Embedded Systems with ARM Cortex-M Microcontrollers in Assembly Language and C

Chapter 7
Structured Programming

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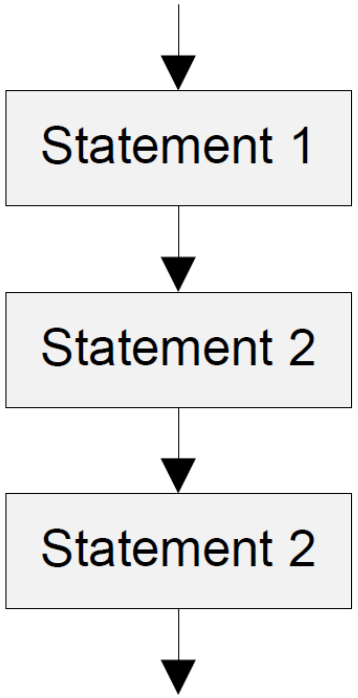
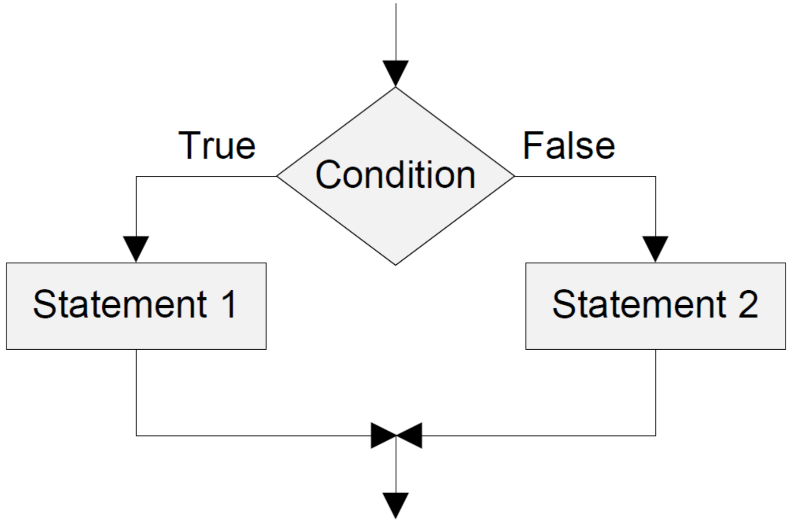
Acknowledgement: Lecture slides based on Embedded Systems with ARM Cortex-M Microcontrollers in Assembly Language and C, University of Maine https://web.eece.maine.edu/~zhu/book/

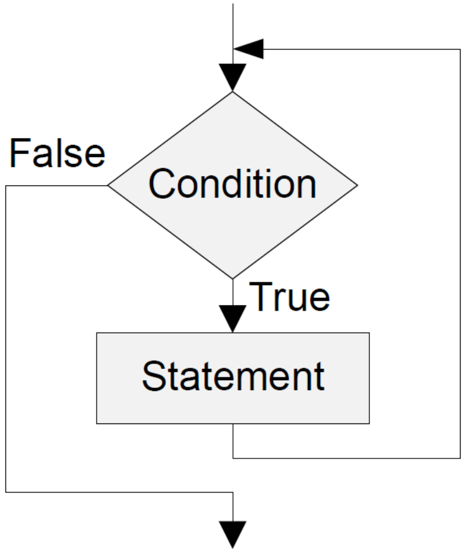
Basic Control Structures



Sequence Structure



Selection Structure



loop: Structure

History

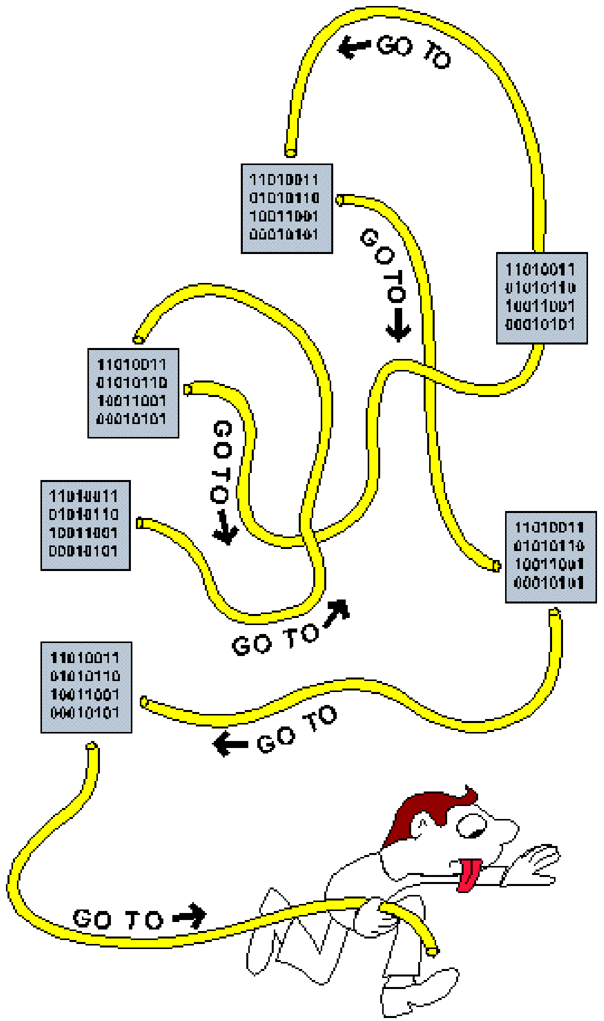
- Spaghetti Code
  - Before the 1980s, program flow bounces around anywhere the programmer wanted.
  - Culprit: overusing "GOTO" statements

Spaghetti code in BASIC

```
1 i=0
2 i=i+1
3 PRINT i; "squared=";i*i
4 IF i>=100 THEN GOTO 6
5 GOTO 2
6 PRINT "Program Completed."
7 END
```

Structured programming in BASIC

```
1 FOR i=1 TO 100
2   PRINT i;"squared=";i*i
3 NEXT i    'termination of loop: body
4 PRINT "Program Completed."
5 END
```

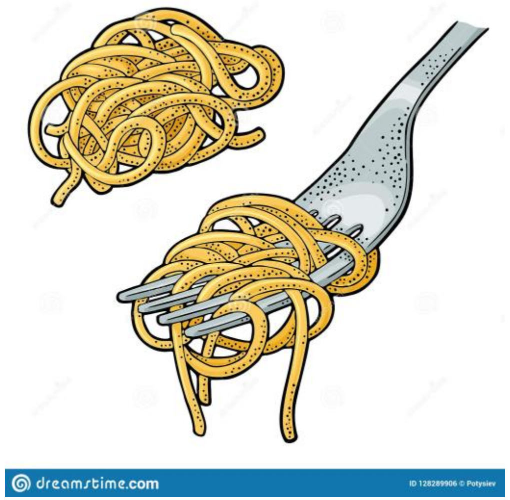


https://en.wikipedia.org/wiki/Spaghetti_code

https://commons.wikimedia.org/wiki/File:Spagetti_code_structural_graphic.GIF

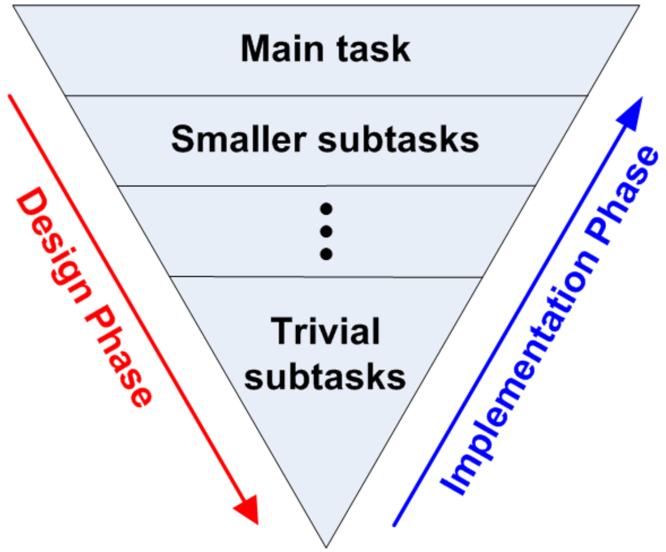
Importance of Structured Programming

- Assembly is not a structured programming language
  - Does not directly support selection and loop:
  - Branch in assembly = “goto” in C
  - Break the single-entry single-exit rule
- Easy to generate spaghetti code in assembly
  - Twisted and tangled
  - Difficult to debug & maintain
- One strategy to alleviate the challenge
  - Use **flowcharts** to facilitate assembly programming
  - That is why textbook has many flowcharts
  - How to build flowcharts?



Software Design Strategy: Top-Down Design

- Three common design strategies
  - Top-down, also known as stepwise refinement
  - Bottom up
  - Object oriented
- Top-down: Repeatedly break down tasks into smaller and smaller pieces until they are easy to solve
- Example: Planning a picnic
  - Task 1: Where
  - Task 2: When
  - Task 3: Who
  - Task 4: Food



Top-Down Design Example

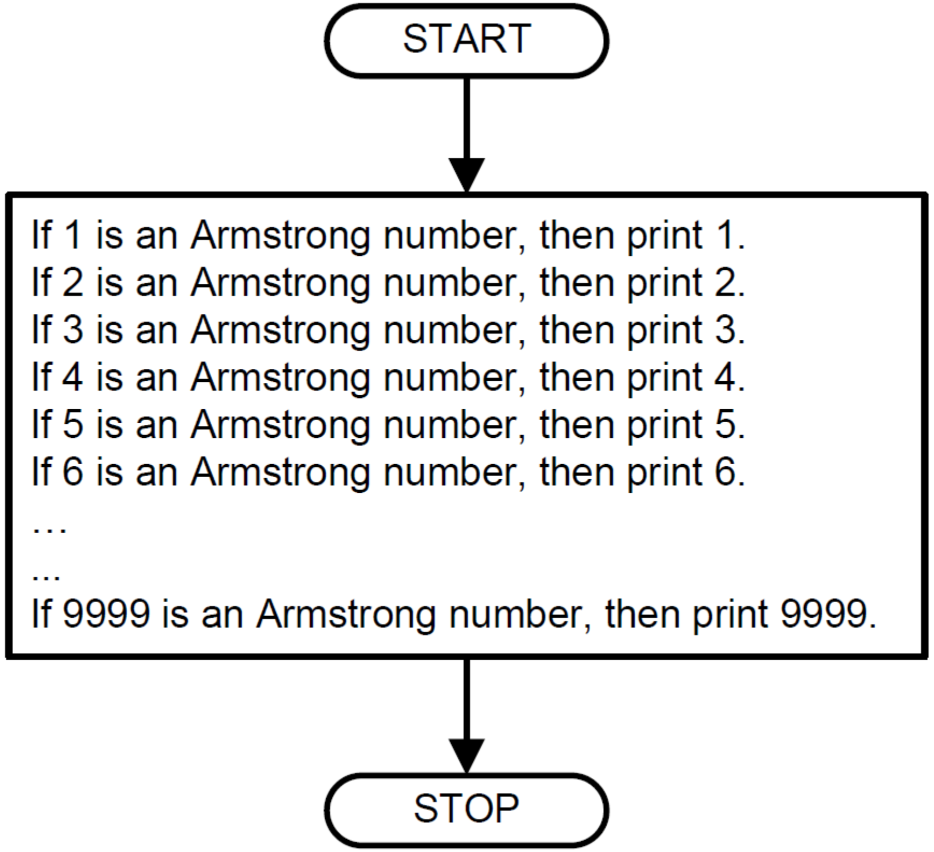
- Find all Armstrong numbers less than `10,000`
  - Given a positive integer that has *n* digits, it is an Armstrong number if the sum of the n^{th} powers of its digits equals the number itself.

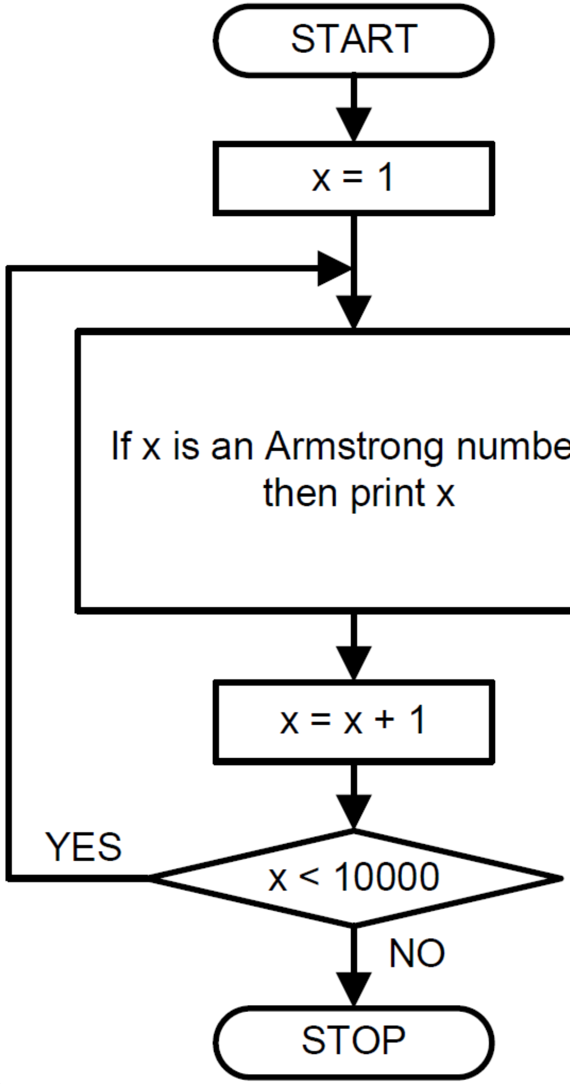
$$153 = 1^3 + 5^3 + 3^3$$

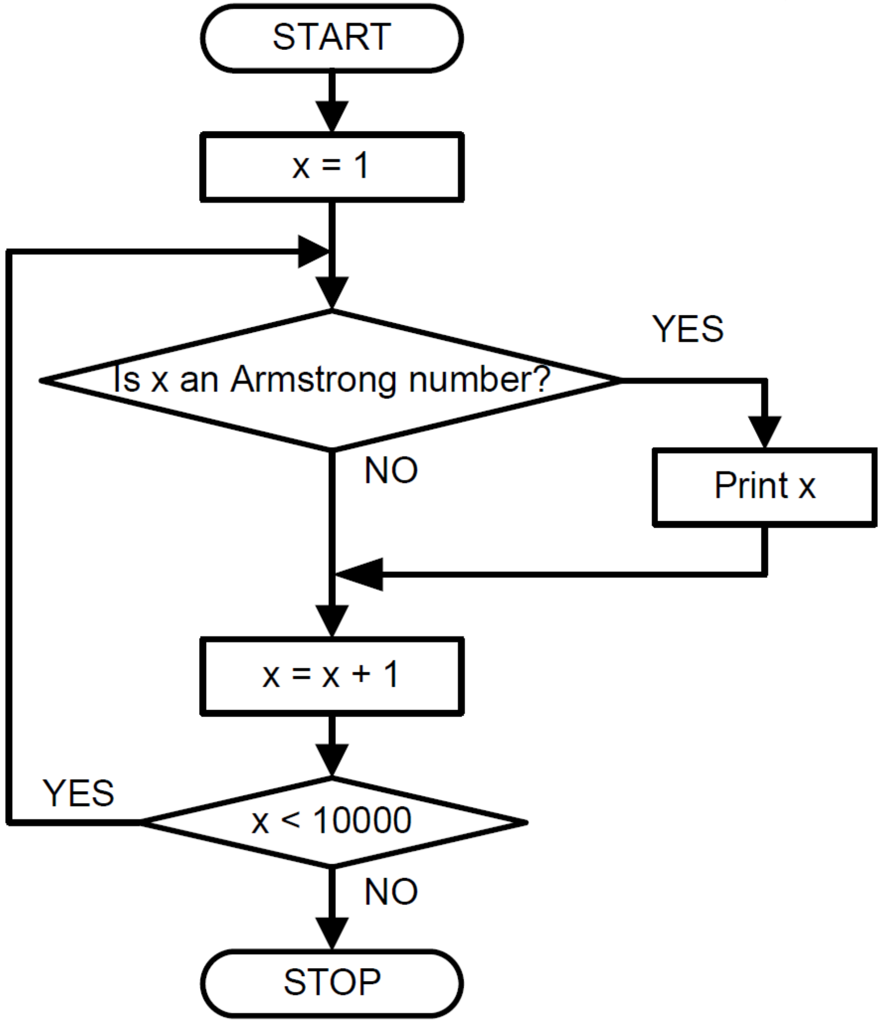
$$371 = 3^3 + 7^3 + 1^3$$

$$1634 = 1^4 + 6^4 + 3^4 + 4^4$$

Top-Down Design Example





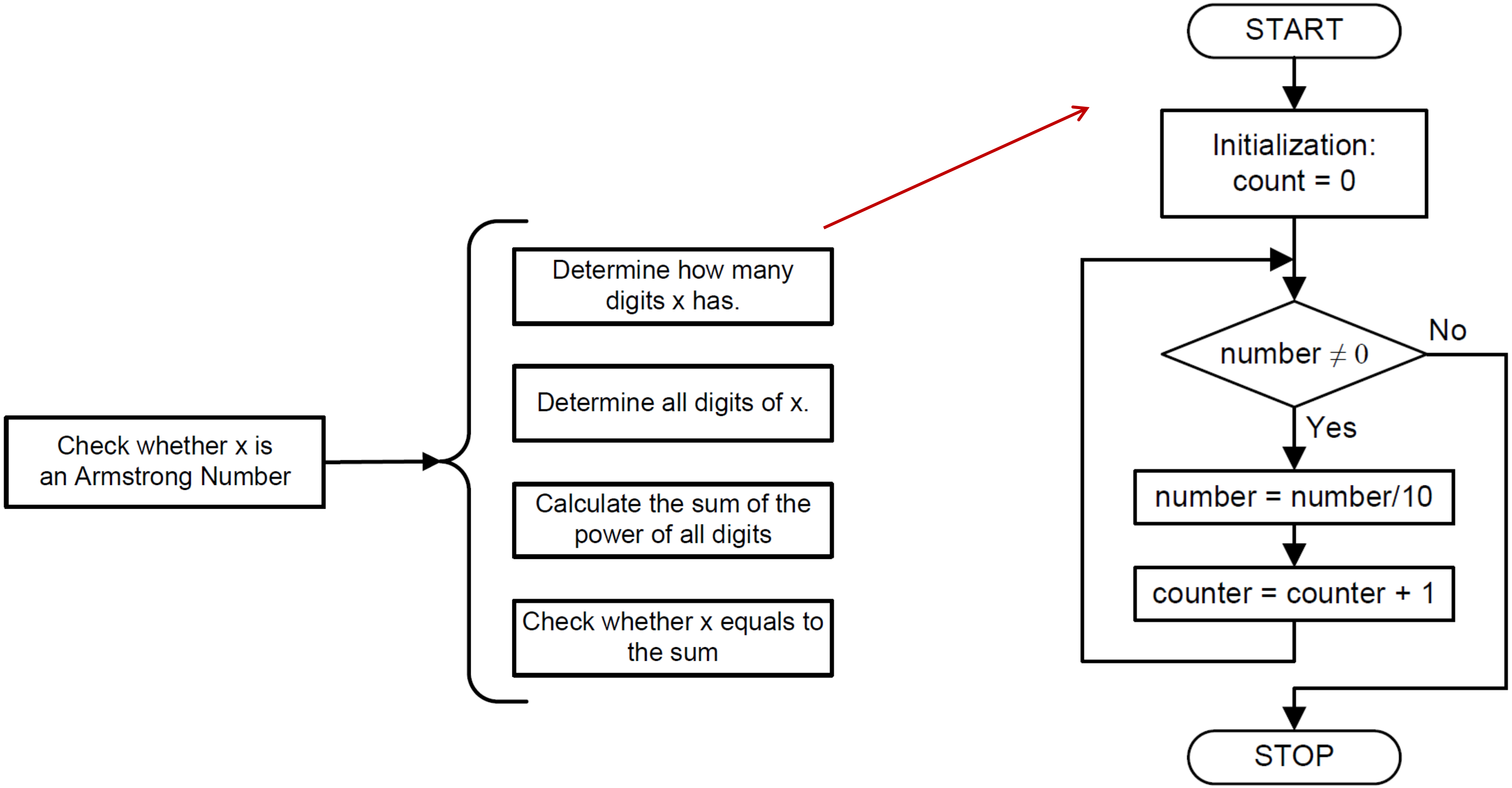


Step 1

Step 2

Step 3

Top-Down Design Example:
Counting digits



Reuse Registers

```
int A = 0;  // 0x00000000
int B = -1; // 0xFFFFFFFF
int C = -2; // 0xFFFFFFFE
int D = 2;  // 0x00000002

void main(void){
  A = B + C – D;
  return;
}
```

Data memory

Little-Endian

Address	*Data*	
0x2000,000F	0x00	D = 0x0000,0002 = 2
0x2000,000E	0x00	
0x2000,000D	0x00	
0x2000,000C	0x02	
0x2000,000B	0xFF	C = 0xFFFF,FFFE = -2
0x2000,000A	0xFF	
0x2000,0009	0xFF	
0x2000,0008	0xFE	
0x2000,0007	0xFF	B = 0xFFFF,FFFF = -1
0x2000,0006	0xFF	
0x2000,0005	0xFF	
0x2000,0004	0xFF	
0x2000,0003	0x00	A = 0x0000,0000 = 0
0x2000,0002	0x00	
0x2000,0001	0x00	
0x2000,0000	0x00	

Reuse Registers

```
int A = 0;  // 0x00000000
int B = -1; // 0xFFFFFFFF
int C = -2; // 0xFFFFFFFE
int D = 2;  // 0x00000002

void main(void){
  A = B + C – D;
  return;
}
```

Eight registers are used:
R0,r1,r2,r3,r4,r5,r6,r7

```
AREA myCode, CODE
   EXPORT __main
   ENTRY
__main PROC

   LDR r2, =B       ; r2 = 0x2000,0004
   LDR r3, [r2]     ; r3 = B = -1
   LDR r4, =C       ; r4 = 0x2000,0008
   LDR r5, [r4]     ; r5 = C = -2
   LDR r6, =D       ; r6 = 0x2000,000B
   LDR r7, [r6]     ; r7 = D = 2
   ADD r1, r3, r5   ; r1 = B + C
   SUB r1, r1, r7   ; r1 = B + C - D
   LDR r0, =A       ; r0 = 0x2000,0000
   STR r1, [r0]     ; Save A
   ENDP

   AREA myData, DATA
A  DCD  0
B  DCD  -1
C  DCD  -2
D  DCD  2

   END
```

Reuse Registers

The lifetime of a value in a register starts when the value is written into the register and ends when that value is no longer needed (either overwritten or no longer used in future instructions).

```
        AREA myCode, CODE
        EXPORT __main
        ENTRY
__main PROC

        LDR r2, =B
        LDR r3, [r2]
        LDR r4, =C
        LDR r5, [r4]
        LDR r6, =D
        LDR r7, [r6]
        ADD r1, r3, r5
        SUB r1, r1, r7
        LDR r0, =A
        STR r1, [r0]
        ENDP

        AREA myData, DATA
A       DCD  0
B       DCD  -1
C       DCD  -2
D       DCD  2

        END
```

Lifetime of r3

8 registers used

```
        AREA myCode, CODE
        EXPORT __main
        ENTRY
__main PROC

        LDR r2, =B
        LDR r3, [r2]
        LDR r2, =C
        LDR r5, [r2]
        LDR r2, =D
        LDR r7, [r2]
        ADD r3, r3, r5
        SUB r3, r3, r7
        LDR r2, =A
        STR r3, [r2]
        ENDP

        AREA myData, DATA
A       DCD  0
B       DCD  -1
C       DCD  -2
D       DCD  2

        END
```

Lifetime of r2

Lifetime of r2

LDR r2, [r2]: loads from memory address r2 into register value r2. It is OK since memory address r2 is never used again.

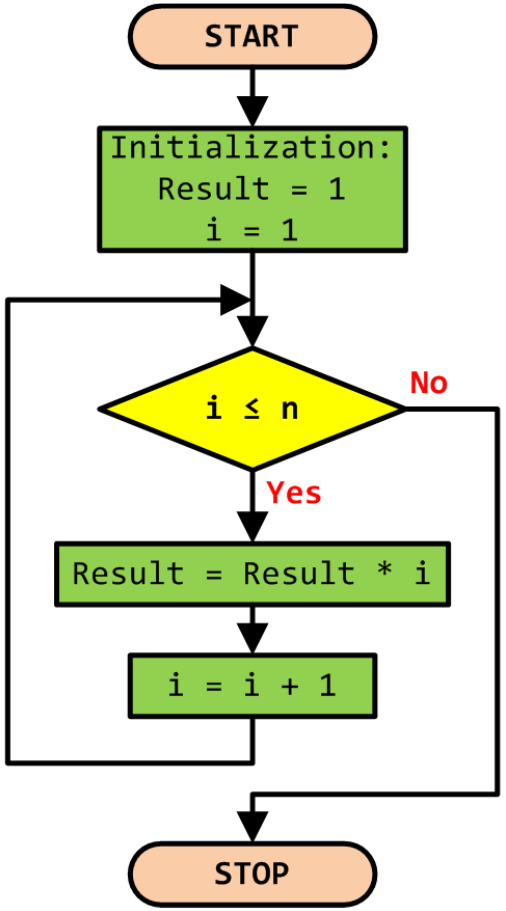
4 registers used

```
        AREA myCode, CODE
        EXPORT __main
        ENTRY
__main PROC

        LDR r2, =B
        LDR r3, [r2]
        LDR r2, =C
        LDR r5, [r2]
        LDR r2, =D
        LDR r2, [r2]
        ADD r3, r3, r5
        SUB r3, r3, r2
        LDR r2, =A
        STR r3, [r2]
        ENDP

        AREA myData, DATA
A       DCD  0
B       DCD  -1
C       DCD  -2
D       DCD  2

        END
```

Reuse r2

3 registers used

Example 1: Factorial Numbers



$$n! = \prod_{i=1}^{n} i = n \times (n-1) \times (n-2) \cdots \times 2 \times 1$$

Example 1: Factorial Numbers

C Program	Assembly Program 1	Assembly Program 2

int main(void) {
  int result, n, i;
	AREA factorial, CODE, READONLY
	        EXPORT __main
	        ENTRY
	__main PROC
		AREA factorial, CODE, READONLY
		        EXPORT __main
		        ENTRY
		__main PROC

result = 1;
  n = 5;
	MOV r1, #4 ; r1 = n
	        MOV r0, #1 ; r0 = result.
		MOV r1, #4 ; r1 = n
		    MOVS r0, r1 ; r0 = n. Also sets flags based on r0 (so we can handle n==0)
		    MOVEQ r0, #1 ; if n == 0, set r0 = 1

for (i = 1; i <= n; i++)
    result = result * i;
	MOV r2, #1 ; r2 = i = 1
	loop: CMP r2, r1 ;compare r2 and n
	        BGT stop ; if i > n, stop
	        MUL r0, r2, r0 ; result *= i
	        ADD r2, r2, #1 ; i++
	        B loop
		loop: SUBNES r1, r1, #1 ; if r1 != 0: r1 = r1 - 1 (and set flags)
		      MULNE r0, r1, r0 ; if r1 != 0: r0 = r1 * r0
		      BNE loop ; if r1 != 0, jump to loop label

}	stop: B stop
	        ENDP
	        END
		stop: B stop
		        ENDP
		        END

Worked example for N = 4

- Assembly Program 1:
  - r2 is loop counter (i) initialized to 1, r0 is running product (result) initialized to 1, r1 holds n.
    Entry: r1 = 4 (input). MOV r0, #1 → r0 = 1 (initialize result). MOV r2, #1 → r2 = 1 (start i = 1).
  - Loop iteration 1: CMP r2, r1 compares 1 and 4 (1 ≤ 4), so continue. MUL r0, r2, r0 → r0 = 1 * 1 = 1. ADD r2, r2, #1 → r2 = 2. B loop branches back.
  - Iteration 2: CMP r2, r1 compares 2 and 4 (2 ≤ 4), continue. MUL r0, r2, r0 → r0 = 2 * 1 = 2. ADD r2, r2, #1 → r2 = 3. B loop.
  - Iteration 3: CMP r2, r1 compares 3 and 4 (3 ≤ 4), continue. MUL r0, r2, r0 → r0 = 3 * 2 = 6. ADD r2, r2, #1 → r2 = 4. B loop.
  - Iteration 4: CMP r2, r1 compares 4 and 4 (4 ≤ 4), continue. MUL r0, r2, r0 → r0 = 4 * 6 = 24. ADD r2, r2, #1 → r2 = 5. B loop.
  - Iteration 5 (exit test): CMP r2, r1 compares 5 and 4 (5 > 4), BGT stop taken, loop ends. Fall through to return.
  - Return: MOV pc, r14 (or BX lr), function returns with r0 = 24 (which is 4!).
    Final registers of interest: r0 = 24 (result), r1 = 4 (n), r2 = 5 (loop counter one past n).
- Assembly Program 2:
  - r1 is loop counter initialized to 4, r0 is running product initialized to r1 = 4.
  - Entry: r0=4 (input). MOVS r1,r0 → r1=4, Z=0. MOVEQ skipped.
  - Loop iteration 1: SUBS r1,r1,#1 → r1=3 (Z=0). MUL r0 = r1 * r0 → r0 = 3*4 = 12. BNE true → repeat.
  - Iteration 2: SUBS → r1=2. MUL → r0 = 2*12 = 24. BNE true.
  - Iteration 3: SUBS → r1=1. MUL → r0 = 1*24 = 24. BNE true.
  - Iteration 4: SUBS → r1=0, sets Z=1. MULNE skipped (NE false), BNE not taken, fall through to MOV pc,r14. Return r0 = 24 (which is 4!).
- Assembly Program 3 (omitted):
  - r0 is running product initialized to r1 = 1, and the loop counter counts up to n.

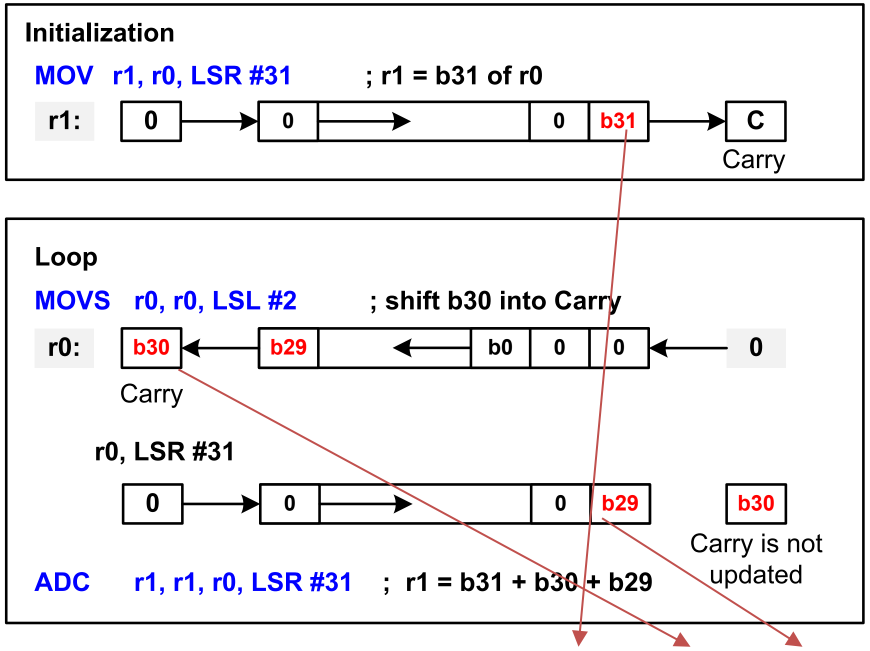
Stop B stop

- “stop B stop” means an infinite loop: that repeatedly branches to the label "stop".
  - Literal translation to C is while(1);
  - B is the branch instruction in ARM, which causes the program to jump to the specified label or address.
  - Here, the label and destination are both "stop". This creates a loop: where execution never moves past this point.
  - It is commonly used to halt the program or wait indefinitely, often when the program completes or to prevent it from running into uninitialized memory.
  - Why? Bare-metal ARM code (no OS, no runtime, no C library) has nowhere to “exit” to. So the safest thing is to fall into a loop that guarantees the processor doesn’t wander off into uninitialized memory and start executing garbage. When working in a more civilized environment, such as Linux running on ARM, you really would return from main or call a system call like exit(0). Bare-metal code, though, tends to end with a little self-referential loop

Example 2: Counting Ones in a Word

```
Assembly Program
        AREA Count_Ones, CODE
        EXPORT __main
        ALIGN
        ENTRY
__main  PROC
        ; r0 = Input = x
        ; r1 = Number of ones = counter
        LDR  r0, =0xAAAAAAAA

        ; r1 = r0 >> 31
        MOV  r1, r0, LSR #31

        ; r0 = r0 << 2 and change Carry
loop:   MOVS r0, r0, LSL #2

        ; r1 = r1 + r0 >> 31 + Carry
        ADC    r1, r1, r0, LSR #31
        BNE  loop:

Stop:   B  stop
        ENDP
        END
```

After LDR: r0=10101010101010101010101010101010
(Load input data into r0)
After MOV: r1=r0 >> 31 = 1 (Initialize r1 with the most significant bit of r0. r0 logical shift right by 31 bits, take the leftmost bit b31)
After MOVS: r0 = r0 << 2
=10101010101010101010101010101000
(Logical shift left r0 by 2 bits and update C = 0, as the last shifted out bit b30)
After ADC: r1 = r1 + r0 >> 31 + Carry = b31 + b29 + b30 =1 + 1 + 0 = 2
2^{nd} iteration: r1 = r1 + b28 + b27 = 2 + 1 + 0 = 3
If after MOVS, the result in r0 is zero, (no more 1's), Z flag is set to 1 and the loop: exits



At the end of the first loop:: **r1 = b31 + b30 + b29**

Example 2: Counting Ones in a Word: Explanations

Iteration	Shifted r0 value (MSB bit)	Carry bit (last shifted out)	r1 (accumulated count)	Notes
0 (init)	—	—	b31 = 1	r1 initialized with b31
1	b29 = 1	b30 = 0	1 (b31) + 1 (b29) + 0 (b30) = 2	r0 shifted left by 2 bits
2	b27 = 1	b28 = 0	2 + 1 (b27) + 0 (b28) = 3	
3	b25 = 1	b26 = 0	3 + 1 (b25) + 0 (b26) = 4	
4	b23 = 1	b24 = 0	4 + 1 (b23) + 0 (b24) = 5	

- In 0xAAAAAAAA, bits at odd positions (31, 29, 27, ..., 1) are all 1, bits at even positions (30, 28, 26, ..., 0) are all 0.
- Carry bit is always the even bit index at each iteration.
- At each iteration, r1 accumulates 1 (highest bit, odd index) + 0 (carry bit, even index).
- The loop: ends when r0 becomes zero after the last shift, triggering the Zero flag and exiting the branch.
- The count accumulates to 16, consistent with the fact that 0xAAAAAAAA has exactly 16 ones in 32 bits.
- This program counts two bits per loop iteration, leveraging the Carry bit, and will take 16 iterations for a 32-bit word.

Example 2: Counting Ones in a Word: Simpler Programs

Algo 1

```
    LDR r0, =0xAAAAAAAA     ; Load input data into r0
    MOV r2, #0              ; Initialize count (r2) to 0

loop:
    MOV r1, r0, LSR #31     ; Extract leftmost bit (MSB) of r0 into r1 (0 or 1)
    ADD r2, r2, r1          ; Add extracted bit to count in r2
    MOVS r0, r0, LSL #1     ; Shift r0 left by 1 bit, update flags
    BNE loop                ; If r0 != 0, repeat loop(may loop less than 32 iters)
```

Algo 2

```
    LDR r0, =0xAAAAAAAA     ; Load input data into r0
    MOV r2, #0              ; Initialize bit count accumulator (r2) to 0

loop:
    MOVS r0, r0, LSL #1     ; Shift left by 1 bit, carry gets old MSB
    ADC r2, r2, #0          ; Add carry (0 + carry) to r2
    BNE loop          ; Loop while r0 != 0 (Zero flag clear)
```

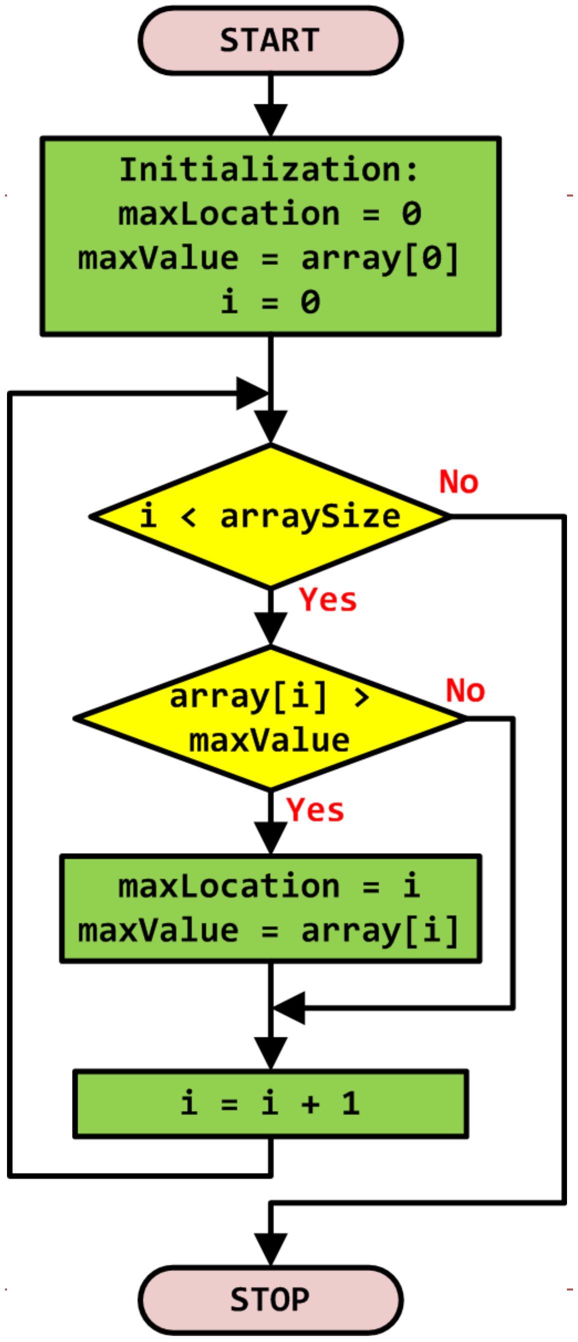
- Algo 1: use MOV r1, r0, LSR #31 to extract the highest bit from r0 and accumulates the per-bit count. (Carry flag is set but ignored.)
- Algo 2: use MOVS r0, r0, LSL #1 to shift left by 1 bit and update the carry flag with the bit shifted out (the leftmost bit of the original value). Use ADC (Add with Carry) to add the carry bit to accumulator r2 without needing to move the leftmost bit explicitly.
- Both programs count one bit per loop iteration. Algo 1 uses r1 to store the MSB of intermediate values of r0, and Algo 2 uses C flag to store it.

Quiz

- Q: In Algo 1 and Algo 2, can we change MOVS r0, r0, LSL #1 to MOV r0, r0, LSL #1?
  - ANS: No, since the C carry flag, which captures the leftmost bit shifted out, is needed for bit counting in Algo 2, and for loop condition checking in both Algos (exit loop when Z flag set, and r0 is zero)
- Q: In Algo 1, can we change MOV r1, r0, LSR #31 to MOVS r1, r0, LSR #31
  - ANS: Yes, MOVS sets flags, but they are not used by later instructions.
- Q: In Algo 2, can we change ADC r2, r2, #0 to ADD r2, r2, #0?
  - ANS: No, ADC (Add with Carry) adds two operands **plus** the **carry flag**. ADD only adds the two operands without considering the carry flag
- Q: In Algo 1, can we change ADD r2, r2, r1 to ADC r2, r2, r1?
  - ANS: No. ADC will add the C flag set by "MOVS r0, r0, LSL #1" in the previous iteration, resulting in double-counting of 1's.

Example 3: Finding Max of an Array

```
// Initialize max and location
maxLocation = 0;
maxValue = array[0];

// loop: through the array
for (i = 0; i < arraySize; i++) {
    if (array[i] > maxValue) {
        maxValue  = array[i];
        maxLocation = i;
    }
}
```



Example 3: Finding Max of an Array

C Program	Assembly Program

`int array[10] = {-1, 5, 3, 8, 10, 23, 6, 5, 2, -10};`
 	
`int size = 10;`
	`AREA myData, DATA`
	`ALIGN`
	`array DCD -1,5,3,8,10,23,6,5,2,-10`
	`size DCD 10`

`int main(void) {`
`  int i, maxLocation, maxValue;`
	`AREA findMax, CODE`
	`EXPORT __main`
	`ALIGN`
	`ENTRY`
	`__main PROC`
	`; Identify the array size`
	`LDR r3, =size`
	`LDR r3, [r3] ; r3 = array size = 10`

`  // Initialize max and location`
`  maxLocation = 0;`
`  maxValue = array[0];`
	`; Initialize max value and location`
	`LDR r4, =array`
	`LDR r0, [r4] ; r0 = default max`
	`MOV r1, #0 ; r1 = max location`

`  // loop: through the array`
`  for (i = 0; i < size; i++){`
`    if (array[i] > maxValue) {`
`        maxValue = array[i];`
`        maxLocation = i;`
`    }`
`  }`
	`; loop: over the array`
	`MOV r2, #0 ; loop: index i`
	`loop: CMP r2, r3 ; compare i & size`
	`BGE stop ; stop if i ≥ size`
	`LDR r5, [r4,r2,LSL #2] ; array[i]`
	`CMP r5, r0 ; compare with max`
	`MOVGT r0, r5 ; update max value`
	`MOVGT r1, r2 ; update location`
	`ADD r2, r2, #1 ; update index i`
	`B loop:`

`  while(1); //dead loop:`
`}`
	`stop B stop ; dead loop:`
	`ENDP`
	`END`

Quiz

- Instruction LDR r5, [r4,r2,LSL #2] has the form:
- LDR <destination register>, [<base register>, <index register>, LSL #<shift amount>]
- Address=value in r4+(value in $r2 \times 2^2$)
  - The memory address is calculated by taking the value in the <base register> (here r4) plus the value in the <index register> (here r2) shifted left (logical shift left, LSL) by a certain number of bits (#2 means shifted by 2 bits, or multiplied by 4).
- Q: why do we perform $r2 \times 2^2$ here?
- ANS: Since each element is a 32-bit integer (word), we need to multiply by 4 to convert from array index to memory address