EE3220 System-on-Chip Design

Lecture Note 6

C as Implemented in Assembly Language

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Overview

- We program in C for convenience
- There are no MCUs which execute C, only machine code
- So we compile the C to assembly code, a human-readable representation of machine code
- We need to know what the assembly code implementing the C looks like
  - To use the processor efficiently
  - To analyze the code with precision
  - To find performance and other problems
- An overview of what C gets compiled to
  - C start-up module, subroutines calls, stacks, data classes and layout, pointers, control flow, etc.

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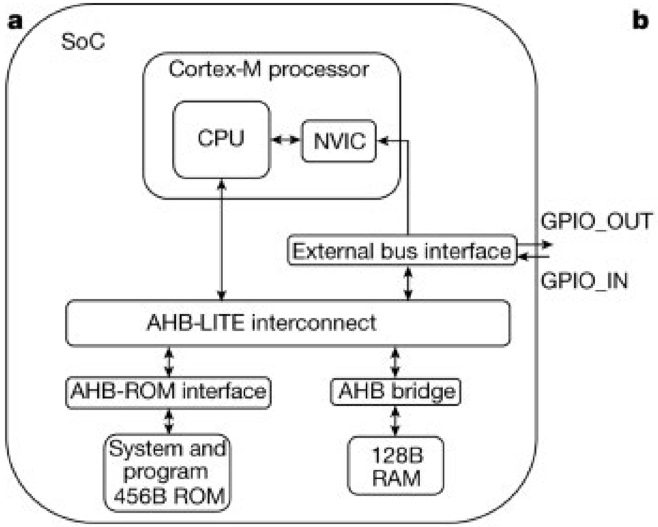
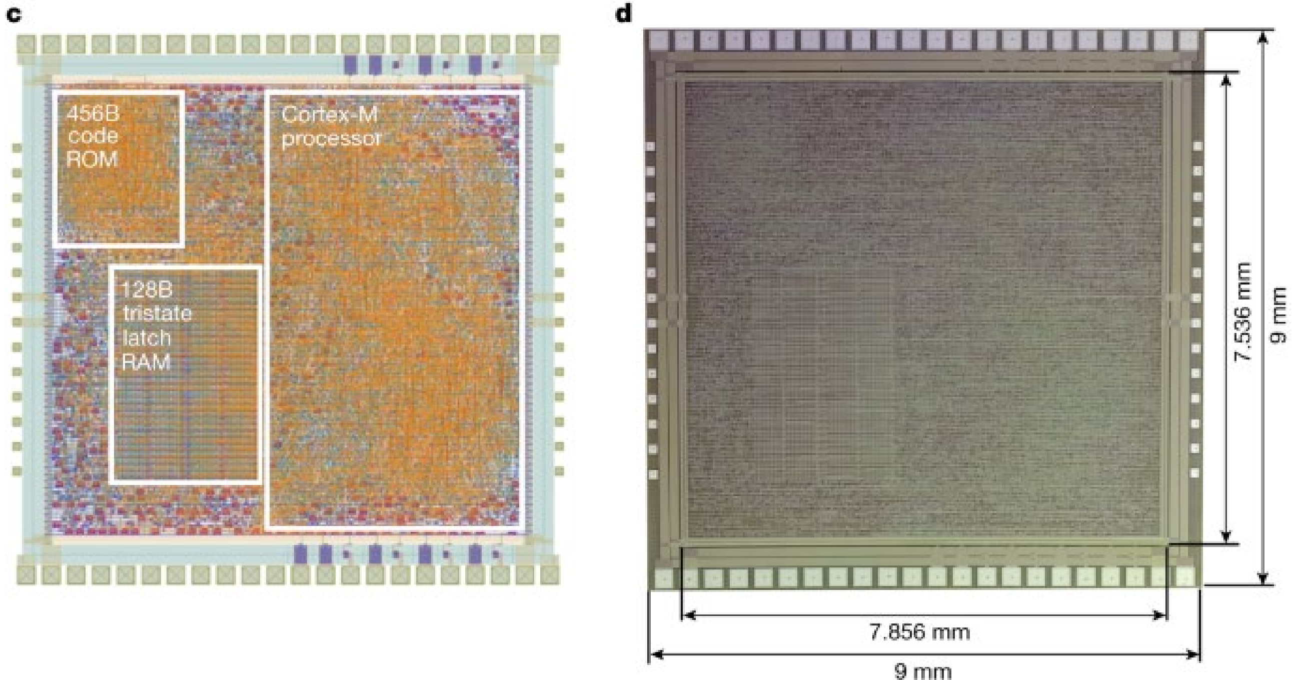
nature 2021: A natively flexible 32-bit ARM microprocessor

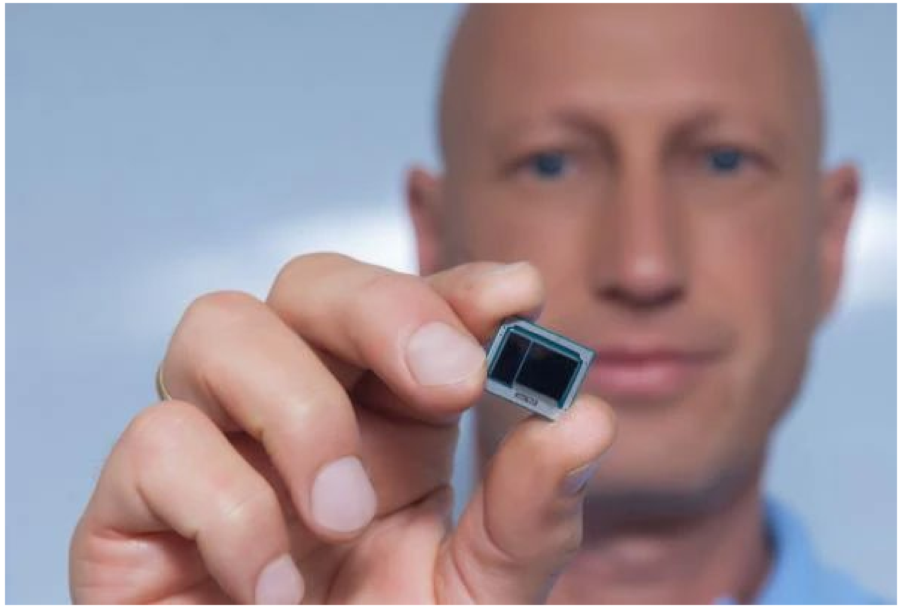


b

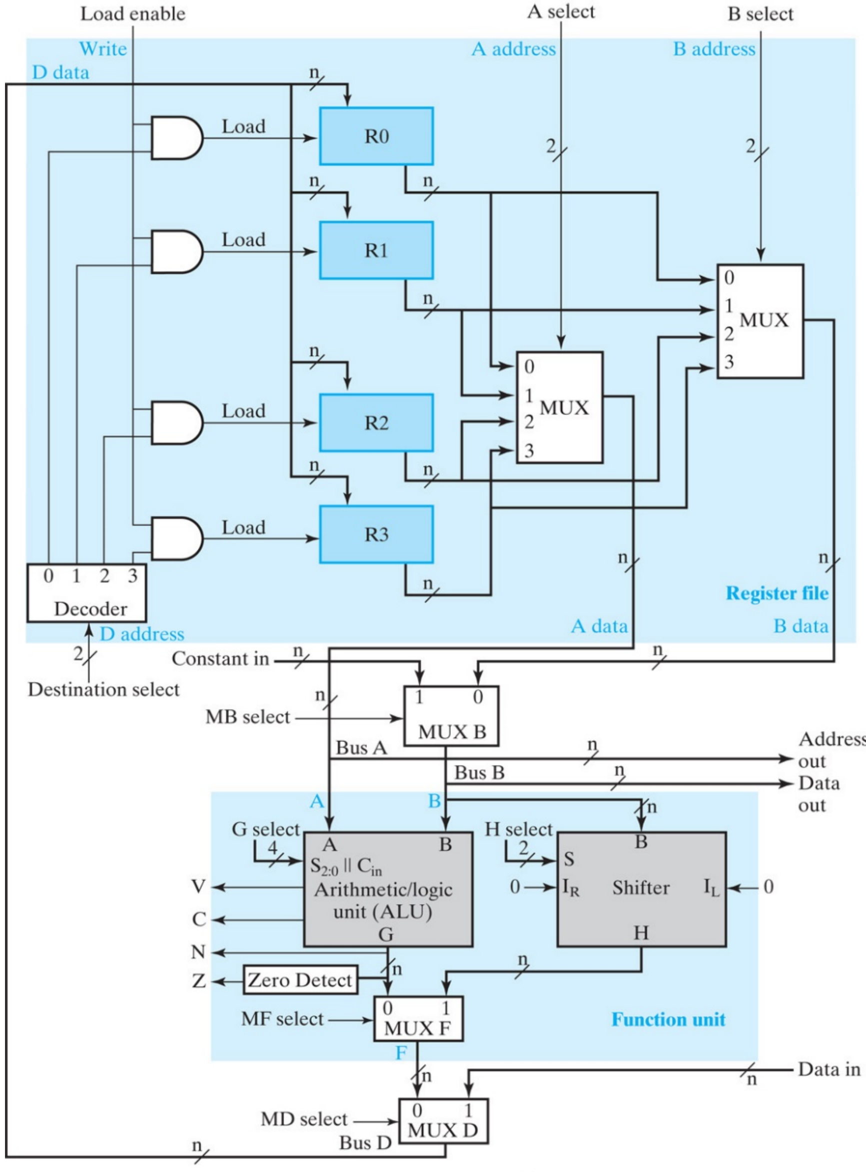
Features	Cortex-M0+ CPU	Cortex-M CPU in PlasticARM
Processor architecture	ARMv6-M	ARMv6-M
Instruction set architecture	16-bit Thumb and a subset of 32-bit Thumb	16-bit Thumb and a subset of 32-bit Thumb
Data and address width	32	32
Number of instructions	86	86
Pipeline	2-stage	2-stage
Architectural register file	Inside the CPU	Mapped to RAM external to the CPU
Binary compatibility	Can run code from other Cortex-M CPUs	Can run code from other Cortex-M CPUs including Cortex-M0+

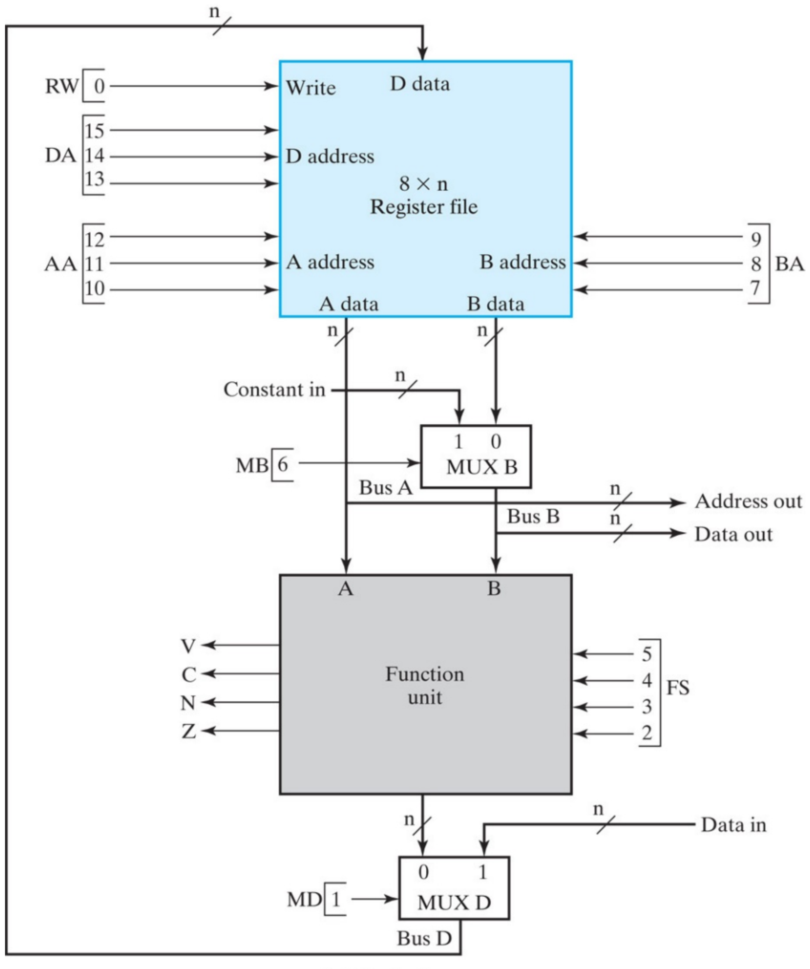


- https://www.nature.com/articles/s41586-021-03625-w
- https://www.intel.com/content/www/us/en/history/museum-story-of-intel-4004.html

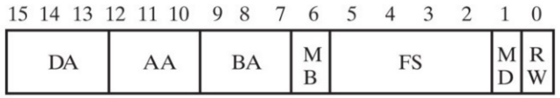


Typical CPU Datapath & Assembly Code





(a) Block diagram



(b) Control word

TABLE 8-6
Examples of Microoperations for the Datapath, Using Symbolic Notation

Micro-operation	DA	AA	BA	MB	FS	MD	RW
$R1 \leftarrow R2 - R3$	$R1$	$R2$	$R3$	Register	$F = A + \overline{B} + 1$	Function	Write
$R4 \leftarrow$ sl R6	$R4$	—	$R6$	Register	$F =$ sl B	Function	Write
$R7 \leftarrow R7 + 1$	$R7$	$R7$	—	—	$F = A + 1$	Function	Write
$R1 \leftarrow R0 + 2$	$R1$	$R0$	—	Constant	$F = A + B$	Function	Write
Data out $\leftarrow R3$	—	—	$R3$	Register	—	—	No Write
$R4 \leftarrow$ Data in	$R4$	—	—	—	—	Data in	Write
$R5 \leftarrow 0$	$R5$	$R0$	$R0$	Register	$F = A \oplus B$	Function	Write

TABLE 8-7
Examples of Microoperations from Table 8-6, Using Binary Control Words

Micro-operation	DA	AA	BA	MB	FS	MD	RW
$R1 \leftarrow R2 - R3$	001	010	011	0	0101	0	1
$R4 \leftarrow$ sl R6	100	XXX	110	0	1110	0	1
$R7 \leftarrow R7 + 1$	111	111	XXX	X	0001	0	1
$R1 \leftarrow R0 + 2$	001	000	XXX	1	0010	0	1
Data out $\leftarrow R3$	XXX	XXX	011	0	XXXX	X	0
$R4 \leftarrow$ Data in	100	XXX	XXX	X	XXXX	1	1
$R5 \leftarrow 0$	101	000	000	0	1010	0	1

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Programmer's World: The Land of Chocolate!

- As many functions and variables as you want!
- All the memory you could ask for!
- So many data types! Integers, floating point,
- So many data structures! Arrays, lists, trees, sets, dictionaries
- So many control structures! Subroutines, if/then/else, loops, etc.
- Iterators! Polymorphism!

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Processor's World

- Data types
  - Integers
  - More if you're lucky!
- Instructions
  - Math: +, -, *
  - Logic: and, or
  - Shift, rotate
  - Move, swap
  - Compare
  - Jump, branch

23	251	151	11	3	l	l	l
213	6	234	2	u	l	l	l
2	33	72	l	a	l	l	a
a	4	h	e	l	l	o	l
67	96	a	0	9	9	9	l
6	11	d	72	7	0	0	0
28	289	37	54	42	0	0	0
213	6	234	2	31	l	l	l

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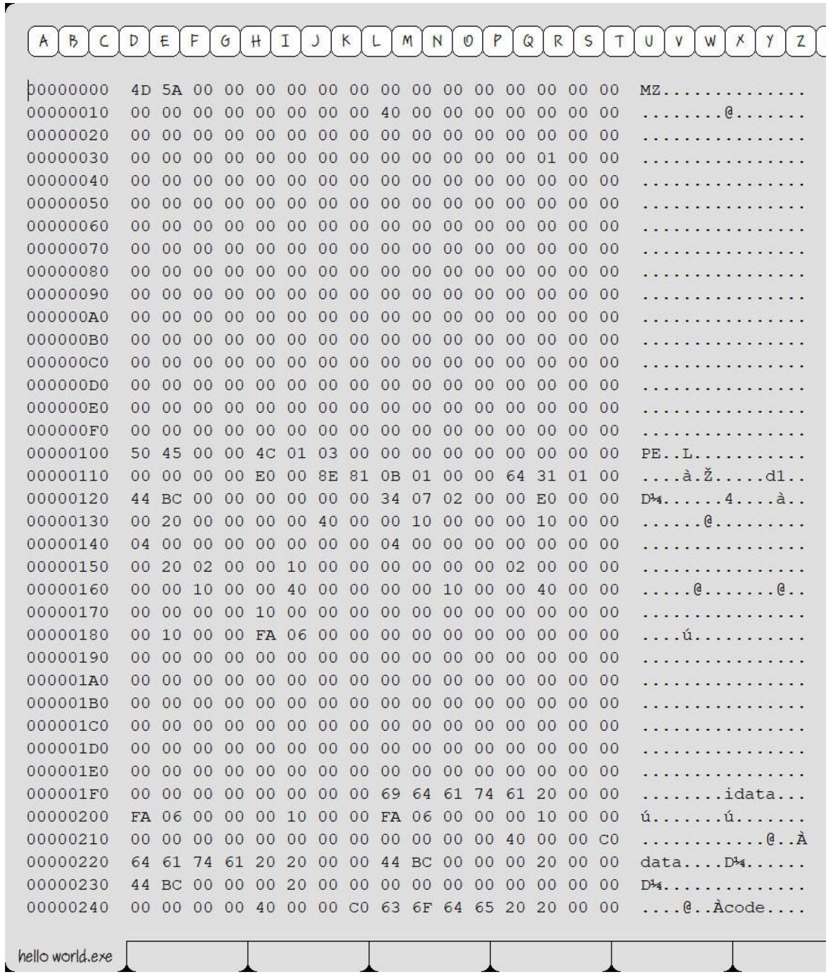
Compiler Stages

- Parser
  - reads in C code,
  - checks for syntax errors,
  - forms intermediate code (tree representation)
- High-Level Optimizer
  - Modifies intermediate code (processor-independent)
- Code Generator
  - Creates assembly code step-by-step from each node of the intermediate code
  - Allocates variable uses to registers
- Low-Level Optimizer
  - Modifies assembly code (parts are processor-specific)
- Assembler
  - Creates object code (machine code)
- Linker/Loader
  - Creates executable image from object file

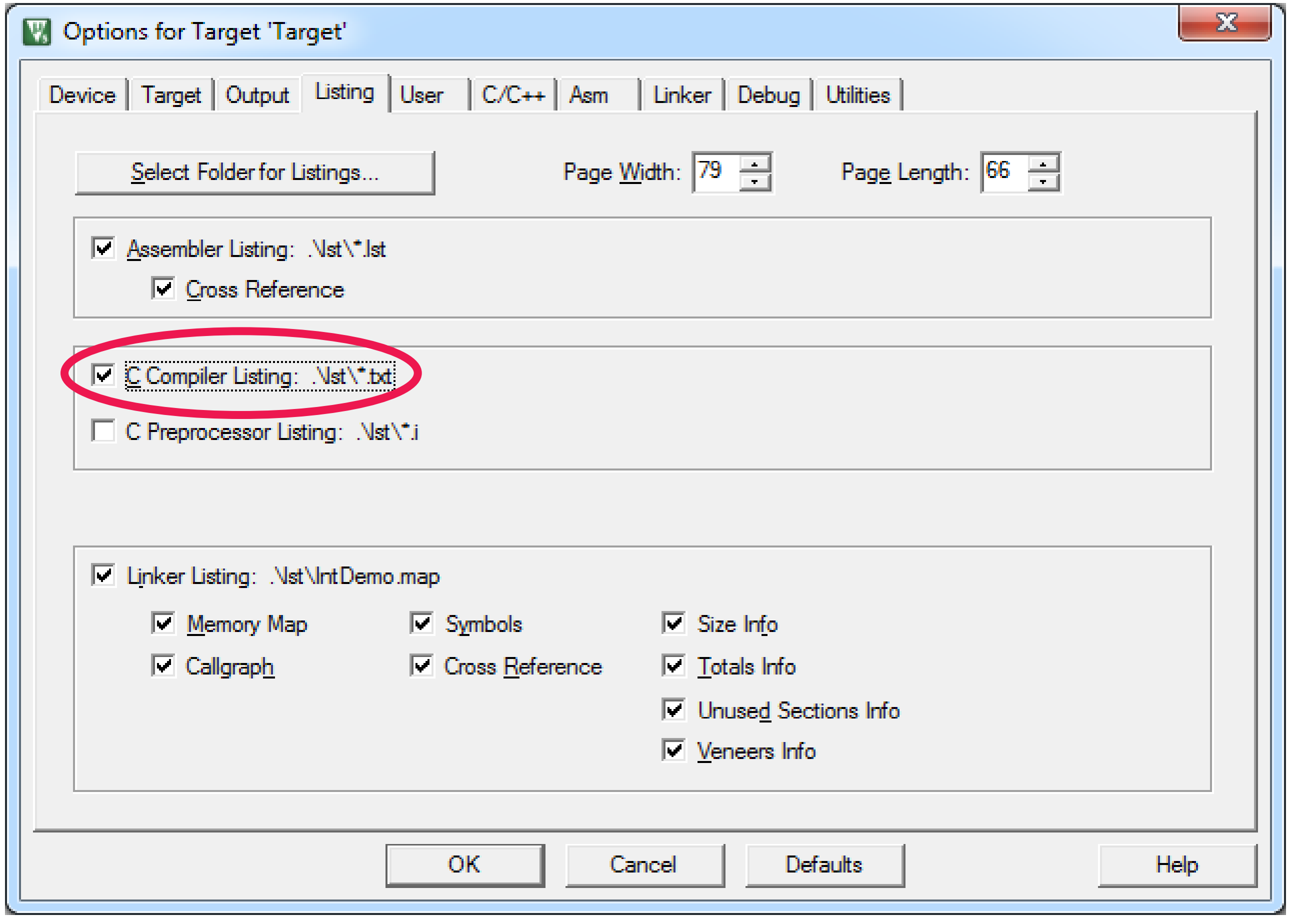
Compilation Flow

- Pre-processor
  - Convert .c / .cpp file into expanded source code, with .h header files
- Compiler
  - Generate the compiled assembly code in .s format
- Assembler
  - Generate the machine readable object code in .o / .obj format
- Linker
  - Produce a machine executable file in .exe / a.out / other binary format
  - More advanced topics include: Macros, Directives, and etc.



Examining Assembly Code before Debugger

- Compiler can generate assembly code listing for reference
- Select in project options



Examining Disassembled Program in Debugger

```c
#include "project.h"
#include "data.h"

int main(void)
{
    arrays(2, 4);
    fun4(1,2000,3);
    static_auto_local();

    while (1)
      ;
}

// *********************************ARM Univ
```

```
0x00000208 D2F9      BCS       0x000001FE
0x0000020A BD70      POP       {r4-r6,pc}
     6:                  arrays(2, 4);
0x0000020C 2104      MOVS      r1,#0x04
0x0000020E 2002      MOVS      r0,#0x02
0x00000210 F000F858  BL.W      arrays (0x000002C4)
     7:                  fun4(1,2000,3);
0x00000214 2203      MOVS      r2,#0x03
0x00000216 217D      MOVS      r1,#0x7D
0x00000218 0109      LSLS      r1,r1,#4
0x0000021A 2001      MOVS      r0,#0x01
0x0000021C F000F88D  BL.W      fun4 (0x0000033A)
     8:                  static_auto_local();
     9:
0x00000220 F000F802  BL.W      static_auto_local (0x00000228)
    10:                  while (1)
0x00000224 BF00      NOP
0x00000226 E7FE      B         0x00000226
```

A Word on Code Optimizations

- Compiler and rest of tool-chain try to optimize code:
  - Simplifying operations
  - Removing "dead" code
  - Using registers

- These optimizations often get in way of understanding what the code does
  - Fundamental trade-off: Fast or comprehensible code?
  - Compiler optimization levels: Level 0 to Level 3

- Code examples here may use "volatile" data type modifier to reduce compiler optimizations and improve readability

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Application Binary Interface

- Defines rules which allow separately developed functions to work together
- ARM Architecture Procedure Call Standard (AAPCS)
  - Which registers must be saved and restored
  - How to call procedures
  - How to return from procedures
- C Library ABI (CLIBABI)
  - C Library functions
- Run-Time ABI (RTABI)
  - Run-time helper functions: 32/32 integer division, memory copying, floating-point operations, data type conversions, etc.

Arm® Compiler

Version 6.9

Arm C and C++ Libraries and Floating-Point Support User Guide

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ARM Architecture Procedure Call Standard

- The AAPCS defines how subroutines can be separately written, separately compiled, and separately assembled to work together.
- https://developer.arm.com/documentation/ihi0042/j/

Procedure Call Standard for the Arm Architecture

Release 2020Q2

Document number: IHI 0042J

Arm Ltd

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Using Registers

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AAPCS Register Use Conventions

- Make it easier to create modular, isolated and integrated code
- Scratch registers are not expected to be preserved upon returning from a called subroutine
  - A register used to hold an intermediate value during a calculation (usually, such values are not named in the program source and have a limited lifetime).
  - r0-r3
- Preserved ("variable") registers (v-register) are expected to have their original values upon returning from a called subroutine
  - A register used to hold the value of a variable, usually one local to a routine, and often named in the source code.
  - r4-r8, r10-r11

AAPCS Core Register Use

Register	Synonym	Special	Role in the procedure call standard
r15		PC	The Program Counter.
r14		LR	The Link Register.
r13		SP	The Stack Pointer.
r12		IP	The Intra-Procedure-call scratch register.
r11	v8		Variable-register 8.
r10	v7		Variable-register 7.
r9		v6,SB,TR	Platform register. The meaning of this register is defined by the platform standard.
r8	v5		Variable-register 5.
r7	v4		Variable register 4.
r6	v3		Variable register 3.
r5	v2		Variable register 2.
r4	v1		Variable register 1.
r3	a4		Argument / scratch register 4.
r2	a3		Argument / scratch register 3.
r1	a2		Argument / result / scratch register 2.
r0	a1		Argument / result / scratch register 1.

Must be saved, restored by callee-procedure it may modify them.

Must be saved, restored by callee-procedure it may modify them.
Calling subroutine expects these to retain their value.

Don't need to be saved. May be used for arguments, results, or temporary values.

Memory requirements

What Memory Does a Program Need?

```
int a, b;
const char c=123;
int d=31;
void main(void) {
   int e;
   char f[32];
   e = d + 7;
   a = e + 29999;
   strcpy(f,“Hello!”);
}
```

- Five possible types
  - Code
  - Read-only static data
  - Writable static data
  - Initialized
  - Zero-initialized (Memory that's initialized to zero)
  - Uninitialized
  - Heap
  - Stack
- What goes where?
  - Code is obvious
  - And the others?

What Memory Does a Program Need?

```
int a, b;
const char c=123;
int d=31;
void main(void) {
   int e;
   char f[32];
   e = d + 7;
   a = e + 29999;
   strcpy(f,“Hello!”);
}
```

- Can the information change?
  - No? Put it in read-only, nonvolatile memory
  - Instructions
  - Constant strings
  - Constant operands
  - Initialization values
  - Yes? Put it in read/write memory
  - Variables
  - Intermediate computations
  - Return address
  - Other housekeeping data

What Memory Does a Program Need?

```
int a, b;
const char c=123;
int d=31;
void main(void) {
   int e;
   char f[32];
   e = d + 7;
   a = e + 29999;
   strcpy(f,"Hello!");
}
```

- How long does the data need to exist? Reuse memory if possible.
  - Statically allocated
  - Exists from program start to end
  - Each variable has its own fixed location
  - Space is not reused
  - Automatically allocated
  - Exists from function start to end
  - Space can be reused
  - Dynamically allocated
  - Exists from explicit allocation to explicit deallocation
  - Space can be reused

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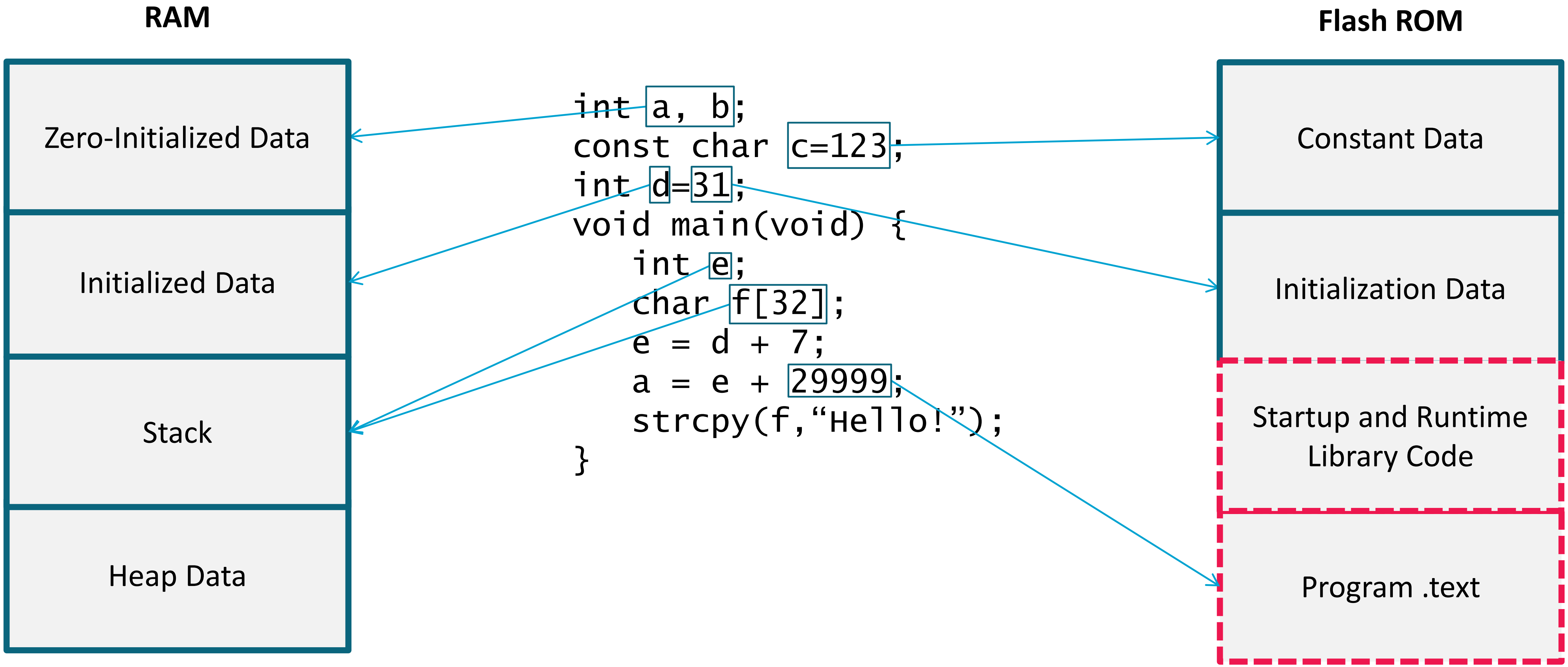
Program Memory Use



Activation Record

- Activation records are located on the stack
  - Calling a function creates an activation record
  - Returning from a function deletes the activation record

- Automatic variables and housekeeping information are stored in a function's activation record

Lower address		(Free stack space)	
	Activation record for current function	Local storage	<- Stack ptr
		Return address	
		Arguments	
	Activation record for caller function	Local storage	
		Return address	
		Arguments	
	Activation record for caller's caller function	Local storage	
		Return address	
		Arguments	
Higher address	Activation record for caller's caller's caller function	Local storage	
		Return address	
		Arguments	

- Not all fields (LS, RA, Arg) may be present for each activation record

Type and Class Qualifiers

- Const
  - Never written by program, can be put in ROM to save RAM
- Volatile
  - Can be changed outside of normal program flow: ISR, hardware register
  - Compiler must be careful with optimizations
  - https://www.ibm.com/support/knowledgecenter/en/ssw_ibm_i_71/rzarg/volatile_type_qualifier.htm
- Static
  - Declared within function, retains value between function invocations
  - Scope is limited to function

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Linker Map File

- Contains extensive information on functions and variables
  - Value, type, size, object
- Cross references between sections
- Memory map of image
- Sizes of image components
- Summary of memory requirements

```
Linker script and memory map

.text               0x0000000000001000
 ***(.isr_vector)**
 .isr_vector        0x0000000000001000
                    0x0000000000001000
 *(.text*)
 .text              0x0000000000001200
 .text              0x0000000000001240
                    0x0000000000001240
                    0x0000000000001240
 .text              0x00000000000012b4
                    0x00000000000012b4
                    0x00000000000012dc
```


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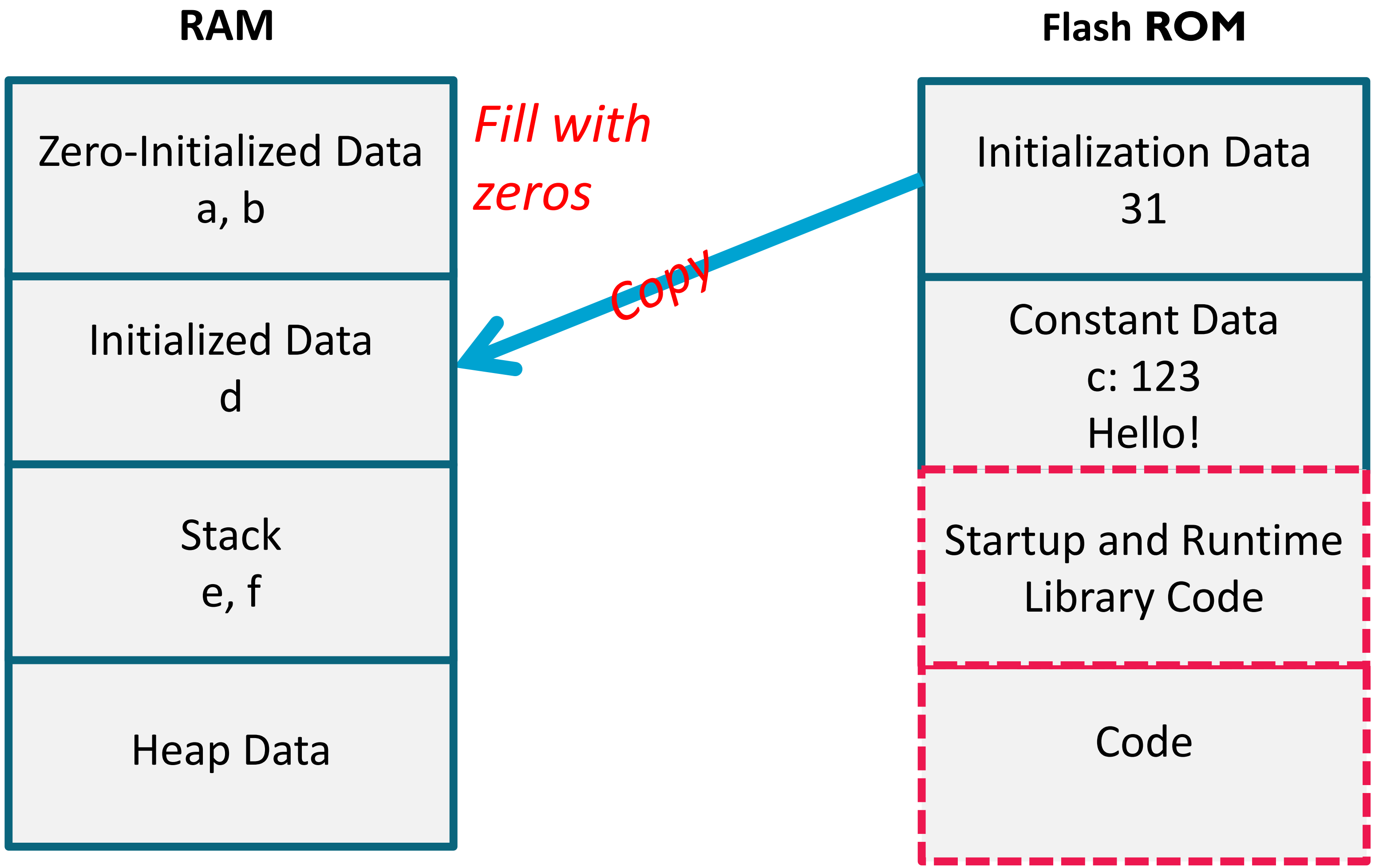
C Run-Time Start-Up Module

- After reset, MCU must…
- Initialize hardware
  - Peripherals, etc.
  - Set up stack pointer
- Initialize C or C++ run-time environment
  - Set up heap memory
  - Initialize variables



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Accessing data in Memory

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Accessing Data

- What does it take to get at a variable in memory?
  - Depends on location, which depends on storage type (static, automatic, dynamic)

```
int siA;
void static_auto_local() {
        int aiB;
        static int siC=3;
        int * apD;
        int aiE=4, aiF=5, aiG=6;

        siA = 2;
        aiB = siC + siA;
        apD = & aiB;
        (*apD)++;
        apD = &siC;
        (*apD) += 9;
        apD = &siA;
        apD = &aiE;
        apD = &aiF;
        apD = &aiG;
        (*apD)++;
        aiE+=7;
        *apD = aiE + aiF;
}
```

Static Variables

- Static var can be located anywhere in 32-bit memory space, so need a 32-bit pointer
- Can't fit a 32-bit pointer into a 16-bit instruction (or a 32-bit instruction), so save the pointer separate from instruction, but nearby so we can access it with a short PC-relative offset
- Load the pointer into a register (r0)
- Can now load variable's value into a register (r1) from memory using that pointer in r0
- Similarly can store a new value to the variable in memory

```
Load r0 with pointer to variable
Load r1 from [r0]
Use value of variable

Label:
32-bit pointer to Variable





Variable
```


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Static Variables

- Key
  - variable's value
  - variable's address
  - address of copy of variable's address
- Addresses of siA and siC are stored as literals to be loaded into pointers
- Variables siC and siA are located in .data section with initial values

DCD typically refers to Define Constant Double-word

```
AREA ||.text||, CODE, READONLY, ALIGN=2
;;;20            siA = 2;
00000e  2102  MOVS     r1,#2         ; r1 = 2
000010  4a37  LDR      r2,|L1.240|   ; r2 = &siA
000012  6011  STR      r1,[r2,#0]    ; *r2 = r1
;;;21          aiB = siC + siA;
000014  4937  LDR      r1,|L1.244|   ; r1 = &siC
000016  6809  LDR      r1,[r1,#0]    ; r1 = *r1
000018  6812  LDR      r2,[r2,#0]    ; r2 = *r2
00001a  1889  ADDS     r1,r1,r2      ; r1 = r1 + r2
...

|L1.240|
                DCD      ||siA||
|L1.244|
                DCD      ||siC||
          AREA ||.data||, DATA, ALIGN=2
||siC||
                DCD      0x00000003
||siA||
                DCD      0x00000000
```


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Automatic Variables Stored on Stack

- Automatic variables are stored in a function's activation record (unless optimized and promoted to register)
- Activation records are located on the stack
- Calling a function creates an activation record, allocating space on stack
- Returning from a function deletes the activation record, freeing up space on stack
- Variables in C are implicitly automatic, there is no need to specify the keyword

```
int main(void) {
    auto vars;
    a();
}

void a(void) {
    auto vars;
    b();
}

void b(void) {
    auto vars;
    c();
}

void c(void) {
    auto vars;
    …
}
```

Automatic Variables

```
int main(void) {
    auto vars;
    a();
}

void a(void) {
    auto vars;
    b();
}

void b(void) {
    auto vars;
    c();
}

void c(void) {
    auto vars;
    …
}
```

Lower address

<table>
<tr><td></td><td>(Free stack space)</td><td></td></tr>
<tr><td rowspan="3">Activation record for current function C</td><td>Local storage</td><td><- Stack pointer while executing C</td></tr>
<tr><td>Saved regs</td><td></td></tr>
<tr><td>Arguments (optional)</td><td></td></tr>
<tr><td rowspan="3">Activation record for caller function B</td><td>Local storage</td><td><- Stack pointer while executing B</td></tr>
<tr><td>Saved regs</td><td></td></tr>
<tr><td>Arguments (optional)</td><td></td></tr>
<tr><td rowspan="3">Activation record for caller's caller function A</td><td>Local storage</td><td><- Stack pointer while executing A</td></tr>
<tr><td>Saved regs</td><td></td></tr>
<tr><td>Arguments (optional)</td><td></td></tr>
<tr><td rowspan="3">Activation record for caller's caller's caller function main</td><td>Local storage</td><td><- Stack pointer while executing main</td></tr>
<tr><td>Saved regs</td><td></td></tr>
<tr><td>Arguments (optional)</td><td></td></tr>
</table>

Higher address

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Addressing Automatic Variables

- Program must allocate space on stack for variables
- Stack addressing uses an offset from the stack pointer: [sp, #offset]
- Items on the stack are word aligned
  - In instructions, one byte used for offset, which is multiplied by four
  - Possible offsets: 0, 4, 8, …, 1020
  - Maximum range addressable this way is 1024 bytes

Address	Contents
SP	
SP+0x4	
SP+0x8	
SP+0xC	
SP+0x10	
SP+0x14	
SP+0x18	
SP+0x1C	
SP+0x20	

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Automatic Variables

Address	Contents
SP	aiG
SP+4	aiF
SP+8	aiE
SP+0xC	aiB
SP+0x10	r0
SP+0x14	r1
SP+0x18	r2
SP+0x1C	r3
SP+0x20	lr

```
;;;14     void static_auto_local( void ) {
000000  b50f PUSH {r0-r3,lr}
;;;15  int aiB;
;;;16  static int siC=3; (not to stack)
;;;17  int * apD;
;;;18  int aiE=4, aiF=5, aiG=6;
000002  2104 MOVS  r1,#4
000004  9102 STR   r1,[sp,#8]
000006  2105 MOVS  r1,#5
000008  9101 STR   r1,[sp,#4]
00000a  2106 MOVS  r1,#6
00000c  9100 STR   r1,[sp,#0]
…
;;;21       aiB = siC + siA;
…
00001c  9103 STR   r1,[sp,#0xc]
```

- Initialize aiE
- Initialize aiF
- Initialize aiG

- Store value for aiB

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Using Pointers

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Using Pointers to Automatics

- C Pointer: a variable which holds the data's address

- aiB is on stack at SP+0xc
- Compute r0 with variable's address from stack pointer and offset (0xc)
- Load r1 with variable's value from memory
- Operate on r1, save back to variable's address

```
;;;22          apD = & aiB;
00001e  a803  ADD   r0,sp,#0xc
;;;23          (*apD)++;
000020  6801  LDR   r1,[r0,#0]
000022  1c49  ADDS  r1,r1,#1
000024  6001  STR   r1,[r0,#0]
```


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Using Pointers to Statics

- Load r0 with variable's address from address of copy of variable's address
- Load r1 with variable's value from memory
- Operate on r1, save back to variable's address

```
;;;24            apD = &siC;
000026  4833 LDR   r0,|L1.244|
;;;25            (*apD) += 9;
000028  6801 LDR   r1,[r0,#0]
00002a  3109 ADDS  r1,r1,#9
00002c  6001 STR   r1,[r0,#0]
|L1.244|
                 DCD       ||siC||
             AREA ||.data||, DATA, ALIGN=2
||siC||
                 DCD       0x00000003
```

Array Access

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Array Access

- What does it take to get at an array element in memory?
  - Depends on how many dimensions
  - Depends on element size and row width
  - Depends on location, which depends on storage type (static, automatic, dynamic)

```
uint8 buff2[3];
uint16 buff3[5][7];

uint32 arrays(uint8 n, uint8 j) {
  volatile uint32 i;
  i = buff2[0] + buff2[n];
  i += buff3[n][j];
  return i;
}
```

Accessing 1-D Array Elements

- Need to calculate element address: sum of…
  - array start address
  - offset: index * element size
- buff2 is array of unsigned characters

Address	Contents
buff2	buff2[0]
buff2 + 1	buff2[1]
buff2 + 2	buff2[2]

- Move n (argument) from r0 into r2
- Load r3 with pointer to buff2
- Load (byte) r3 with first element of buff2
- Load r4 with pointer to buff2
- Load (byte) r4 with element at address buff2+r2
  - r2 holds argument n
- Add r3 and r4 to form sum

```
00009e   4602  MOV   r2,r0
;;;76      i = buff2[0] + buff2[n];
0000a0   4b1b  LDR   r3,|L1.272|
0000a2   781b  LDRB  r3,[r3,#0]   ; buff2
0000a4   4c1a  LDR   r4,|L1.272|
0000a6   5ca4  LDRB  r4,[r4,r2]
0000a8   1918  ADDS  r0,r3,r4
|L1.272|
                   DCD   buff2
```


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Accessing 2-D Array Elements

`uint16 buff3[5][7]`

Address	Contents
buff3	buff3[0][0]
buff3+1	
buff3+2	buff3[0][1]
buff3+3	
(etc.)	
buff3+10	buff3[0][5]
buff3+11	
buff3+12	buff3[0][6]
buff3+13	
buff3+14	buff3[1][0]
buff3+15	
buff3+16	buff3[1][1]
buff3+17	
(etc.)	
buff3+68	buff3[4][6]
buff3+69	

- var[rows][columns]
- Sizes
  - Element: 2 bytes
  - Row: 7*2 bytes = 14 bytes (0xe)
- Offset based on row index and column index
  - column offset = column index * element size
  - row offset = row index * row size

Code to Access 2-D Array

Instruction	r0	r1	r2	r3	r4	Description
;;; i += buff3[n][j];	i	j	n	-	-	
MOVS r3,#0xe	-	-	-	0xe	-	Load row size
MULS r3,r2,r3	-	-	n	n*0xe	-	Multiply by row number
LDR r4,|L1.276|	-	-	-	-	&buff3	Load address of buff3
ADDS r3,r3,r4	-	-	-	&buff3+n*0xe	-	Add buff3 address to row offset
LSLS r4,r1,#1	-	j	-	-	j<<1	Multiply column number by 2 (buff3 is uint16 array)
LDRH r3,[r3,r4]	-	-	-	*(uint16)(&buff3+n*0xe+j<<1) = buff3[n][j]	j<<1	Load halfword r3 with element at r3+r4 (buff3 + row offset + col offset)
ADDS r0,r3,r0	i+buff3[n][j]	-	-	buff3[n][j]		Add r3 to r0 (i)

Function Prolog and Epilog

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Prolog and Epilog

- A function's P&E are responsible for creating and destroying its activation record
- Remember AAPCS
  - Scratch registers r0-r3 are not expected to be preserved upon returning from a called subroutine, can be overwritten
  - Preserved ("variable") registers r4-r8, r10-r11 must have their original values upon returning from a called subroutine
  - Prolog must save preserved registers on stack
  - Epilog must restore preserved registers from stack
- Prolog also may
  - Handle function arguments
  - Allocate temporary storage space on stack (subtract from SP)
- Epilog
  - May deallocate stack space (add to SP)
  - Returns control to calling function

Return Address

- Return address stored in LR by bl, blx instructions

- Consider case where a() calls b() which calls c()
  - On entry to b(), LR holds return address in a()
  - When b() calls c(), LR will be overwritten with return address in b()
  - After c() returns, b() will have lost its return address

- Does this function call a subroutine?
  - Yes: must save and restore LR on stack just like other preserved registers, but LR value is popped into PC rather than LR
  - No: don't need to save or restore LR, as it will not be modified

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Function Prolog and Epilog

- Save r4 (preserved register) and link register (return address)
- Allocate 32 (0x20) bytes on stack for array x by subtracting from SP
- Compute return value, placing in return register r0
- Deallocate 32 bytes from stack
- Pop r4 (preserved register) and PC (return address)

```
 fun4 PROC
;;;102  int fun4(char a, int b, char c)
{
;;;103    volatile int x[8];
00010a  b510 PUSH {r4,lr}
00010c  b088 SUB  sp,sp,#0x20
...
;;;106       return a+b+c;
00011c  1858 ADDS r0,r3,r1
00011e  1880 ADDS r0,r0,r2
;;;107    }
000120  b008 ADD  sp,sp,#0x20
000122  bd10 POP  {r4,pc}
             ENDP
```


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Activation Record Creation by Prolog

Smaller address	space for x[0]	Array x	<- 3. SP after sub sp,sp,#0x20
	space for x[1]		
	space for x[2]		
	space for x[3]		
	space for x[4]		
	space for x[5]		
	space for x[6]		
	space for x[7]		
	lr	Return address	<- 2. SP after push {r4,lr}
	r4	Preserved register	
Larger address		Caller's stack frame	<- 1. SP on entry to function, before push {r4,lr}

Activation Record Destruction by Epilog

Smaller address	space for x[0]	Array x	<- 1. SP before add sp,sp,#0x20
	space for x[1]		
	space for x[2]		
	space for x[3]		
	space for x[4]		
	space for x[5]		
	space for x[6]		
	space for x[7]		
	lr	Return address	<- 2. SP after add sp,sp,#20
	r4	Preserved register	
Larger address		Caller's stack frame	<- 1. SP after pop {r4,pc}

Calling Functions

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AAPCS Core Register Use

Register	Synonym	Special	Role in the procedure call standard
r15		PC	The Program Counter.
r14		LR	The Link Register.
r13		SP	The Stack Pointer.
r12		IP	The Intra-Procedure-call scratch register.
r11	v8		Variable-register 8.
r10	v7		Variable-register 7.
r9		v6,SB,TR	Platform register. The meaning of this register is defined by the platform standard.
r8	v5		Variable-register 5.
r7	v4		Variable register 4.
r6	v3		Variable register 3.
r5	v2		Variable register 2.
r4	v1		Variable register 1.
r3	a4		Argument / scratch register 4.
r2	a3		Argument / scratch register 3.
r1	a2		Argument / result / scratch register 2.
r0	a1		Argument / result / scratch register 1.

Function Arguments and Return Values

- First, pass the arguments
  - How to pass them?
    - Much faster to use registers than stack
    - But quantity of registers is limited
  - Basic rules
    - Process arguments in order they appear in source code
    - Round size up to be a multiple of 4 bytes
    - Copy arguments into core registers (r0-r3), aligning doubles to even registers
    - Copy remaining arguments onto stack, aligning doubles to even addresses
    - Specific rules in AAPCS, Section 5.5
- Second, call the function
  - Usually as subroutine with branch link (bl) or branch link and exchange instruction (blx)
  - Exceptions in AAPCS

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Return Values

- Callee passes Return Value in register(s) or stack
- Registers
- Stack
  - Caller function allocates space for return value, then passes pointer to space as an argument to callee
  - Callee stores result at location indicated by pointer

Return value size	Registers used for passing	
	Fundamental Data Type	Composite Data Type
1-4 bytes	r0	r0
8 bytes	r0-r1	stack
16 bytes	r0-r3	stack
Indeterminate size	n/a	stack

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Call Example

```
int fun2(int arg2_1, int arg2_2) {
  int i;
  arg2_2 += fun3(arg2_1, 4, 5, 6);
  …
}
```

- Argument 4 into r3
- Argument 3 into r2
- Argument 2 into r1
- Argument 0 into r0
- Call fun3 with BL instruction
- Result was returned in r0, so add to r4 (arg2_2 += result)

```
fun2 PROC
;;;85     int fun2(int arg2_1, int
arg2_2) {
...
0000e0  2306 MOVS  r3,#6
0000e2  2205 MOVS  r2,#5
0000e4  2104 MOVS  r1,#4
0000e6  4630 MOV   r0,r6


0000e8  f7fffffe   BL     fun3

0000ec  1904 ADDS  r4,r0,r4
```


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Call and Return Example

```
int fun3(int arg3_1, int arg3_2,
  int arg3_3, int arg3_4) {
  return    arg3_1*arg3_2*
            arg3_3*arg3_4;
}
```

- Save r4 and Link Register on stack
- r0 = arg3_1*arg3_2
- r0 *= arg3_3
- r0 *= arg3_4
- Restore r4 and return from subroutine
- Return value is in r0

```
 fun3 PROC
;;;81     int fun3(int arg3_1, int arg3_2,
int arg3_3, int arg3_4) {

0000ba  b510 PUSH {r4,lr}


0000c0  4348 MULS r0,r1,r0
0000c2  4350 MULS r0,r2,r0
0000c4  4358 MULS r0,r3,r0

0000c6  bd10 POP  {r4,pc}
```


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Control Flow

Control Flow: Conditionals and Loops

- How does the compiler implement conditionals and loops?

```
if (x){
    y++;
} else {
    y--;
}
```

```
switch (x) {
  case 1:
    y += 3;
    break;
  case 31:
    y -= 5;
    break;
  default:
    y--;
    break;
}
```

```
for (i = 0; i < 10; i++){
    x += i;
}

while (x<10) {
    x = x + 1;
}

do {
    x += 2;
} while (x < 20);
```


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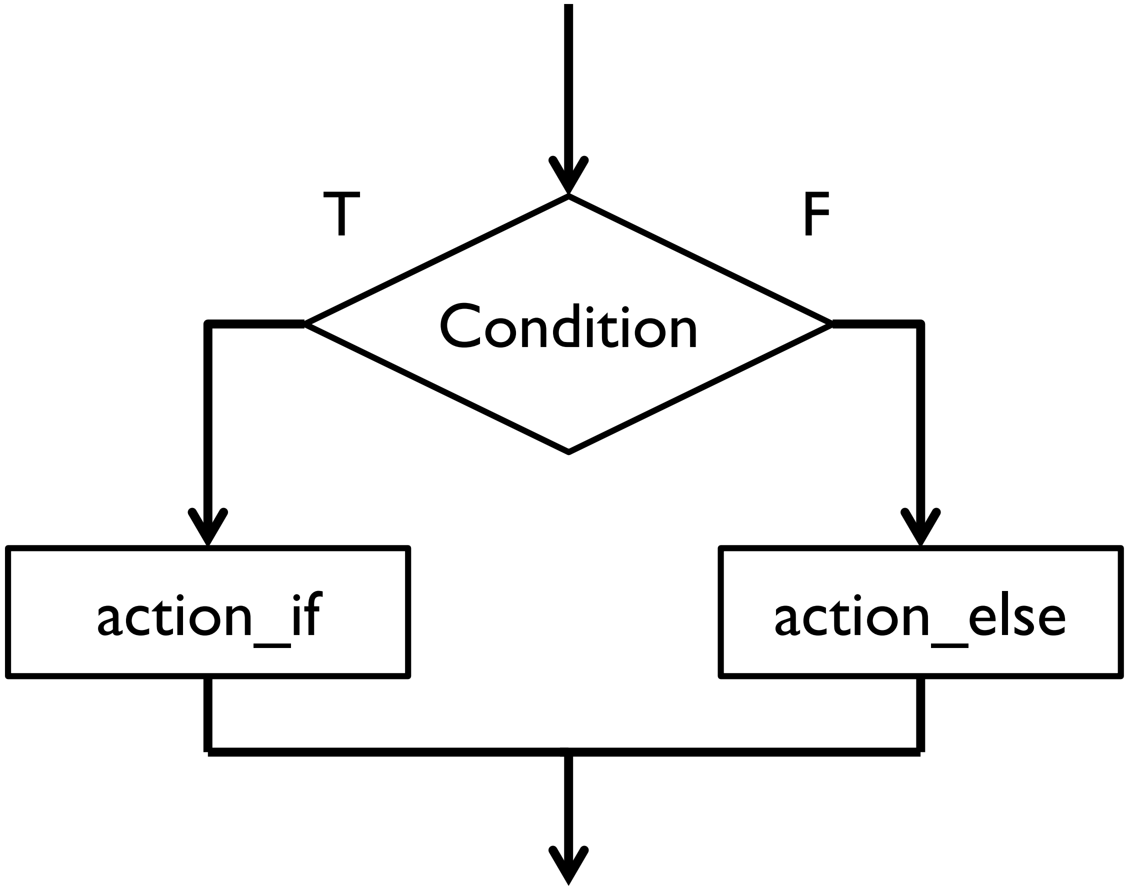
Control Flow: If/Else




```
;;;39          if (x){
000056  2900 CMP   r1,#0
000058  d001 BEQ   |L1.94|

;;;40             y++;
00005a  1c52 ADDS  r2,r2,#1
00005c  e000 B     |L1.96|

   |L1.94|
;;;41          } else {
;;;42            y--;
00005e  1e52 SUBS  r2,r2,#1

   |L1.96|
;;;43          }
```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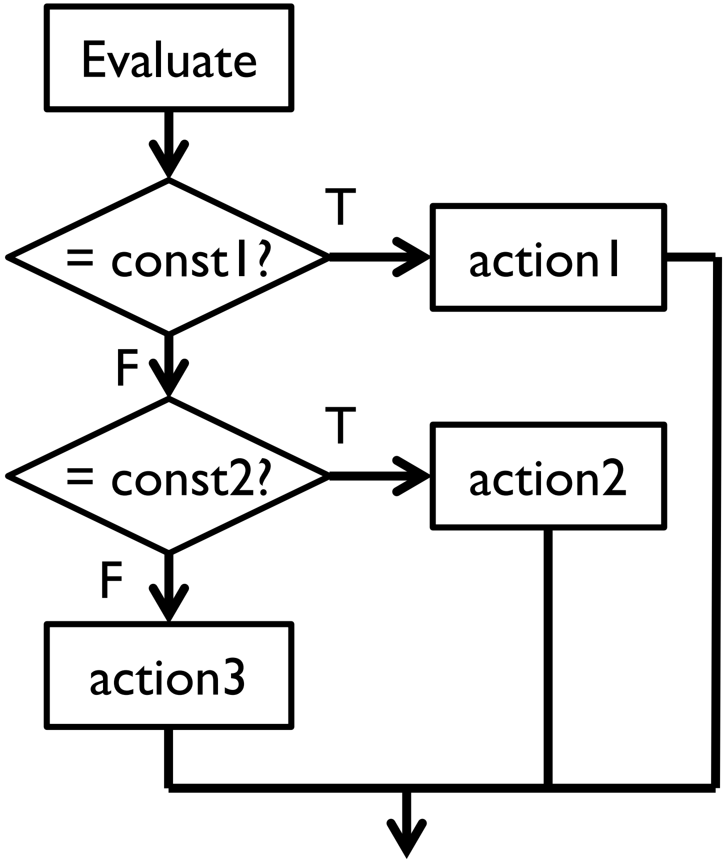
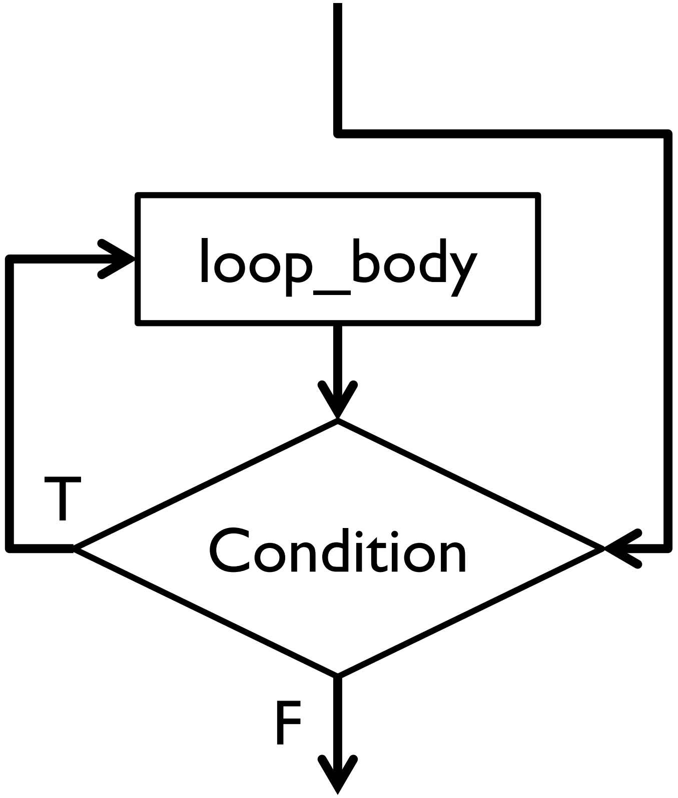
Control Flow: Switch




```
;;;45        switch (x) {
000060  2901     CMP    r1,#1
000062  d002     BEQ    |L1.106|
000064  291f     CMP    r1,#0x1f
000066  d104     BNE    |L1.114|
000068  e001     B      |L1.110|
    |L1.106|
;;;46          case 1:
;;;47            y += 3;
00006a  1cd2     ADDS   r2,r2,#3
;;;48            break;
00006c  e003     B      |L1.118|
|L1.110|
;;;49          case 31:
;;;50            y -= 5;
00006e  1f52     SUBS   r2,r2,#5
;;;51            break;
000070  e001     B      |L1.118|
|L1.114|
;;;52          default:
;;;53            y--;
000072  1e52     SUBS   r2,r2,#1
;;;54            break;
000074  bf00     NOP
|L1.118|
000076  bf00     NOP
;;;55          }
```

Iteration: While




```
;;;57        while (x<10) {
000078  e000 B      |L1.124|
             |L1.122|
;;;58         x = x + 1;
00007a  1c49 ADDS r1,r1,#1
             |L1.124|
00007c  290a CMP  r1,#0xa
;57
00007e  d3fc BCC  |L1.122|
;;;59        }
```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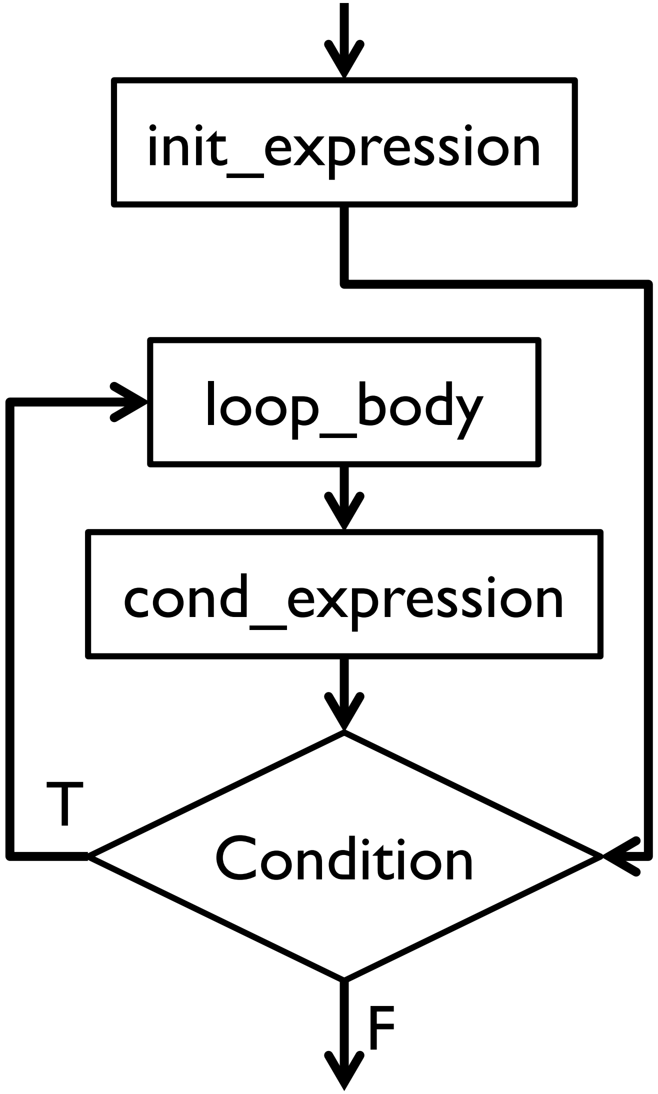
Iteration: For

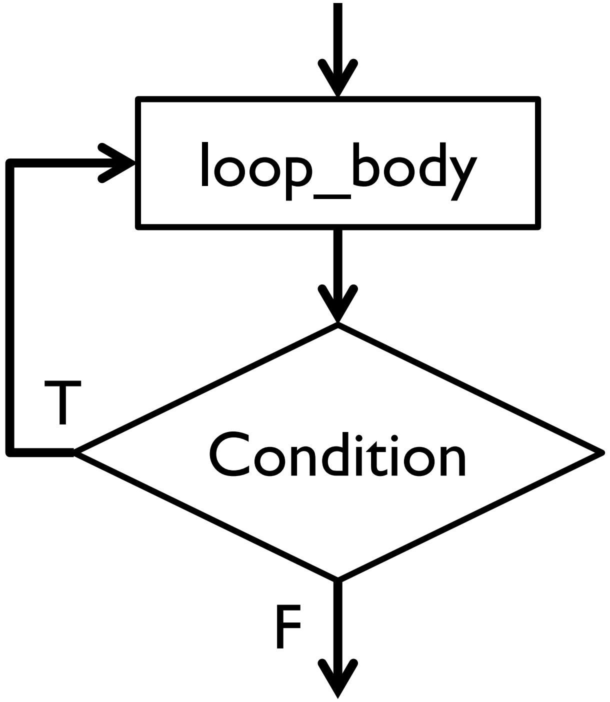



```
;;;61        for (i = 0; i < 10; i++){
000080  2300 MOVS  r3,#0
000082  e001 B     |L1.136|

             |L1.132|
;;;62         x += i;
000084  18c9 ADDS  r1,r1,r3
000086  1c5b ADDS  r3,r3,#1
;61

             |L1.136|
000088  2b0a CMP   r3,#0xa
;61
00008a  d3fb BCC   |L1.132|
;;;63        }
```

Iteration: Do/While




```
;;;65          do {
00008c  bf00 NOP

                |L1.142|
;;;66           x += 2;
00008e  1c89 ADDS  r1,r1,#2
;;;67          } while (x < 20);
000090  2914 CMP   r1,#0x14
000092  d3fc BCC   |L1.142|
```

BCC (short for "Branch if Carry is Clear")

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Summary

- We program in C for convenience
- There are no MCUs which execute C, only machine code
- So we compile the C to assembly code, a human-readable representation of machine code
- We need to know what the assembly code implementing the C looks like
  - To use the processor efficiently
  - To analyze the code with precision
  - To find performance and other problems
- An overview of what C gets compiled to
  - C start-up module, subroutines calls, stacks, data classes and layout, pointers, control flow, etc.

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