Agenda

- **Introduction**

  Architecture

  Programmers Model

  Instruction Set

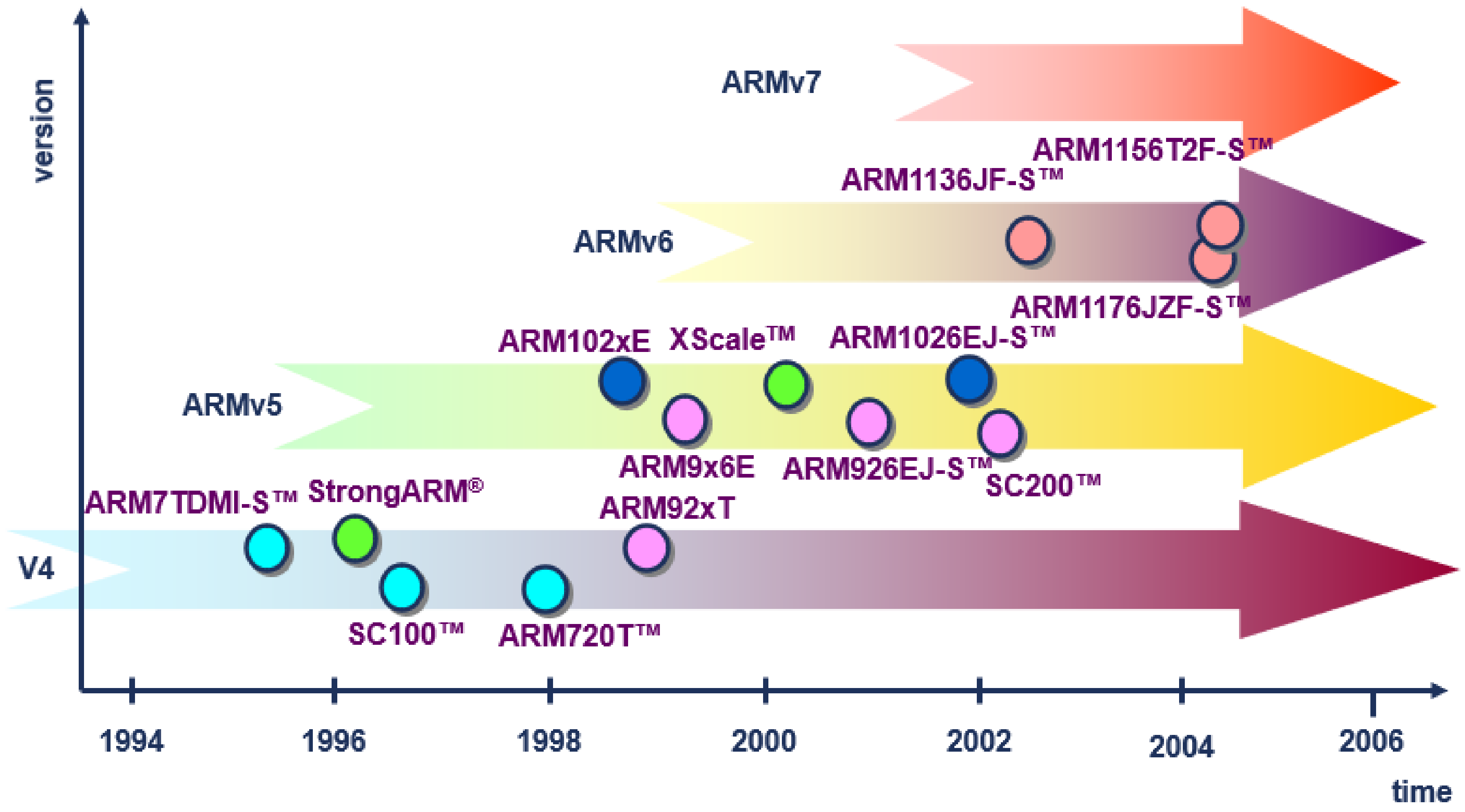
History of ARM

- **ARM (Acorn RISC Machine) started as a new, powerful, CPU design for the replacement of the 8-bit 6502 in Acorn Computers (**Cambridge, UK, 1985**)**
- **First models had only a 26-bit program counter, limiting the memory space to 64 MB (**not too much by today standards, but a lot at that time**).**
- **1990 spin-off: ARM renamed Advanced RISC Machines**
- **ARM now focuses on Embedded CPU cores**
  - IP licensing: Almost every silicon manufacturer sells some microcontroller with an ARM core. Some even compete with their own designs.
  - Processing power with low current consumption
    - Good MIPS/Watt figure
    - Ideal for portable devices
  - Compact memories: 16-bit opcodes (Thumb)
- **New cores with added features**
  - Harvard architecture (ARM9, ARM11, Cortex)
  - Floating point arithmetic
  - Vector computing (VFP, NEON)
  - Java language (Jazelle)

ARM®

Facts

- **32-bit CPU**
- **3-operand instructions (typical): ADD Rd,Rn,Operand2**
- **RISC design…**
  - Few, simple, instructions
  - Load/store architecture (instructions operate on registers, not memory)
  - Large register set
  - Pipelined execution
- **… And some very specific details**
  - No stack. Link register instead
  - PC as a regular register
  - Conditional execution of all instructions
  - Flags altered or not by data processing instructions (selectable)
  - Concurrent shifts/rotations (at the same time of other processing)
  - …


version
ARMv7
ARM1156T2F-S™
ARM1136JF-S™
ARMv6
ARM1176JZF-S™
ARM102xE
XScale™
ARM1026EJ-S™
ARMv5
ARM9x6E
ARM926EJ-S™
SC200™
ARM7TDMI-S™
StrongARM®
ARM92xT
V4
SC100™
ARM720T™
1994
1996
1998
2000
2002
2004
2006
time

ARM

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■ **Architecture**

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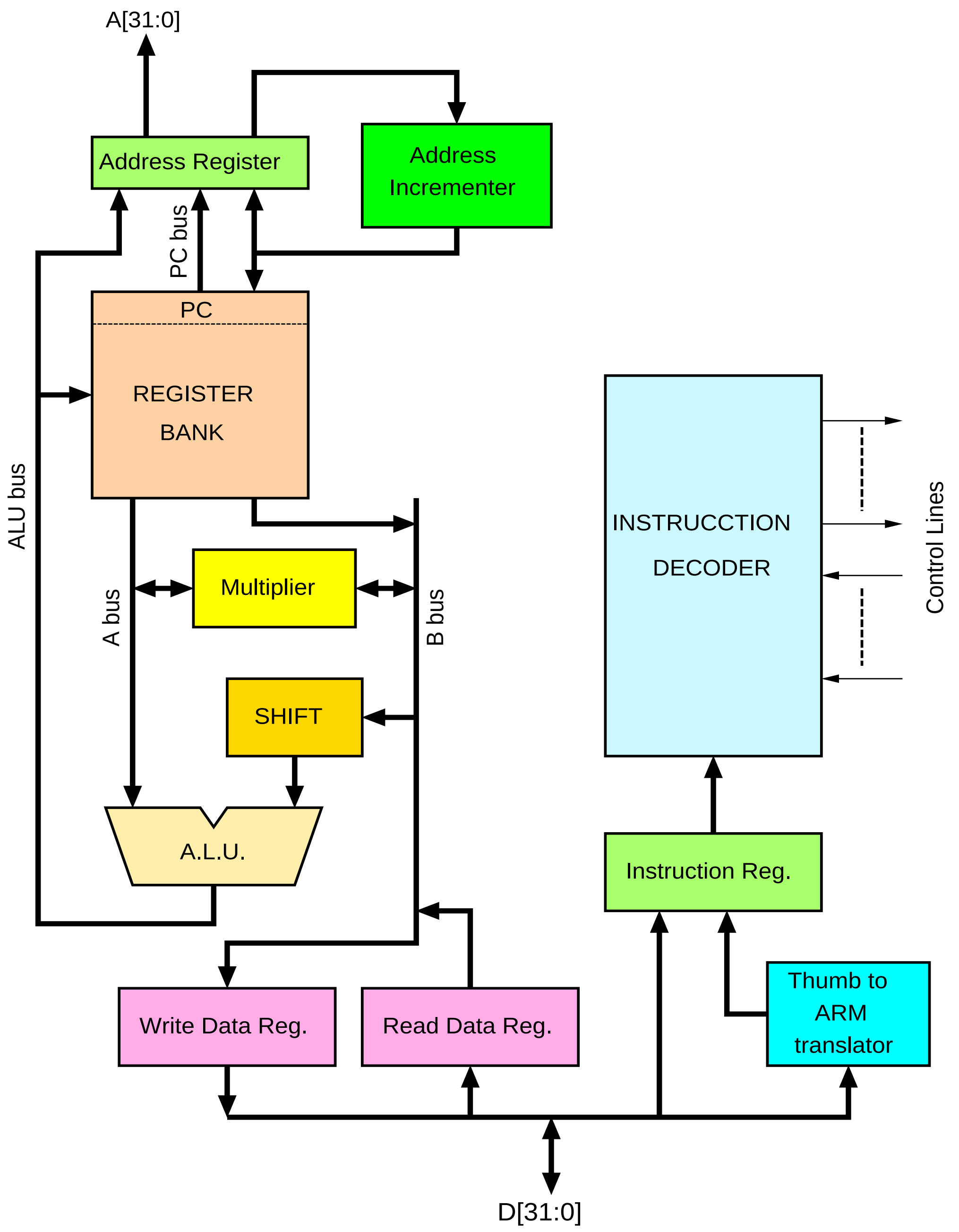
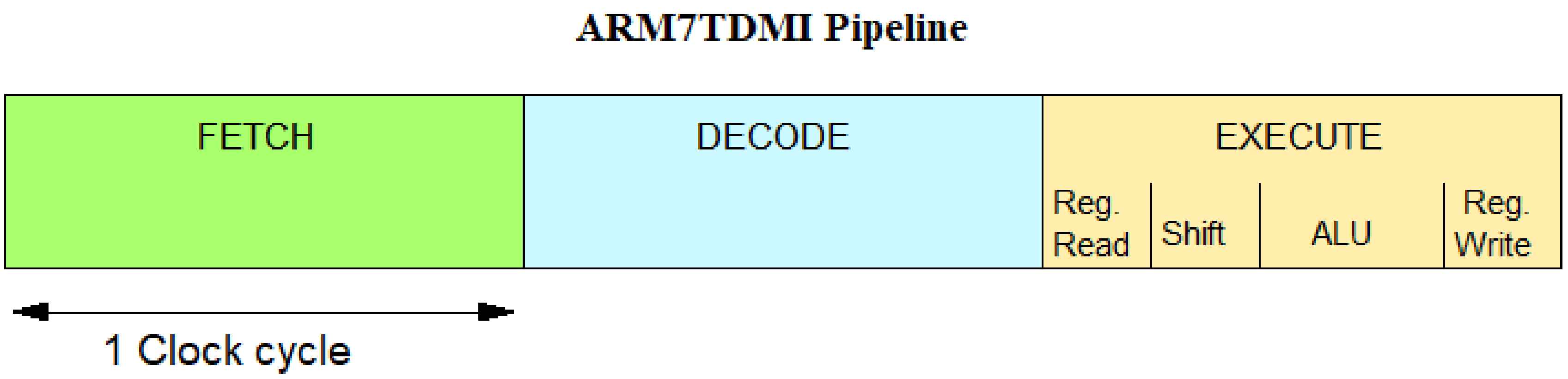
ARM7TDMI Block Diagram



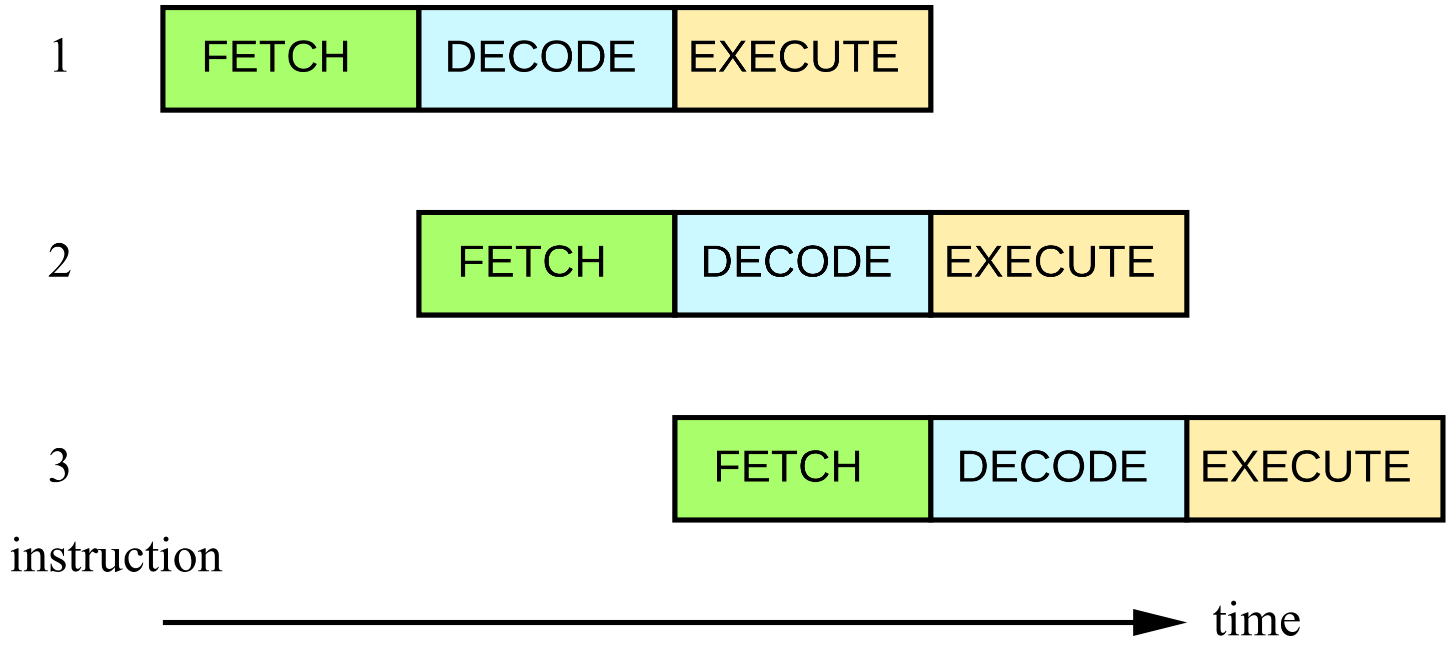
ARM Pipelining examples



- Fetch: Read Op-code from memory to internal Instruction Register
- Decode: Activate the appropriate control lines depending on Opcode
- Execute: Do the actual processing

ARM

ARM7TDMI Pipelining (I)



- Simple instructions (like ADD) Complete at a rate of one per cycle

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Data Sizes and Instruction Sets

- **The ARM is a 32-bit architecture.**

- **When used in relation to the ARM:**
  - **Byte** means 8 bits
  - **Halfword** means 16 bits (two bytes)
  - **Word** means 32 bits (four bytes)

- **Most ARM’s implement two instruction sets**
  - 32-bit **ARM** Instruction Set
  - 16-bit **Thumb** Instruction Set

ARM

Processor Modes

- **The ARM has seven operating modes:**
  - **User** : unprivileged mode under which most tasks run
  - **FIQ** : entered when a high priority (fast) interrupt is raised
  - **IRQ** : entered when a low priority (normal) interrupt is raised
  - **SVC** : (Supervisor) entered on reset and when a Software Interrupt instruction is executed
  - **Abort** : used to handle memory access violations
  - **Undef** : used to handle undefined instructions
  - **System** : privileged mode using the same registers as user mode

The Registers

- **ARM has 37 registers all of which are 32-bits long.**
  - 1 dedicated program counter
  - 1 dedicated current program status register
  - 5 dedicated saved program status registers
  - 30 general purpose registers

- **The current processor mode governs which of several banks is accessible. Each mode can access**
  - a particular set of r0-r12 registers
  - a particular r13 (the stack pointer, sp) and r14 (the link register, lr)
  - the program counter, r15 (pc)
  - the current program status register, cpsr

Privileged modes (except System) can also access

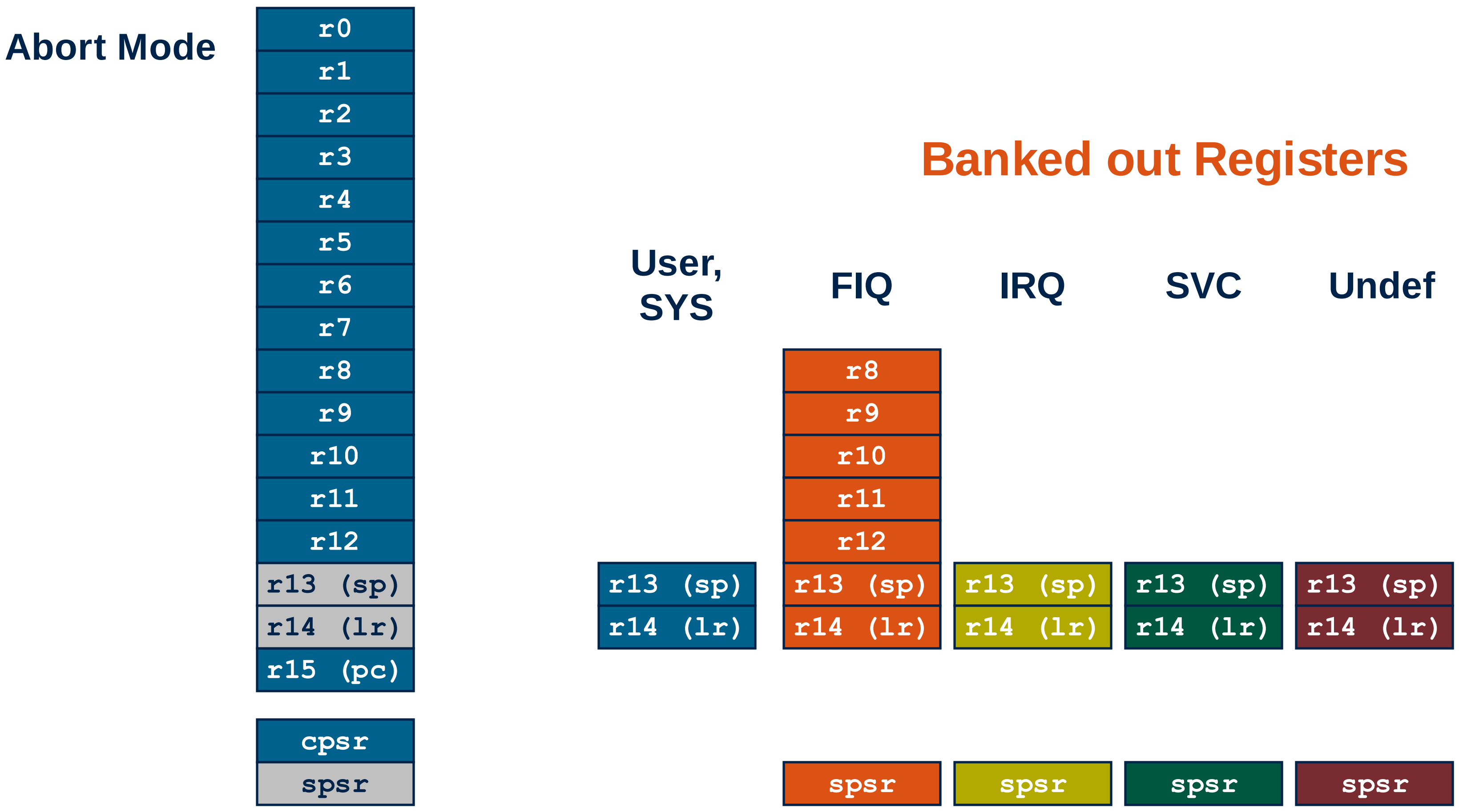
- a particular spsr (saved program status register)

ARM

The ARM Register Set

Current Visible Registers

Banked out Registers



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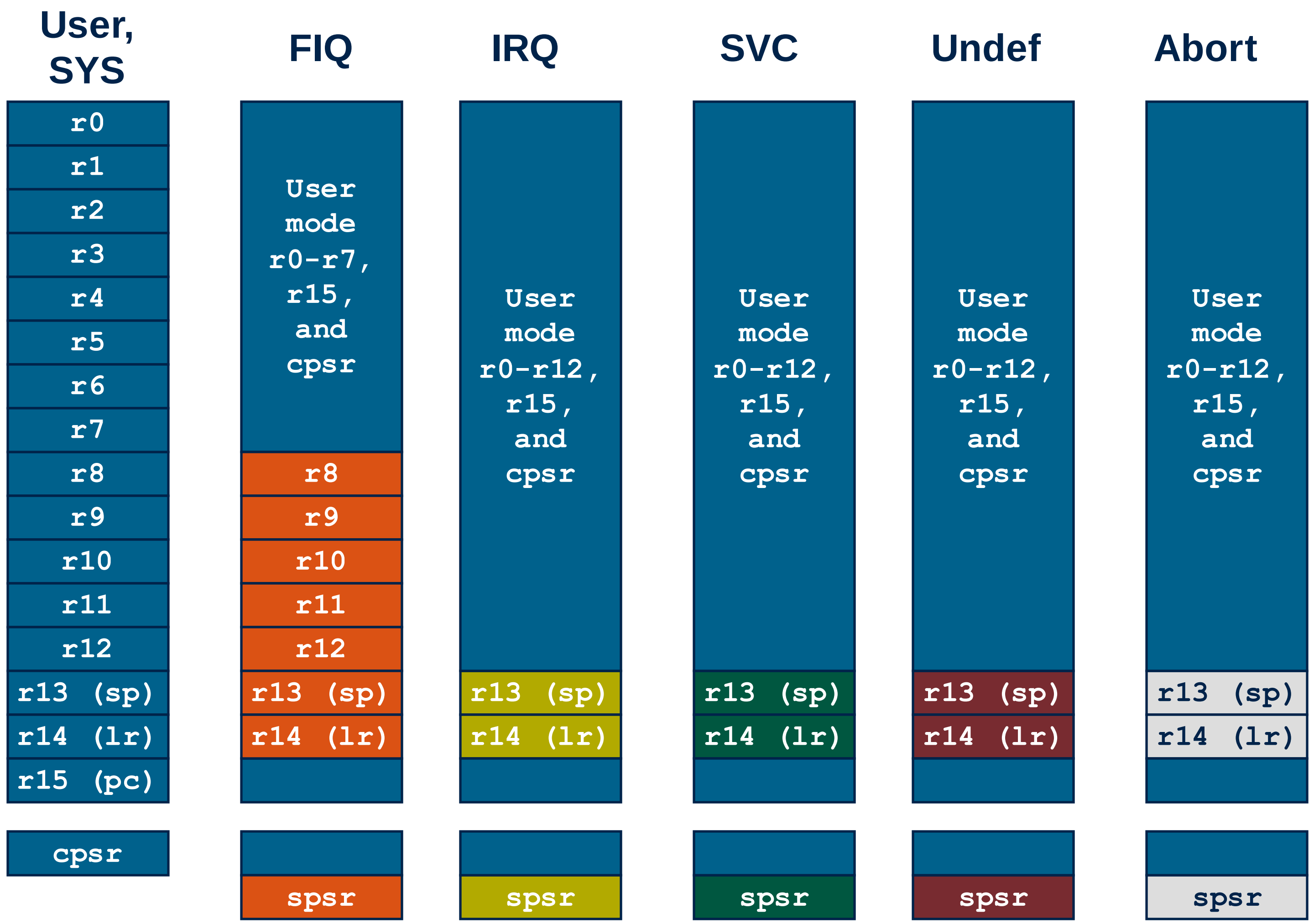
Special Registers

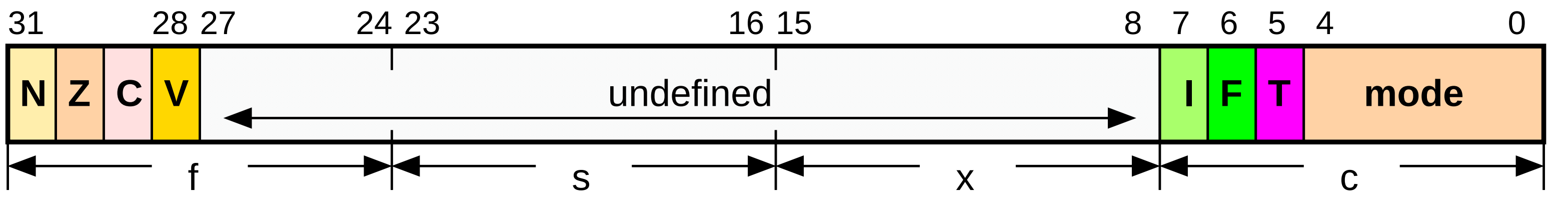
- **Special function registers:**
  - **PC** (R15): Program Counter. Any instruction with PC as its destination register is a program branch
  - **LR** (R14): Link Register. Saves a copy of PC when executing the BL instruction (subroutine call) or when jumping to an exception or interrupt routine
    - It is copied back to PC on the return from those routines
  - **SP** (R13): Stack Pointer. There is **no stack** in the ARM architecture. Even so, R13 is usually reserved as a pointer for the program-managed stack
  - **CPSR** : Current Program Status Register. Holds the visible status register
  - **SPSR** : Saved Program Status Register. Holds a copy of the previous status register while executing exception or interrupt routines
    - It is copied back to CPSR on the return from the exception or interrupt
    - No SPSR available in User or System modes

Register Organization Summary



Note: System mode uses the User mode register set

Program Status Registers



- **Condition code flags**
  - N = **N**egative result from ALU
  - Z = **Z**ero result from ALU
  - C = ALU operation **C**arried out
  - V = ALU operation o**V**erflowed

- **Mode bits**

10000	**User**
10001	**FIQ**
10010	**IRQ**
10011	**Supervisor**
10111	**Abort**
11011	**Undefined**
11111	**System**

Interrupt Disable bits.

I = 1: Disables the IRQ.

F = 1: Disables the FIQ.

T Bit **(Arch. with Thumb mode only)**

T = 0: Processor in ARM state

T = 1: Processor in Thumb state

Never change T directly (use BX instead)

Changing T in CPSR will lead to unexpected behavior due to pipelining

Tip: Don't change undefined bits.

This allows for code compatibility with newer ARM processors

Program Counter (R15)

- **When the processor is executing in ARM state:**
  - All instructions are 32 bits wide
  - All instructions must be word aligned
  - Therefore the PC value is stored in bits [31:2] and bits [1:0] are zero
  - Due to pipelining, the PC points 8 bytes ahead of the current instruction, or 12 bytes ahead if current instruction includes a register-specified shift

- **When the processor is executing in Thumb state:**
  - All instructions are 16 bits wide
  - All instructions must be halfword aligned
  - Therefore the PC value is stored in bits [31:1] and bit [0] is zero

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Introduction

Architecture

Programmers Model

- **Instruction Set (for ARM state)**

Conditional Execution and Flags

- **ARM instructions can be made to execute conditionally by postfixing them with the appropriate condition code field.**
  - This improves code density *and* performance by reducing the number of forward branch instructions.

```
  CMP    r3,#0
   BEQ    skip
   ADD    r0,r1,r2
skip
```

```
CMP    r3,#0
 ADDNE r0,r1,r2
```

- **By default, data processing instructions do not affect the condition code flags but the flags can be optionally set by using "S" (comparisons always set the flags).**

```
loop
   …
   SUBS r1,r1,#1
   BNE  loop
```

decrement r1 and set flags

if Z flag clear then branch

ARM

Condition Codes

- **The 15 possible condition codes are listed below:**
  - Note AL is the default and does not need to be specified

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	N=1
`PL`	Positive or Zero	N=0
`VS`	Overflow	V=1
`VC`	No overflow	V=0
`HI`	Unsigned higher	C=1 & Z=0
`LS`	Unsigned lower or same	C=0 or Z=1
`GE`	Greater or equal	N=V
`LT`	Less than	N!=V
`GT`	Greater than	Z=0 & N=V
`LE`	Less than or equal	Z=1 or N=!V
`AL`	Always	

ARM

Advantages of conditional execution

C source code

```
if (r0 == 0)
{
  r1 = r1 + 1;
}
else
{
  r2 = r2 + 1;
}
```

ARM instructions

unconditional

```
    CMP r0, #0
    BNE else
    ADD r1, r1, #1
    B end
else
    ADD r2, r2, #1
end
    ...
```

- 5 instructions
- 5 words
- 5 or 6 cycles

conditional

```
    CMP r0, #0
    ADDEQ r1, r1, #1
    ADDNE r2, r2, #1
    ...
```

- 3 instructions
- 3 words
- 3 cycles

ARM

Examples of conditional execution

- Use a sequence of several conditional instructions

```
if (a==0) func(1);
    CMP       r0,#0
    MOVEQ     r0,#1
    BLEQ      func
```

- Set the flags, then use various condition codes

```
if (a==0) x=0;
if (a>0)  x=1;
    CMP       r0,#0
    MOVEQ     r1,#0
    MOVGT     r1,#1
```

- Use conditional compare instructions

```
if (a==4 || a==10) x=0;
    CMP       r0,#4
    CMPEQ     r0,#10
    MOVEQ     r1,#0
```

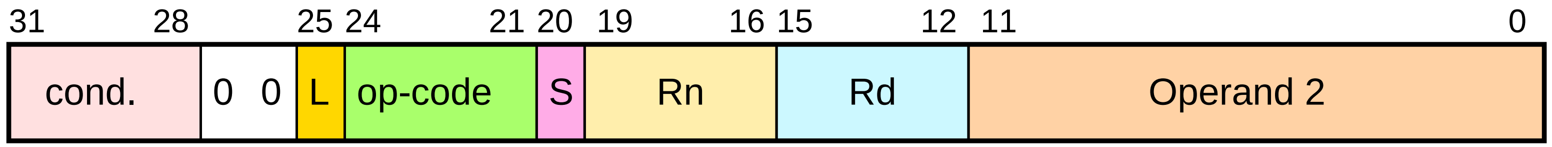
ARM

Data processing Instructions

- **Consist of :**

Arithmetic:	`ADD`	`ADC`	`SUB`	`SBC`	`RSB`	`RSC`
Logical:	`AND`	`ORR`	`EOR`	`BIC`		
Comparisons:	`CMP`	`CMN`	`TST`	`TEQ`		
Data movement:	`MOV`	`MVN`				

- **These instructions only work on registers, NOT memory.**



L, Literal: 0: Operand 2 from register, 1: Operand 2 immediate

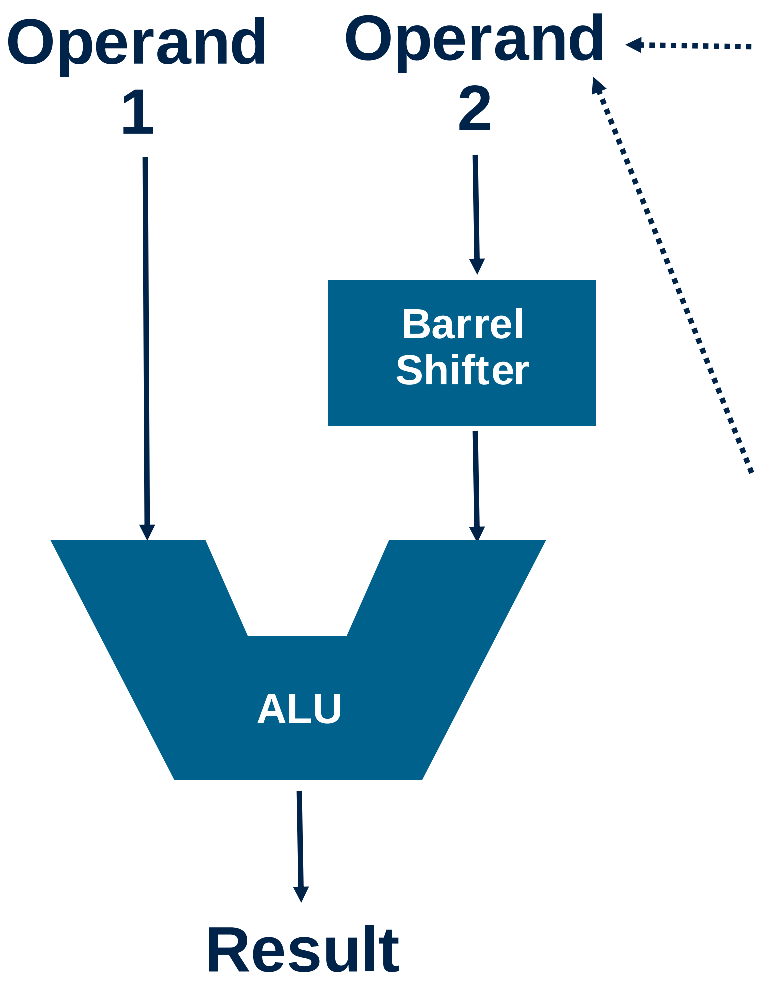
- **Syntax:**

`<Operation>{<cond>}{S} Rd, Rn, Operand2`

  - {S} means that the Status register is going to be updated
  - Comparisons always update the status register. Rd is not specified
  - Data movement does not specify Rn

- **Second operand is sent to the ALU via barrel shifter.**

Using the Barrel Shifter: The Second Operand



Register, optionally with shift operation

- Shift value can be either be:
  - 5 bit unsigned integer
  - Specified in bottom byte of another register.
- Used for multiplication by a power of 2

Example: ADD R1, R2, R3, LSL #2

(R2 + R3*4) -> R1

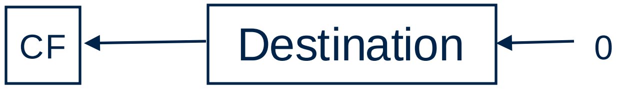
Immediate value

- 8 bit number, with a range of 0-255.
  - Rotated right through even number of positions
- Allows increased range of 32-bit constants to be loaded directly into registers

ARM

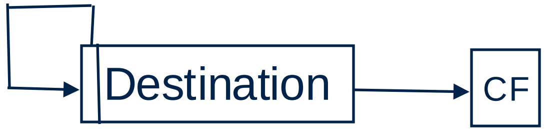
The Barrel Shifter

LSL : Logical Left Shift



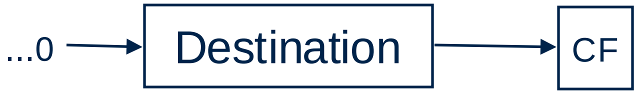
Multiplication by a power of 2

ASR: Arithmetic Right Shift



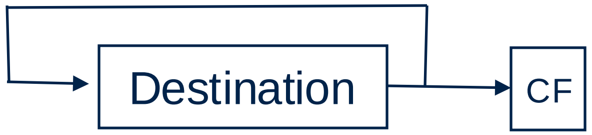
Division by a power of 2, preserving the sign bit

LSR : Logical Shift Right



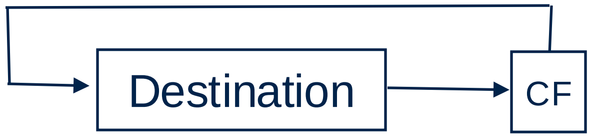
Division by a power of 2

ROR: Rotate Right



Bit rotate with wrap around from LSB to MSB

RRX: Rotate Right Extended



Single bit rotate with wrap around from CF to MSB

ARM

Loading 32 bit constants

- **To allow larger constants to be loaded, the assembler offers a pseudo-instruction:**
  - `LDR rd, =const` (notice the “=“ sign)
- **This will either:**
  - Produce a **`MOV`** or **`MVN`** instruction to generate the value (if possible).

or

  - Generate a **`LDR`** instruction with a PC-relative address to read the constant from a *literal pool* (Constant data area embedded in the code).
- **For example**

```
LDR r0,=0xFF           =>      MOV r0,#0xFF
LDR r0,=0x55555555     =>      LDR r0,[PC,#Imm12]
                               ...
                               ...
                               DCD 0x55555555
```

- **This is the recommended way of loading constants into a register**

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Data processing instr. FLAGS

- **Flags are changed only if the S bit of the op-code is set:**

  Mnemonics ending with "**s**", like "movs", and comparisons: **cmp**, **cmn**, **tst**, **teq**
- **N and Z have the expected meaning for all instructions**
  - **N**: bit 31 (sign) of the result
  - **Z**: set if result is zero
- **Logical instructions (AND, EOR, TST, TEQ, ORR, MOV, BIC, MVN)**
  - **V**: unchanged
  - **C**: from **barrel shifter** if shift ≠ 0. Unchanged otherwise
- **Arithmetic instructions (SUB, RSB, ADD, ADC, SBC, RSC, CMP, CMN)**
  - **V**: Signed overflow from **ALU**
  - **C**: Carry (bit 32 of result) from **ALU**
- **When PC is the destination register** (exception return)
  - CPSR is copied from SPSR. This includes all the flags.
  - No change in **user** or **system** modes

  Example:

```
SUBS    PC,LR,#4    @ return from IRQ
```

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Arithmetic Operations

Operations are:

ADD	operand1 + operand2
ADC	operand1 + operand2 + carry
SUB	operand1 - operand2
SBC	operand1 - operand2 + carry -1
RSB	operand2 - operand1
RSC	operand2 - operand1 + carry - 1

Syntax:

```
<Operation>{<cond>}{S} Rd, Rn, Operand2
```

Examples

```
ADD r0, r1, r2
SUBGT r3, r3, #1
RSBLES r4, r5, #5
```

ARM

Comparisons

The only effect of the comparisons is to

UPDATE THE CONDITION FLAGS. Thus no need to set S bit.

Operations are:

CMP	operand1 - operand2, but result not written
CMN	operand1 + operand2, but result not written
TST	operand1 AND operand2, but result not written
TEQ	operand1 EOR operand2, but result not written

Syntax:

```
<Operation>{<cond>} Rn, Operand2
```

Examples:

```
CMP     r0, r1
TSTEQ   r2, #5
```

Logical Operations

Operations are:

AND	operand1 AND operand2
EOR	operand1 EOR operand2
ORR	operand1 OR operand2
BIC	operand1 AND NOT operand2 [ie bit clear]

Syntax:

```
<Operation>{<cond>}{S} Rd, Rn, Operand2
```

Examples:

```
AND     r0, r1, r2
BICEQ   r2, r3, #7
EORS    r1,r3,r0
```

Data Movement

Operations are:

MOV	operand2
MVN	NOT operand2

Note that these make no use of operand1.

Syntax:

<Operation>{<cond>}{S} Rd, Operand2

Examples:

```
MOV    r0, r1
MOVS   r2, #10
MVNEQ  r1,#0
```

ARM

Multiply

- **Syntax:**

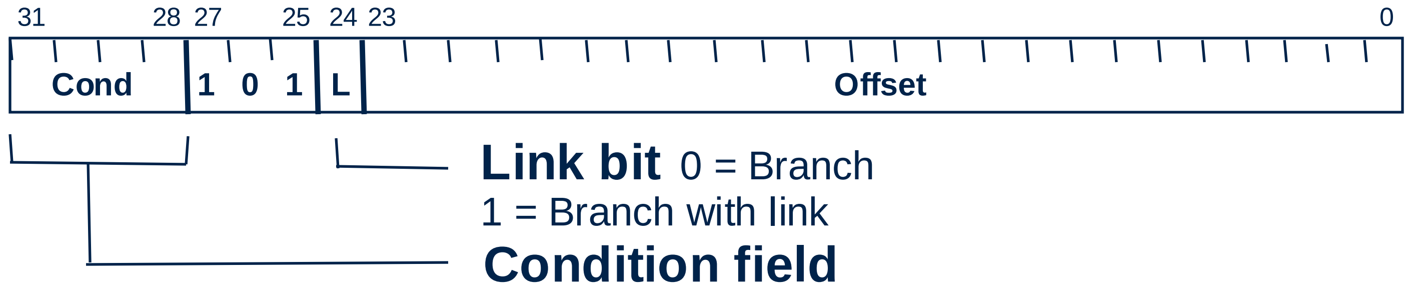
MUL{<cond>}{S} Rd, Rm, Rs	Rd = Rm * Rs
MLA{<cond>}{S} Rd,Rm,Rs,Rn	Rd = (Rm * Rs) + Rn
[U|S]MULL{<cond>}{S} RdLo, RdHi, Rm, Rs	RdHi,RdLo := Rm*Rs
[U|S]MLAL{<cond>}{S} RdLo, RdHi, Rm, Rs	RdHi,RdLo:=(Rm*Rs)+RdHi,RdLo

- **Cycle time**
  - Basic MUL instruction
    - 2-5 cycles on ARM7TDMI
    - 1-3 cycles on StrongARM/XScale
    - 2 cycles on ARM9E/ARM102xE
  - +1 cycle for ARM9TDMI (over ARM7TDMI)
  - +1 cycle for accumulate (not on 9E though result delay is one cycle longer)
  - +1 cycle for “long”

- **Above are “general rules” - refer to the TRM for the core you are using for the exact details**

Branch instructions

- **Branch :** `B{<cond>} label`
- **Branch with Link :** `BL{<cond>} subroutine_label`



- **The processor core shifts the offset field left by 2 positions, sign-extends it and adds it to the PC**
  - ± 32 Mbyte range
  - How to perform longer branches or absolute address branches?

    solution: LDR PC,…

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Single register data transfer

`LDR`	`STR`	Word
`LDRB`	`STRB`	Byte
`LDRH`	`STRH`	Halfword
`LDRSB`		Signed byte load
`LDRSH`		Signed halfword load

- **Memory system must support all access sizes**

- **Syntax:**
  - `LDR`{<cond>}{<size>} Rd, <address>
  - `STR`{<cond>}{<size>} <address>, Rn

  e.g. `LDREQB`

ARM

Address accessed

- **Address accessed by LDR/STR is specified by a base register plus an offset**
- **For word and unsigned byte accesses, offset can be**
  - An unsigned 12-bit immediate value (ie 0 - 4095 bytes).

```
LDR r0,[r1,#8]
```

  - A register, optionally shifted by an immediate value

```
LDR r0,[r1,r2]
LDR r0,[r1,r2,LSL#2]
```

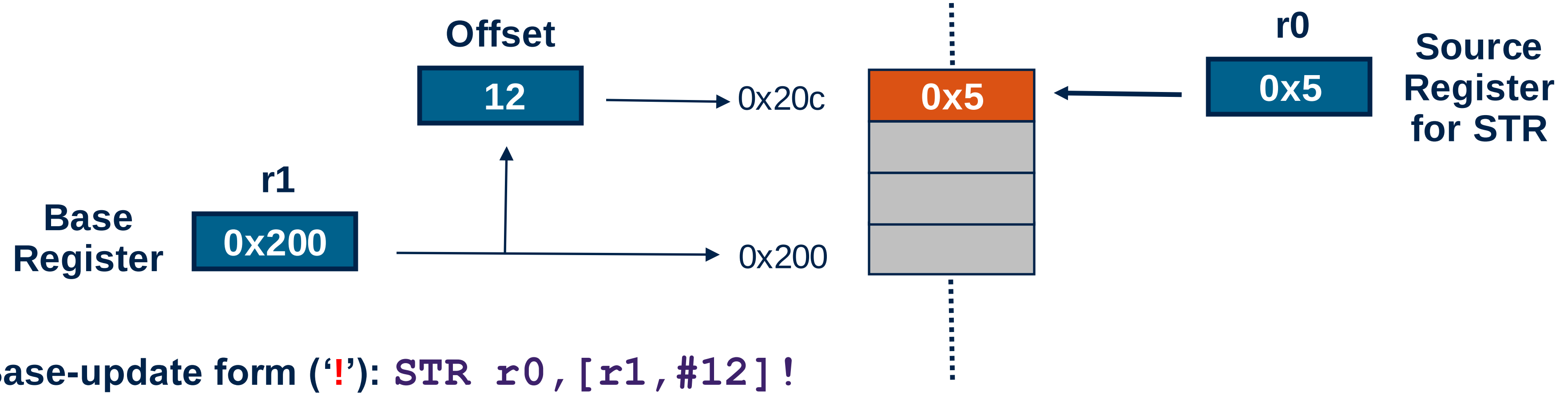
- **This can be either added or subtracted from the base register:**

```
LDR r0,[r1,#-8]
LDR r0,[r1,-r2]
LDR r0,[r1,-r2,LSL#2]
```

- **For halfword and signed halfword / byte, offset can be:**
  - An unsigned 8 bit immediate value (ie 0-255 bytes).
  - A register (unshifted).
- **Choice of *pre-indexed* or *post-indexed* addressing**

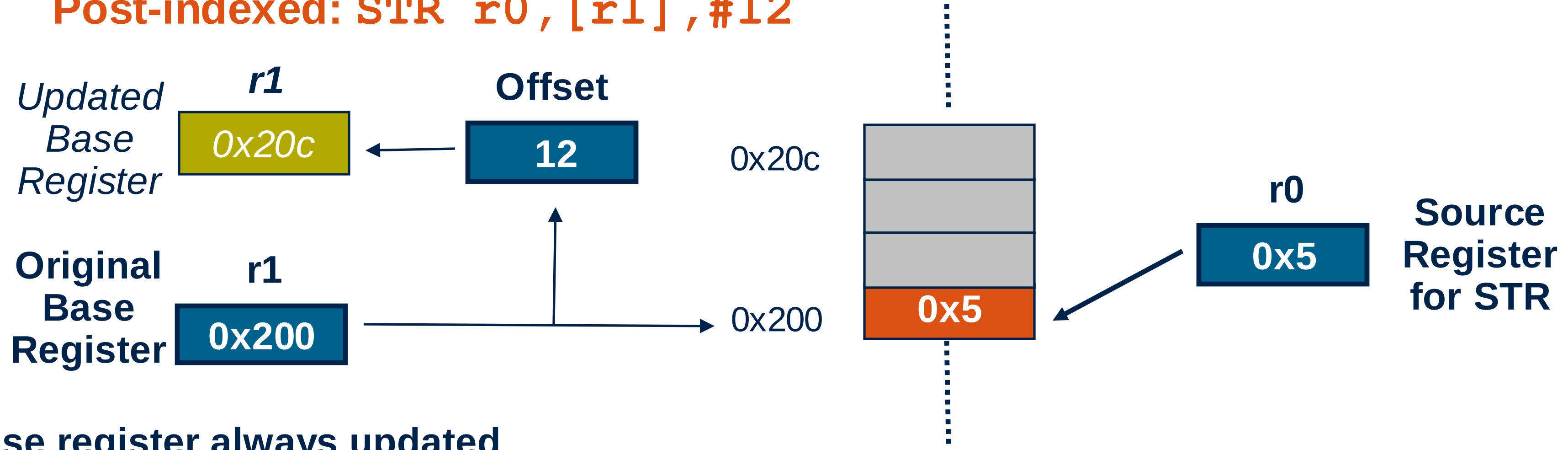
Pre or Post Indexed Addressing?

- **Pre-indexed: `STR r0,[r1,#12]`**



Base-update form ('!'): `STR r0,[r1,#12]!`

- **Post-indexed: `STR r0,[r1],#12`**



Base register always updated

ARM

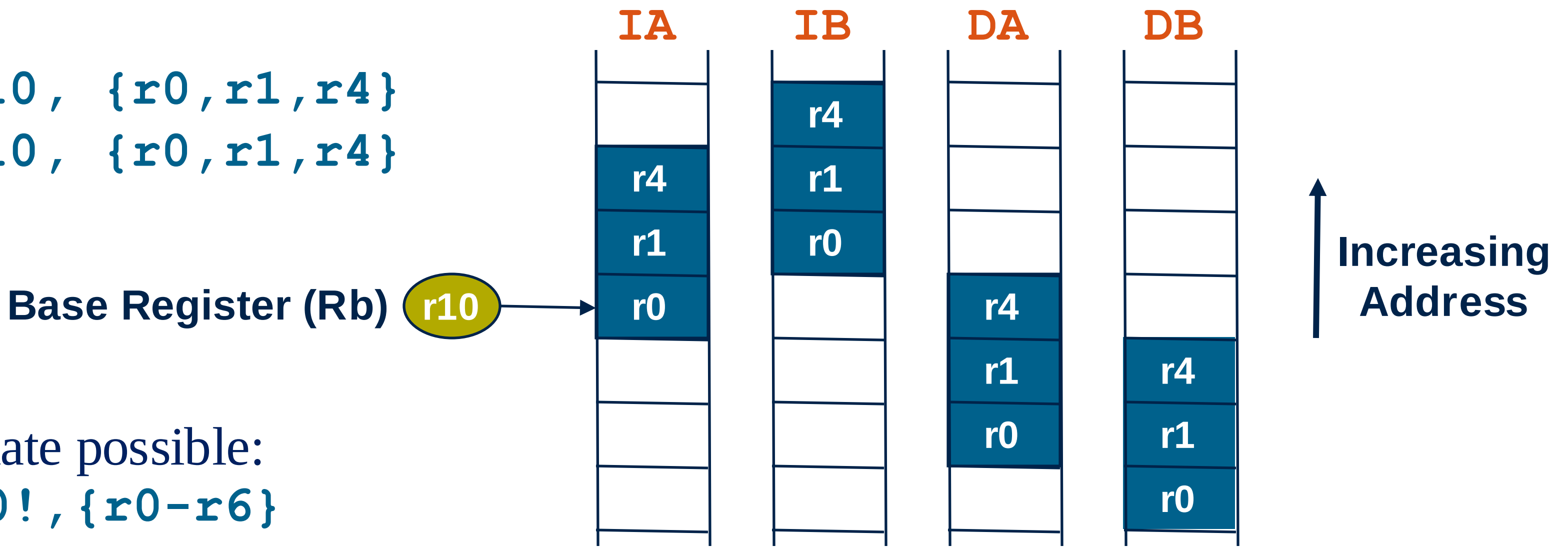
LDM / STM operation

- **Load/Store Multiple Syntax:**
  `<LDM|STM>`{<cond>}<addressing_mode> Rb{!}, <register list>

- **4 addressing modes:**

`LDMIA` / `STMIA`	increment after
`LDMIB` / `STMIB`	increment before
`LDMDA` / `STMDA`	decrement after
`LDMDB` / `STMDB`	decrement before

```
LDMxx r10, {r0,r1,r4}
STMxx r10, {r0,r1,r4}
```



Base-update possible:
`LDM r10!,{r0-r6}`