

Thumb Instruction Programming

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Based on

ARM System-on-Chip Architecture, 2nd ed, Steve Furber

Introduction to ARM Cortex-M Microcontrollers
– Embedded Systems, Jonathan W. Valvano

Digital Design and Computer Architecture,
D. M. Harris and S. L. Harris

ARM assembler in Raspberry Pi
Roger Ferrer Ibáñez

<https://thinkingeek.com/arm-assembler-raspberry-pi/>

Thumb Instruction Programming

ARM vs. Thumb programmer's models

| |
|----------|
| R0 |
| R1 |
| R2 |
| R3 |
| R4 |
| R5 |
| R6 |
| R7 |
| R8 |
| R9 |
| R10 |
| R11 |
| R12 |
| R13 (SP) |
| R14 (LR) |
| R15 (PC) |

CPSR

ARM state

| |
|-----|
| R0 |
| R1 |
| R2 |
| R3 |
| R4 |
| R5 |
| R6 |
| R7 |
| R8 |
| R9 |
| R10 |
| R11 |
| R12 |
| SP |
| LR |
| PC |

CPSR

Thumb state

ARM state

- $16 + 1 = 17$ normal registers

Thumb state

- $11 + 1 = 12$ normal registers

ARM Register Sets (2-1)

- The biggest register difference involves the **SP** register.
 - the **Thumb** state
 - unique stack mnemonics (**PUSH**, **POP**)
 - the **ARM** state.
 - no such stack mnemonics (**PUSH**, **POP**)
- **PUSH**, **POP** instructions assume the existence of a **stack pointer** (**R13**)
- **PUSH**, **POP** instructions translate into **load** and **store** instructions in the **ARM** state.

<https://www.embedded.com/introduction-to-arm-thumb/>

ARM Register Sets (2-2)

- The **CPSR** register holds
 - **processor mode** bits (**user** or **exception flag**)
 - **interrupt mask** bits
 - **condition codes** and
 - **Thumb status** bit

- The **Thumb status** bit (**T**) indicates the processor's current state:
 - **0** for **ARM** state (default)
 - **1** for **Thumb**.

- Although other bits in the **CPSR** may be modified in software, it's dangerous to write to **T** directly;
 - the results of an improper state change are *unpredictable*.

N Negative flag
Z Zero flag
C Carry flag
V Overflow flag

To disable Interrupt (**IRQ**), set **I**
To disable Fast Interrupt (**FIQ**), set **F**

USR User mode
FIQ Fast Interrupt mode
SVC Supervisor mode
ABT Abort mode
UND Undefined mode
SYS System mode



<https://www.embedded.com/introduction-to-arm-thumb/>

Branch instructions (1)

| | |
|------------|------------|
| B, | BL, |
| BX, | BLX |

BL and **BLX** copy the return address into **LR (R14)**

| | |
|------------|------------|
| B, | BL, |
| BX, | BLX |

BX and **BLX** can change the processor state

<https://developer.arm.com/documentation/dui0489/c/arm-and-thumb-instructions/branch-and-control-instructions/b--bl--bx--blx--and-bxj>

Branch instructions (2) label or Rm

| | |
|----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none">• B{cond}Rm• B{cond}label | <ul style="list-style-type: none">• BL{cond}Rm• BL{cond}label |
| <ul style="list-style-type: none">• BX{cond}Rm• BX{cond}label | <ul style="list-style-type: none">• BLX{cond}Rm• BLX{cond}label |

B Branch
B Branch with **L**ink
Brand and **eX**change
Brand with **L**ink and **eX**change

- **B**{cond}label
- **BL**{cond}label
- **BLX**{cond}label
- **BX**{cond}Rm
- **BLX**{cond}Rm

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch, and Branch and Link (1)

- **B**{~~cond~~}**Rm**
- **B**{~~cond~~} **label**

- **BL**{~~cond~~}**Rm**
- **BL**{~~cond~~} **label**

-
- **cond** is an optional condition code
- **label** is a program-relative expression

- The **B** instruction
 - causes a branch to **label**.

- The **BL** instruction
 - copies the address of the **next instruction** into **r14** (**lr**, the **link register**)
 - causes a branch to **label**.

B Branch
B Branch with **L**ink
Brand and **eX**change
Brand with **L**ink and **eX**change

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch, and Branch and Link (2)

- Machine-level **B** and **BL** instructions have a range of $\pm 32\text{Mb}$ from the address of the current instruction.
- However, you can use these instructions even if **label** is out of range.
- Often you do not know where **label** is placed by the linker.
- When necessary, the ARM linker adds **veneer** code to allow longer branches

2^{24} Byte = 2^4 MB = 16 MB

➔ +/- 8 MB (forward, backward)

➔ +/- 32 MB (2 lsb's : 4 bytes alignment)

<https://www.embedded.com/introduction-to-arm-thumb/>

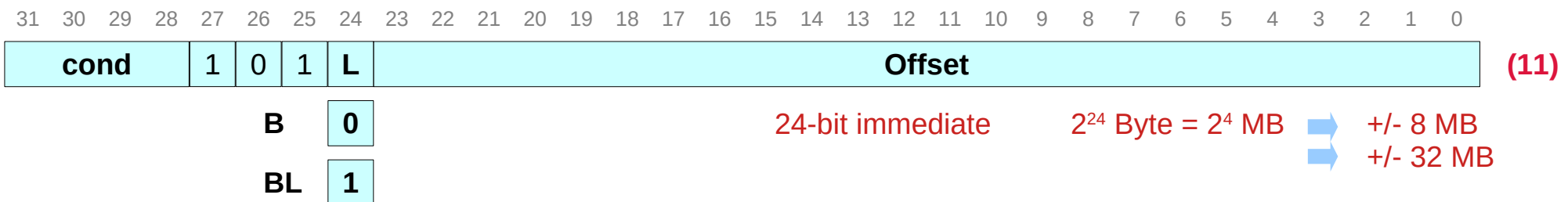
Branch, and Branch and Link (3)

- The ARM **BL** instruction has a **24-bit immediate** for encoding the **branch offset**
- this would give you a range of **2^{24} bytes**, or **+/-8MB** (given that the **immediate** allows forwards or backwards).
- all ARM instructions are 4 bytes long, and must be size aligned.
- no need to consider the **two least significant bits** of the address
- taking our branch range from **+/-8MB** to **+/-32MB**.

2^{24} Byte = 2^4 MB = 16 MB

➔ +/- 8 MB (forward, backward)

➔ +/- 32 MB (2 lsb's : 4 bytes alignment)



<https://community.arm.com/support-forums/f/architectures-and-processors-forum/3061/range-of-bl-instruction-in-arm-state>

B and eXchange, and BL and eXchange (1)

- **BX** {cond} Rm
- **BX**{cond} label

- **BLX** {cond} Rm
- **BLX** {cond} label

- cond is an optional condition code
- label is a program-relative expression
- Rm is a register containing an address to branch to

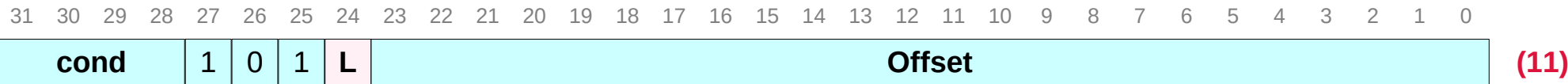
- The **BX** instruction
 - causes a branch to the address contained in Rm
 - exchanges the instruction set, if required:

- The **BLX** instruction
 - copies the address of the **next instruction** into **r14** (**lr**, the link register)
 - causes a branch to **label**.
 - can change the instruction set

Branch
Branch with **L**ink
Branch and **eX**change
Branch with **L**ink and **eX**change

<https://www.embedded.com/introduction-to-arm-thumb/>

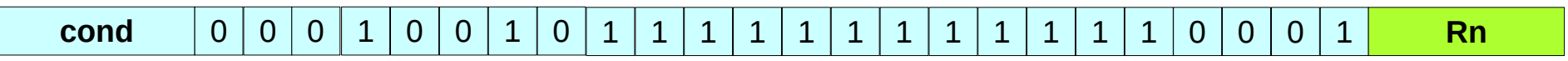
3. Branch and Branch and eXchange (B, BX)



Branch B 0 R14 := PC+8; PC := Offset

BL 1

(11)



Branch and Exchange PC := Rn; (Rn[0]=1 Thumb, else ARM)

(5)



Branch with Link and Exchange BLX{<cond>} <address> PC := Offset

H Half Word Address

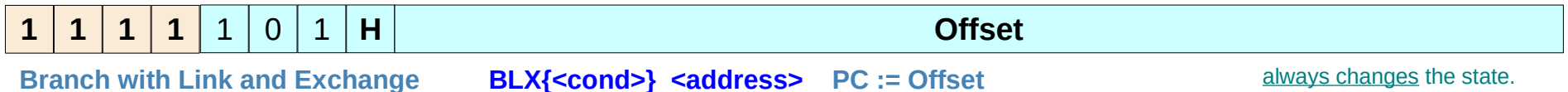
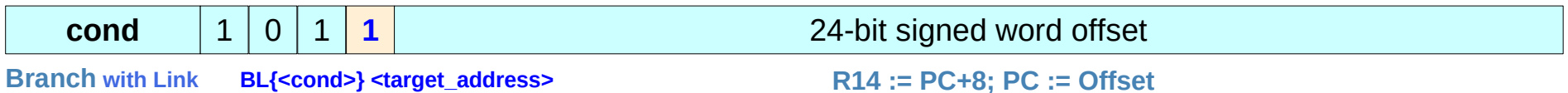
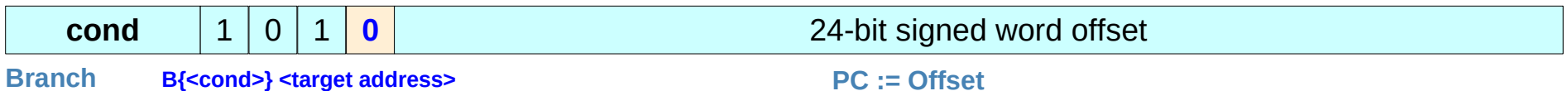
always changes the state.
ARM state → Thumb state
Thumb state → ARM state

Branch and Branch with Link (B, BL)

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0



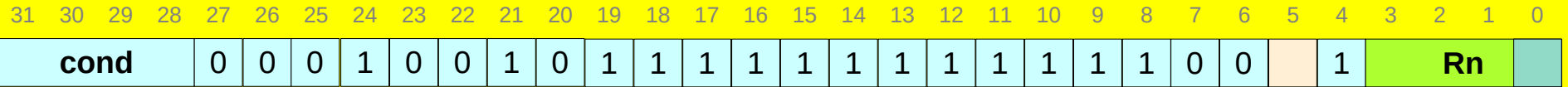
B 0
BL 1



H Half Word Address

always changes the state.
ARM state → Thumb state
Thumb state → ARM state

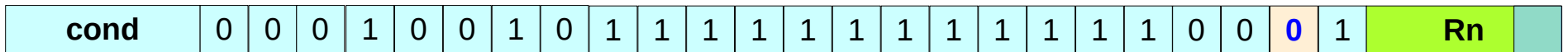
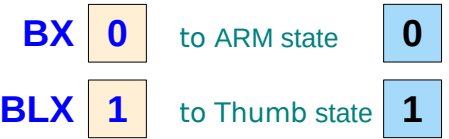
B and eXchange, BL and eXchange (BX, BLX)



(5)

Branch and Exchange

PC := Rn; (Rn[0]=1 Thumb, else ARM)

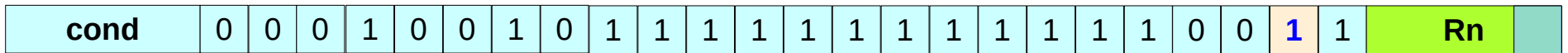


Branch and Exchange

BX{<cond>} Rn

PC := Rn;
(Rn[0]=1 Thumb, else ARM)

Rn[0] = 0 → to ARM state
Rn[0] = 1 → to Thumb state

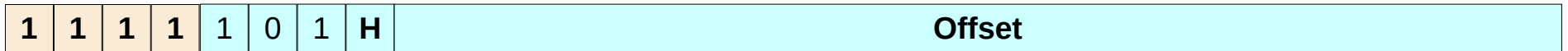


Branch with Link and Exchange

BLX{<cond>} Rn

R14 := PC+8; PC := Rn;
(Rn[0]=1 Thumb, else ARM)

Rn[0] = 0 → to ARM state
Rn[0] = 1 → to Thumb state



Branch with Link and Exchange

BLX{<cond>} <address> PC := Offset

always changes the state.
ARM state → Thumb state
Thumb state → ARM state

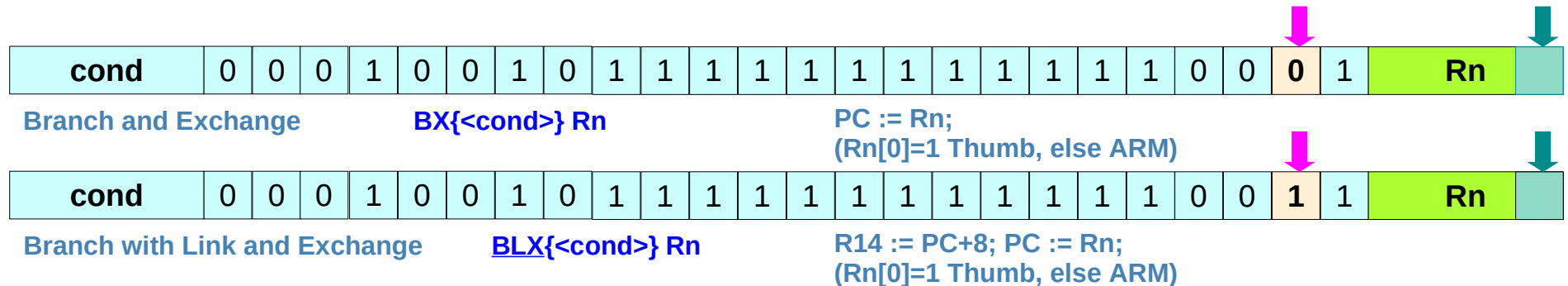
H Half Word Address

Branch instructions – changing the state

BX **Rn**
BLX **Rn**

changes the state depending on **bit[0]** of **Rn**:

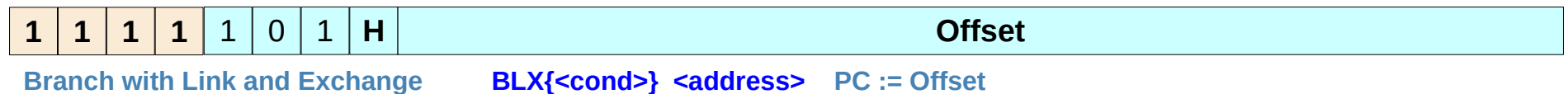
Rn[0] = 0 → ARM state
Rn[0] = 1 → Thumb state



BLX **label**

always changes the state.

ARM state → Thumb state
Thumb state → ARM state



<https://developer.arm.com/documentation/dui0489/c/arm-and-thumb-instructions/branch-and-control-instructions/b--bl--bx--blx--and-bxj>

Branch and link operation (1)

Both the **ARM** and **Thumb** instruction sets contain a primitive subroutine call instruction, **BL**, which performs a **branch-with-link** operation.

LR ← the **return address**
the next value of the **PC**

PC ← the **destination address**

LR[0] ← 1 if the **BL** executed from **Thumb** state

LR[0] ← 0 if the **BL** executed from **ARM** state

The result is to transfer control to the **destination address**, passing the **return address** in LR as an additional parameter to the called subroutine

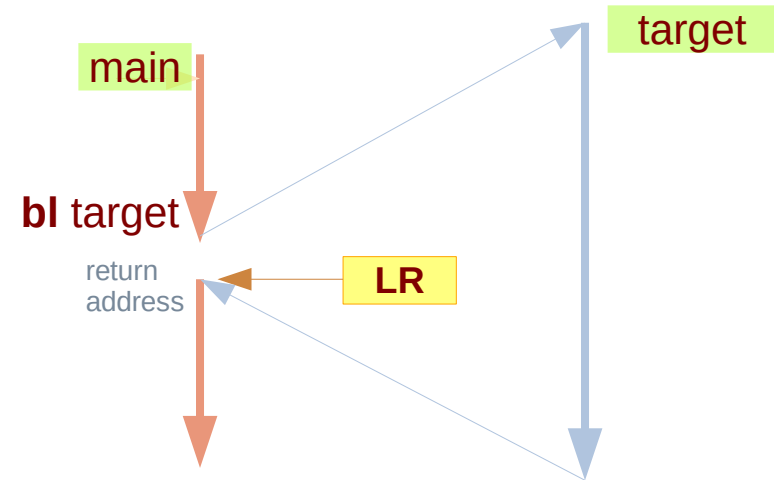
/IHI0042E_aapcs.pdf

Branch and link operation (2)

Control is returned to **the instruction following the BL** when the return address is loaded back into the PC

A **subroutine call** can be synthesized by any instruction sequence that has the effect:

LR[31:1] ← return address
LR[0] ← code type **at** return address
(0 ARM, 1 Thumb)
PC ← subroutine address ... return address:



LR ← the return address
PC ← the destination address

LR[31:1] ← the return address
LR[0] ← 0 ARM code at the return address
LR[0] ← 1 Thumb code at the return address

/IHI0042E_aapcs.pdf

Branch and exchange operations

- There are several ways to enter or leave the **Thumb state** properly.
- The usual method is via the **Branch and Exchange (BX)** instruction.
- See also **Branch, Link, and Exchange (BLX)** with version 5 architecture.
- During the branch, the CPU examines the **least significant bit (LSb)** of the **destination address** to determine the new state.
- Since all ARM instructions will align themselves on either a **32-** or **16-bit** boundary, the LSB of the address is not used in the branch directly.
- However, if the **LSB** is **1** when branching **from ARM state**, the processor switches **to Thumb state** before it begins executing from the **new address**;
- if **0** when branching **from Thumb state**, back **to ARM state** it goes.

the LSB of **BX** destination
the LSB of **BX** return address

0 : ARM state
1 : thumb state

<https://community.arm.com/developer/ip-products/processors/f/cortex-a-forum/5655/question-about-a-code-snippet-on-arm-thumb-state-change>

32-bit / 16-bit alignment

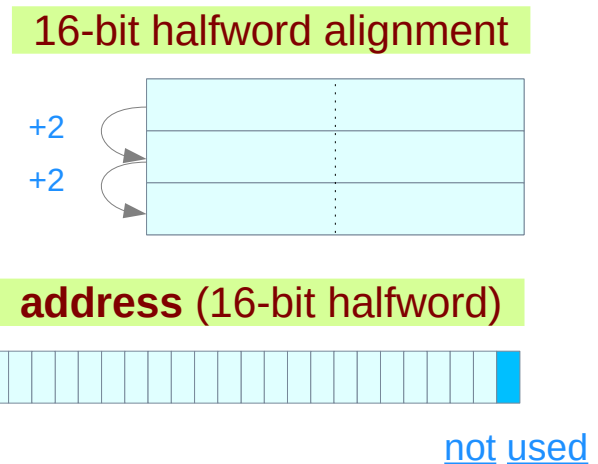
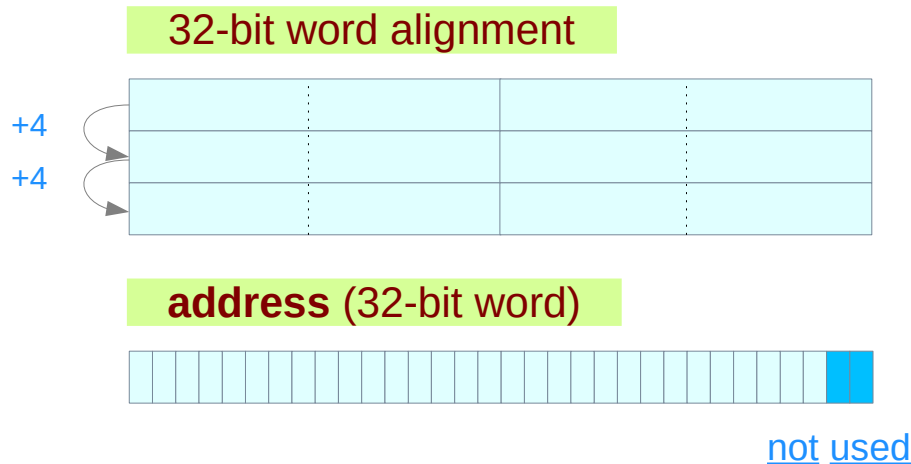
Since all ARM instructions have
either a 32- or 16-bit alignment

the LSB of the address is not used in the branch directly.

32-bit (4 bytes) - the least significant **2 bits** of the target address

16-bit (2 bytes) - the least significant **1 bit** of the target address

use the the **least significant bit** is used to **change the state**



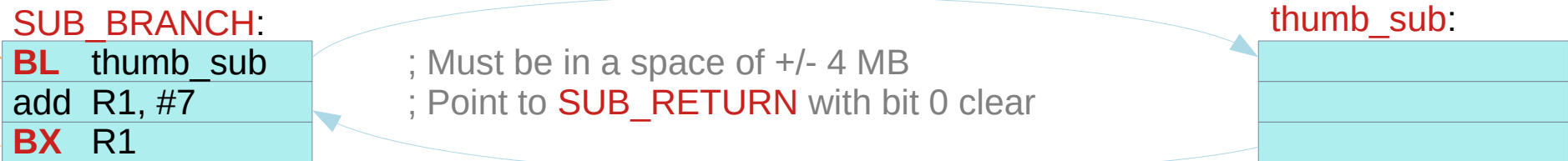
<https://www.cs.princeton.edu/courses/archive/fall13/cos375/ARMthumb.pdf>

State changing example (1)

Change into Thumb state, then back

| | | |
|-----------------------------|--|-----------------------------------------------------------------|
| <code>mov R0, #5</code> | | ; argument to function is in R0 |
| <code>add R1, PC, #1</code> | | ; Load address of SUB_BRANCH , Set for THUMB by adding 1 |
| BX R1 | | ; R1 contains address of SUB_BRANCH+1 |

; Assembler-specific instruction to switch to Thumb



; Assembler-specific instruction to switch to ARM

| | |
|--------------------|--|
| SUB_RETURN: | |
| | |
| | |

<https://community.arm.com/developer/ip-products/processors/f/cortex-a-forum/5655/question-about-a-code-snippet-on-arm-thumb-state-change>

State changing example (2)

Change into Thumb state, then back

| | |
|----------------|--|
| mov R0, #5 | |
| add R1, PC, #1 | |
| BX R1 | |

; switch to Thumb

| | |
|---------------------|--|
| SUB_BRANCH: | |
| BL thumb_sub | |
| add R1, #7 | |
| BX R1 | |

; switch to ARM

| | |
|--------------------|--|
| SUB_RETURN: | |
| | |
| | |

In ARM mode, **PC** indicates 2 instructions ahead

PC of '**ADD R1,PC,#1**' is the address of **SUB_BRANCH**

execution mode switch from **ARM** to **Thumb** at the **SUB_BRANCH** and the program will execute in **Thumb** mode.

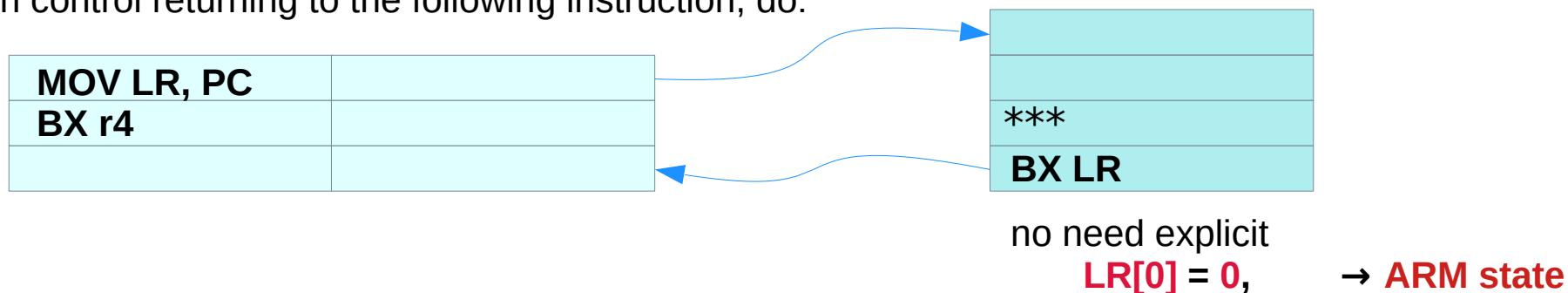
And **R1** is now '**SUB_BRANCH+1**' and by adding to 7 it will become '**SUB_BRANCH+8**'.

'**SUB_BRANCH+8**' is the address of '**SUB_RETURN**' and the program jumps to the address of which **LSB value is 0** and the execution mode will become from **Thumb** mode to **ARM** mode.

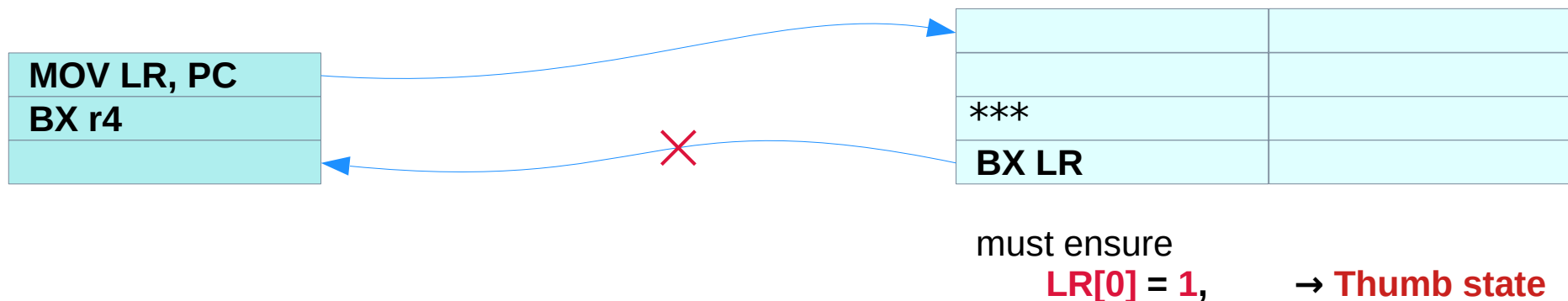
[https://community.arm.com/developer/ip-products/processors/f/cortex-a-forum/!](https://community.arm.com/developer/ip-products/processors/f/cortex-a-forum/)

State changing example (3)

in ARM-state, to call a subroutine addressed by **r4** with control returning to the following instruction, do:



The equivalent sequence will not work from Thumb state because the instruction that sets LR (**MOV LR, PC**) does not copy the **Thumb-state bit** to **LR[0]**.



/IHI0042E_aapcs.pdf

Thumb long branch with link **BL** instruction (1)

THUMB assembler : **BL** label

H=0

$LR := PC + \text{OffsetHigh} \ll 12$

H=1

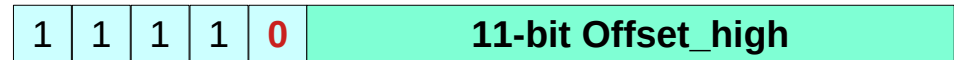
$\text{temp} := \text{next instruction address}$

$PC := LR + \text{OffsetLow} \ll 1$

$LR := \text{temp} | 1$

$PC := PC + (\text{OffsetHigh} \ll 12) + (\text{OffsetLow} \ll 1)$

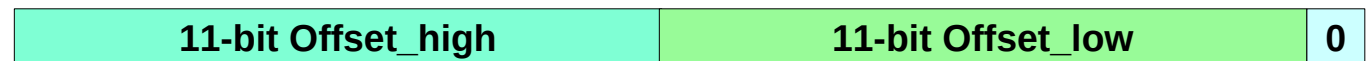
H=0



H=1



23-bit Offset

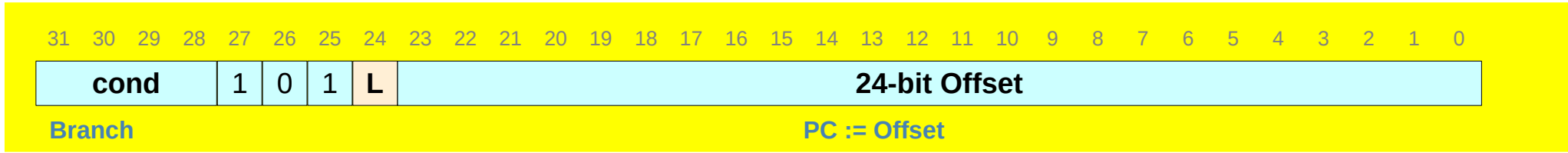


http://bear.ces.cwru.edu/eecs_382/ARM7-TDMI-manual-pt3.pdf?ref=zdimension.fr

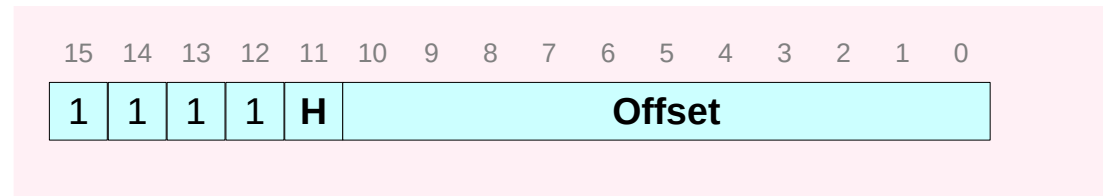
Thumb long branch with link **BL** instruction (2)



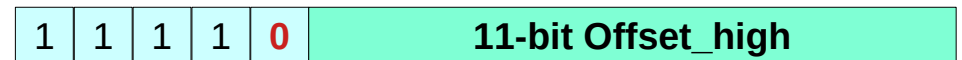
ARM **B** or **BL** instruction



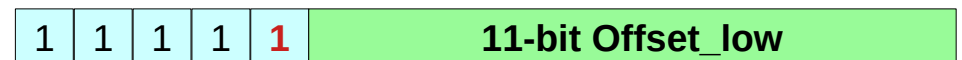
Thumb **BL** instruction



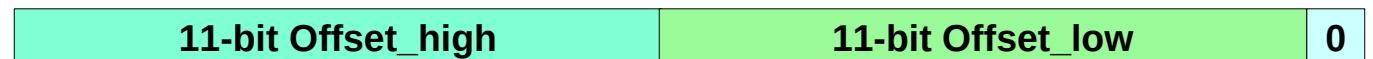
H=0



H=1



23-bit Offset



http://bear.ces.cwru.edu/eecs_382/ARM7-TDMI-manual-pt3.pdf?ref=zdimension.fr

Thumb long branch with link **BL** instruction (3)

Examples

```
BL faraway ; Unconditionally Branch to 'faraway'  
next ... ; and place following instruction address,  
; ie 'next', in R14, the Link Register (LR)  
; and set bit 0 of LR high (1)  
; Note that the THUMB opcodes will contain  
; the number of halfwords to offset.
```

```
faraway ... ; Must be Half-word aligned.
```

H=0

LR := PC + OffsetHigh << 12

H=1

temp := next instruction address

PC := LR + OffsetLow << 1

PC := PC + (OffsetHigh << 12) + (OffsetLow << 1)

LR := temp | 1

http://bear.ces.cwru.edu/eecs_382/ARM7-TDMI-manual-pt3.pdf?ref=zdimension.fr

Thumb long branch with link **BL** instruction (4)


- This format specifies a long branch with link.
- The assembler splits the **23-bit** two's complement half-word **offset** specified by the label into *two 11-bit halves*, ignoring bit 0 (which must be 0), and creates two THUMB instructions.
- **Instruction 1 (H = 0)**
 - In the *first* instruction the Offset field contains
 - the **upper 11 bits** of the **target** address.
 - this is shifted left by 12 bits and
 - added to the current PC address.
 - The resulting address is placed in **LR**.
- **Instruction 2 (H = 1)**
 - In the *second* instruction the Offset field contains
 - the **lower 11-bit** of the **target** address.
 - this is shifted left by 1 bit and
 - added to **LR**.
 - **LR**, which now contains the full 23-bit address, is placed in **PC**,
 - the address of the instruction following the **BL** is placed in **LR** and bit 0 of **LR** is set.
 - the branch **offset** must take account of the **prefetch** operation,
 - which causes the **PC** to be 1 word (4 bytes) ahead of the current instruction

http://bear.ces.cwru.edu/eecs_382/ARM7-TDMI-manual-pt3.pdf?ref=zdimension.fr


Branch and Exchange (1)

- the **Branch** and **Exchange (BX)** instruction.
- also **Branch, Link, and Exchange (BLX)** if you're using an ARM with version 5 architecture.
- During the branch, the CPU examines the least significant bit (**lsb**) of the **destination address** to determine the *new state*.

BX R0 ; to ARM state
BLX R0 ; to ARM state

R0 

BX R0 ; to Thumb state
BLX R0 ; to Thumb state

R0 

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch and Exchange (2)

- Since all ARM instructions will align themselves on either a 32- or 16-bit boundary, the **lsb** of the **address** is not used in the branch directly.
- if the **lsb** is **1** when branching from ARM state, the processor switches to Thumb state before it begins executing from the new address;
- if the **lsb** is **0** when branching from Thumb state, the processor switches back to ARM state it goes.

BX Rm

BLX Rm

; destination address in the register Rm

If **Rm[0]** is **0**, to **ARM** state.

If **Rm[0]** is **1**, to **Thumb** state.

BLX *label*

; destination address is the PC-relative *label* expression

always change: (ARM → Thumb, Thumb → ARM)

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch and Exchange (2)

change into Thumb state, then back

```
mov R0, #5    ; argument to function is in R0
add R1, PC, #1 ; load address of SUB_BRANCH,
                ; set for THUMB by adding 1
BX  R1       ; R1 contains address of SUB_BRANCH+1
                ; assembler-specific instruction
                ; to switch to Thumb
```

SUB_BRANCH:

```
BL  thumb_sub ; must be in a space of +/- 4 MB
add R1, #7    ; point to SUB_RETURN with bit 0 clear
BX  R1
                ; assembler-specific instruction to switch to ARM
```

SUB_RETURN:

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch and Exchange (3)

- the **BX** instruction example to go from **ARM** to **Thumb** state and back.
- first switches to **Thumb** state (**BX R1**)
- then calls a subroutine written in **Thumb** code (**BL thumb_sub**)
- upon return from the subroutine (**BX R1**) the system again switches back to **ARM** state;

```
mov R0, #5      ; argument to function is in R0
add R1, PC, #1  ; load address of SUB_BRANCH,
                 ; set for THUMB by adding 1
BX R1          ; R1 contains address
                 ; of SUB_BRANCH+1
                 ; to switch to Thumb
```

SUB_BRANCH:

```
BL thumb_sub
```

```
                 ; must be in a space of +/- 4 MB
add R1, #7      ; point to SUB_RETURN
                 ; with bit 0 clear
```

```
BX R1          ; to switch to ARM
```

SUB_RETURN:

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch and Exchange (4)

- this example assumes that **R1** is *preserved* by the subroutine.
- The **PC** always contains the **address** of the current instruction **plus 8**
 - **add R1, PC,#1**
 - (4 bytes)
 - **BX R1**
 - (4 bytes)
 - **SUB_BRANCH**
 - (**PC** of **add** inst. + 8 bytes)
 -
 -

```
mov R0, #5 ; argument to function is in R0
add R1, PC,#1 ; load address of SUB_BRANCH,
               ; set for THUMB by adding 1
               ; R1 contains address
               ; of SUB_BRANCH+1
               ; to switch to Thumb
BX R1

SUB_BRANCH:
BL thumb_sub

add R1, #7 ; must be in a space of +/- 4 MB
           ; point to SUB_RETURN
           ; with bit 0 clear
BX R1 ; to switch to ARM
SUB_RETURN:
```

<https://www.embedded.com/introduction-to-arm-thumb/>

Branch and Exchange (5)

- The **Thumb BL** instruction actually resolves into two instructions, so 8 bytes are used between **SUB_BRANCH** and **SUB_RETURN**.
- **BL thumb_sub** (4 bytes)
 - **BL (H=0)** Offset_high (2 bytes)
 - **BL (H=1)** Offset_low (2 bytes)
- **add R1, #7** (2 bytes)
- **BX R1** (2 bytes)

```
mov R0, #5 ; argument to function is in R0
add R1, PC,#1 ; load address of SUB_BRANCH,
               ; set for THUMB by adding 1
BX R1 ; R1 contains address
       ; of SUB_BRANCH+1
       ; to switch to Thumb
```

SUB_BRANCH:

```
BL thumb_sub
```

```
 ; must be in a space of +/- 4 MB
add R1, #7 ; point to SUB_RETURN
           ; with bit 0 clear
```

```
BX R1 ; to switch to ARM
```

SUB_RETURN:

<https://www.embedded.com/introduction-to-arm-thumb/>

Switching the state (1) **BX** or **BLX**

- There are several ways to enter or leave the **Thumb** state properly.
- The usual method is via the **Branch** and **Exchange (BX)** instruction.
- also **Branch, Link, and Exchange (BLX)** if you're using an ARM with version 5 architecture.
- During the branch, the CPU examines the least significant bit (**lsb**) of the destination address to determine the new state.

R0 0

BX R0 ; to **ARM** state
BLX R0 ; to **ARM** state

R0 1

BX R0 ; to **Thumb** state
BLX R0 ; to **Thumb** state

<https://www.embedded.com/introduction-to-arm-thumb/>

Switching the state (2) Exception Handler

- When an **exception** occurs, the processor automatically begins executing in **ARM state** at the address of the **exception vector**.
- So another way to change state is to place your 32-bit code in an **exception handler**.
- If the CPU is running in **Thumb state** when that **exception** occurs, you can count on it being in **ARM state** within the **handler**.
- If desired, you can have the **exception handler** put the CPU into **Thumb state** via a branch.

<https://www.embedded.com/introduction-to-arm-thumb/>

Switching the state (3) T bit in the SPSR

The final way to change the state is via a **return** from **exception**.

- When **returning** from the processor's **exception mode**, the saved value of **T** in the **SPSR** register is used to restore the **state**.
- This **T** bit can be used, for example, by an operating system to manually restart a task in the **Thumb state** – if that's how it was running previously.

<https://www.embedded.com/introduction-to-arm-thumb/>

Thumb instruction set benefits

- The biggest reason to look for an ARM processor with the **Thumb instruction set** is if you need to reduce **code density**.
- In addition to reducing the total amount of **memory required**, you may also be able to narrow the **data bus** to just 16 bits.
- With the **narrower bus**, it will take two **bus cycles** to fetch a single 32-bit instruction;
- but you'll only pay that penalty in the parts of your code that can't be implemented with the **Thumb instructions**.
- And you'll still have the benefits of a powerful 32-bit RISC processor. A nifty trick indeed.

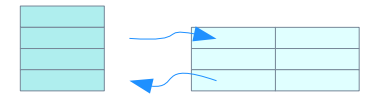
<https://www.embedded.com/introduction-to-arm-thumb/>

BLX in ARM Architecture v5

In ARM Architecture v5
both **ARM** and **Thumb state**
provide a **BLX** instruction
that will call a subroutine addressed by a register
and **correctly sets the return address**
to the sequentially next value of the **program counter**.

/IHI0042E_aapcs.pdf

Thumb → ARM interworking call



to **BL** to an **intermediate Thumb code** segment that executes the **BX** instruction.

the **BL** instruction loads the **link register** immediately before the **BX** instruction is executed.

In addition, the **Thumb instruction set** version of **BL** sets **bit 0** when it loads the **link register** with the **return address**.

When a **Thumb-to-ARM** interworking subroutine call returns using a **BX LR** instruction, it causes the required **state change** to occur automatically.

BL `__call_via_r4`

BX r4

Stop

BX r4

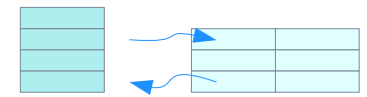
LR[0] = 0 → **ARM state**

BX LR

| | | |
|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------|
| <pre>CODE16 ThumbProg MOV r0, #2 MOV r1, #3 ADR r4, ARMSubroutine BL __call_via_r4</pre> | <pre>Stop MOV r0, #0x18 LDR r1, =0x20026 SWI 0xAB __call_via_r4 BX r4</pre> | <pre>CODE32 ARMSubroutine ADD r0, r0, r1 BX LR END</pre> |
|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------|

<https://developer.arm.com/documentation/dui0040/d/Interworking-ARM-and-Thumb/Basic-assembly-language-interworking/Implementing-interworking-assembly-language-subroutines>

Thumb → ARM interworking call



If you always use the same register to store the **address** of the **ARM subroutine** that is being called from **Thumb**, this segment can be used to send an interworking call to any ARM subroutine.

You must use a **BX LR** instruction at the end of the ARM subroutine to return to the caller.

You cannot use the **MOV pc,lr** instruction to return in this situation because it does not cause the required change of state.

```
ADR r4, ARMSubroutine
```

```
CODE16
```

```
ThumbProg
```

```
***
```

```
ADR r4, ARMSubroutine
```

```
BL __call_via_r4
```

```
***
```

```
__call_via_r4
```

```
BX r4
```

```
CODE32
```

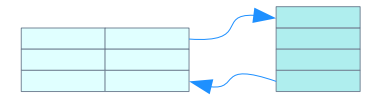
```
ARMSubroutine
```

```
***
```

```
BX LR
```

<https://developer.arm.com/documentation/dui0040/d/Interworking-ARM-and-Thumb/Basic-assembly-language-interworking/Implementing-interworking-assembly-language-subroutines>

ARM → Thumb interworking call



no need to set bit 0 of the **link register** because the routine is returning to **ARM state**.

store the return address by copying **PC** into **LR** with a **MOV lr,pc** instruction immediately before the **BX** instruction.

Remember that the address operand to the **BX** instruction that calls the **Thumb subroutine** must have **bit 0 set** so that the processor executes in **Thumb state** on arrival.

As with Thumb-to-ARM interworking subroutine calls, you must use a **BX** instruction to return.

LR[0] = 0 → ARM state

```
ADR r4, ThumbSub + 1
BX r4
```

CODE16

```
ADR r4, ThumbSub + 1
```

...

```
MOV lr, pc
```

```
BX r4
```

CODE16

ThumbSub

```
ADD r0, r0, r1
```

```
BX LR
```

```
END
```

<https://developer.arm.com/documentation/dui0040/d/Interworking-ARM-and-Thumb/Basic-assembly-language-interworking/Implementing-interworking-assembly-language-subroutines>

ARM → Thumb interworking call example code (1)

```
AREA ArmAdd,CODE,READONLY
```

```
ENTRY
```

```
main
```

```
ADR r2, ThumbProg + 1
```

```
BX r2
```

```
CODE16
```

```
ThumbProg
```

```
MOV r0, #2
```

```
MOV r1, #3
```

```
ADR r4, ARMSubroutine
```

```
BL __call_via_r4
```

```
Stop
```

```
MOV r0, #0x18
```

```
LDR r1, =0x20026
```

```
SWI 0xAB
```

```
__call_via_r4
```

```
BX r4
```

```
; name this block of code.  
; Mark 1st instruction to call.  
; Assembler starts in ARM mode.
```

```
; Generate branch target address and set bit 0,  
; hence arrive at target in Thumb state.  
; Branch exchange to ThumbProg.  
; Subsequent instructions are Thumb.
```

```
; Load r0 with value 2.  
; Load r1 with value 3.  
; Generate branch target address, leaving bit 0  
; clear in order to arrive in ARM state.  
; Branch and link to Thumb code segment that will  
; carry out the BX to the ARM subroutine.  
; The BL causes bit 0 of Ir to be set.  
; Terminate execution.  
; angel_SWIreason_ReportException  
; ADP_Stopped_ApplicationExit  
; Angel semihosting Thumb SWI  
; This Thumb code segment will  
; BX to the address contained in r4.  
; Branch exchange.
```

<https://developer.arm.com/documentation/dui0040/d/Interworking-ARM-and-Thumb/Basic-assembly-language-interworking/Implementing-interworking-assembly-language-subroutines>

ARM → Thumb interworking call example code (2)

```
CODE32
ARMSubroutine
  ADD  r0, r0, r1
  BX   LR

END
```

```
; Subsequent instructions are ARM.

; Add the numbers together
; and return to Thumb caller
; (bit 0 of LR set by Thumb BL).
; Mark end of this file.
```

<https://developer.arm.com/documentation/dui0040/d/Interworking-ARM-and-Thumb/Basic-assembly-language-interworking/Implementing-interworking-assembly-language-subroutines>

Thumb → ARM interworking call example code (1)

```
AREA ThumbAdd, CODE, READONLY
ENTRY
```

main

```
MOV    r0, #2
MOV    r1, #3
ADR    r4, ThumbSub + 1
```

```
MOV    lr, pc
BX     r4
```

Stop

```
MOV    r0, #0x18
LDR    r1, =0x20026
SWI    0x123456
```

```
CODE16
```

ThumbSub

```
ADD    r0, r0, r1
BX     LR
END
```

```
; Name this block of code.
; Mark 1st instruction to call.
; Assembler starts in ARM mode.
```

```
; Load r0 with value 2.
; Load r1 with value 3.
; Generate branch target address and set bit 0,
; hence arrive at target in Thumb state.
; Store the return address.
; Branch exchange to subroutine ThumbSub.
; Terminate execution.
; angel_SWIreason_ReportException
; ADP_Stopped_ApplicationExit
; Angel semihosting ARM SWI
```

```
; Subsequent instructions are Thumb.
```

```
; Add the numbers together
; and return to ARM caller.
; Mark end of this file.
```

<https://developer.arm.com/documentation/dui0040/d/Interworking-ARM-and-Thumb/Basic-assembly-language-interworking/Implementing-interworking-assembly-language-subroutines>

Cortex-M3 : 32-bit processor

- The **Thumb** instruction set is a subset of the most commonly used 32-bit **ARM** instructions.
- **Thumb** instructions are each **16 bits** long, and have a corresponding **32-bit ARM** instruction that has the same effect on the processor model.
- The **Cortex-M3 processor** is a high performance **32-bit** processor designed for the **microcontroller** market.
- It offers significant benefits to developers, including: outstanding processing performance combined with
 - fast interrupt handling.
 - enhanced **system debug** with
 - extensive **breakpoint** and **trace** capabilities.

<https://developer.arm.com/documentation/dui0552/a/introduction/about-the-cortex-m3-processor-and-core-peripherals>

Cortex-M3 : Thumb state only

- The **Cortex-M3** processor only supports execution of instructions in **Thumb state**. (**T = 1**)

- The following can clear the **T** bit to **0**:

- instructions **BLX**, **BX** and **POP {PC}**
- **restoration** from the stacked **xPSR** value on an **exception return**
- bit[0] of the **vector value** on an **exception entry** or **reset**.

- In the **Cortex-M3** processor, attempting to execute instructions when the **T** bit is **0** results in a **fault** or **lockup**. See Lockup for more information.

- The **Thumb status** bit (**T**) indicates the processor's current state:
 - **0** for **ARM** state (default)
 - **1** for **Thumb**.



<https://developer.arm.com/documentation/dui0552/a/the-cortex-m3-processor/programmers-model/core-registers>

Thumb Instruction

Thumb instructions (1)

- The **Thumb instructions**
 - **16-bit** instructions
 - a compact *shorthand* for a subset of the **32-bit** ARM instructions
- every **Thumb instruction** has the *equivalent* **32-bit ARM instruction**.

• not every **ARM instructions** has the *equivalent* **Thumb subset**;

• a single **ARM instruction** can only be simulated with a sequence of **Thumb instructions**



• for example, there's no way to access **status** or **coprocessor registers**.



• a long branch with link (**BL**)
• the assembler splits
Instruction 1 (**H = 0**)
Instruction 2 (**H = 1**)

<https://www.cs.princeton.edu/courses/archive/fall13/cos375/ARMthumb.pdf>

Thumb instructions (2)

- the ARM contains only one instruction set: the 32-bit set.
- When it's operating in the **Thumb state**, the processor simply expands the smaller shorthand instructions fetched from memory into their 32-bit equivalents.
- The difference between two equivalent instructions (the ARM and Thumb instructions) lies in how the *instructions* are fetches and interpreted prior to execution, not in how they *function*.
- dedicated hardware expands the 16-bit instruction into 32-bit it doesn't slow execution even a bit.
- the narrower 16-bit instructions do offer memory advantages.

<https://www.cs.princeton.edu/courses/archive/fall13/cos375/ARMthumb.pdf>

Thumb instructions (3)

- Roughly speaking, a CPU **instruction** is a particular *sequence of bits*
- to the CPU, a particular *sequence of bits* could mean "add two 32-bit values and carry"
- The exact value of *bits in this sequence* has nothing to do with values being added.
- In the **ARM mode**, this *sequence of bits* has **32 bits**.
- In the **thumb mode**, it only has **16 bits**.
- apparently, the **thumb** mode has less number of encoded instructions than the **ARM** mode (less bits to encode them),
- for a same function, most instructions are encoded differently for the **ARM** and the **thumb** modes, respectively,

<https://electronics.stackexchange.com/questions/353192/how-does-an-arm-processor-in-thumb-state-execute-32-bit-values>

Thumb instructions (4)

- for example, the **x86** uses **8-bit instructions** but is also able to work on **32 bit** values.
- For **ARM**, the *instruction length* is what changes when you switch to/from **ARM** and **thumb** modes.
- For example, the instruction **MOV R0, R1** copy the contents of the 32-bit **R1** register to the **R0** register is encoded in the following way:
 - **E1A00001** for **ARM** (32 bit : 4 bytes)
 - **4608** for **Thumb** (16-bit : 2 bytes)
- But the processor will perform exactly the same operation, and it will do it on **32-bit wide data**, whatever the **mode**.

<https://electronics.stackexchange.com/questions/353192/how-does-an-arm-processor-in-thumb-state-execute-32-bit-values>

Thumb instructions (5)

- The **Thumb** instruction set is a **subset** of the most commonly used 32-bit **ARM** instructions.
- **Thumb** instructions are **16 bits** long, and have a corresponding **32-bit ARM** instruction that has the same effect on the processor model.
- **Thumb** instructions operate with the **standard ARM register configuration**, enabling excellent interoperability between ARM and Thumb states.
- Thumb has all the advantages of a 32-bit core:
 - **32-bit address space**
 - **32-bit registers**
 - **32-bit** shifter and Arithmetic Logic Unit (**ALU**)
 - **32-bit memory transfer**

<https://developer.arm.com/documentation/ddi0333/h/introduction/arm1176jz-s-architecture-with-jazelle-technology/the-thumb-instruction-set>

Thumb instructions (6)

- The ARM processor can *manipulate 32 bit values* because it is a *32-bit processor*, *whatever mode* it is running in (*Thumb* or *ARM*).
- thus, *registers* are *32 bits* wide
- *register width* doesn't change when you switch *mode (state)*
- the *data bus width* of the processor has nothing to do with the *length* of the *instructions*.
- The *instructions* could be encoded in any length.

<https://electronics.stackexchange.com/questions/353192/how-does-an-arm-processor-in-thumb-state-execute-32-bit-values>

Thumb instructions (7)

- The **Thumb** instruction set provides *most of the functionality* of a typical application.
 - **arithmetic** and **logical** operations
 - **load/store** data movements
 - **conditional** and **unconditional** branches
- any code written in **C** could be executed successfully in **Thumb** state.
- However, **device drivers** and **exception handlers** must often be written at least partly **in ARM state**

<https://www.cs.princeton.edu/courses/archive/fall13/cos375/ARMthumb.pdf>

Thumb instructions (8)

- **Switching modes** allows programmers to decide on the compromise between **code density** and **flexibility**
- can pack more instructions in a kB of code with **16-bit** instructions,
- but the **32 bit** instructions are more *flexible*
 - they offer more features and
 - you can do more with a single instruction

<https://electronics.stackexchange.com/questions/353192/how-does-an-arm-processor-in-thumb-state-execute-32-bit-values>

Thumb instructions (9)

- All **Thumb instructions** are **16 bits** in length.
- **Thumb** provides approximately 30% better **code density** over ARM code.
- Most code written for **Thumb** is in a high-level language such as **C** and **C++**.
- **ATPCS** (ARM Thumb Procedure Call Standard) defines how **ARM** and **Thumb** code **call** each other, called **ARM-Thumb interworking**.
- **Interworking** uses the **branch exchange (BX)** instruction and **branch exchange with link (BLX)** instruction to *change state* and *jump* to a specific routine.

<https://www.sciencedirect.com/topics/computer-science/thumb-instruction-set>

Thumb instructions (10)

- In **Thumb**, *only* the **branch instructions** are **conditionally executed**.
- The **barrel shift operations** are separate instructions
 - **ASR**
 - **LSL**
 - **LSR**
 - **ROR**
- The **multiple-register load-store** instructions only support the **increment after (IA)** addressing mode.
- The **Thumb** instruction set includes **POP** and **PUSH** instructions as stack operations.
- **POP** and **PUSH** instructions only support a **full descending stack**.
- There are no **Thumb** instructions to access the **coprocessors**, **cpsr**, and **spsr**.

<https://www.sciencedirect.com/topics/computer-science/thumb-instruction-set>

Thumb instructions (11)

| | ARM (CPSR T=0) | Thumb (CPSR T=1) |
|------------------------------|----------------------------------|-----------------------------------------------------|
| Instruction size | 32-bit | 16-bit |
| Core instructions | 58 | 30 |
| Conditional execution | most | <u>only</u> branch instruction |
| Data Processing Instructions | access to barrel shifter and ALU | <i>separate</i> barrel shifter and ALU instructions |
| Program Status Reg | R/W in privileged mode | <u>no</u> direct access |
| Register usage | 15 general purpose reg + PC | 8 general purpose reg + 7 high reg + PC |



<https://electronics.stackexchange.com/questions/353192/how-does-an-arm-processor-in-thumb-state-execute-32-bit-values>

Thumb-2 Instruction

Thumb-2 Instructions (1)

- Thumb-1 only does 16 bit instructions
- Thumb-2 can do both 16 bit & 32 bit instructions
- Thumb-1 and Thumb-2
 - share same architecture for 32 bit data.
 - share the same data bus since only the instruction registers are *different*.
- for 64 bit processors, Thumb (T32) can support both 16 & 32 bit instructions with some different in each set in order to conserve code space for some applications but at the expense of duplicate libraries.

Thumb-1
16-bit
instructions
32-bit GP regs

Thumb-2
Mixed 16- and 32-bit
instructions
32-bit GP regs

T32
Mixed 16- and 32-bit
instructions
32-bit GP regs

A32
32-bit instructions
32-bit GP regs

A64
32-bit instructions
32- and 64-bit GP regs

<https://electronics.stackexchange.com/questions/353192/how-does-an-arm-processor-in-thumb-state-execute-32-bit-values>

Thumb-2 Instructions (2)

- **Thumb-2** is an enhancement to the **16-bit Thumb** instruction set.
- **Thumb-2** **adds 32-bit instructions** that can be *freely intermixed* with **16-bit instructions** in a program.
- the additional **32-bit instructions** enable **Thumb-2**
 - to cover the functionality of the **ARM** instruction set.
 - to combine the **code density** of earlier versions of **Thumb**, with **performance** of the **ARM** instruction.

| | | |
|---------|--------|--------|
| ARM | | 32-bit |
| Thumb | 16-bit | |
| Thumb-2 | 16-bit | 32-bit |

↑
*added
32-bit
Thumb-2
instruction*

<https://developer.arm.com/documentation/ddi0344/c/programmer-s-model/thumb-2-instruction-set>

Thumb-2 Instructions (3)

- The most important difference between the **Thumb-2 instruction set** and the **ARM instruction set** is

that most **32-bit Thumb instructions** are **unconditional**, whereas most **ARM instructions** can be **conditional**.

- Thumb-2** introduces a **conditional execution instruction**, **IT**, that is a *logical if-then-else function* that you can apply to following instructions to make them conditional.
- If cond **T**hen ... **E**lse ...

| | | |
|---------|---------------------------|---------------------------|
| ARM | | 32-bit (conditional) |
| Thumb | 16-bit (unconditional) | |
| Thumb-2 | 16-bit (unconditional) | 32-bit (unconditional) |

IT**TET** EQ
ADD r0,r0,r0
ADD r1,r0,r0
ADD r2,r0,r0
ADD r3,r0,r0



IT**TET** EQ
T EQ + ADD r0,r0,r0
T EQ + ADD r1,r0,r0
E EQ + ADD r2,r0,r0
T EQ + ADD r3,r0,r0

ADDEQ r0,r0,r0 (Always if for 1st one)
ADDEQ r1,r0,r0 (T for 2nd one)
ADDNE r2,r0,r0 (E for 3rd one)
ADDEQ r3,r0,r0 (T for 4th one)

<https://developer.arm.com/documentation/ddi0344/c/programmer-s-model/thumb-2-instruction-set>

Thumb-2 Instructions (4)

- **Thumb-2** instructions are accessible as were **Thumb** instructions when the processor is in **Thumb state**, that is, the **T bit** in the **CPSR** is **1** and the **J bit** in the **CPSR** is **0**.
- In addition to the **32-bit Thumb** instructions, there are several **16-bit Thumb** instructions and a few **32-bit ARM** instructions, introduced as part of the **Thumb-2 architecture**.

TJ = 10

<https://en.wikipedia.org/wiki/Jazelle#Implementation>

New 32-bit Thumb Instructions (1-1)

- The new 32-bit Thumb instructions are added in the space previously occupied by the Thumb **BL** and **BLX** instructions.
- This is made possible by treating **BL** and **BLX** as 32-bit instructions, instead of treating them as two 16-bit instructions.
- This means that **BL** and **BLX**, and all the other 32-bit Thumb instructions, can only take exceptions on their start address.
- They cannot take exceptions at the boundary between *halfword1* and *halfword2* of the instruction.

TJ = 10

<https://developer.arm.com/documentation/ddi0308/d/Introduction-to-Thumb-2/New-32-bit-Thumb-instructions>

New 32-bit Thumb Instructions (1-2)

- All implementations must ensure that both *halfwords* are fetched and consolidated before they are issued and executed to *comply* with this **exception event restriction**.
- This is a change from **Thumb**.
- Before **Thumb-2**, the two *halfwords* of **BL** and **BLX** instructions execute independently, and can take **exceptions** independently.

TJ = 10

<https://developer.arm.com/documentation/ddi0308/d/Introduction-to-Thumb-2/New-32-bit-Thumb-instructions>

New 32-bit Thumb Instructions (2-1)

- The new 32-bit Thumb instructions are designed for:
- the existing ARM/Thumb Programmers' Model, with as few modifications as possible.
- Certain changes are essential to introduce the 32-bit Thumb instructions, notably to the Prefetch abort and Undefined Instruction exceptions.
- There is no increase in the number of registers (general purpose or special purpose registers), and no increase in register sizes.
- existing compiler code generation techniques, as far as possible.

TJ = 10

<https://developer.arm.com/documentation/ddi0308/d/Introduction-to-Thumb-2/New-32-bit-Thumb-instructions>

New 32-bit Thumb Instructions (2-2)

- New concepts are supplementary rather than obligatory.
- For example, **literals** can still be loaded using **PC-relative** instructions, or use **in-line immediate values** embedded in the **MOV 16-bit immediate** and **MOVT** instructions.

TJ = 10

<https://developer.arm.com/documentation/ddi0308/d/Introduction-to-Thumb-2/New-32-bit-Thumb-instructions>

New 32-bit Thumb Instructions (3)

- You may not need to rewrite too much depending on what features of the **ARM instruction set** and **ARM variant** you've used.
- It's also possible that your **ARM code** is already compatible with **Thumb-2**.
- ARM created **Unified Assembly Language (UAL)** once **Thumb-2** was introduced in order to increase the **portability** of code.
- it is not a significant deviation from ARM assembly of olden days, with the biggest change being the introduction of the **IT(E)** directive for **conditional execution**.

TJ = 10

<https://developer.arm.com/documentation/ddi0308/d/Introduction-to-Thumb-2/New-32-bit-Thumb-instructions>

New 32-bit Thumb Instructions (4)

- There are some other constructs that won't port directly, and if you are using features of a more advanced or complex ARM core that the Cortex-M4 doesn't have, then that will require a rewrite of that portion.
- I think if the code is not already written in **ARM UAL** that, while it would take time, it would be relatively simple to run a **script** over the code that can flag the usage of features that are not written correctly for **UAL**.
- A simple regular expression could check for conditionals on the end of instructions, and it may even be relatively easy to then convert those constructs to use **IT(E) <cond>**.
 - **If** cond **Then** ... **Else** ...

TJ = 10

<https://developer.arm.com/documentation/ddi0308/d/Introduction-to-Thumb-2/New-32-bit-Thumb-instructions>

Thumb 2 instruction set (4)



- The main enhancements are:
 1. **32-bit instructions** added to the **Thumb instruction** set to:
 - provide support for **exception handling in Thumb state**
 - provide access to **coprocessors**
 - include Digital Signal Processing (**DSP**)
 - and **media** instructions
 2. improve **performance** in cases where a single **16-bit instruction** *restricts* functions available to the compiler.
 3. addition of a **16-bit IT instruction** that enables *one to four* following **Thumb instructions**, the IT block, to be **conditional**

<https://developer.arm.com/documentation/ddi0344/c/programmer-s-model/thumb-2-instruction-set>

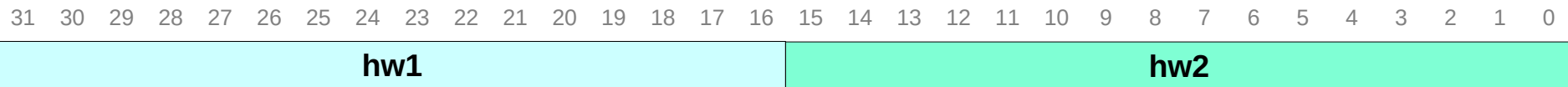
Thumb 2 instruction set (5)

- The main enhancements are:
4. addition of a 16-bit CZB instruction
 - Compare with Zero and Branch (CZB) to improve code density by replacing two-instruction sequence with a single instruction.
 5. The 32-bit ARM Thumb-2 instructions are added in the space occupied by the Thumb BL and BLX instructions

<https://developer.arm.com/documentation/ddi0344/c/programmer-s-model/thumb-2-instruction-set>

32-bit ARM Thumb-2 Instruction Format (1)

- The first halfword (hw1) determines the instruction **length** and **functionality**.
- If the processor decodes the instruction as **32-bit long**, then the processor fetches the second halfword (hw2) of the instruction from the instruction **address plus two**.
- The availability of both **16-bit Thumb** and **32-bit instructions** in the **Thumb-2 instruction sets**, gives you the **flexibility** to emphasize **performance** or **code size** on a **subroutine** level, according to the requirements of their applications.



<https://developer.arm.com/documentation/ddi0344/c/programmer-s-model/thumb-2-instruction-set>

32-bit ARM Thumb-2 Instruction Format (2)

- For example, you can code **critical loops** for applications such as **fast interrupts** and **DSP algorithms** using the **32-bit media instructions** in Thumb-2 and use the smaller **16-bit classic Thumb instructions** for the rest of the application. This is for **code density** and does not require any **mode change**.



<https://developer.arm.com/documentation/ddi0344/c/programmer-s-model/thumb-2-instruction-set>

ARM, Thumb, Thumb 2 instruction encodings (1)

- officially there's no "*Thumb-2 instruction set*".
- Ignoring **ARMv8**
 - where everything is renamed and **AArch64** complicates things),
 - from **ARMv4T** to **ARMv7-A**
 - there are two **instruction sets**: **ARM** and **Thumb**.
- they are both "**32-bit**" in the sense that they operate on
 - up-to-32-bit-wide **data**
 - in 32-bit-wide **registers**
 - with 32-bit **addresses**.
- In fact, they represent the exact **same instructions**
- it is only the **instruction encoding** which differs
- the CPU has two **different decode front-ends** to its pipeline which it can switch between.

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

ARM, Thumb, Thumb 2 instruction encodings (2)

- ARM instructions have
 - fixed-width 4-byte encodings
 - which require 4-byte alignment.
- Thumb instructions have variable-length
 - 2-byte “narrow” encoding
 - 4-byte “wide” encoding
- requiring 2-byte alignment
- most instructions have 2-byte encodings,
- but **bl** and **blx** have always had 4-byte encodings*.
-

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

ARM, Thumb, Thumb 2 instruction encodings (3)

- The really confusing bit came in ARMv6T2, which introduced "**Thumb-2 Technology**".
- **Thumb-2** encompassed not just
 - *adding* a load more instructions to Thumb (mostly with 4-byte encodings) to bring it almost to comparable to ARM,
 - but also *extending* the execution state to allow for **conditional execution** of most **Thumb** instructions,
 - and finally introducing a whole new assembly syntax (UAL, "Unified Assembly Language")
 - which *replaced* the previous separate ARM and Thumb syntaxes
 - and allowed *writing* code once and *assembling* it to either **ARM** or **Thumb** instruction set without modification.

Thumb-2 Technology

4-byte encodings
conditional execution

UAL (Unified Assembly Language)
unify **ARM** and **Thumb** syntaxes
*assembling to either **ARM** or **Thumb***

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

ARM, Thumb, Thumb 2 instruction encodings (4)

- The **Cortex-M architectures** only implement the **Thumb instruction set** -
 - **ARMv7-M** (Cortex-M3/M4/M7) supports most of "**Thumb-2 Technology**", including **conditional execution** and encodings for **VFP** instructions,
 - whereas **ARMv6-M** (Cortex-M0/M0+) only uses **Thumb-2** in the form of a handful of **4-byte system instructions**.
 - Thus, the new **4-byte encodings** (and those added later in ARMv7 revisions) are still **Thumb instructions**
 - the "**Thumb-2**" aspect of them is that they can have **4-byte encodings**, and that they can (mostly) be **conditionally executed** via it
- their mnemonics are seemed to be only defined in UAL

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

ARM, Thumb, Thumb 2 instruction encodings (7)

- **Thumb**: 16 bit instruction set
- **ARM**: 32 bit wide instruction set hence more flexible instructions and less code density
- **Thumb2 (mixed 16/32 bit)**:
a compromise between **ARM** and **thumb(16)** (mixing them), to get both performance/flexibility of ARM and instruction density of Thumb.
- so a **Thumb2** instruction can be either an **ARM** (only a subset of) with 32 bit wide instruction or a **Thumb** instruction with 16 bit wide.

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

UAL (Unified Assembly Language) (1-1)

- **Unified assembly language (UAL)** is the new assembly syntax introduced by ARM Ltd.
 - to handle the ambiguities introduced by the original **Thumb-2** assembly syntax and
 - provide similar syntax for **ARM**, **Thumb** and **Thumb-2**.
- **UAL** is backwards compatible with old **ARM** assembly, but incompatible with the **Thumb** assembly syntax.
- **UAL** syntax is the default assembly syntax beginning with ARMv7 architectures.

<http://downloads.ti.com/docs/esd/SPNU118/unified-assembly-language-syntax-support-spnu1184444.html>

UAL (Unified Assembly Language) (1-2)

- When writing assembly code, the `.arm` and `.thumb` directives are used to specify ARM and Thumb UAL syntax, respectively.
- The `.state32` and `.state16` directives remain to specify **non-UAL ARM** and **Thumb** syntax.
- The `.arm` and `.state32` directives are equivalent since UAL syntax is backwards compatible in ARM mode.
- Since **non-UAL** syntax is not supported for **Thumb-2** instructions, **Thumb-2** instructions cannot be used inside of a `.state16` section.
- However, assembly code with `.state16` sections that contain only non-UAL Thumb code can be assembled for ARMv7 architectures to allow easy porting of older code.

<http://downloads.ti.com/docs/esd/SPNU118/unified-assembly-language-syntax-support-spnu1184444.html>

UAL (Unified Assembly Language) (2-1)

- the ARM **Unified Assembler Language (UAL)** syntax provides a canonical form for *all* **ARM** and **Thumb** instructions.
- **UAL** describes the syntax for the **mnemonic** and the **operands** of each instruction.
- In addition, it assumes that **instructions** and **data** items can be given **labels**.
- It does not specify the syntax to be used for **labels**, nor what assembler **directives** and **options** are available.
-

<https://developer.arm.com/documentation/ddi0406/c/Application-Level-Architecture/The-Instruction-Sets/Unified-Assembler-Language>

UAL (Unified Assembly Language) (2-2)

- Most earlier ARM assembly language **mnemonics** are still supported as synonyms
- Most earlier Thumb assembly language **mnemonics** are not supported.
-

<https://developer.arm.com/documentation/ddi0406/c/Application-Level-Architecture/The-Instruction-Sets/Unified-Assembler-Language>

UAL (Unified Assembly Language) (3)

- UAL includes **instruction selection rules** that specify which instruction encoding is selected when more than one can provide the required functionality.
- For example, both **16-bit** and **32-bit encodings** exist for an **ADD R0, R1, R2** instruction.
- The most common instruction selection rule is that when both **16-bit** and **32-bit encodings** are available, the **16-bit encoding** is selected, to optimize **code density**.
- **Syntax options** exist to override the normal instruction selection rules and ensure that a particular encoding is selected.
- These are useful when **disassembling** code, to ensure that subsequent assembly produces the original code, and in some other situations.

<https://developer.arm.com/documentation/ddi0406/c/Application-Level-Architecture/The-Instruction-Sets/Unified-Assembler-Language>

NEON and VFP

- For **armv7** ISA (and variants)
- The **NEON** is a **SIMD** and **parallel data processing unit** for integer and floating point data
- the **VFP** is a fully IEEE-754 compatible **floating point unit**
- In particular on the **A8**, the **NEON** unit is much faster for just about everything,
- even if you don't have highly parallel data, since the **VFP** is **non-pipelined**.
- So why would you ever use the VFP?!
- The most major difference is that the **VFP** provides **double precision** floating point.
- Secondly, there are some **specialized instructions** that that VFP offers that there are no equivalent implementations for in the NEON unit.
- SQRT comes to mind, perhaps some type conversions.

<https://stackoverflow.com/questions/4097034/arm-cortex-a8-whats-the-difference-between-vfp-and-neon>

Jezelle DBX (Direct Bytecode Execution)

Jazelle (1)

- **Jazelle DBX** (direct bytecode execution) is an extension that allows some ARM processors to execute Java bytecode in hardware as a third execution state alongside the existing ARM and Thumb modes.
- **Jazelle functionality** was specified in the **ARMvTEJ** architecture
- the first **processor** with **Jazelle** technology was the **ARM926EJ-S**.
- Jazelle is denoted by a "**J**" appended to the CPU name except for post-v5 cores where it is required (albeit only in trivial form) for architecture conformance.

TJ = 10

<https://en.wikipedia.org/wiki/Jazelle#Implementation>

Jazelle (2)

- The **J bit**

- The **J bit** in the **CPSR** indicates when the processor is in **Jazelle state**.

- When **J = 0**

the processor is in **ARM** or **Thumb state**, depending on the T bit.

TJ = 00 **ARM**
TJ = 10 **Thumb**

- When **J = 1**

the processor is in **Jazelle state**.

TJ = 01 **Jazelle**
TJ = 11 **undef**

<https://developer.arm.com/documentation/ddi0301/h/programmer-s-model/the-program-status-registers/the-j-bit>

Jazelle (3)

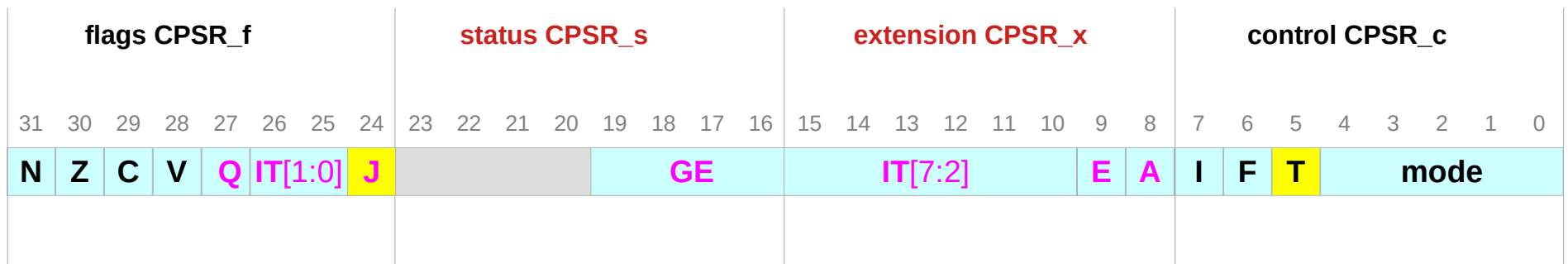
- The combination of **J = 1** and **T = 1** causes similar effects to setting **T=1** on a **non Thumb-aware** processor.
- That is, the next instruction executed causes entry to the **Undefined Instruction exception**.
- entry to the **exception handler** causes the processor to re-enter **ARM state**, and
- the **handler** can detect that this was the cause of the **exception** because **J** and **T** are both set in **SPSR_und**.
- **MSR** cannot be used to change the **J bit** in the **CPSR**.

| | |
|----------------|---------|
| TJ = 00 | ARM |
| TJ = 10 | Thumb |
| TJ = 01 | Jazelle |
| TJ = 11 | undef |

<https://developer.arm.com/documentation/ddi0301/h/programmer-s-model/the-program-status-registers/the-j-bit>

Jazelle (4)

- The placement of the **J bit** avoids the **status** or **extension** bytes in code running on ARMv5TE or earlier processors.
- This ensures that OS code written using the deprecated syntax CPSR, SPSR, CPSR_all, or SPSR_all for the destination of an **MSR** instruction continues to work.
- The **MSR** instruction is used to write
 - to the **CPSR** or
 - to the **SPSR** of the current mode.

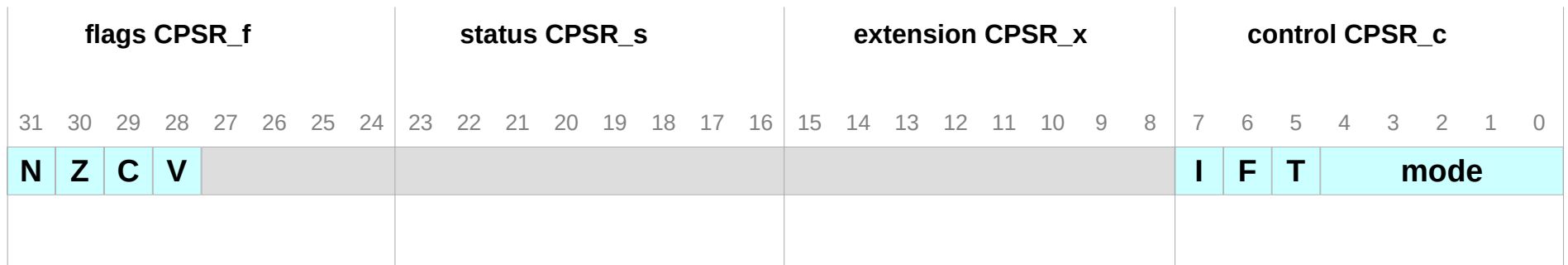


Current Program Status Register (CPSR)

<https://developer.arm.com/documentation/ddi0301/h/programmer-s-model/the-program-status-registers/the-j-bit>

CPSR Bits (1)

| Bit | Field | Description | Bit | Field | Description | Bit | Field | Description |
|-----|-------|---------------|-----|-------|-------------------------------------------------------------------------------------------------|-------|-------|-------------|
| 31 | N | Negative flag | 27 | I | To <u>disable</u> Interrupt (IRQ), set I | 10000 | USR | 10000 |
| 30 | Z | Zero flag | 26 | F | To <u>disable</u> Fast Interrupt (FIQ), set F | 10001 | FIQ | 10001 |
| 29 | C | Carry flag | 25 | T | the T bit shows whether the processor runs in ARM state or in Thumb state. | 10010 | IRQ | 10010 |
| 28 | V | Overflow flag | 24 | | never set this bit | 10011 | SVC | 10011 |
| | | | 23 | | can be changed only in a <u>privileged</u> mode | 10111 | ABT | 10111 |
| | | | 22 | | | 11011 | UND | 11011 |
| | | | 21 | | | 11111 | SYS | 11111 |



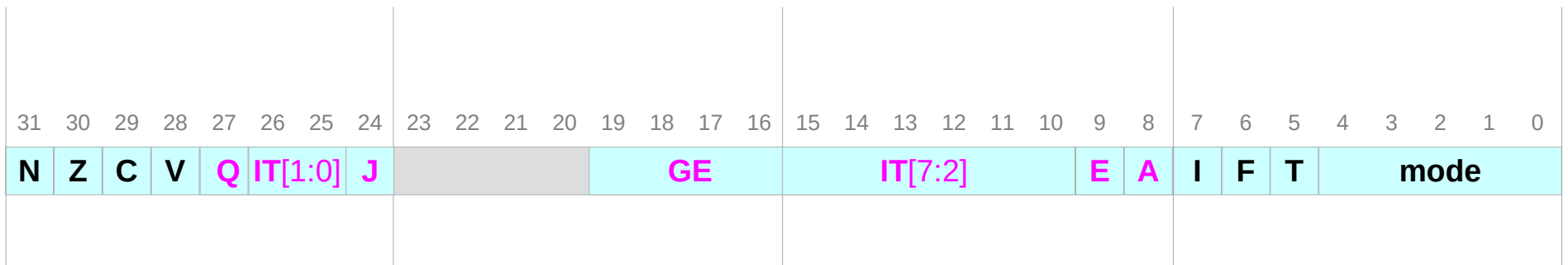
Current Program Status Register (CPSR)

<https://developer.arm.com/documentation/ddi0301/h/programmer-s-model/the-program-status-registers/the-j-bit>
https://courses.washington.edu/cp105/02_Exceptions/Status_Register_Instructions.html

CPSR Bits (2)



- Q** Cumulative saturation bit
- IT[1:0]** if-Then execution state bits for the Thumb IT (If-Then) instruction
- J** Jazelle bit
- GE** greater than or equal to flags
- IT[7:2]** if-Then execution state bits for the Thumb IT (If-Then) instruction
- E** Endianness execution state bit
0 - Little-endian, 1 - Big-endian
- A** Asynchronous abort mask bit



Current Program Status Register (CPSR)

https://www.keil.com/pack/doc/CMSIS/Core_A/html/group__CMSIS__CPSR.html

MRS – Move to Register from Status

- **MRS** is use to read
 - from the **CPSR** or
 - from the **SPSR** of the current mode
- It move the value from the **status register** into a regular register.
- The **SPSR** that will be read is the one that is active for the CPU's current mode.

MRS R0, CPSR

MRS R1, SPSR

- Reading the **SPSR** while in **user** or **system** mode is not valid and yields unpredictable results.

https://courses.washington.edu/cp105/02_Exceptions/Status_Register_Instructions.html

MSR – Move to Status from Register

- The **MSR** instruction is used to write
 - to the **CPSR** or
 - to the **SPSR** of the current mode.
- Writing to the **SPSR** while in the **user** or **system** mode is not valid and the results are not predictable.
- Any writes to the **CPSR** in **user** mode are ignored.
- The **CPSR** can only be written to in a **priveleged** mode.

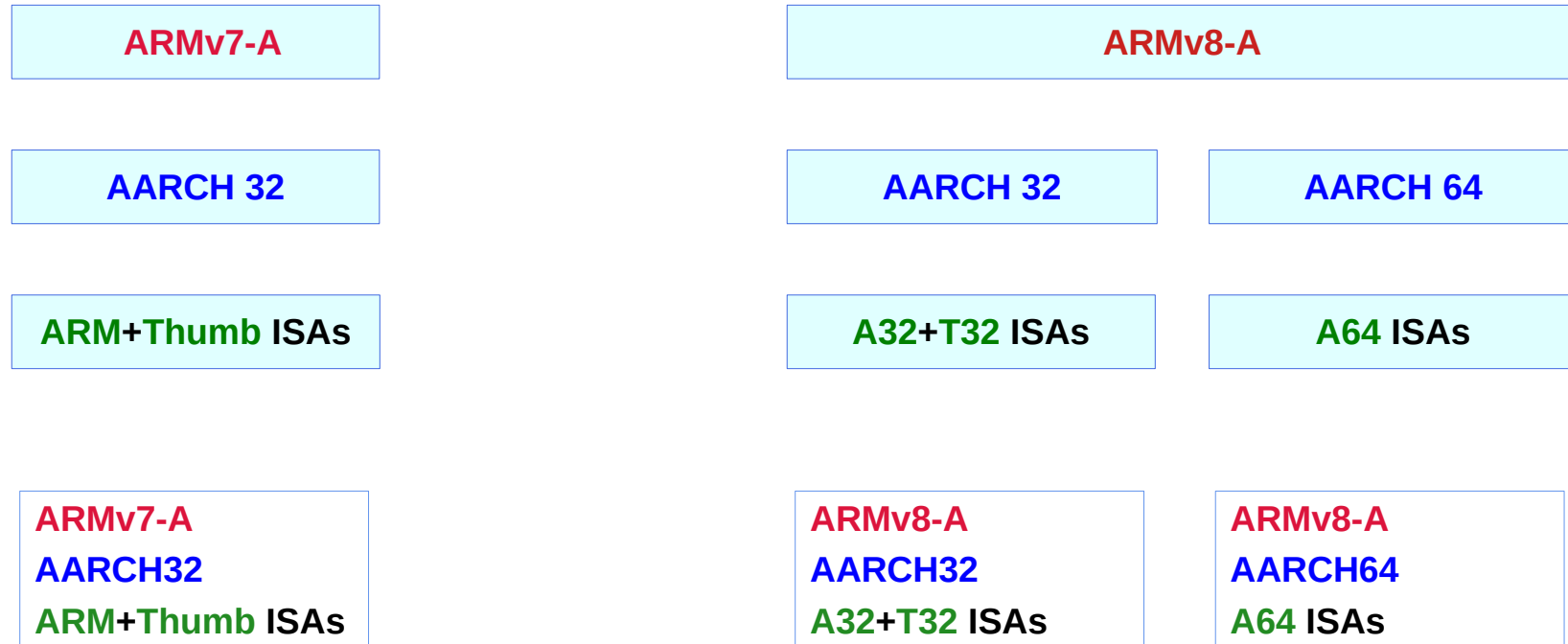
- **MSR CPSR, R0**
- **MSR SPSR, R1**

https://courses.washington.edu/cp105/02_Exceptions/Status_Register_Instructions.html

64-bit Processors

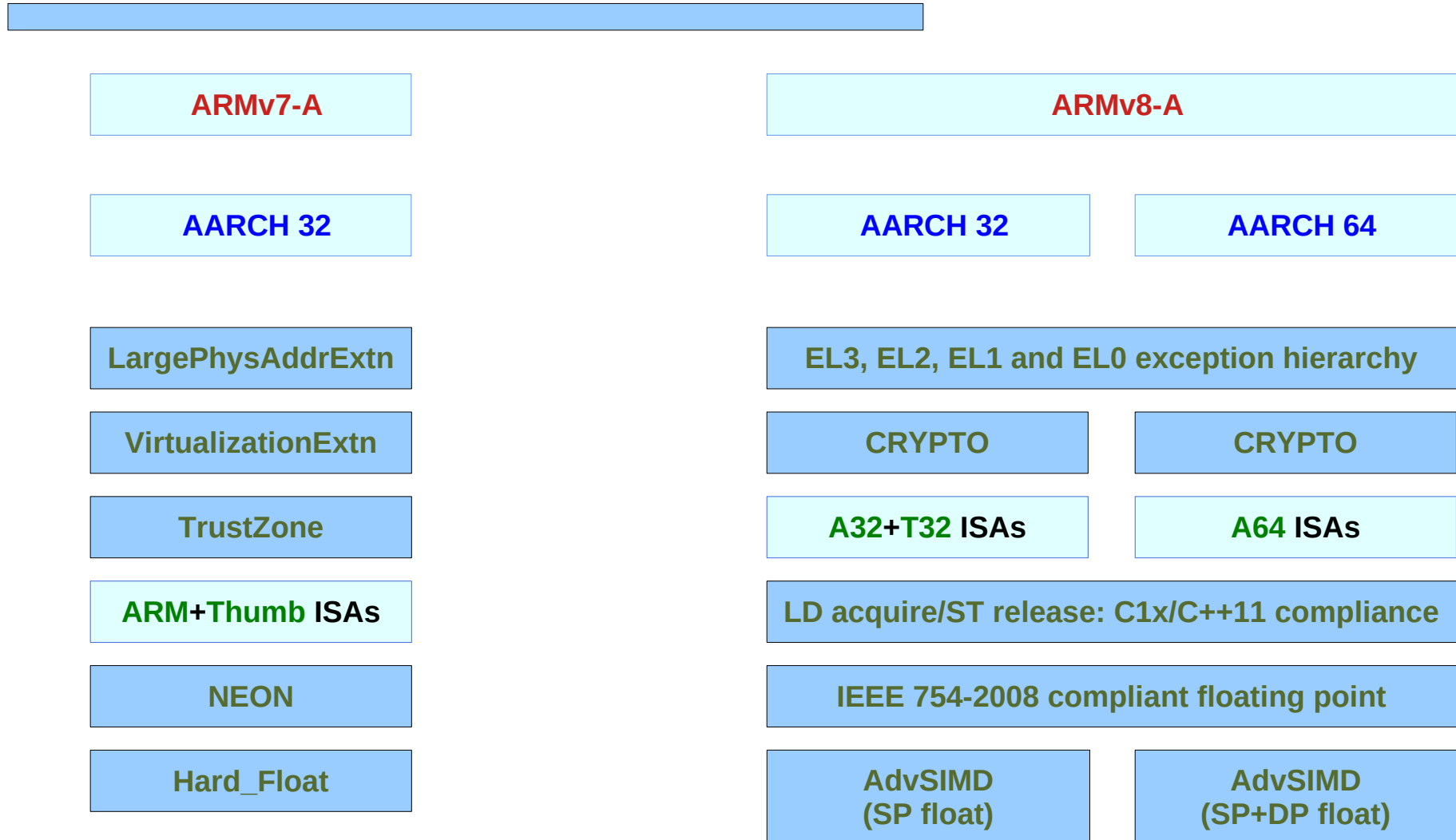
A32 + T32 ISA's
A64 ISA

64-bit processor (1)



<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (1)



<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

ARM, Thumb, Thumb 2 instruction encodings (5)

- there is a 32-bit execution state (AArch32) and a 64-bit execution state (AArch64).
- the 32-bit execution state supports two different instruction sets:
 - T32 ("Thumb") and
 - A32 ("ARM").
- The 64-bit execution state supports only one instruction set - A64.
- All A64, like all A32, instructions are 32-bit (4 byte) in size, requiring 4-byte alignment.
- Many/most A64 instructions can operate on both 32-bit and 64-bit registers (or arguably 32-bit or 64-bit views of the same underlying 64-bit register).

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

ARM, Thumb, Thumb 2 instruction encodings (6)

- All **ARMv8** processors (like all **ARMv7** processors) that implement **AArch32** support **Thumb-2** instructions in the **T32** instruction set.
- Not all **ARMv8-A** processors implement **AArch32**, and some don't implement **AArch64**.
- Some Processors support both, but only support **AArch32** at lower **exception levels**.

<https://stackoverflow.com/questions/28669905/what-is-the-difference-between-the-arm-thumb-and-thumb-2-instruction-encodings>

64-bit processor (1)

- Evolution of the ARM architecture
- The diagram shows how all the features present in **ARMv7-A** have been carried forward into **ARMv8-A**.
- But **ARMv8** supports two **execution states**:
 - **AArch32**
the **A32** and **T32** instruction sets
(**ARM** and **Thumb** in **ARMv7-A**) are supported
 - **AArch64**
the new **A64** instruction set is introduced.
- Although backwards compatible with **ARMv7-A**, the exception, privilege and security model has been significantly *extended* and is now classified as a set of **exception levels**, **EL0** to **EL3**, in a four-level hierarchy.

ARMv7-A
AArch32
ARM+Thumb ISAs

ARMv8-A
AArch32
A32+T32 ISAs,
AArch64
A64 ISAs

<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (2)

- In **AArch32**, the **ARMv7-A** Large Physical Address Extensions are supported, providing
 - 32-bit virtual addressing and
 - 40-bit physical addressing.
- In **AArch64**, this is extended, again in a backward compatible way, to provide
 - 64-bit virtual addresses and
 - 48-bit physical address
- Other additions include cryptographic support at instruction level.

ARMv7-A
AArch32
ARM+Thumb ISAs

ARMv8-A
AArch32,
A32+T32 ISAs,
AArch64
A64 ISAs

<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (3)

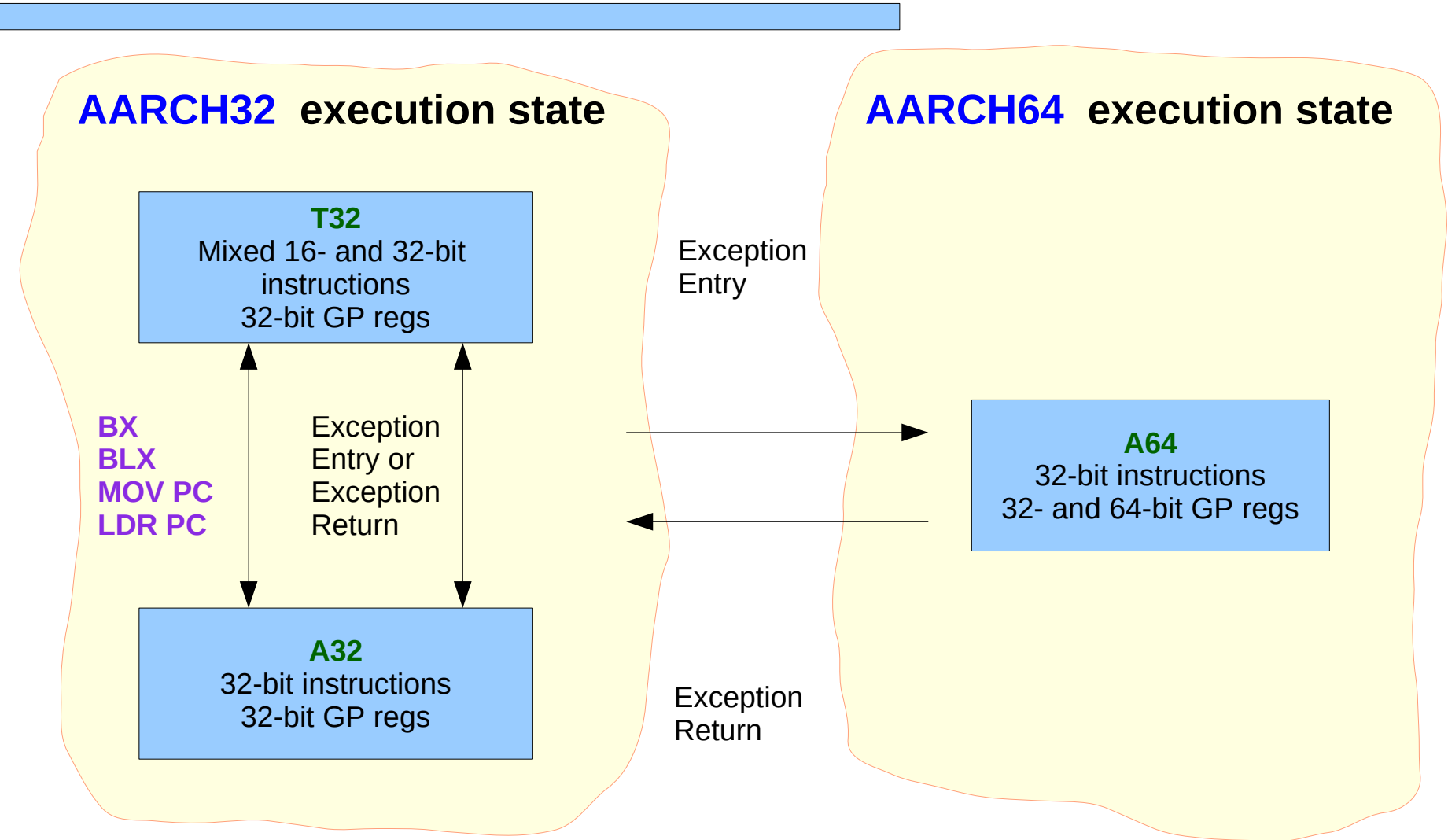
- Overview of **AArch64** in **ARMv8-A**
- The **A64** instruction set, defined in **AArch64**, has been designed from the ground up as a clean, modern instruction set which operates on 64-bit or 32-bit native datatypes or registers.
- **A64** is a fixed-length instruction set in which all instructions are 32 bits in length.
- It does, as you might expect, have many similarities with the **A32** instruction set which you'll be familiar with from earlier ARM architectures.
- There are some things you'll find which are new and some things which you'll go looking for and aren't there!

ARMv7-A
AArch32
ARM+Thumb ISAs

ARMv8-A
AArch32,
A32+T32 ISAs,
AArch64
A64 ISAs

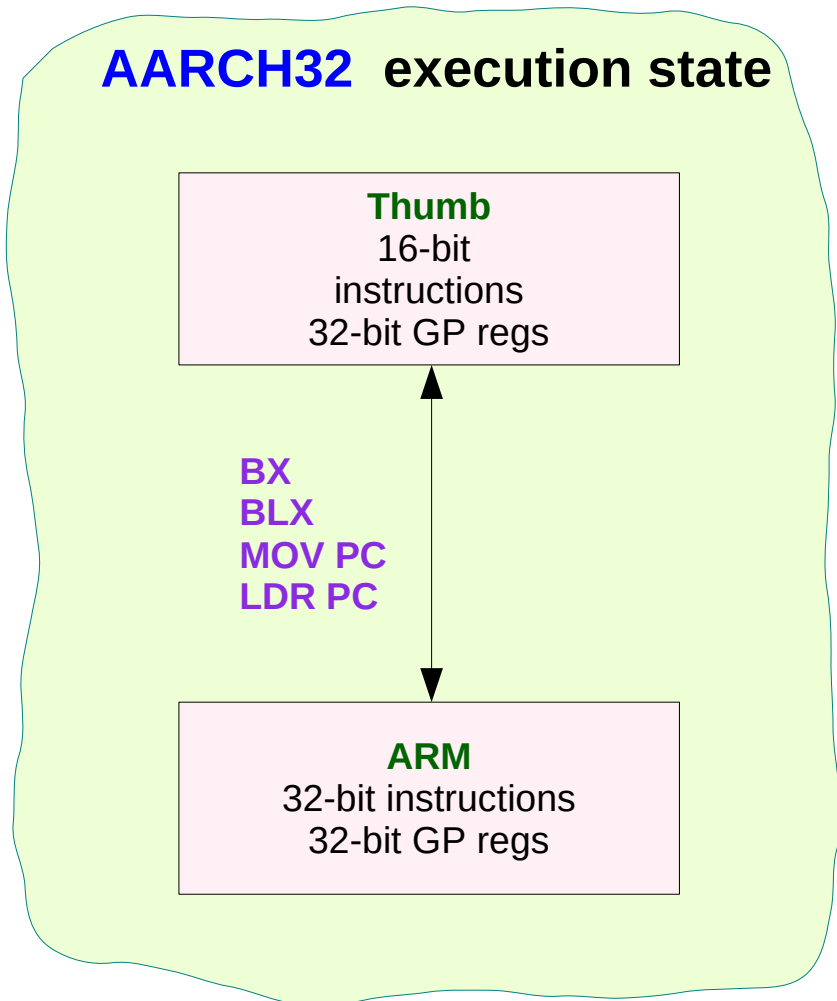
<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (4)



<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (5)

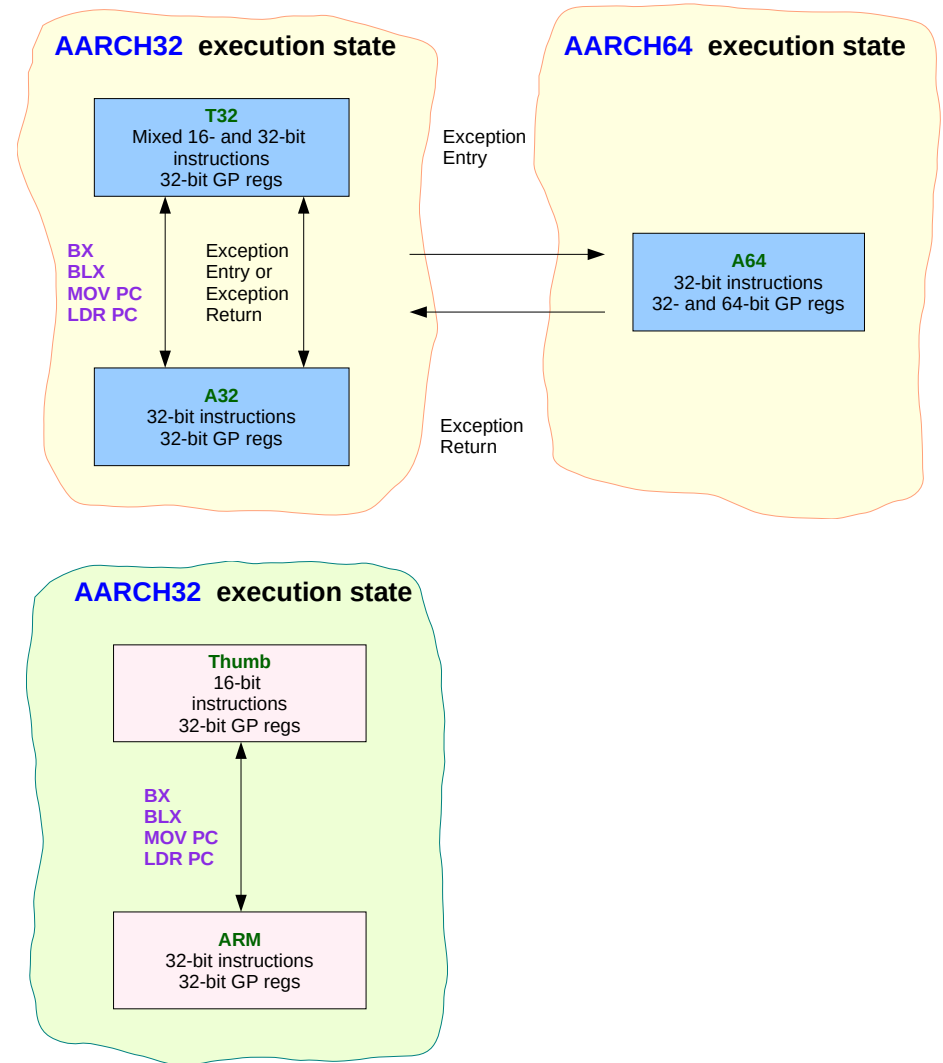


<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (6)

Changing Execution state and Instruction set

- A fully-populated **ARMv8-A** processor supports both **AArch32** and **AArch64** execution states.
- **Transition** between the two is always across an exception boundary.
- This differs from **ARMv7-A** in which a **change** of instruction set is triggered by an **interworking branch** (e.g. **BLX**).

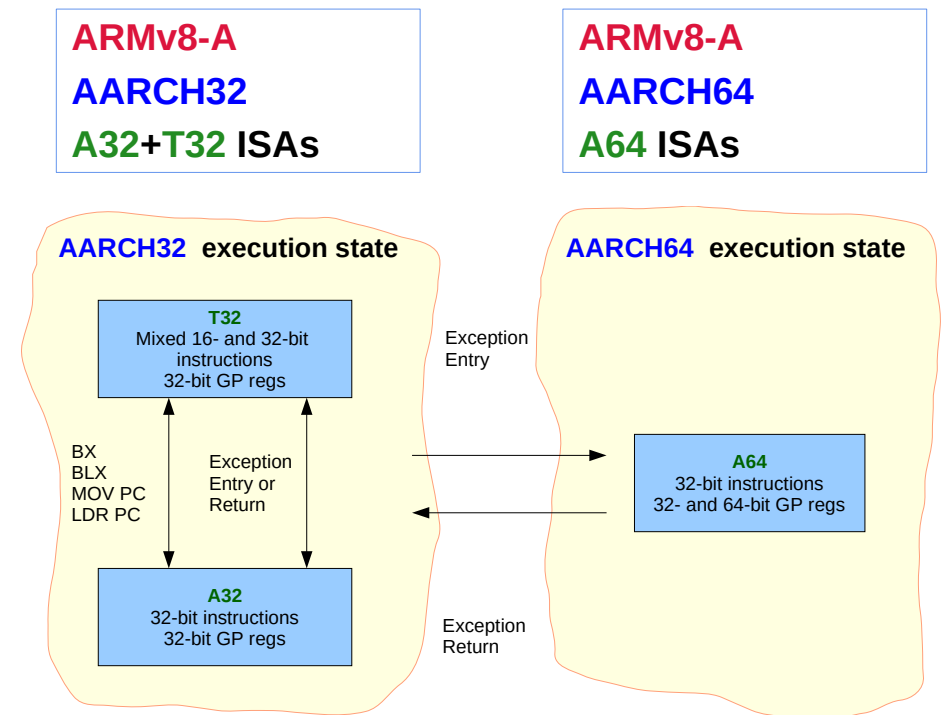


<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

64-bit processor (7)

Changing Execution state and Instruction set

- the relationship between the **T32**, **A32** and **A64** instruction sets and
- the events which can cause a switch between them.
- the execution state
 - can stay the same or
 - go from 32-bit to 64-bit
 - when taking an exception, or
 - when returning from an exception
- This introduces a natural hierarchy of 64-bit and 32-bit support at each level



<https://armkeil.blob.core.windows.net/developer/Files/pdf/graphics-and-multimedia/Porting%20to%20ARM%2064-bit.pdf>

References

- [1] http://wiki.osdev.org/ARM_RaspberryPi_Tutorial_C
- [2] <http://blog.bobuhiro11.net/2014/01-13-baremetal.html>
- [3] <http://www.valvers.com/open-software/raspberry-pi/>
- [4] <https://www.cl.cam.ac.uk/projects/raspberrypi/tutorials/os/downloads.html>