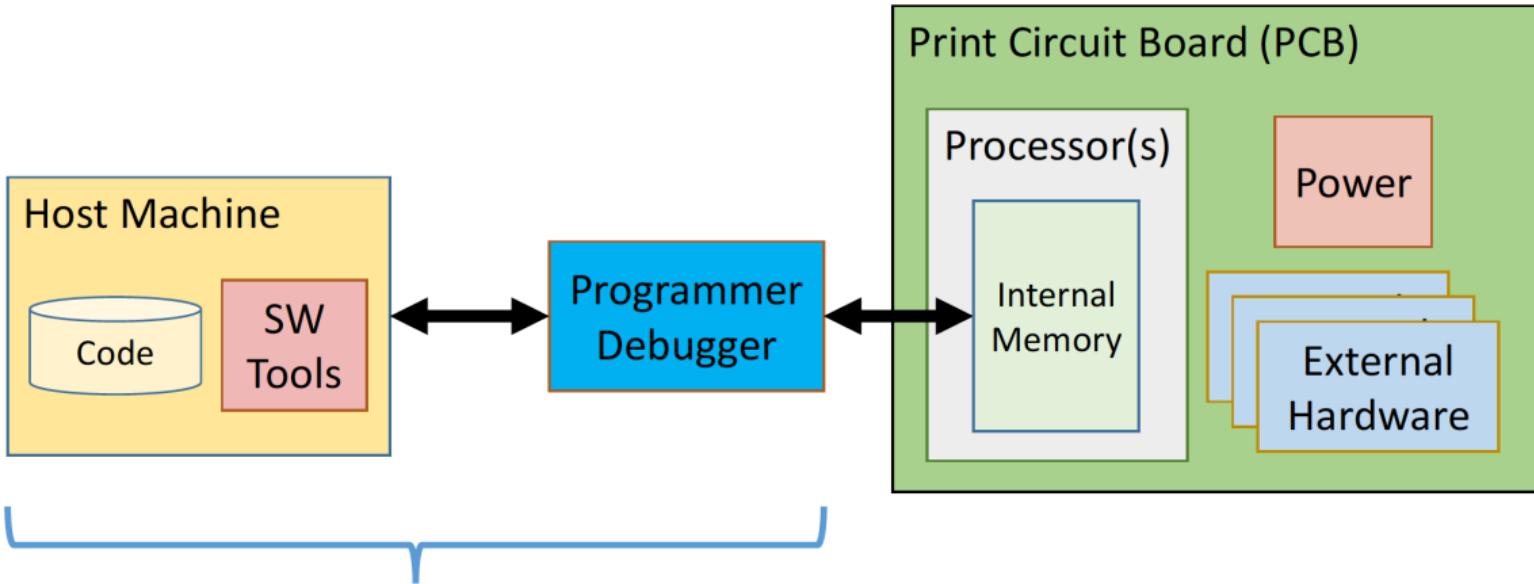
Real-time C++: efficient object-oriented and template microcontroller programming



FIG 4. C can be used even on very small micro-controllers

The ATTiny20-UUR is an AVR micro-controller that is smaller than a grain of rice. It is an 8-Bit IC that runs at 12MHz 2KB (1K x 16) FLASH and 12-WLCSP (1.56x1.4)

Embedded software development process



Software Engineer's Tools

FIG 5. Embedded System Development Platform

The host machine contains the build environment for an embedded system. It contains a cross compiler and a cross debugger. The debug allows communication between the target processor through a special processor interface, the JTAG

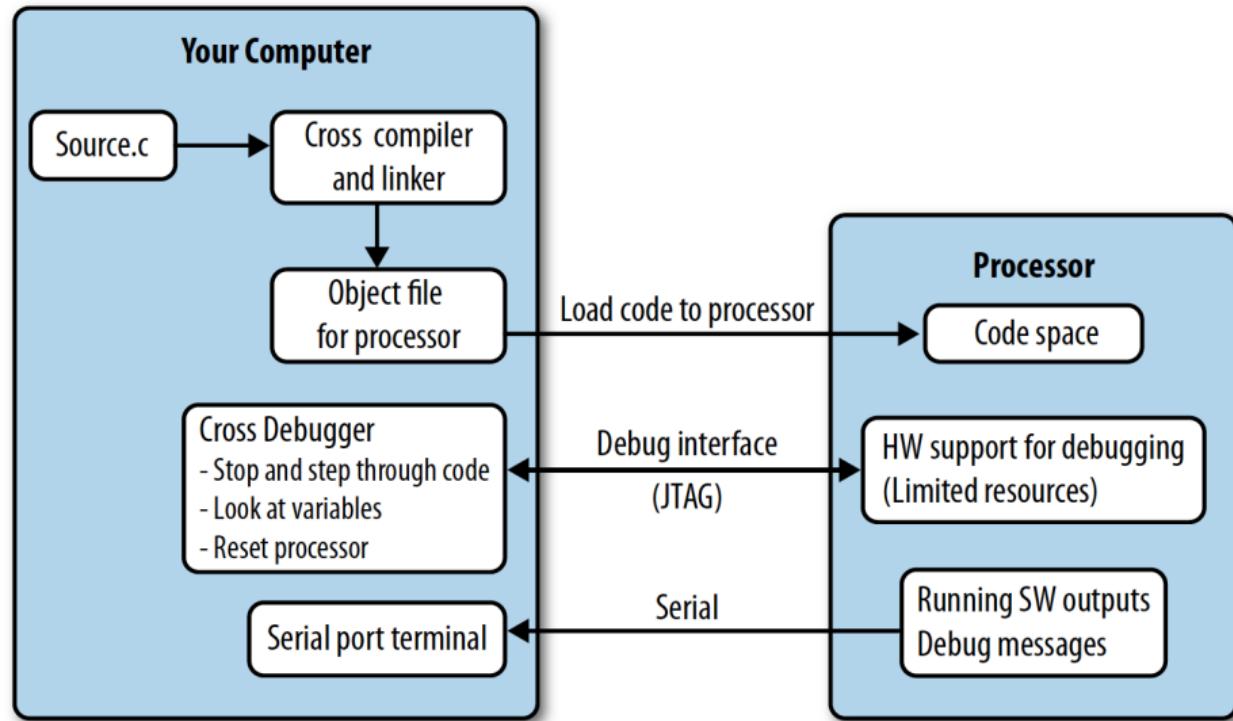


FIG 6. Computer and target processor

Source Files usually
mostly in High Level
Languages

Compiler Toolchain

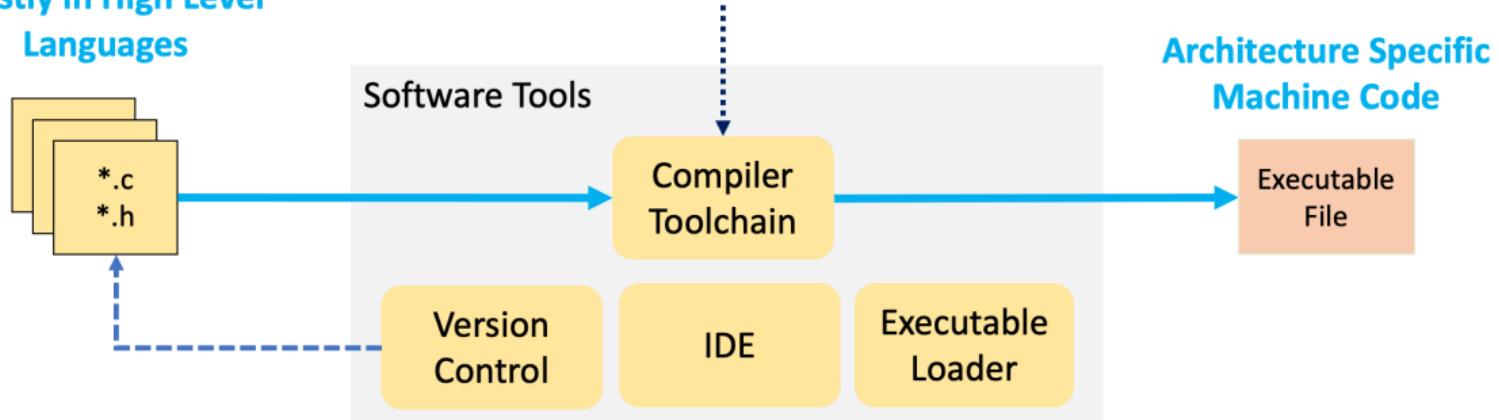


FIG 7. Software tools

The software tools include compiler toolchain (e.g., AVR GCC, gdb make files), linker, emulators, simulators, SDK, text editors/IDE, version control, etc

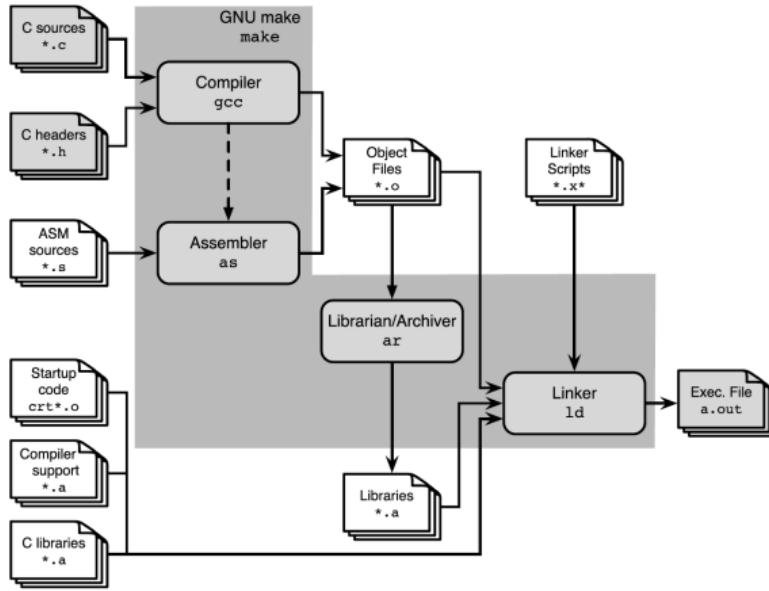
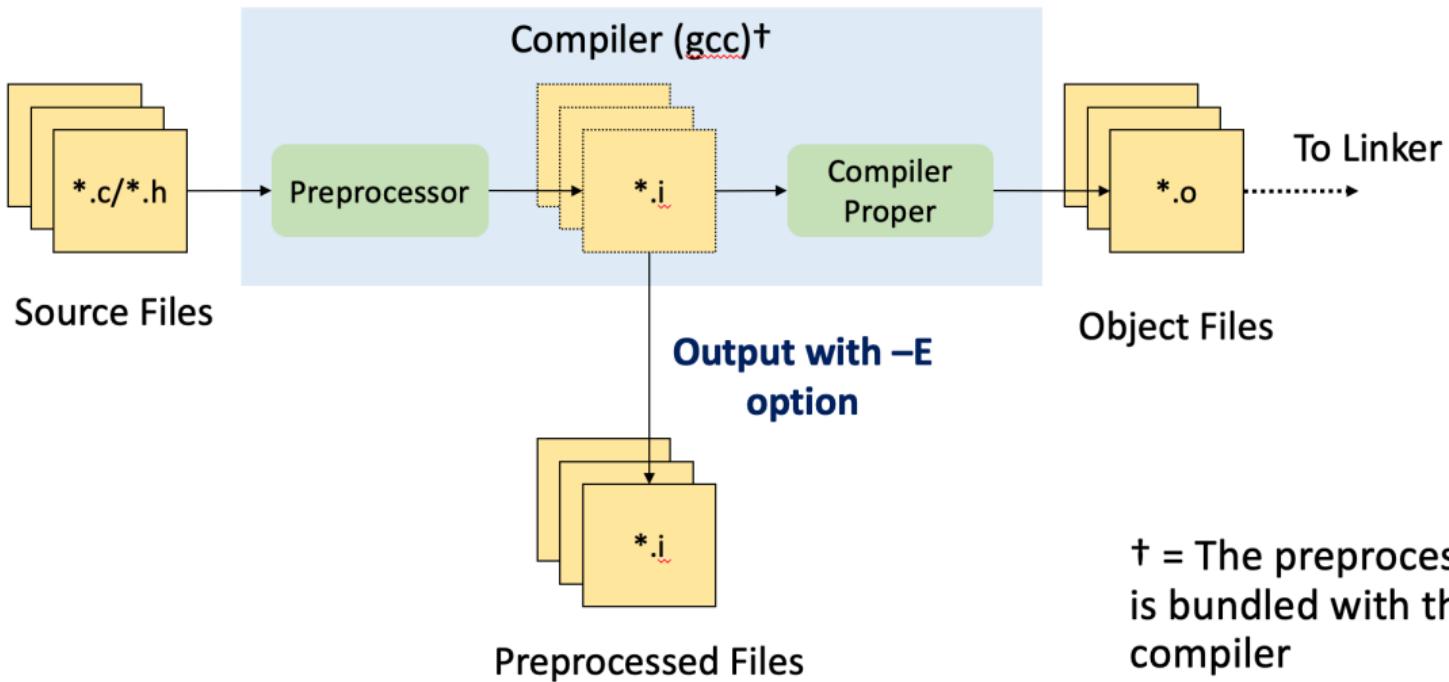


FIG 8. Detailed embedded C compilation process

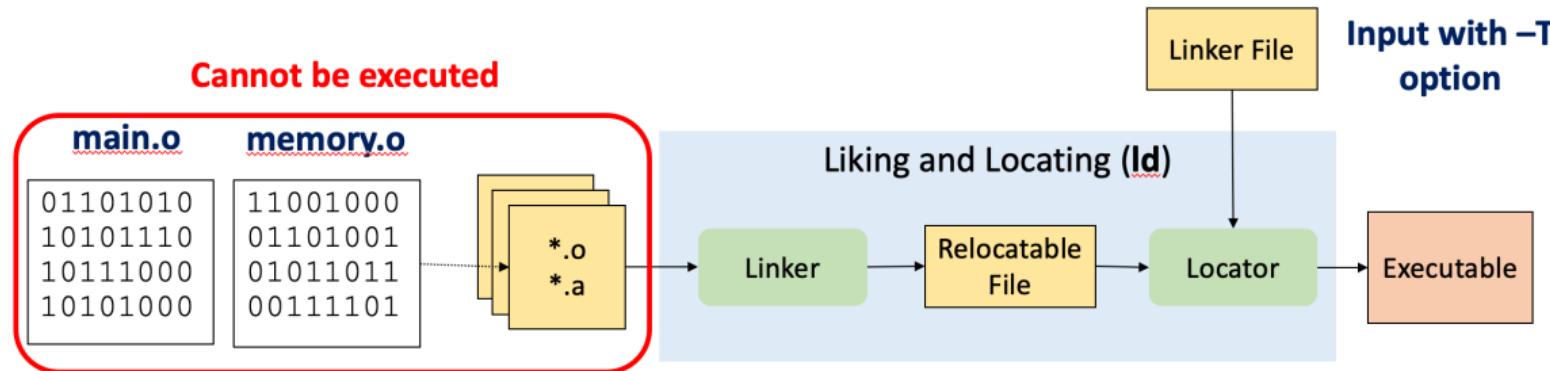
The C preprocessor transform the program before actual compilation. The compiler translate the source code into opcode (object files) for the target processor. The linker combine these object files and resolve all of the unresolved symbols. The locator assign physical memory addresses to each of the code and data and produce an output file containing a binary memory image that can be loaded into the target ROM.



^t = The preprocessor is bundled with the compiler

FIG 9. The role of a preprocessor

The C preprocessor is the macro preprocessor for the C compiler. The preprocessor provides the ability for the inclusion of header files, macro expansions, conditional compilation, and line control.



Invoke the linker indirectly from compiler (and with no options)

```
$ gcc -o main.out main.c
```

FIG 10. The role of a linker

The linker combines all of objects files into a single executable object code uses symbols to reference other functions/variables

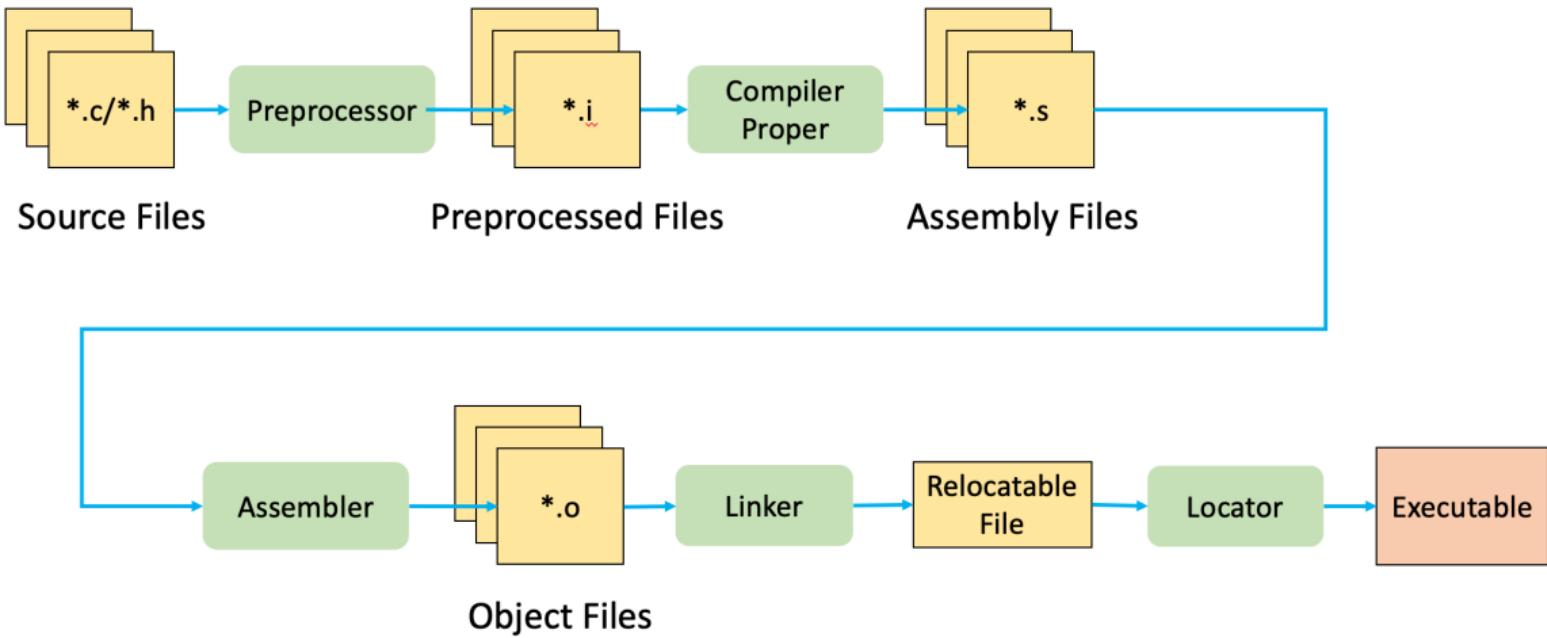
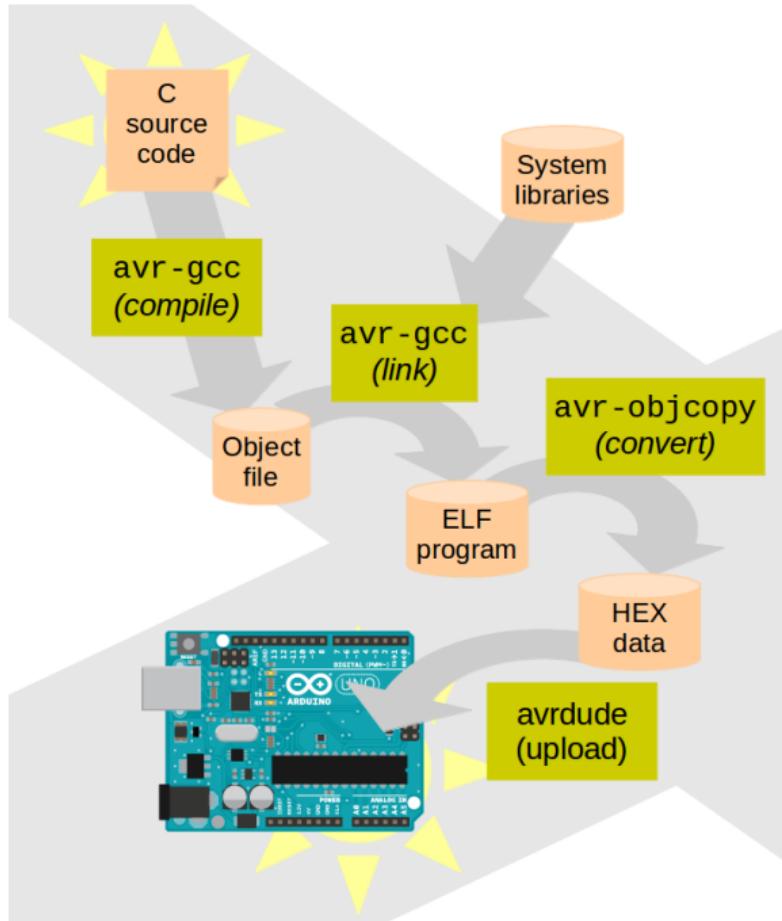


FIG 11. Linear detailed embedded C compilation process

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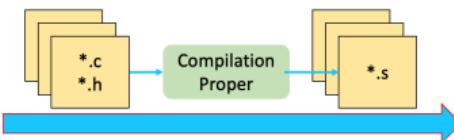
Introduction to Build Systems using AVR GNU Toolsets

Translation of C code into machine code

```
#include <avr/io.h>
int main (void){
    DDRB |= _BV(DDB0);
    while(1) {
        PORTB ^= _BV(PB0);
        _delay_ms(500);
    }
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```

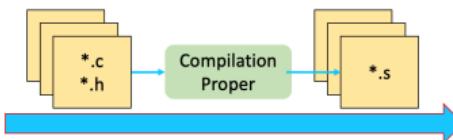
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:0C000000B89A91E088B38
:00000001FF

Translation of C code into machine code

GCC compiles a C/C++ program into executable in 4 steps:

- 1 **Pre-processing**—via the AVR GNU C Preprocessor (`avr-cpp`), which includes the headers (`#include`) and expands the macros (`#define`).

```
avr-cpp -mmcu=attiny13 blink.c > blink.i
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The resultant intermediate file `blink.i` contains the expanded source code.

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The *-S* option specifies to produce assembly code, instead of object code. The resultant assembly file is "blink.s".

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- 3 **Assembly** —the assembler (`avr-as`) converts the assembly code into machine code in the object file "hello.o".

```
avr-as -o blink.o blink.s
```

Translation of C code into machine code

- 4 Linker: Finally, the linker links the object code with the library code to produce an executable and linkable format (.elf) file "blink.elf".

```
avr-gcc blink.o -o blink.elf
```

This generates an .elf file isn't directly executable by the MCU. Thus, one needs to extract the machine code from it in the Intel Hex format

```
avr-objcopy -O ihex -R .eeprom blink.elf blink.ihex
```

Notes:

- You can see the detailed compilation process by enabling -v (verbose) option.
For example,

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avr-gcc -v -mmcu=attiny13 -o blink.bin blink.c
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- You should always enable optimization with the -Os parameter

```
avr-gcc -v -Os -mmcu=attiny13 -save-temp blink.c
```

Building automation

The need for building automation

- Building can be tedious
 - Many GCC flags
 - Many independent commands
 - Many build targets
 - Many supported architectures
 - Many source files
- Building manually can cause consistency issues waste development time
- Real world software is complex. For example, the Linux kernel contains:

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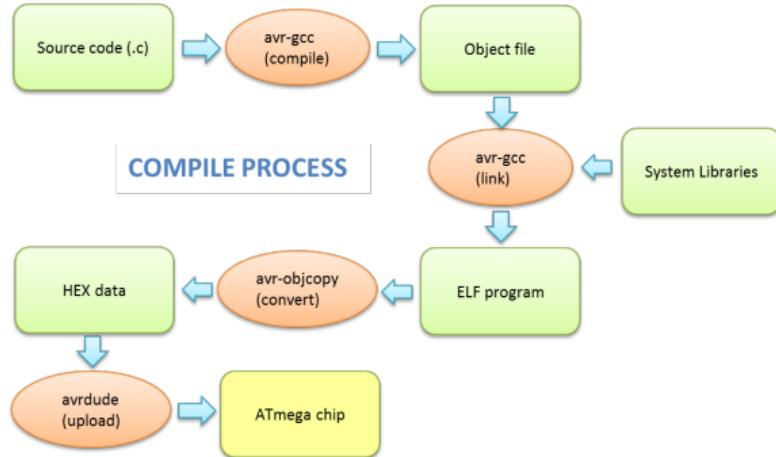
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Why use an automatic build system?

Build Management Software (or Build Automation) provides a simple and consistent method for producing a target executable

Build Management Software

- Automated the process of
 - Preprocessing
 - Assembling
 - Compiling
 - Linking
 - Relocating
 - Upload the machine code to the microcontroller
- GNU Toolset performs all operations using make
- Real world make files are complex¹, but are often preferred to using IDE²



¹https://www.gnu.org/software/make/manual/html_node/Complex-Makefile.html

²<https://www.embeddedrelated.com/showthread/comp.arch.embedded/252000-1.php>

Example make file

```
FILENAME      = blink
PORT         = /dev/cu.usbserial-00000000
DEVICE        = attiny13
PROGRAMMER    = arduino
BAUD          = 115200
COMPILE       = avr-gcc -Wall -Os -mmcu=$(DEVICE)

default: compile upload clean

compile:
    $(COMPILE) -c $(FILENAME).c -o $(FILENAME).o
    $(COMPILE) -o $(FILENAME).elf $(FILENAME).o
    avr-objcopy -j .text -j .data -O ihex $(FILENAME).elf $(FILENAME).hex
    avr-size --format=avr --mcu=$(DEVICE) $(FILENAME).elf

upload:
    avrdude -v -p $(DEVICE) -c $(PROGRAMMER) -P $(PORT) -b $(BAUD) -U flash:w:$(FILENAME).elf

clean:
    rm $(FILENAME).o
    rm $(FILENAME).elf
    rm $(FILENAME).hex
```