ALU instructions

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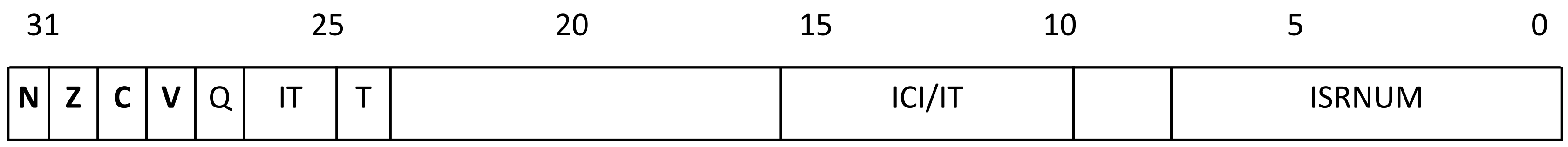
Flags

- The uppermost nibble of the program status register contains the flags.



- Flags are set and cleared by means of:
  - comparison instructions, e.g., `CMP` and `TST`
  - ALU instructions if they have the suffix ‘`S`’
  - a direct write to the program status register.

Carry flag C

- After a sum, C = 1 if the result size is 33 bit.

```
    1010 0001 0001 0001 0001 0001 0001 0001 +
    1011 0101 0101 0101 0101 0101 0101 0101 =
  -------------------------------------------
C = 1 0101 0110 0110 0110 0110 0110 0110 0110
```

- After a subtraction, C is inverted. Here C = 1:

```
    1101 0000 0000 0000 0000 0000 0000 0000 -
    0101 0000 0000 0000 0000 0000 0000 0000 =
  -------------------------------------------
    1000 0000 0000 0000 0000 0000 0000 0000
```

- After a move or logical instruction, C is the result of an inline barrel shifter operation.

Carry Flag C

In unsigned arithmetic, watch the carry flag to detect errors.
In signed arithmetic, the carry is used for comparisons together with other flags .

1. The carry flag is set if the addition of two numbers causes a carry out of the most significant (leftmost) bits added.
   - 1111 + 0001 = 0000 (carry flag is turned on)

2. The carry (borrow) flag is also set if the subtraction of two numbers requires a borrow into the most significant (leftmost) bits subtracted.
   - 0000 - 0001 = 1111 (carry flag is turned on)

Otherwise, the carry flag is turned off (zero).

- 0111 + 0001 = 1000 (carry flag is turned off [zero])
- 1000 - 0001 = 0111 (carry flag is turned off [zero])

Negative flag N

- It corresponds to the first bit of the result.
- If N =1, a 2's complement number is negative.
- Example: -4 + (-3) = -7 -> N = 1

```
        1111 1111 1111 1111 1111 1111 1111 1100 +
        1111 1111 1111 1111 1111 1111 1111 1101 =
    ---------------------------------------------
N =     1111 1111 1111 1111 1111 1111 1111 1001
```

- Why N = 1 in the following sum?

```
        0111 0001 0001 0001 0001 0001 0001 0001 +
        0011 0101 0101 0101 0101 0101 0101 0101 =
    ---------------------------------------------
N =     1010 0110 0110 0110 0110 0110 0110 0110
```

Overflow flag V

- It is set if, in a sum of values with the same sign, there is a change in the MSB

```
This is a carry    1010 0001 0001 0001 0001 0001 0001 0001 +
                   1011 0101 0101 0101 0101 0101 0101 0101 =
                 ----------------------------------------------
(V = 1) 1          0101 0110 0110 0110 0110 0110 0110 0110
```

- V = 0 if both conditions occur: the result is right

```
                    1110 0001 0001 0001 0001 0001 0001 0001 +
                    1011 0101 0101 0101 0101 0101 0101 0101 =
                 ----------------------------------------------
(V = 0)           1 1001 0110 0110 0110 0110 0110 0110 0110
```

Zero flag Z

- It is set if the result is zero.

```
       1111 1111 1111 1111 1111 1111 1111 1101 +
       0000 0000 0000 0000 0000 0000 0000 0011 =
----------------------------------------------------
 Z =   0000 0000 0000 0000 0000 0000 0000 0000
```

Comparison instructions

- They compare the value or test some bits:

```
compare/test <Rd>, <operand2>
```

- They set the flags without updating `Rd`.
- The second operand can be:
  - a register with an optional shift
  - a constant obtained by shifting left an 8-bit value
  - a constant of the form 0x00XY00XY
  - a constant of the form 0xXY00XY00
  - a constant of the form 0xXYXYXYXY.

CMP and CMN

- `CMP` (compare) substracts `operand2` from `Rd` and updates the flags.
- `CMN` (compare negative) adds `operand2` to `Rd` and updates the flags.
  - The execution of the arithmetic operations at the base of the `CMP` and `CMN` is not modifying the content of the operands.
- Examples with `r0` = #12
  - `CMP r0, #10` -> N = 0, Z = 0, C = 1, V = 0
  - `CMP r0, #12` -> N = 0, Z = 1, C = 1, V = 0
  - `CMP r0, #14` -> N = 1, Z = 0, C = 0, V = 0
- The assembler can change `CMP` and `CMN`:
  - `CMP r0, #-8` becomes `CMN r0, #8`

TST and TEQ

- `TST` (test) computes the logical AND between `operand2` and `Rd`; then updates all the flags except `V`.
- `TEQ` (test equivalence) computes the logical EOR between `operand2` and `Rd`; then updates all the flags except `V`.
- Examples with `r0` = #1
  - `TST r1, r0, LSL#4` -> is the 4th bit of `r1` set?
  - `TEQ r2, r3` -> are `r2` and `r3` equal?

Accessing Program Status Register

- `MRS <Rn>, <Sreg>` copies a special register into a register.
- `MSR <Sreg>, <Rn>` copies a general purpose register into a special register.
- `Sreg` can be `APSR`, `EPSR`, `IPSR`, and `PSR`.
- `MRS r0, APSR` reads the flags and copies them to the uppermost nibble of `r0`.

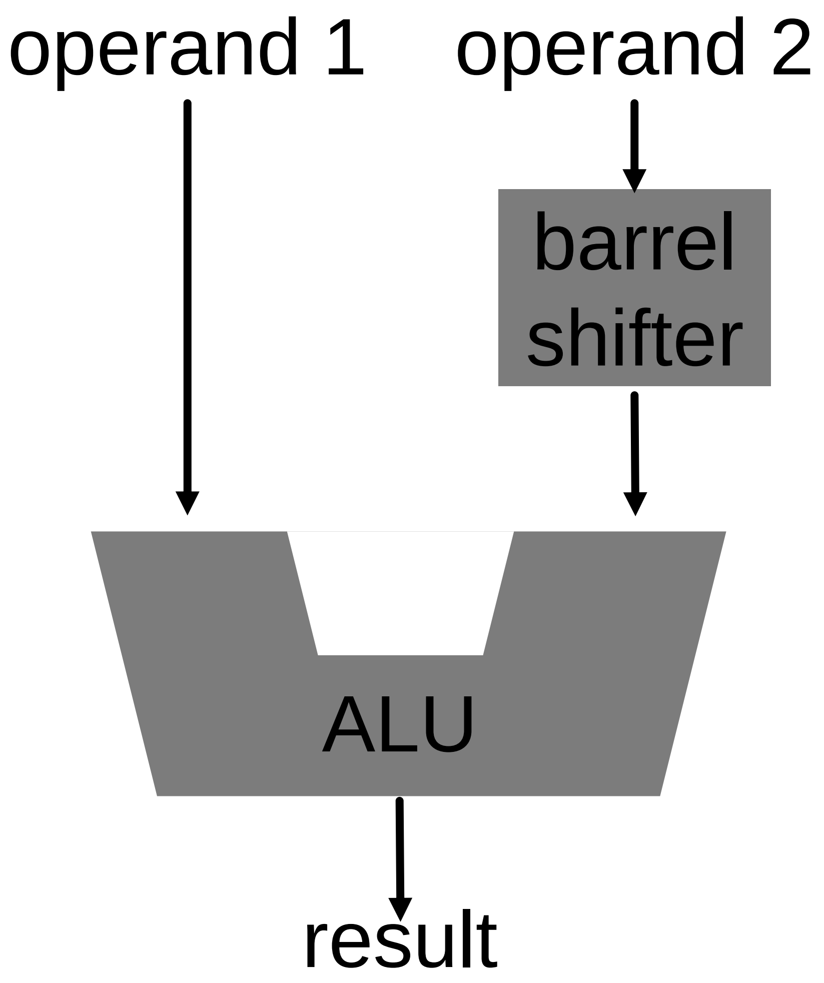
ALU instructions and flags

- ALU can perform:
  - arithmetic operations
  - logic operations
  - shift and rotate operations.
- The flags are affected only if the suffix ‘S’ is appended to the instruction.

-
  ```
  LDR r0, =0xFFFFFFF9
  ADDS r1, r0, #7
  ```

  Flags are N = 0, Z = 1, C = 1, V = 0.

Internal data path to ALU



Operand 1 is a register.

Operand 2 can be:

- shifted register
- shifted 8-bit constant
- 0x00XY00XY
- 0xXY00XY00
- 0xXYXYXYXY
- 12-bit constant (`ADD` and `SUB` only).

Arithmetic instructions

- Addition
  - addition with carry
- Subtraction
  - subtraction with carry
  - reverse subtraction
- Multiplication
  - multiplication with accumulation
  - multiplication with subtraction
- Division

Addition

- `ADD <Rd>,<Rn>,<op2>  Rd = Rn + op2`
- `ADC <Rd>,<Rn>,<op2>`

  `Rd = Rn + op2 + C`
- `ADDW` is like `ADD`, but it takes only a 12-bit value and it can not update flags.
- With `ADC` it is possible to add 64-bit values:

```
ADDS r4,r0,r2
ADC r5,r1,r3
```

In the example `r5,r4 = r1,r0 + r3,r2`

Subtraction

- `SUB <Rd>,<Rn>,<op2>  Rd = Rn - op2`
- `SBC <Rd>,<Rn>,<op2>`

  `Rd = Rn - op2 + C - 1`
- `SUBW` is like `SUB`, but it takes only a 12-bit value and it can not update flags.
- With `SBC` it is possible to subtract 64-bit values

```
SUBS r4,r0,r2
SBC r5,r1,r3
```

In the example `r5,r4 = r1,r0 - r3,r2`

Reverse subtraction

- `RSB <Rd>,<Rn>,<op2>`

  `Rd` = `op2` - `Rn` + C – 1
- Advantages:
  - either one or the other operand can be shifted before the subtraction

```
SUB r0, r1, r2, LSL #2    ;r0 = r1 - r2*4
RSB r0, r2, r1, LSL #2    ;r0 = r1*4 - r2
```

  - a register can be subtracted from a constant.

Multiplication

- multiplication with 32-bit result

```
    MUL <Rd>, <Rn>, <Rm>
```

- unsigned multiplication with 64-bit result

```
    UMULL <Rd1>, <Rd2>, <Rn>, <Rm>
```

- signed multiplication with 64-bit result

```
    SMULL <Rd1>, <Rd2>, <Rn>, <Rm>
```

- Note 1: there is no distinction between signed and unsigned multiplication with 32-bit result.
- Note 2: all operands must be registers.

Multiplication with accumulation

- `MLA <Rd>, <Rn>, <Rm>, <Ra>`

  `Rd = Rn * Rm + Ra`
- `MLS <Rd>, <Rn>, <Rm>, <Ra>`

  `Rd = Rn * Rm – Ra`
- `UMLAL <Rd1>, <Rd2>, <Rn>, <Rm>`

  `Rd1,Rd2 = Rn * Rm + Rd1,Rd2`
- `SMLAL <Rd1>, <Rd2>, <Rn>, <Rm>`

  same as `UMLAL`, but with signed values.

Division

- unsigned division

```
UDIV <Rd>, <Rn>, <Rm>
```

- signed division

```
SDIV <Rd>, <Rn>, <Rm>
```

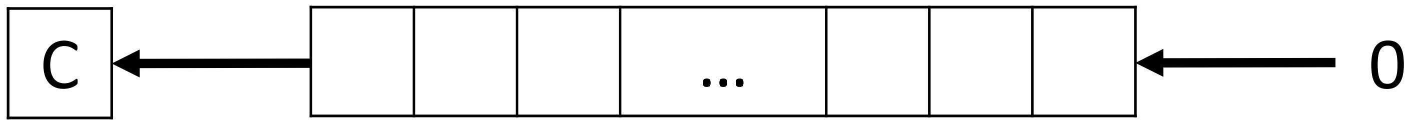
- If `Rn` is not exactly divisible by `Rm`, the result is rounded toward zero.
- `UDIV` and `SDIV` do not change the flags (the suffix ‘S’ can not be added).

Logic instructions

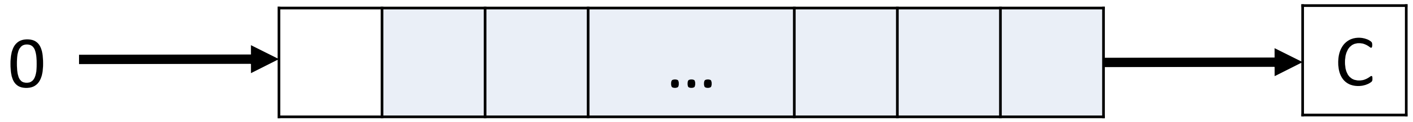
- `AND <Rd>, <Rn>, op2` ;`Rn` AND `op2`
- `BIC <Rd>, <Rn>, op2` ;`Rn` AND NOT `op2`
- `ORR <Rd>, <Rn>, op2` ;`Rn` OR `op2`
- `EOR <Rd>, <Rn>, op2` ;`Rn` XOR `op2`
- `ORN <Rd>, <Rn>, op2` ;`Rn` OR NOT `op2`
- `MVN <Rd>, <Rn>` ; NOT `Rn`

Shift instructions

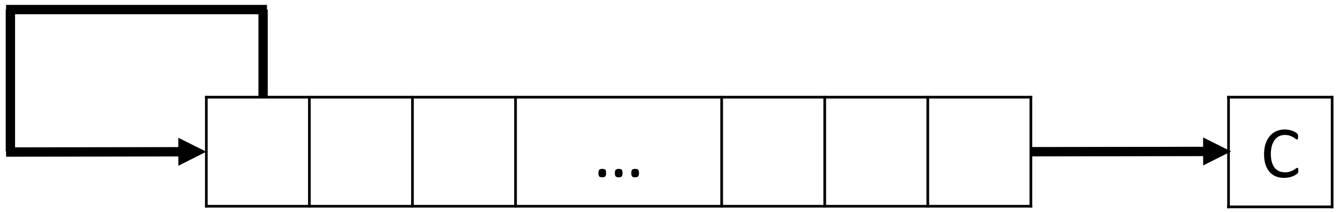
- `LSL <Rd>, <Rn>, <op2>`



- `LSR <Rd>, <Rn>, <op2>`

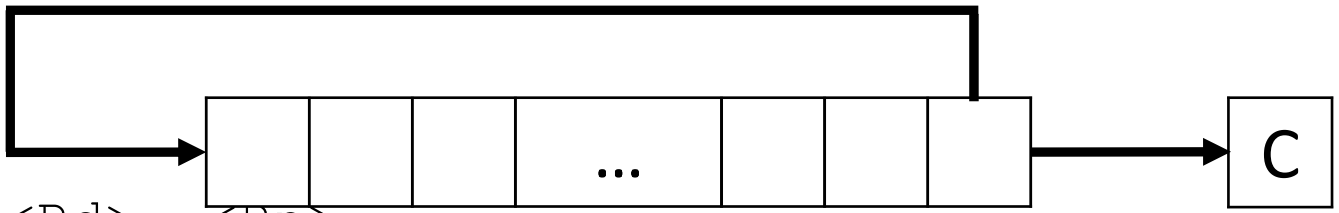


- `ASR <Rd>, <Rn>, <op2>`

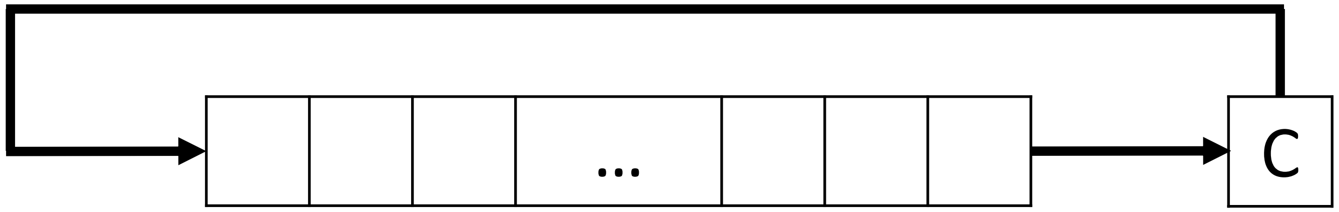


Rotate instructions

- `ROR <Rd>, <Rn>, <op2>`



- `RRX <Rd>, <Rn>`



Exercise: 64-bit routines for shift

- shift left `r1,r0` by one bit and save the result in `r3,r2`.
- logical shift right `r1,r0` by one bit and save the result in `r5,r4`.
- arithmetic shift right `r1,r0` by one bit and save the result in `r7,r6`.
- rotate right `r1,r0` by one bit and save the result in `r9,r8`.
- rotate right through carry flag `r1,r0` by one bit and save the result in `r11,r10`.