

CEG 3136 Summary Sheet

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1 Data Representation

One **Byte** is defined as 8 bits. In 32 bit architecture, one **Word** is 32 bits, and therefore a half word is 16 bits, and a double word is 64 bits.

We have unsigned integers and signed integers. Unsigned is simple, signed can be represented in either signed magnitude, twos complement, or ones complement.

Ex. Show -5 in 4 bits in all 3 forms

Positive 5: 0101

Signed Magnitude: 1101

Twos Complement: 1011

Ones Complement: 1010

In an adder/subtractor, we generate a carry flag (C) (carry out of most significant bit [MSB]) and an overflow flag (V). If we are doing unsigned, the carry flag signifies something is wrong (C=1 for addition, C=0 for subtraction). For signed, we ignore C, and use V. If V=1, something went wrong.

Overflow is the XOR of the carry out of the MSB and the carry in to the MSB.

We typically use twos complement since it makes addition and subtraction able to use the same logic.

1.1 Strings

Strings are represented using **ASCII** codes. Each string is compared using its ASCII value.

$$CAT < Cat < DOG < Dog < cat < dog$$

Letter	A	B	C	...	X	Y	Z	...	a	b	c	...	x	y	z
ASCII Code	41	42	43		58	59	5A		61	62	63		78	79	7A

1.2 Fixed Point

The **Q Notation** represents the type of fixed point using UQ_{m.n}.

U	Unsigned. Remove if we are doing signed
Q	Means Q notation
m	Number of integer bits
n	number of fractional bits

Ex. Approximate $-\pi$ using Q3.12

This means we have the sign bit, then 3 integer bits and 12 fractional bits.

We can represent pi as:

0011.001001000100

So after taking the twos complement $-\pi$ becomes:

1100.110110111100

If it was UQ4.12 we could only represent π not $-\pi$ but it would be:

0011.001001000100

To add fixed point numbers, it is very simple. We just treat it as if the radix is non existent.

1.3 Floating Point

Floating point is similar to scientific notation in decimal. We first need to normalize it. So we make it in the form of $1.xxxxxxx \times 2^{exp}$. We then hide the 1 as it is implied.

Using single precision, we have 1 bit for the sign, 8 for exponent, and 23 for the fractional.

To represent negative and positive exponents, we add 127 to the exponent.

Ex. Express $(36.5625)_{10}$ as a 32 bit floating point number using the IEEE standard.

The value in binary is 100100.1001 and normalized is 1.001001001×2^5 .

1. Sign: 0
2. Exponent: $5+127 = 132 = 10000100$
3. Mantissa: 001001001000000000000000

So the 32 bit number is: 0 10000100 001001001000000000000000 (without the spaces ofc)

We reserve some values for special cases:

Sign	Exponent	Fraction	Meaning
1 / 0	0000 0000	0000 ... 0000	0
1 / 0	1111 1111	0000 ... 0000	+ / - infinity
x	1111 1111	any non zero value	NaN (Not a Number)

Floating point has big dynamic range, but is less precise and more complicated than fixed point.

2 ARM Instructions

ARM has 3 main processor families;

CORTEX-A	High performance Application processors
CORTEX-R	Reliable Real time processors for mission critical purposes
CORTEX-M	Low cost, Low power Microcontroller

ARM has a few different instruction sets. The CORTEX-M series supports the T32 instruction set which includes both space saving 16 bit instructions, and high performance 32 bit instructions.

Other architectures such as CORTEX-A support T32 and A32 instructions with some supporting A64 as well.

ARM is a RISC architecture, so it cannot directly access memory through instructions. It must first **load** from memory into registers, then **modify**, and finally **store** back into memory.

We have 16 **core registers** and some **special purpose registers** as well. Since we are 32 bit, the registers are all 32 bits wide.

Register	General or Special	Purpose
R0	C	General Purpose
R1	C	General Purpose
R2	C	General Purpose
R3	C	General Purpose
R4	C	General Purpose
R5	C	General Purpose
R6	C	General Purpose
R7	C	General Purpose
R8	C	General Purpose
R9	C	General Purpose
R10	C	General Purpose
R11	C	General Purpose
R12	C	Intra Procedure Call Register (IR)
R13	C	Stack Pointer (SP) - Often there are two: MSP (Main) and PSP (Process)
R14	C	Link Register (LR)
R15	C	Program Counter (PC)
xPSR	S	Program Status Register
BASEPRI	S	Interrupt Priorities
PRIMASK	S	Enabling and Disabling Interrupts
FAULTMASK	S	Fault Handling
CONTROL	S	

Often we map some hardware device to a memory to make it easier to work with. For example, we may have it set up so bit 7 of R0 is 1 if an LED is on, or 0 if the LED is off.

Assembly has 4 main classes of instructions:

- Arithmetic and Logic
- Data Movement
- Compare and Branching
- Miscellaneous

Each instruction has 4 parts:

General From	label	mnemonic	operand(s)	comments
Ex		BX	LR	; branch to LR
Ex	LOOP	CMP	R1, R2	; start of loop, compares R1 and R2
Ex		STR	R1, R2	
Ex		ADD	R3, R5, R8	

We also have assembly directives which are just information for the assembler such as ALIGN, EXPORT, and ENDP.

Directive	Meaning
AREA	Make a new block of data or code
ENTRY	Declare an entry point where the program execution starts
ALIGN	Align data or code to a particular memory boundary
DCB	Allocate one or more bytes (8 bits) of data
DCW	Allocate one or more half-words (16 bits) of data
DCD	Allocate one or more words (32 bits) of data
SPACE	Allocate a zeroed block of memory with a particular size
FILL	Allocate a block of memory and fill with a given value
EQU	Give a symbol name to a numeric constant
RN	Give a symbol name to a register
EXPORT	Declare a symbol and make it referable by other source files
IMPORT	Provide a symbol defined outside the current source file
INCLUDE/GET	Include a separate source file within the current source file
PROC	Declare the start of a procedure
ENDP	Designate the end of a procedure
END	Designate the end of a source file

2.1 Arithmetic and Logic

Here are just a few of the arithmetic instructions for T32.

Mnemonic	Syntax	Meaning	Operation
ADD	{Rd,} Rn, Op2	Add	$Rd \leftarrow Rn + Op2$
ADC	{Rd,} Rn, Op2	Add w/ carry	$Rd \leftarrow Rn + Op2 + Carry$
SUB	{Rd,} Rn, Op2	Subtract	$Rd \leftarrow Rn - Op2$
SBC	{Rd,} Rn, Op2	Subtract w/ carry	$Rd \leftarrow Rn - Op2 + Carry - 1$
RSB	{Rd,} Rn, Op2	Reverse subtract	$Rd \leftarrow Op2 - Rn$
MUL	{Rd,} Rn, Rm	Multiply	$Rd \leftarrow (Rn \times Rm)[31 : 0]$
MLA	Rd, Rn, Rm, Ra	Multiply and accumulate	$Rd \leftarrow (Ra + (Rn \times Rm))[31 : 0]$
MLS	Rd, Rn, Rm, Ra	Multiply and subtract	$Rd \leftarrow (Ra - (Rn \times Rm))[31 : 0]$
SDIV	{Rd,} Rn, Rm	Signed divide	$Rd \leftarrow Rn \div Rm$
UDIV	{Rd,} Rn, Rm	Unsigned divide	$Rd \leftarrow Rn \div Rm$

There are also lots of logic ones such as AND, ORR, EOR (XOR), ORN (NOR) and so on.

There are many other instructions, the ARM T32 instruction set has a lot.

2.1.1 NZCV Flags

These flags are stored in bits 28 to 31 of the PSR.

Flag	Meaning
N	Negative - Result is Negative
Z	Zero - Result is Zero
C	Carry - Unsigned Arithmetic out of range
V	Overflow - Signed Arithmetic out of range

To update these flags, we add an S to the end of the instruction.

Ex.

Does not update NZCV flags: ADD, SUB, MUL, etc

Does update NZCV flags: ADDS, SUBS, MULS, etc

Always updates NZCV flags: CMP, CMN, TST, TEQ

2.1.2 Saturation

Saturation is a logical operation that deals with the case where overflow occurs.

Normally, it will wrap back around to the lowest value. However, sometimes we want to cap the highest value.

With Saturation (4 bits)	7+1=-8
Without Saturation (4 bits)	7+1=7

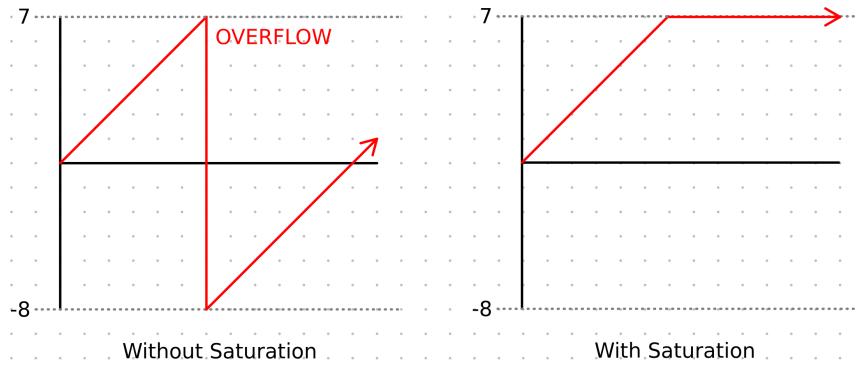


Figure 1: Saturation

2.1.3 Other Instructions

Instruction	Description	Similar Instructions
RBIT Rd, Rn	Reverses bit order in word	REV (byte order), REV16 (For half words), REVSH (Sign Extend)
SXTB {Rd,} Rm	Sign Extension (Byte)	SXTH (Half word), UXTB/UXTH (Zero extend)
MOV Rd, Rx	Move from Rx to Rd	MVN (MV and NOT), MRS (From special reg), MSR (From gen to special)
LSL Rd, Rn, #	Move Rn to Rd and left shift	LSR (right logical), ASR (Right arithmetic), ROR (rotate right)

2.2 Memory

Memory is byte addressable, but we typically only start a 32 bit word at a multiple of 4, a 16 bit half word at a multiple of 2, and a byte at any point.

LDRxx R0, [R1]	Load from memory at R1 into R0
STRxx R0, [R1]	Store contents of R0 into memory at R1

If we are storing something smaller than the memory width (byte, or halfword) we need to differentiate between signed (add S) [LDRSB, LDRSH] and unsigned (do not add S) [LDRB, LDRH].

When loading and storing, we can also address bits after the location we specify. This is useful for arrays. We have a few modes:

Register Offset	LDR r0, [r1, r2]	Target: r1+r2
Immediate Offset	LDR r0, [r1, #8]	Target: r1 + 8
Pre-Index	LDR r0, [r1, #4]!	Target: r1+4, update r1 to r1+4 after read
PostIndex	LDR r0, [r1], #4	Target: r1, increase r1 by 4 after read

2.3 Endianess

Endianess means within a 32 bit word (or any multi byte data structure) do we start the LSB at the low address (little endian) or high address (big endian)?

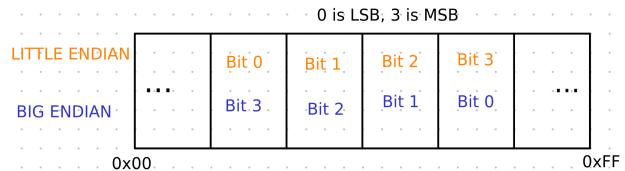


Figure 2: Endianess

2.4 Control Flow Instructions

We have 4 variations of the branch command. These will branch to either a label, or an address.

Instruction	Operands	Description
B	label	Branch
BL	label	Branch with link
BLX	Rm	Branch and Exchange with link
BX	Rm	Branch and Exchange

We have condition codes. These are appended to almost any instruction and they will only execute the instruction if the condition is true. It uses the status flags NZCV. These are typically performed after a CMP operation.

Suffix	Description	Flags tested
EQ	Equal	$Z = 1$
NE	Not Equal	$Z = 0$
CS/HS	Unsigned Higher or Same	$C = 1$
CC/LO	Unsigned Lower	$C = 0$
MI	Minus (Negative)	$N = 1$
PL	Plus (Positive or Zero)	$N = 0$
VS	Overflow Set	$V = 1$
VC	Overflow Cleared	$V = 0$
HI	Unsigned Higher	$C = 1 \& Z = 0$
LS	Unsigned Lower or Same	$C = 0 \mid Z = 1$
GE	Signed Greater or Equal	$N = V$
LT	Signed Less Than	$N \neq V$
GT	Signed Greater Than	$Z = 0 \& N = V$
LE	Signed Less than or Equal	$Z = 1 \mid N \neq V$
AL	Always	None

Ex. Branch to FOO if r0 is less than 0.

```
CMP r0, #0           ; compare r0 with 0
BLE FOO             ; branch to FOO if LE (Z=1)
```

This is similar to some c code doing:

```
if (a < 0) { //assuming a is in r0
    foo(); //or something else, whatever code is located at FOO
}
```

ARM assembly lets us use the IT (If Then) syntax as well.

Ex.

```
ITTE NE          ; Two commands will follow with NE
ANDNE r0, r0, r1 ; Then one command with the opposite
ANDNE r2, r2, #1 ; of NE which is EQ
MOVEQ r2, r3     ; 

ITT EQ           ; The IT can be omitted from code
MOVEQ ...        ; and the assembler will add it.
ADDEQ ...
```

3 Subroutines

The link register LR contains the return address of the subroutine. This is copied back to the PC when the subroutine is finished.

In ARM, we store any parameters in registers R0 through R3. Any additional parameters need to be put on the stack. Also, if the parameters are larger than 32 bits, they can take up more than one register (a 128 bit parameter would take up R0, R1, R2, R3).

It returns the return value in R0.

Registers R0 through R3 can be freely changed by the subroutine, as well as R12 and R14 (LR). In other words, the calling function cannot expect them to keep the same data when the subroutine returns. The opposite is true with registers R4 to R11 where they must be preserved. If the subroutine changes anything in those registers, it must return them to the previous value before returning.

We use BL or BLX to call a subroutine.

3.1 Stack

The ARM stack uses a full descending stack. This means that the stack pointer points to the top piece of data on the stack. The stack also grows down to memory address 0 as items are pushed to it.

We have the instructions `PUSH{reg_list}` and `POP{reg_list}`.

When we push or pop multiple registers, the highest number register is pushed first, and popped last.

Ex. `PUSH{r6,lr8,lr7}`

This instruction will first push `r8`, followed by `r7` and then finally `r6`.

It would be equivalent to `PUSH{r6,lr7,lr8}` and to `PUSH{r8,lr6,lr7}` and so on.

Ex. `POP{r6,lr8,lr7}`

This instruction will first pop `r6`, followed by `r7` and then finally `r8`.

It would be equivalent to `POP{r6,lr7,lr8}` and to `POP{r8,lr6,lr7}` and so on.

Ex.

```
...                                ; main program
    BL foo
...
foo PROC
    PUSH {r4}          ;we are using r4 which must be preserved
    ...
    MOV r4, #1         ;this changes r4, good thing we saved it
    ...
    POP {r4}          ;this restores r4 for the caller function
    BX LR             ;goes back to caller
ENDP
```

We also need to preserve the LR on the stack if we call a subroutine from inside a subroutine since it could be overridden. Then we would have no way to return to the main program.

Often we have two stack pointers, the MSP (main) and PSP (process). This is toggled by a bit in the CONTROL register.

4 C and Assembly

When we have C code, it goes through a lot of steps to get into ARM assembly to be loaded onto the microcontroller.

Preprocessor → Compiler → Assembler → Linker → Loader → MCU (thru programmer)
→ Debugger

Typically, C will set up data so every word starts at an even multiple of 4 bits address. This is for efficiency. Same idea with half words, but every 2 bits. C does this by padding extra

space. We can use the `__packed` keyword in C to not pad the extra space. But this can cause weird behavior.

If we want to mix C and assembly, we can do this. In assembly, we call a C function using the `import` keyword, and export a function to C using the `export` keyword. Similarly, in C we can import something from assembly using the `extern` keyword. This can work with data as well as functions.

4.1 Volatile Datatypes

The `volatile` keyword means each time we use a variable, we need to import it from memory into a register. This is useful when an external event may change memory at any point. In this case, we need to ensure that we don't use an old version of the variable.

4.2 Interrupts

An interrupt is a signal that occurs that tells the controller that it needs to stop whatever it is currently doing, save the state using the stack, and then move on to the interrupt service routine (ISR). After it then restores the stack, and goes back to the user program.

It needs to save xPSR, PC, LR, R12, R3, R2, R1, and R0 . Therefore it can use any of those registers to store data. Any other registers that are used must be returned to their original state.

5 FPU

The Floating Point Unit (FPU) greatly improves efficiency when dealing with floats over software floating point calculations. These FPUs are however quite large and expensive to implement, so they are not found on all systems.

By default, this FPU is disabled due to power usage. It can easily be enabled.

The FPU coprocessor has its own bank of general purpose registers, and special purpose registers labeled as:

s1	s0
s3	s2
s5	s4
...	...
s31	s30
FPCAR	
FPSCR	
FPCCR	

If we are operating with doubles instead of floats, then we use two of those registers to hold a double. So d0 would use s1 and s0. We can copy to and from the s registers to the r registers.

d0[0]	d0[1]
d1[0]	d1[1]
d2[0]	d2[1]
...	...
d14[0]	d14[1]
d15[0]	d15[1]

We have similar instructions to the regular CPU, but for the FPU they are prefixed with V. So LDR becomes VLDR. There are even a few advanced functions not present in the standard CPU such as VSQRT.

Standard	FPU
LDR	VLDR
STR	VSTR
MOV	VMOV
ADD	VADD
MLA	VMLA
CMP	VCMP
N/A	VABS
N/A	VSQRT

We often suffix the commands with something like F32/F64 or U32/S32. These signify float/double, and unsigned/signed. They are appended to the instruction like VLDR.F32.S32. These are used to convert from one format to another.

6 GPIO

To access our GPIO devices, we use memory mapped IO. This is where a section of the memory addresses are mapped to the IO device such as LED and speaker. All the bits we access through software are found in these registers such as the clock enable, GPIO port enable, GPIO mode, and so on.

The GPIO speed can be configured where a higher speed is faster, but uses more power and has more noise.

The GPIO pin can be set up in different modes such as input, output, analog, or alternate function.

The GPIO pin can be either in open drain, or pull push mode. This changes how the physical transistors are set up. We also have a pull up or pull down resistor that can also be enabled/disabled.

We have a certain number of GPIO devices, each device has a certain number of pins. So we could have 8 devices with 16 pins each for a total of 128 inputs/outputs.

6.1 Debouncing

Debouncing is needed for any sort of input switch. If we do not have debouncing, then the hardware will detect multiple presses per single button press, which is not what we want. We can either debounce using hardware with an RC circuit (or an SR latch and dual throw switch if we are fancy), or through software with a delay.

6.2 Interrupts

An interrupt is an external signal sent into the CPU for processing. So when a button is pressed, or motion is detected on a motion detector, an interrupt will be generated.

7 Timers

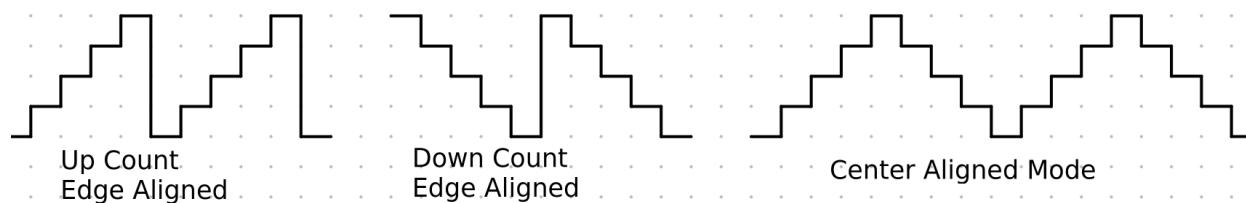
Timers generate interrupts at a fixed interval. This is what the SYSTICK driver does, it generates an interrupt every say 1ms. SYSTICK is a hardware component in ARM CORTEX M.

We have a reload value stored in a register (**ARR**). This is the starting value that the counter starts up, and then counts down to 0 when it creates the interrupt.

We also have a current value register to get the current value of the counter. This needs to be cleared on startup before running a timer since it has a random value.

We also often have some other timers that are independent of the processor. These are useful for peripheral devices. They can either operate in **capture** mode, or **compare** mode (useful for PWM, 1 if below Comp value, 0 if above). Capture will record the time when events occur, and compare will trigger events at specific times.

When counting, we can either use down counting, up counting, or center counting.



We can also change the repetitions. This allows us to determine the number of reloads between events. This uses the repetition counter register (**RCR**). This is done using an input prescaler which is basically another timer.

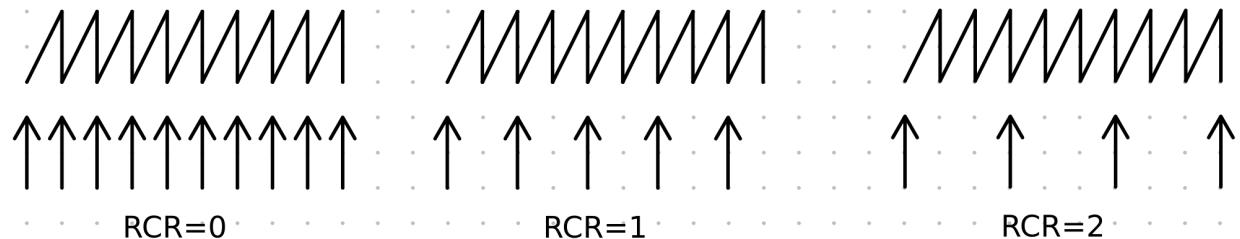


Figure 3:

8 Direct Memory Access (DMA)

By default, when we copy from a peripheral to memory, we need to go through the CPU. This is inefficient, the DMA lets us directly go from the peripheral to the memory. This is better since it uses much less CPU. We have a separate DMA controller that can initialise the transfers. The data can either flow through the DMA, or directly fly by to the memory (does not directly go through DMA).

9 DAC and ADC (Analog Interfacing)

When interfacing with analogue devices, we need to either convert a digital signal to analogue, or convert an analogue signal to digital, depending on whether or not it is an output or input.

9.1 DAC

For the digital to analog converter, we have a certain number of bits which gives the range of analog values.

The DAC can be implemented in a few ways such as a string of resistors with switches acting as a voltage divider, or as a combination of resistors with switches (same idea, but we use combinations of resistors for more possible outputs with less resistors), and we can also use PWM with a filter.

9.2 ADC

When converting from analog to digital, we need to sample at a certain frequency, and each sample again has a bit depth (resolution). The sampling rate that we need to reconstruct the analog signal is called the Nyquist rate which is twice the max frequency of the signal.

One way to do this is to use Successive Approximations (SAR). This basically uses a comparator to test all the digital values compared to the raw analog signal using a binary search.

Ex. We have a 12 bit ADC, where it takes 4 cycles to sample the signal. What is the total sampling time?

For the total sampling time, we need to account for the time to sample the signal, and then the time to determine the actual signal using the SAR. Since this is a binary search,

it will take at most 12 cycles.

$$T = 4 + 12 = 16 \text{ cycles}$$

10 Serial Communications

10.1 I2C

I2C is a 2 wire communication standard. It has a data line (SDA), and a clock line (SCL). It is relatively low speed. Both wires use open drain drivers with a pull up resistor (so are logic 1 by default).

- START is when SDA has falling edge when SCL is HI
- STOP is when SDA has rising edge when SCL is HI
- DATA can only change when SCL is LO

We have a target, which can be 7 or 10 bits, and then we have the data. If we have more than 1 controller, then the arbitration works by each controller checking SDA. If SDA is LO when it is driving SDA HI, then that controller backs off and waits. This works since SDA is pulled up to HI.

10.2 SPI

SPI (Serial Peripheral Interface) is a full duplex connection. It has the following wires:

- SCLK - Clock
- \overline{SS} - Peripheral Select (n SS lines for n slaves) [Active LO]
- MOSI - Master Out, Slave In
- MISO - Master In, Slave Out

We have some parameters for the SPI clock such as CPHA [phase] (0 uses first edge of clock, 1 uses second edge) and CPOL [polarity] (0 has idle low clk, 1 has idle high clk).

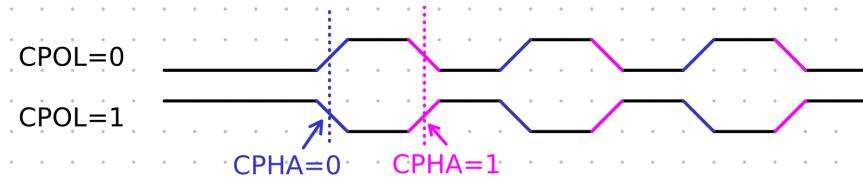


Figure 4: CPOL vs CPHA

10.3 UART

UART is a very widely used protocol to transfer data asynchronously (without a clock wire). It uses only two wires, Tx (transmit) and Rx (receive).

The data frame is idle HI, and contains a start bit followed by a certain number of data bits (usually 8), optionally a parity bit, and then a stop bit.

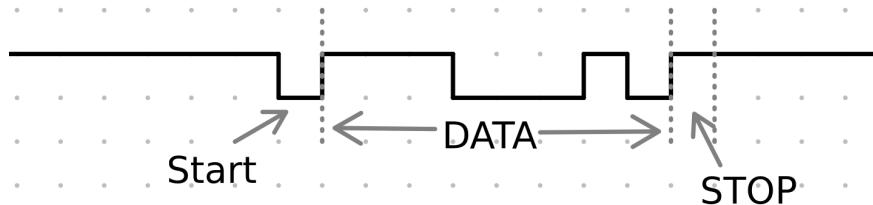


Figure 5: UART Bit Stream

Since UART is asynchronous, the receiver and transmitter must each know the clock rate (to within 10% error). This is known as the BAUD rate (bits per second).

The receiver typically oversamples the signal to get each pulse in the middle (to account for error). It is often 8x or 16x oversampling.

When the receiver receives a byte, and puts it in the register, it sends an interrupt. Then upon reading from that register, the interrupt is cleared and it can be populated with the next received byte.

There are a few protocols to send this bit stream such as RS-232 where Logic 1 is +5V to +15V, and Logic 0 is -5V to -15V.

10.4 USB

USB is a much more complicated protocol which is not covered in depth in this course. USB has a Data + and Data -. These form a differential pair. This is the only wire we care about.

We use a Non Return to Zero Inverted scheme for the bitstream. This is where Logic 0 is represented by a change in voltage, and Logic 1 by the same voltage.

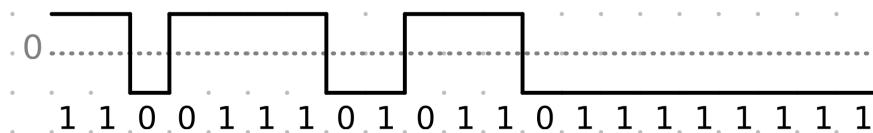


Figure 6: USB NZRI Bit Stream

In terms of actually framing the data, it is very complicated, where there are multiple layers.

11 The Bus (Bus Interfaces)

The BUS is basically a huge set of wires that everything is connected to. This include the CPU, MEMORY, GPIO, SPI, I2C, TIMER, ADC, DAC, RTC, and so on.

We have two main architectures for the bus and how it connects to the rest of the system. Von-Neumann means that the instructions and data share memory, and therefore share a bus interface. In a Harvard architecture, the instruction memory is separate from the data memory, and there are two separate bus interfaces.

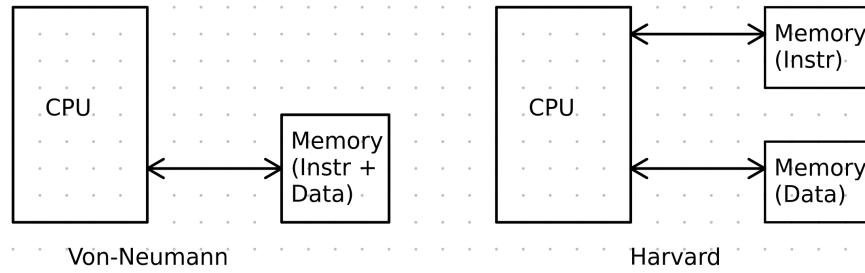


Figure 7: Von Neumann vs Harvard Architecture

We usually use a matrix to connect all the master devices to the slave devices. This matrix is good because multiple devices can communicate at once if they are different masters and different slaves.

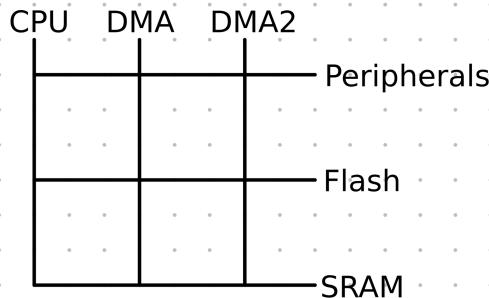


Figure 8: Bus Matrix Example

We have a bunch of different bus architectures used in ARM such as:

- Advanced Peripheral Bus (APB)
- Advanced System Bus (ASB)
- Advanced High-performance Bus (AHB)
- Advanced Extensible Interface (AXI)

Typically we use APB or AHB. APB is lower power, and simpler, while AHB is higher performance partially because it is pipelined.

12 Appendix

Cortex-M4F Instructions used in ARM Assembly for Embedded Applications (ISBN 978-1-09254-223-4)

Function Call/Return	Operation	Notes	Clock Cycles	
BL <i>label</i>	$LR \leftarrow \text{return address}; PC \leftarrow \text{address of label}$	BL is used to call a function BX LR is used as function return	2-4	
BLX <i>Rn</i>	$LR \leftarrow \text{return address}; PC \leftarrow R_n$			
BX <i>Rn</i>	$PC \leftarrow R_n$			
B <i>label</i>	$PC \leftarrow \text{address of label}$			
Load Integer Constant	Operation	Flags	Notes	
ADR <i>Rd,label</i>	$R_d \leftarrow \text{address of label}$		$PC-4095 \leq \text{address} \leq PC+4095$	
MOV{S} <i>Rd, constant</i>	$R_d \leftarrow \text{constant}$	NZ	$0 \leq \text{constant} \leq 255 (FF_{16}) \text{ & a few others}$	
MVN{S} <i>Rd, constant</i>	$R_d \leftarrow \sim \text{constant}$	NZ	$0 \leq \text{constant} \leq 255 (FF_{16}) \text{ & a few others}$	
MOVW <i>Rd, constant</i>	$R_d \leftarrow \text{constant}$		$0 \leq \text{constant} \leq 65535 (FFFF_{16})$	
MOVT <i>Rd, constant</i>	$R_d<31..16> \leftarrow \text{constant}$		$0 \leq \text{constant} \leq 65535 (FFFF_{16})$	
Load/Store Memory	Operation	Bits	Notes	
LDRB <i>Rd,[address mode]</i>	$R_d \leftarrow \text{memory}<7..0> \text{ (zero extended)}$	8	$R_d<31..8> \leftarrow 24 \text{ 0's}$	
LDRSB <i>Rd,[address mode]</i>	$R_d \leftarrow \text{memory}<7..0> \text{ (sign extended)}$	8	$R_d<31..8> \leftarrow 24 \text{ copies of } R_d<7>$	
LDRH <i>Rd,[address mode]</i>	$R_d \leftarrow \text{memory}<15..0> \text{ (zero extended)}$	16	$R_d<31..16> \leftarrow 16 \text{ 0's}$	
LDRSH <i>Rd,[address mode]</i>	$R_d \leftarrow \text{memory}<15..0> \text{ (sign extended)}$	16	$R_d<31..16> \leftarrow 16 \text{ copies of } R_d<16>$	
LDR <i>Rd,[address mode]</i>	$R_d \leftarrow \text{memory}<31..0>$	32		
LDRD <i>Rt,Rt2,[address mode]</i>	$R_{t2}.R_t \leftarrow \text{memory}<63..0>$	64	Can't use register offset adrs mode	
STRB <i>Rd,[address mode]</i>	$R_d \rightarrow \text{memory}<7..0>$	8		
STRH <i>Rd,[address mode]</i>	$R_d \rightarrow \text{memory}<15..0>$	16		
STR <i>Rd,[address mode]</i>	$R_d \rightarrow \text{memory}<31..0>$	32		
STRD <i>Rt,Rt2,[address mode]</i>	$R_{t2}.R_t \rightarrow \text{memory}<63..0>$	64	Can't use register offset adrs mode	
Load/Store Multiple	Operation	Notes	Clock Cycles	
POP <i>{register list}</i>	$\text{registers} \leftarrow \text{memory}[SP]; SP += 4 \times \# \text{ registers}$	regs: Not SP; PC/LR, but not both	1 + #registers	
PUSH <i>{register list}</i>	$SP -= 4 \times \# \text{ registers}; \text{ registers} \rightarrow \text{memory}[SP]$	regs: Neither SP or PC.		
LDMIA <i>Rn!, {register list}</i>	$\text{registers} \leftarrow \text{memory}[R_n]$	if "!" is appended, then $R_n += 4 \times \# \text{ registers}$		
STMIA <i>Rn!, {register list}</i>	$\text{registers} \rightarrow \text{memory}[R_n]$			
LDMDB <i>Rn!, {register list}</i>	$\text{registers} \leftarrow \text{memory}[R_n - 4 \times \# \text{ registers}]$	if "!" is appended, then $R_n -= 4 \times \# \text{ registers}$		
STMDB <i>Rn!, {register list}</i>	$\text{registers} \rightarrow \text{memory}[R_n - 4 \times \# \text{ registers}]$			
Move / Add / Subtract	Operation	Flags	operand2 options:	Clock Cycles
MOV{S} <i>Rd,Rn</i>	$R_d \leftarrow R_n$	NZ		1
ADD{S} <i>Rd,Rn,operand2</i>	$R_d \leftarrow R_n + \text{operand2}$	NZCV	1. constant	
ADC{S} <i>Rd,Rn,operand2</i>	$R_d \leftarrow R_n + \text{operand2} + C$	NZCV	2. R_m (a register)	
SUB{S} <i>Rd,Rn,operand2</i>	$R_d \leftarrow R_n - \text{operand2}$	NZCV	3. $R_m, shift$ (Any kind of shift)	
SBC{S} <i>Rd,Rn,operand2</i>	$R_d \leftarrow R_n - \text{operand2} + C - 1$	NZCV		
RSB{S} <i>Rd,Rn,operand2</i>	$R_d \leftarrow \text{operand2} - R_n$	NZCV		

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Multiply / Divide	Operation	Flags	Notes	Clock Cycles
MUL{S}	$R_d \leftarrow (R_n \times R_m) < 31..0 >$	NZC	$32 \leftarrow 32 \times 32$; C undefined	1
MLA	$R_d \leftarrow R_a + (R_n \times R_m) < 31..0 >$		$32 \leftarrow 32 + 32 \times 32$	
MLS	$R_d \leftarrow R_a - (R_n \times R_m) < 31..0 >$		$32 \leftarrow 32 - 32 \times 32$	
SMMUL{R}	$R_d \leftarrow (R_n \times R_m) < 63..32 >$		Upper half of signed 64-bit product;	
SMMLA{R}	$R_d \leftarrow R_a + (R_n \times R_m) < 63..32 >$		Append R: Round towards $+\infty$ (Adds 0x80000000 to the 64-bit product)	
SMMLS{R}	$R_d \leftarrow R_a - (R_n \times R_m) < 63..32 >$			
[S]MULL	$R_{dlo}, R_{dhi}, R_n, R_m$	$R_{dhi}R_{dlo} \leftarrow R_n \times R_m$	Signed/U signed: $64 \leftarrow 32 \times 32$	
[S]MLAL	$R_{dlo}, R_{dhi}, R_n, R_m$	$R_{dhi}R_{dlo} \leftarrow R_{dhi}R_{dlo} + R_n \times R_m$	Signed/U signed: $64 \leftarrow 64 + 32 \times 32$	
[S]DIV	$R_d \leftarrow R_n / R_m$		Signed/U signed: $32 \leftarrow 32 \div 32$	2-12
Saturating Instructions	Operation	Min	Max	operand2 options
SSAT	$R_d \leftarrow \text{operand2}$	-2^{n-1}	$2^{n-1}-1$	1. R_m (a register) 2. R_m, ASR constant 3. R_m, LSL constant
USAT	$R_d \leftarrow \text{operand2}$	0	2^n-1	
QADD	$R_d \leftarrow R_n + R_m$	-2^{31}	$2^{31}-1$	(Q $\leftarrow 1$ if saturates)
QSUB	$R_d \leftarrow R_n - R_m$			
SIMD Signed Saturating ADD/SUB	Operation	Min to Max	Notes	Clock Cycles
QADD [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] + R_m[\text{bits}]$	8: -2^7 to $+2^7-1$ 16: -2^{15} to $+2^{15}-1$	For bytes 0-3: bits 7..0, 15..8, 23..16, & 31..24 (No flags affected)	1
QSUB [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] - R_m[\text{bits}]$			
SIMD Unsigned Saturating ADD/SUB	Operation	Min to Max	Notes	Clock Cycles
UQADD [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] + R_m[\text{bits}]$	8: 0 to 2^8-1 16: 0 to $2^{16}-1$	For halfwords 0 and 1: bits 15..0 & 31..16 (No flags affected)	1
UQSUB [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] - R_m[\text{bits}]$			
SIMD Signed Non-Saturating ADD/SUB	Operation	GE Flags	Notes	Clock Cycles
SADD [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] + R_m[\text{bits}]$	sum ≥ 0 ? 1 : 0	Parallel operations: Four 8-bit operations, or two 16-bit operations	1
SSUB [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] - R_m[\text{bits}]$	diff ≥ 0 ? 1 : 0		
SIMD Unsigned Non-Saturating ADD/SUB	Operation	GE Flags	Notes	Clock Cycles
UADD [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] + R_m[\text{bits}]$	overflow ? 1 : 0	Parallel operations: Four 8-bit operations, or two 16-bit operations	1
USUB [8] [16]	$R_d[\text{bits}] \leftarrow R_n[\text{bits}] - R_m[\text{bits}]$	diff ≥ 0 ? 1 : 0		

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Q and GE Flag Instructions		Operation	Notes	Clock Cycles
SEL	R _d , R _n , R _m	R _d [bits] ← (GE[byte] = 1) ? R _n [bits] : R _m [bits]	For bytes 0-3: bits 7..0, 15..8, 23..16, & 31..24	1
MRS	R _d , APSR	R _d <31..27> ← NZCVQ R _d <19..16> ← GE flags	All other bits of R _d are filled with zeroes.	
MSR	APSR_nzcvq, R _n	NZCVQ ← R _n <31..27>	Other flags in the PSR are not affected.	
MSR	APSR_g, R _n	GE flags ← R _n <19..16>		

SIMD Multiply Instructions		Operation	Notes	Clock Cycles
SMUAD	R _d , R _n , R _m	R _d ← R _n <15..00> × R _m <15..00> + R _n <31..16> × R _m <31..16>	Sets Q flag if an addition or subtraction overflows; does not saturate.	1
SMUSD	R _d , R _n , R _m	R _d ← R _n <15..00> × R _m <15..00> - R _n <31..16> × R _m <31..16>		
SMLAD	R _d , R _n , R _m , R _a	R _d ← R _a + R _n <15..00> × R _m <15..00> + R _n <31..16> × R _m <31..16>		
SMLSD	R _d , R _n , R _m , R _a	R _d ← R _a + R _n <15..00> × R _m <15..00> - R _n <31..16> × R _m <31..16>		
SMLALD	R _{dlo} , R _{dhi} , R _n , R _m	R _{dhi} , R _{dlo} += R _n <15..00> × R _m <15..00> + R _n <31..16> × R _m <31..16>		
SMLS LD	R _{dlo} , R _{dhi} , R _n , R _m	R _{dhi} , R _{dlo} += R _n <15..00> × R _m <15..00> - R _n <31..16> × R _m <31..16>		

Appending "X" to instruction mnemonic changes operand2s to R_n<15..00> × R_m<31..16> and R_n<31..16> × R_m<15..00>.

Signed Multiply Halfwords		Operation	Notes	Clock Cycles
SMULBB	R _d , R _n , R _m	R _d ← R _n <15..00> × R _m <15..00>	32 ← 16×16	1
SMULBT	R _d , R _n , R _m	R _d ← R _n <15..00> × R _m <31..16>		
SMULTB	R _d , R _n , R _m	R _d ← R _n <31..16> × R _m <15..00>		
SMULLT	R _d , R _n , R _m	R _d ← R _n <31..16> × R _m <31..16>		

Pack Halfwords		Operation	operand2 options:	Notes	Clock Cycles
PKHBT	R _d , R _n , operand2	Btm: R _d <15..00> ← R _n <15..00> Top: R _d <31..16> ← operand2<31..16>	1. R _m (a register) 2. R _m , LSL constant 3. R _m , ASR constant	Shift constants: LSL: 1-31 ASR: 1-32	1
PKHTB	R _d , R _n , operand2	Top: R _d <31..16> ← R _n <31..16> Btm: R _d <15..00> ← operand2<15..00>			

Compare Instructions		Operation	operand2 options:	Notes	Clock Cycles
CMP	R _n , operand2	R _n - operand2	1. constant 2. R _m (a register) 3. R _m , shift (any kind of shift)	Updates: NZCV	1
CMN	R _n , operand2	R _n + operand2		Updates: NZCV	
TST	R _n , operand2	R _n & operand2		Updates: NZC	
TEQ	R _n , operand2	R _n ^ operand2		Updates: NZC	

Zero/Sign-Extend Instructions		Operation	operand2 options:	Clock Cycles
[S] XTB	R _d , operand2	R _d ← Sign (S) extend or Unsigned (U) extend operand2<7..0>	1. R _m (a register) 2. R _m , ROR constant (constant=8, 16 or 24)	1
[S] XTH	R _d , operand2	R _d ← Sign (S) extend or Unsigned (U) extend operand2<15..0>		

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Conditional Branch Instructions		Operation	Notes		Clock Cycles
Bcc	label	Branch to <i>label</i> if "cc" is true	'cc' is a condition code Can't use in an IT block Can't use in an IT block Controls 1-4 instructions	1 (Fail) or 2-4 1	
CBZ	R _n , label	Branch to <i>label</i> if R _n =0			
CBNZ	R _n , label	Branch to <i>label</i> if R _n ≠0			
ITC ₁ C ₂ C ₃	condition code	Each c _i is one of T, E, or empty			

Shift Instructions		Operation	Flags	operand2 options	Notes	Clock Cycles
ASR{S}	R _d ,R _n ,operand2 // 1-32 bits	R _d ← R _n >> operand2 (arithmetic shift right)	NZC	1. constant 2. R _m (a register) When operand2 is a constant: LSL: shifts 0-31 bits; ASR,LSR,ROR: 1-32 bits	Sign extends Zero fills right rotate RRX shifts only by 1 bit. 33-bit rotate w/C	1
LSL{S}	R _d ,R _n ,operand2 // 1-31 bits	R _d ← R _n << operand2 (logical shift left)	NZC			
LSR{S}	R _d ,R _n ,operand2 // 1-32 bits	R _d ← R _n >> operand2 (logical shift right)	NZC			
ROR{S}	R _d ,R _n ,operand2 // 1-31 bits	R _d ← R _n >> operand2 (rotate right)	NZC			
RRX{S}	R _d ,R _n // 1 bit	R _d ← R _n >> 1; R _{d<31>} ← C; C ← R _{n<0>}	NZC			

Bitwise Instructions		Operation	Flags	operand2 options	Notes	Clock Cycles
AND{S}	R _d ,R _n ,operand2	R _d ← R _n & operand2	NZC	1. constant 2. R _m (a register) 3. R _{m,shift} (Any kind of shift)		1
ORR{S}	R _d ,R _n ,operand2	R _d ← R _n operand2	NZC			
EOR{S}	R _d ,R _n ,operand2	R _d ← R _n ^ operand2	NZC			
BIC{S}	R _d ,R _n ,operand2	R _d ← R _n & ~operand2	NZC			
ORN{S}	R _d ,R _n ,operand2	R _d ← R _n ~operand2	NZC			
MVN{S}	R _d ,operand2	R _d ← ~operand2	NZC			

Bitfield Instructions		Operation	Notes		Clock Cycles
BFC	R _d ,lsb,width	SelectedBitfieldOf(R _d) ← 0	Sign extends Zero extends		1
BFI	R _d ,R _n ,lsb,width	SelectedBitfieldOf(R _d) ← LSBitsOf(R _n)			
SBFX	R _d ,R _n ,lsb,width	R _d ← SelectedBitfieldOf(R _n)			
UBFX	R _d ,R _n ,lsb,width	R _d ← SelectedBitfieldOf(R _n)			

Bits / Bytes / Words		Operation	Notes		Clock Cycles
CLZ	R _d ,R _n	R _d ← CountLeadingZeroesOf(R _n)	#leading 0's = 0-32		1
RBIT	R _d ,R _n	R _d ← ReverseBitOrderOf(R _n)			
REV	R _d ,R _n	R _d ← ReverseByteOrderOf(R _n)			

Pseudo-Instructions		Operation	Flags	Replaced by	Clock Cycles
LDR	R _d =constant	R _d ← constant	NZCV	MOV, MVN, MOVW, or LDR	1
NEG	R _d ,R _n	R _d ← -R _n		RSBS R _d ,R _n ,0	
CPY	R _d ,R _n	R _d ← R _n		MOV R _d ,R _n	

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Floating-Point PUSH/POP		Operation	Clock Cycles
VPUSH	{FP register list}	SP -= 4 × # registers, copy registers to memory[SP]	
VPOP	{FP register list}	Copy memory[SP] to registers, SP += 4 × # registers	1 + # registers
Floating-Point Load Constant			Clock Cycles
VMOV	S _d ,fpconstant	fpconstant must be ±m × 2 ⁻ⁿ , (16 ≤ m ≤ 31; 0 ≤ n ≤ 7)	
			1
Floating-Point Copy Registers		Operation	Clock Cycles
VMOV	S _d ,S _m	S _d ← S _m	
VMOV	R _d ,S _m	R _d ← S _m	1
VMOV	S _d ,R _m	S _d ← R _m	
VMOV	R _t ,R _{t2} ,S _m ,S _{m+1}	R _t ← S _m ; R _{t2} ← S _{m+1} (S _m , S _{m+1} adjacent regs)	
VMOV	S _m ,S _{m+1} ,R _t ,R _{t2}	S _m ← R _t ; S _{m+1} ← R _{t2} (S _m , S _{m+1} adjacent regs)	2
Floating-Point Load Registers		Operation	Clock Cycles
VLDR	S _d ,[R _n]	S _d ← memory32[R _n]	
VLDR	S _d ,[R _n ,constant]	S _d ← memory32[R _n + constant]	2
VLDR	S _d ,label	S _d ← memory32[Address of label]	
VLDR	D _d ,[R _n]	D _d ← memory64[R _n]	
VLDR	D _d ,[R _n ,constant]	D _d ← memory64[R _n + constant]	3
VLDR	D _d ,label	D _d ← memory64[Address of label]	
VLDMA	R _n !,{FP register list}	FP registers ← memory, R _n = lowest address; Updates R _n if write-back flag (!) is included.	
VLDMDB	R _n !,{FP register list}	FP registers ← memory, R _{n-4} = highest address; Must append (!) and always updates R _n	
Floating-Point Store Registers		Operation	Clock Cycles
VSTR	S _d ,[R _n]	S _d → memory32[R _n]	
VSTR	S _d ,[R _n ,constant]	S _d → memory32[R _n + constant]	2
VSTR	D _d ,[R _n]	D _d → memory64[R _n]	
VSTR	D _d ,[R _n ,constant]	D _d → memory64[R _n + constant]	3
VSTMIA	R _n !,{FP register list}	FP registers → memory, R _n = lowest address; Updates R _n if write-back flag (!) is included.	
VSTMDB	R _n !,{FP register list}	FP registers → memory, R _{n-4} = highest address; Must append (!) and always updates R _n	

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Floating-Point Convert Representation	Operation	Clock Cycles
VCVT.F32.U32 S_d, S_m	$S_d \leftarrow (\text{float}) S_m$, where S_m is an unsigned integer	1
VCVT.F32.S32 S_d, S_m	$S_d \leftarrow (\text{float}) S_m$, where S_m is a 2's comp integer	
VCVT{R}.U32.F32 S_d, S_m	$S_d \leftarrow (\text{uint32_t}) S_m$	
VCVT{R}.S32.F32 S_d, S_m	$S_d \leftarrow (\text{int32_t}) S_m$ Rounded if suffix "R" is appended using current rounding mode (FPSCR bits 23 and 22, default is nearest even)	

Floating-Point Arithmetic	Operation	Clock Cycles
VADD.F32 S_d, S_n, S_m	$S_d \leftarrow S_n + S_m$	1
VSUB.F32 S_d, S_n, S_m	$S_d \leftarrow S_n - S_m$	
VNEG.F32 S_d, S_m	$S_d \leftarrow -S_m$	
VABS.F32 S_d, S_m	$S_d \leftarrow S_m $; (clears FPU sign bit, N)	
VMUL.F32 S_d, S_n, S_m	$S_d \leftarrow S_n \times S_m$	
VDIV.F32 S_d, S_n, S_m	$S_d \leftarrow S_n \div S_m$	
VSQRT.F32 S_d, S_m	$S_d \leftarrow \sqrt{S_m}$	14
VMLA.F32 S_d, S_n, S_m	$S_d \leftarrow S_d + S_n \times S_m$	3
VMLS.F32 S_d, S_n, S_m	$S_d \leftarrow S_d - S_n \times S_m$	

Floating-Point Compare	Operation	Clock Cycles
VCMP.F32 S_d, S_m	Computes $S_d - S_m$ and updates FPU Flags in FPSCR	1
VCMP.F32 $S_d, 0.0$	Computes $S_d - 0$ and updates FPU Flags in FPSCR	
VMRS APSR_nzcv,FPSCR	Core CPU Flags \leftarrow FPU Flags (Needed between VCMP.F32 and conditional branch)	

Addressing Modes for floating-point load and store instructions (VLDR & VSTR):

Addressing Mode	Syntax	Meaning	Example
Immediate Offset	[R _n]	address = R _n	[R5]
	[R _n ,constant]	address = R _n + constant	[R5,100]

Shift Codes:

Any of these may be applied as the "shift" option of "operand2" in Move / Add / Subtract, Compare, and Bitwise Groups.

Shift Code	Meaning	Notes
LSL constant	Logical Shift Left by constant bits	Zero fills; $0 \leq \text{constant} \leq 31$
LSR constant	Logical Shift Right by constant bits	Zero fills; $1 \leq \text{constant} \leq 32$
ASR constant	Arithmetic Shift Right by constant bits	Sign extends; $1 \leq \text{constant} \leq 32$
ROR constant	ROtate Right by constant bits	$1 \leq \text{constant} \leq 32$
RRX	Rotate Right eXtended (with carry) by 1 bit	

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Addressing Modes for *integer* load and store instructions (LDR, STR, etc.):

Any of these may be used with all variations of LDR/STR except LDRD/STRD, which may not use Register Offset Mode.

Addressing Mode	Syntax	Meaning	Example
Immediate Offset	[R _n]	address = R _n	[R5]
	[R _n ,constant]	address = R _n + constant	[R5,100]
Register Offset	[R _n ,R _m]	address = R _n + R _m	[R4,R5]
	[R _n ,R _m ,LSL constant]	address = R _n + (R _m << constant)	[R4,R5,LSL 3]
Pre-Indexed	[R _n ,constant]!	R _n ← R _n + constant; address = R _n	[R5,100]!
Post-Indexed	[R _n],constant	address = R _n ; R _n ← R _n + constant	[R5],100

Condition Codes:

If appended to an FPU instruction within an IT block, the condition code precedes any extension. (E.g., VADDGT.F32)

Condition Code	CMP Meaning	VCMP Meaning	Requirements
EQ (Equal)	==	==	Z = 1
NE (Not Equal)	!=	!= or unordered	Z = 0
HS (Higher or Same)	unsigned \geq	\geq or unordered	C = 1 Note: Synonym for "CS" (Carry Set)
LO (Lower)	unsigned $<$	$<$	C = 0 Note: Synonym for "CC" (Carry Clear)
HI (Higher)	unsigned $>$	$>$ or unordered	C = 1 & Z = 0
LS (Lower or Same)	unsigned \leq	\leq	C = 0 Z = 1
GE (Greater Than or Equal)	signed \geq	\geq	N = V
LT (Less Than)	signed $<$	$<$ or unordered	N \neq V
GT (Greater Than)	signed $>$	$>$	Z = 0 && N = V
LE (Less Than or Equal)	signed \leq	\leq or unordered	Z = 1 N \neq V
CS (Carry Set)	unsigned \geq	\geq or unordered	C = 1 Note: Synonym for "HS" (Higher or Same)
CC (Carry Clear)	unsigned $<$	$<$	C = 0 Note: Synonym for "LO" (Lower)
MI (Minus)	negative	$<$	N = 1
PL (Plus)	non-negative	\geq or unordered	N = 0
VS (Overflow Set)	overflow	unordered	V = 1
VC (Overflow Clear)	no overflow	not unordered	V = 0
AL (Always)	unconditional	unconditional	Always true

- Notes:
1. This is only a partial list of the most commonly-used ARM Cortex-M4 instructions.
 2. Clock Cycle counts do not include delays due to stalls when an instruction must wait for the previous instruction to complete.
 3. There are magnitude restrictions on immediate constants; see ARM documentation for more information.