

Part 5

CHAPTER 3

Architecture and Organization



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ARM's Data-Processing Instructions

Addition **ADD**, **ADC**,
 ADDS, **ADCS**

Subtraction **SUB**, **RSB**,
 SUBS, **RSBS**

Negation **NEG**,
 NEGS

Move **MOV**, **MVN**,
 MOVS, **MVNS**

Multiplication **MUL**, **MLA**,
 MULS, **MLAS**

Bitwise logic **AND**, **ORR**, **EOR**, **BIC**,
 ANDS, **ORRS**, **EORS**, **BICS**

Comparison **CMP**, **CMN**, **TEQ**, **TST**

Shift **LSL**, **LSR**, **ASR**, **ROR**, **RRX**,
 LSLS, **LSRS**, **ASRS**, **RORS**, **RRXS**

There are 4 groups of ARM's instructions

- ✓ **Data-Processing instructions**
- ✓ **Branching instructions**
- ✓ **Loading/Storing a single-register instructions**
- ✓ **Loading/Storing multi-registers instructions**

To learn more about any ARM assembly instruction,
you can just Google the words
ARM Keil + the operation-code.

For example, to learn more about "**ADD**" instruction,
you need to Google("**ARM Keil add**").
It is usually the first link.

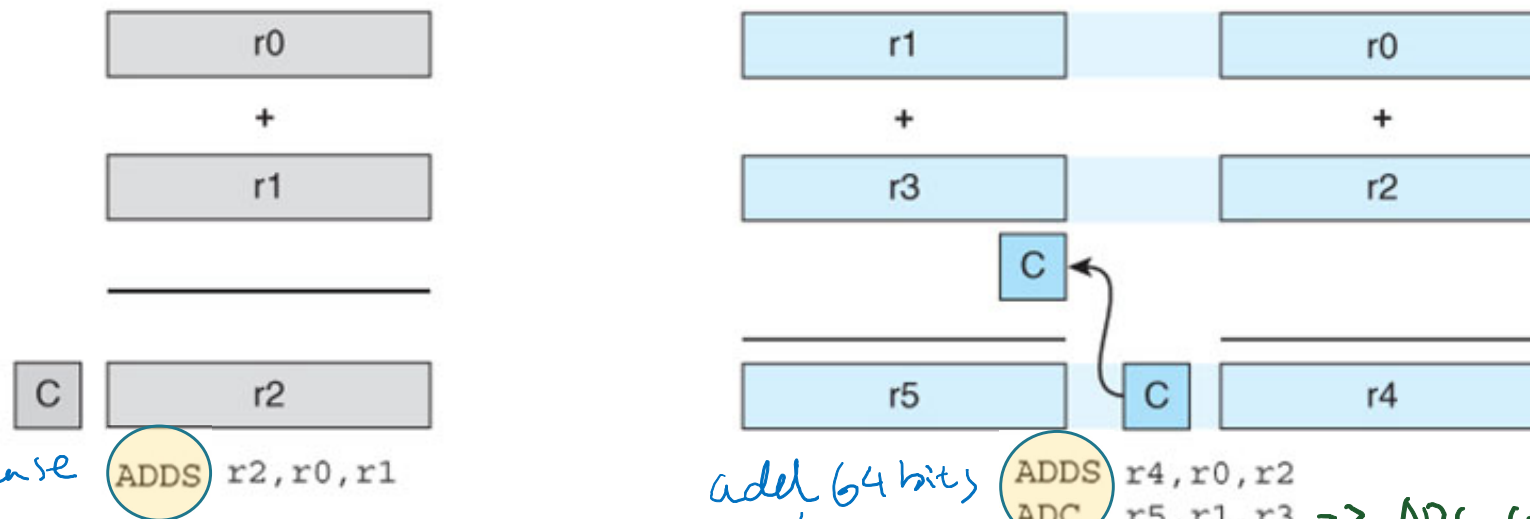
◀ *inbolds are pseudo instructions.*

Any instruction ends with S updating the N, Z, C and V flags according to the result, unless otherwise specified.

ARM's Data-Processing Instructions (Arithmetic Instructions: Addition)

- ❑ A simple ADD (and ADDS) instruction adds two 32-bit values.
- ❑ ARM also has an ADC (add with carry), as well as ADCS, that adds two 32-bit values together with the carry bit.
 - This allows extended precision arithmetic as Figure 3.21 demonstrates.

FIGURE 3.21 Single- and extended-precision addition



It can be extended to integers of arbitrary lengths.

in this case
ADD works
the same
as bit.

(a) Single-precision addition. When `r0` is added to `r1`, the result is loaded into `r2`, and the carry bit is loaded into the carry flag.

add 64 bits
together

(b) Double-precision extended addition. When `r0` is added to `r2`, any carry out is stored in the carry bit. When `r1` is added to `r3`, the carry bit is added to their sum. In other words, the carry out generated by `ADDS r4, r0, r2` becomes the carry in used by `ADC r5, r1, r3`.

-> ADC could add multiple bits.

ARM's Data-Processing Instructions (Arithmetic Instructions: Subtraction)

- Beside the *normal subtraction* (SUB), ARM also provides *reverse subtraction* (RSB)

- SUB **r1**, r2, r3 ; $[r1] \leftarrow [r2] - [r3]$
- RSB **r1**, r2, r3 ; $[r1] \leftarrow [r3] - [r2]$

- RSB is useful, as ARM treats its operands differently.

- For example, to perform $[r1] \leftarrow 10 - [r2]$, you can **not** use
SUB **r1**, #10, r2 ; **THIS IS WRONG**
instead, you can use
RSB **r1**, r2, #10 ; **CORRECT**

ARM's Data-Processing Instructions (Arithmetic Instructions: Subtraction)

□ Note that

RSB **r1**, #5

means

RSB **r1**, r1, #5

ADD **r1**, #5

means

ADD **r1**, r1, #5

When having a 3-operands instruction, if the 1st and 2nd operands are the same registers, it is allowed to short-hand the instruction by typing the register once. The assembler will take care of this short-hand and repeat the operand.

ARM's Data-Processing Instructions (Arithmetic Instructions: Negation)

□ Negation is to subtract a number from 0

(*arithmetic complement, i.e., 2's complement*)

The end effect as if
multiplying the
operand by -1

○ ARM does **not** have a negation instruction as such

○ Instead, ARM provides a *pseudo instruction* called NEG

NEG **r1**, r2

NEG instruction has only two operands.

○ The RSB instruction is utilized to implement NEG

▪ To negate r2 (i.e., calculating $0 - [r2]$) and store the result in r1,

NEG **r1**, r2

or

RSB **r1**, r2, #0

▪ To negate r2 (i.e., calculating $0 - [r2]$) and store the result in r2,

NEG **r2**, r2

or

RSB **r2**, r2, #0

Or simple

RSB **r2**, #0

Can not be shortened to NEG r2

ARM's Data-Processing Instructions (Arithmetic Instructions: Move and Move NOT)

- ❑ ARM provides a MOV instruction that copies the value of the second operand into the first operand

- To copy the content of r1 to r0, *the value of r1 does not change.*

MOV r0, r1 . . .

MOV instruction has only two operands.

- ❑ ARM also provides MVN (*move not*) that performs a *bitwise logical complement operation (i.e., logical NOT)* on the value of the second operand (i.e., *flipping each zero to one and each one to zero*), and places the result into the first operand

- To copy the *logical complement* of the content of r1 to r0,

MVN r0, r1 . . .

MVN instruction has only two operands.

MOVS and MVNS

- ✓ *Update the N, Z and C flags according to the result*
- ✓ *Do NOT affect the V flag*

ARM's Data-Processing Instructions

(Arithmetic Instructions: Multiplication)

MUL can not be shortened to two operands

- ❑ The *multiply* instruction, MUL Rd, Rm, Rs
 - Takes two 32-bit signed integer values from registers Rm and Rs
 - Forms their 64-bit product
 - Stores in 32-bit register Rd *the lower-order 32 bits of the 64-bit product.*

```
MOV    r0, #121      ;load r0 with 121
MOV    r1, #96        ;load r1 with 96
MUL    r2, r0, r1     ;r2 = r0 x r1
```

- ❑ A 32-bit by 32-bit **multiplication** is *truncated* to the **lower-order 32 bits**.
- ❑ In MUL instruction, *same register can't* be used to specify both the *destination* Rd and the *operand* Rm, *since it is implemented by an accumulator*
 - because ARM's implementation uses Rd as a temporary register during multiplication. This is a feature of the ARM processor.
- ❑ ARM does not allow multiply by a constant

MULS

- ✓ Updates the N and Z flags according to the result
- ✓ Corrupts the C and V flags

ARM's Data-Processing Instructions (Arithmetic Instructions: Multiplication)

- ❑ ARM has a *multiply and accumulate* instruction, MLA, that
 - performs a multiplication and adds the product to a running total.

- ❑ MLA instruction has a four-operand form:

MLA **Rd**, Rm, Rs, Rn ; [Rd] = [Rm] × [Rs] + [Rn] .

MLA can not be shortened to three operands

- ❑ As in the normal MUL instruction,
 - A 32-bit by 32-bit **multiplication** is *truncated* to the **lower-order 32 bits**.
 - *same register can't* be used to specify both the *destination* **Rd** and the *operand* Rm
- ❑ ARM *does not* allow *multiply by a constant*

MLAS

- ✓ *Updates the N and Z flags according to the result*
- ✓ *Corrupts the C and V flags*

ARM's Data-Processing Instructions (Arithmetic Instructions: Multiplication)

- ❑ ARM's *multiply and accumulate* supports the calculation of an *inner product* (a.k.a. *dot product*).
- ❑ The inner product of two vectors $\mathbf{a} = [a_1, a_2, \dots, a_n]$ and $\mathbf{b} = [b_1, b_2, \dots, b_n]$ is defined as

$$s = \mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^n a_i b_i = a_1 b_1 + a_2 b_2 + \dots + a_n b_n$$

ARM's Data-Processing Instructions

(Arithmetic Instructions: Multiplication)

- ❑ The following program shows how the multiply and accumulate instruction is used to form the **inner product** between n-component vectors, Vector1 and Vector2

```

AREA MultiplyAndAccumulateExample, CODE, READONLY
ENTRY
n    EQU    4                ;4 components in this example
MOV    r4, #n                ;r4 is the loop counter
MOV    r3, #0                ;clear the inner product
ADR    r5, Vector1           ;r5 points to vector 1
ADR    r6, Vector2           ;r6 points to vector 2

Loop LDR    r0, [r5], #4      ;REPEAT
                                ; read a component of A
                                ; and update the pointer
    LDR    r1, [r6], #4      ; get the second element
                                ; and update the pointer
    MLA    r3, r0, r1, r3    ; add new product term to the total
                                ; (r3 = r3 + r0·r1)
    SUBS    r4, r4, #1      ; decrement the loop counter
                                ; (and remember to set the CCR)
    BNE    Loop             ;UNTIL all done

Vector1 DCD    1, 2, 3, 4
Vector2 DCD    2, 3, 4, 5
END

```

ARM's Data-Processing Instructions (Arithmetic Instructions: Multiplication)

- In addition to the 32-bit MUL and MLA, ARM includes several forms of multiplication instruction, including
- UMLL Unsigned long multiply
 ($R_m \times R_d$ yields 64-bit product in two registers)
 - UMLAL Unsigned long multiply-accumulate
 - SMULL Signed long multiply
 - SMLAL Signed long multiply-accumulate



**We will NOT
cover these
instructions.**

ARM's Data-Processing Instructions (Arithmetic Instructions: Division)

- ❑ ARM does not implement a division operation
- ❑ If needed, the programmer must write a suitable division routine to implement division

ARM's Data-Processing Instructions (Bitwise Logical Operations)

The rest of the bits
in these instructions
are zeros.

- ❑ Logical operations are known as *bitwise operations* because they are applied to the individual bits of a register

It is
ORR,
not
OR.

AND **r2**, r1, r0 → Example: 11001010 . 00001111 → 00001010

ORR **r2**, r1, r0 → Example: 11001010 + 00001111 → 11001111

EOR **r2**, r1, r0 → Example: 11001010 ⊕ 00001111 → 11000101

MVN **r2**, r0 → Example: 11001010 →
1111111111111111111111111111111100110101

- ❑ The **MVN** operation can also be performed by using an **EOR** with the second operand equal to FFFFFFFF₁₆ (i.e., 32 1's in a register)
- the value of $x \oplus (11...1111)_2$ is = **NOT** x .

MOV r1, #0xFFFFFFFF

EOR **r2**, r1, r0 ; Same as MVN **r2**, r0

ANDS, ORRS, EORS, and MVNS

- ✓ Update the N, Z and C flags according to the result
- ✓ Do NOT affect the V flag

ARM's Data-Processing Instructions (Bitwise Logical Operations)

❑ **Example 1:** suppose that


- register r0 contains the 8 bits **bbbbbbxx**,
- register r1 contains the 8 bits **bbbyyybb** and
- register r2 contains the 8 bits **zzzbbbb**,

where

- **xx**, **yyy**, and **zzz** represent the bits of desired fields and
- the **b**'s are unwanted bits.

❑ We wish to pack these bits to get the final value **zzzyyyxx** stored in r0.

❑ We can achieve this by:



```

AND    r0, r0, #2_11           ;Mask r0 to two bits xx
AND    r1, r1, #2_11100        ;Mask r1 to three bits yyy
AND    r2, r2, #2_11100000     ;Mask r2 to three bits zzz
ORR    r0, r0, r1              ;Merge r1 and r0 to get 000yyyxx
ORR    r0, r0, r2              ;Merge r2 and r0 to get zzzzyyyxx
  
```

❑ *The Keil assembler uses a prefix*

- **2_** to indicate binary
- **8_** to indicate octal
- **0x** or **&** to indicate hexadecimal
- **no prefix** to indicate decimal

ARM's Data-Processing Instructions (Bitwise Logical Operations)

- ❑ **Example 2:** suppose we have an 8-bit value **abcdefgh** and
- ❑ we wish to
 - clear bits **b** and **d**,
 - set bits **a**, **e**, and **f**, and
 - toggle (invert) bit **h**,
 i.e., generate the following output **10c011g \bar{h}**

- ❑ We can achieve this by:

```

AND  r0, r0, #2_10101111 ;Clear bits b and d to get  a0c0efgh
ORR  r0, r0, #2_10001100 ;Set bits a, e, and f to get  10c011gh
EOR  r2, r2, #2_1         ;Toggle bit h to get the result

```

ARM's Data-Processing Instructions (Bitwise Logical Operations)

- ❑ **ARM** provides a *bit clear* instruction, **BIC**, that
 - ANDs its first operand with the complement of its second operand.
- ❑ **Example:** suppose we have $r1 = 10101010$ and $r2 = 00001111$.
 - The instruction **BIC r0, r1, r2** yield 10100000

BICS

- ✓ *Updates the N, Z and C flags according to the result*
- ✓ *Does NOT affect the V flag*

ARM's Data-Processing Instructions (Arithmetic Instructions: Comparison)

- ❑ In ARM, updating the condition flags can be *implicit* or *explicit*.
- ❑ Both implicit and explicit flags' updates modify the contents of *the condition code register (CCR)*, a.k.a. *current program status register (CPSR)*, which is later can be tested to determine whether execution continues in sequence, or a branch is taken

- Example of *implicit* updates for the condition flags

SUBS **r1**, r1, r2

- Example of *explicit* updates for the condition flags

CMP r1, r2

This instruction will evaluate $r1 - r2$ *without storing the result*, and set the *condition code register*

```

CMP    r1, r2           ;is r1 = r2?
BEQ    DoThis           ;if equal then goto DoThis
ADD    r1, r1, #1      ;else add 1 to r1
B      Next            ;jump past the then part
.
DoThis SUB r1, r1, #1    ;subtract 1 from r1
Next   ...              ;both forks end up here
  
```

ARM's Data-Processing Instructions (Arithmetic Instructions: Comparison)

- ❑ **ARM** has *four* instructions in its *test-and-compare* group which *explicitly update the condition code flags* (i.e., *no need to append an S to any of them*)
- **CMP** (compare instruction)
 - *Subtracts* the second operand from the first and *update all flags*
 - **TEQ** (test equivalent instruction)
 - Determines whether two operands are equivalent or not (*similar to EORS, except that the result is discarded*)
 - **TST** (test instruction)
 - Compares two operands by **ANDing** them together and *update flags*
 - Usually used to *test individual bits*;
 - `TST r0, #2_00100000 ; AND r0 with 00100000 to test bit 5`
••• BNE LowerCase ; If bit 5 is 1, jump to lowercase
 - **CMN** (compare negative instruction).
 - 2's complements the second operand before performing the comparison
`CMN r1, r2 ; evaluates [r1] - (-[r2])`
; i.e., evaluate [r1] + [r2]

It is
BNE,
not
BEQ.

It is **CMN**, *not* **CPN**. Correct the book, page 178

TEQ and TST

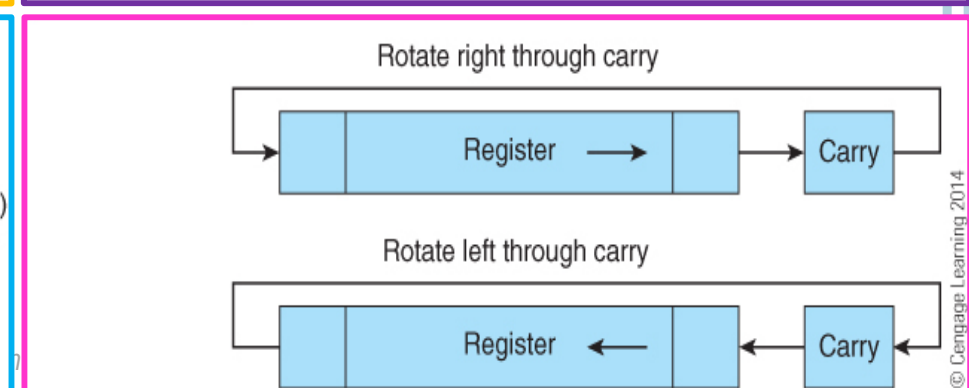
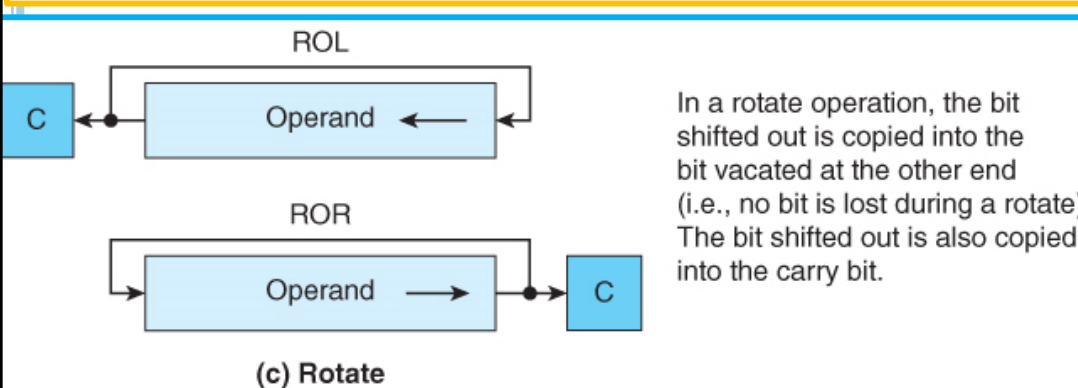
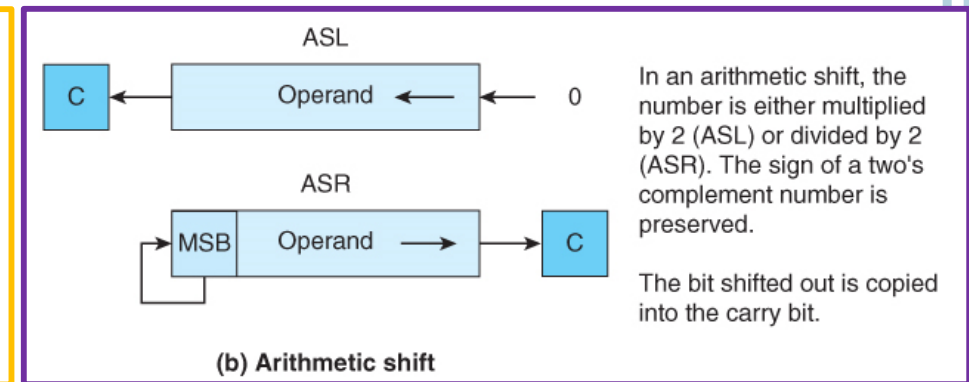
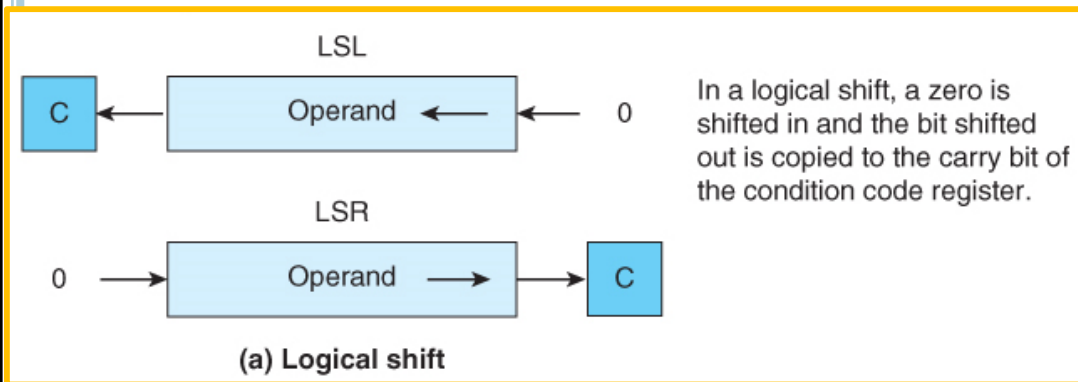
- ✓ *Update the N, Z and C flags according to the result*
- ✓ *Do NOT affect the V flag*

CMP and CMN *update ALL flags according to the result*

ARM's Data-Processing Instructions

(Shift Operations)

- ❑ *Shift* operations **move bits** one **or more** places **left** or **right**.
 - **Logical shifts**
 - *insert a 0* in the vacated position.
 - **Arithmetic shifts**
 - *replicate the sign-bit* during a right shift
 - **Circular shifts**
 - *the bit shifted-out of one end is shifted-in the other end*
i.e., the register is treated as a ring
 - **Circular shifts through carry**
 - *included the carry bit in the shift path*



ARM's Data-Processing Instructions (Shift Operations)

Examples of **logical shifts** on a *16-bit value*

Source string	Direction	Number of shifts	Destination string
0 110011111010111	Left	1	110011111010111 0
01 10011111010111	Left	2	10011111010111 00
011 0011111010111	Left	3	0011111010111 000
011001111101011 1	Right	1	0 011001111101011
01100111110101 11	Right	2	00 01100111110101
0110011111010 111	Right	3	000 0110011111010

These examples are hypothetical, as ARM registers are 32 bits, not 16 bits.

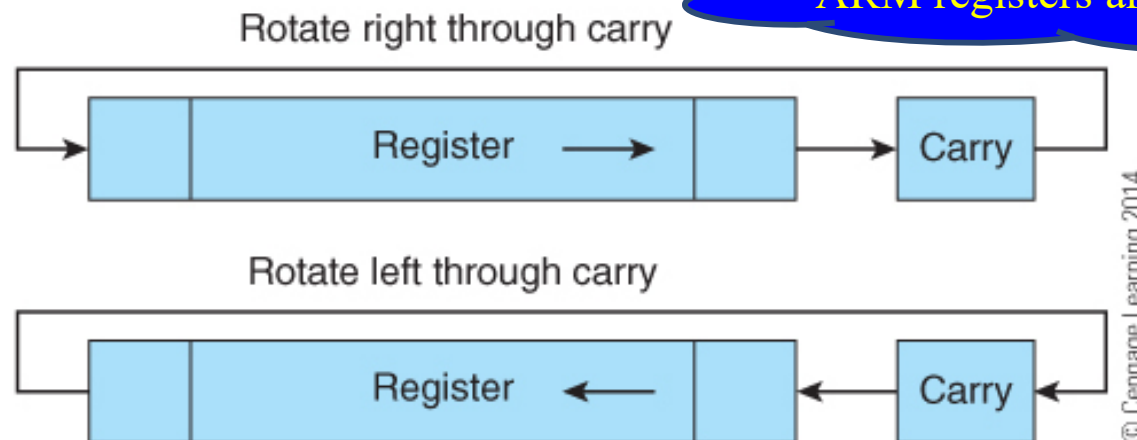
ARM's Data-Processing Instructions (Shift Operations)

- ❑ The *rotate through carry* instruction (sometimes called *extended shift*) included the carry bit in the shift path.
 - The carry bit is shifted into the bit of the word vacated, and
 - the bit of the word shifted out is shifted into the carry.
- ❑ If the **carry** = 1 and the *eight-bit word* to be shifted is 01101110, a *rotate left through carry* would give 11011101 and

carry = 0

FIGURE 3.24

The rotate through carry



This example is hypothetical, as ARM registers are 32 bits, not 8 bits.

Implementing a Shift Operation on the ARM

- ❑ **ARM** *has no explicit shift operations!!*.
- ❑ **ARM** *combines shifting with other data processing operations*, where
 - the **second operand** in the arithmetic operation (i.e., the **LAST parameter in the assembly arithmetic instruction**) is allowed to be shifted **before** it is used.
 - For example,
ADD **r0**, r1, r2, LSL #1 ; $[r0] \leftarrow [r1] + [r2] \times 2$
 - logically shift left the contents of r2,
 - add the result to the contents of r1, and
 - put the results in r0
- ❑ **ARM** *also combines shifting with MOV and MVN instructions*
 - For example,
MOV **r3**, r3, LSL #1 ; $[r3] \leftarrow [r3] \times 2$
 - **ARM** provides **pseudo** shift instructions, which are translated to **MOV** instructions.
 - For example,
LSL **r3**, r3, #1 ; will be converted to:
MOV **r3**, r3, LSL #1
or simply
LSL **r3**, #1

Implementing a Shift Operation on the ARM

- ❑ **ARM** support both *static* and *dynamic* shifts (except *rotate through carry* instruction which allows *only one single shift* per instruction)
 - In *static shift*, the number of shift places
 - is determined *when the code is written*
 - can only have the following values, inclusive:
 - **LSL**: allowable values are from **#0** to **#31** (*32 different values*)
 - **LSR**: allowable values are from **#1** to **#32** (*32 different values*)
 - **ASR**: allowable values are from **#1** to **#32** (*32 different values*)
 - **ROR**: allowable values are from **#1** to **#31** (*31 different values*)
 - The remaining value is used to encode RRX*
 - In *dynamic shift*, the number of shift places
 - is determined *when the code is executed, i.e., at run time*
- ❑ You can perform *dynamic shifts* as follow

MOV **r4**, r3, LSL r2 ; [r4] ← [r3] × 2^{r2}
 or
 LSL **r4**, r3, r2 ; [r4] ← [r3] × 2^{r2}

This instruction

- shifts the contents of r3 left by the value in r2 and
- puts the result in r4.

○ *If the value in r2 is ≥ 32, zero will be stored in r4*

Implementing a Shift Operation on the ARM

- ❑ **ARM** implements only the following five shifts

LSL logical shift left

LSR logical shift right

ASR arithmetic shift right

ASL = LSL

ROR rotate right

ROL = circular

RRX rotate right through carry (one shift)

- ❑ *Other shift operations must be synthesized by the programmer.*

Implementing a Shift Operation on the ARM

❑ *Other shift operations must be synthesized by the programmer.*

- An *arithmetic shift left* is effectively the same as a *logical shift left*
- For a 32-bit value,
an *n-bit rotate shift left* is identical to a *32 – n rotate shift right*
- *Rotate left through carry* can be implemented by means of
ADCS `r0, r0, r0 ; add r0 to r0 with carry and set the flags`
 - The instruction means $r0 + r0 + C$, i.e., $2 \times r0 + C$, i.e.,
 - shifting left the content of r0
 - store the value of C in the vacant bit to the left, and
 - storing the shifted-out bit in the carry flag