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Chapter 4

Addressing Modes

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Addressing Modes

Introduction to Assembly Programming and Addressing Modes

Learning Objectives (4.1)

1. Identify why and when to use assembly language programming.
2. Describe what are addressing modes.

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What is an Assembly Program?

- Unlike high-level programming languages, assembly level statements:
  - Are known as **mnemonics**. Each has a one-to-one correspondence with a binary pattern (**machine code**) that is directly understood by CPU.
  - Are **hardware-dependent** and address the architecture of processor directly. (e.g. they are CPU register-aware and reference them by name).
  - Are converted to machine code by an **assembler**.

```
if (a > c)
  b = a;
else
  b = c;
```

C program example

```
      CMP R0,R2
      BLE Else
      MOV R1,R0 ;b=a
      B   Skip
Else  MOV R1,R2 ;b=c
Skip  :
```

ARM assembly program equivalent

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Why Use Assembly Language?

- More efficient codes can be created:
  - Codes with faster execution **speed**.
    e.g. Algorithms for **real-time** signal processing in handheld devices can be **computationally demanding**.
  - More compact program **size**.
    e.g. Low cost embedded devices may have **small memory** capacity but require many functionalities.
  - Exploit **optimized features** of processor's ISA.
    e.g. High-level language compiled codes may not **exploit optimized** instructions, addressing modes and features available in the processor instruction set architecture to produce efficient run-time code.
  - Many cybersecurity jobs needs good knowledge in assembly programming.

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When to Use Assembly Language?

- Critical parts of the operating system's software.
  Especially parts of system kernel that are constantly being executed (e.g. scheduler, interrupt handlers).
- Input/Output intensive codes.
  Device drivers and "loopy" segments of code that processes streaming data (e.g. video decoders, etc).
- Time-critical codes.
  Code that detect incoming sensor signals and respond rapidly, e.g. Anti-lock brake system (ABS) in cars.

Learn More: Google "Is Linux kernel written in assembly"

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Addressing Modes

- Addressing mode (AM) is concerned with how data is **accessed**, not the way data is processed.
  - The correct AM allows the CPU to identify the actual operand or the address location where operand is stored.
- The ARM processor instruction set architecture supports many different addressing modes.
  - Register direct
  - Immediate data
  - Register indirect
  - Register indirect with offset
  - Register indirect with index register
  - Pre and post auto-indexing

Learn More: Google "addressing modes"

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Addressing Mode Examples

Addressing Mode	ARM	Intel
Absolute (Direct)	None	`MOV AX,[1000h]`
Register Direct	`MOV R1,R0`	`MOV AX,DX`
Immediate	`MOV R1,#3`	`MOV AX,0003h`
Register Indirect	`LDR R1,[R0]`	`MOV AX,[BX]`
Register Indirect with Offset	`LDR R1,[R0,#4]`	`MOV AX,[BX+4]`
Register Indirect with Index	`LDR R1,[R0,R2]`	`MOV AH,[BX+DI]`
Implied	`BNE LOOP`	`JMP -8`

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Summary

- Codes written well in assembly language can usually execute **faster** and are smaller in **size**.
- Code for **low-level** OS kernels, **I/O** intensive and **time**-critical operations can benefit significantly from assembly-level coding.
- Understanding the **characteristics** and **application** of different **addressing modes** available in a processor's ISA allows programmers to write efficient codes.

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Chapter 4

Addressing Modes

Register Direct and Immediate Addressing

Learning Objectives (4.2)

1. Describe what is register direct.
2. Describe what is immediate data and its application.

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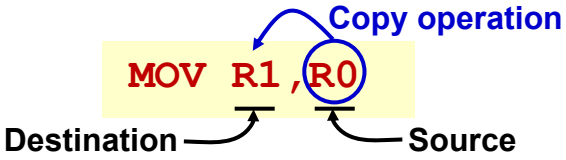
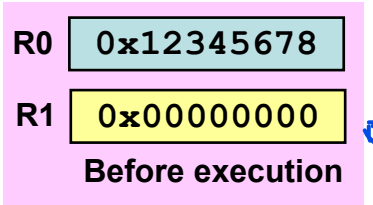
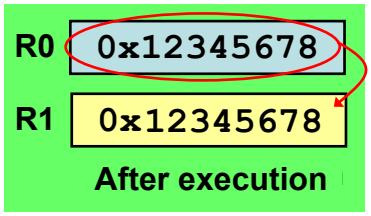
Register Direct

- Operand is the content of the specified **register**.
  - Register direct can be used for both destination and source operand.
  - In the `MOV` instruction, the right operand is the source and left operand is the destination.







  - A **fast** addressing mode since no further memory access is involved during execution.
  - Should be used to optimise execution speed.

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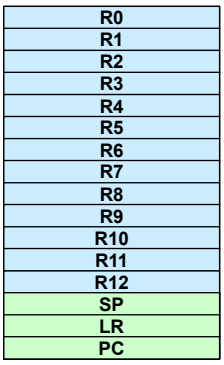
Register Direct (cont)

- All ARM's 16 registers can be a register direct operand.
  - These registers can be either a source or destination operand.

```
MOV   R3,LR  ;make copy of LR in R3
MOVS  R0,R0  ;test for N or Z condition in R0
MOV   PC,R1  ;make a jump to address in R1
```



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Immediate Addresing

- **Operand** is directly specified **within** the **instruction** itself.
  - "**#**" symbol precedes the immediate value.
  - Example: `MOV R1,#3` ← Immediate Value
    Copy operation
  - After execution, the **immediate value** is **copied** into the destination register (left operand).
  - Immediate addressing can only be used as a **source operand**.
  - Used for loading **constant values** into registers. Values must be known at the time of coding (e.g. load loop count into a loop counter register).

R1 0x12345678
Before execution

R1 0x00000003
After execution

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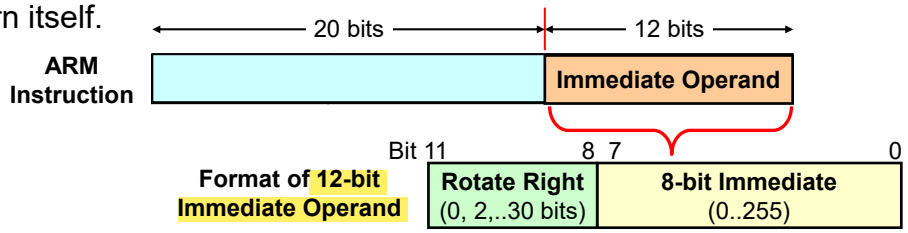
Immediate Addressing (cont)

- How is the 32-bit immediate value encoded?
  - The immediate value is specified **within the instruction** bit pattern itself.



- How can a 12-bit operand encode a 32-bit immediate value?
  - It can only describe a **subset** of all 2^{32} possible values.
  - Immediate value is a number between (**0..255**) rotated right by **2*n*** bits, where the value of ***n*** is given by 4 bits (**0 ≤ *n* ≤ 15**).

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LDR requires a bracket on the second register

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Immediate Addressing (cont)

- Assembler does the necessary calculations and gives warning if requested immediate value cannot be encoded.

```
MOV R3,#0xFF    ;immediate values within 8 bits always valid
MOV R0,#0x100   ;right rotate 8-bit value of 0x01 with n=12
MOV R1,#0x102   ;this is not a valid immediate value
```

- A combination of instructions can be used to achieved the desired immediate values that is not valid.

```
MOV R1,#0x100 ; load 0x100 to R1
ADD R1,R1,#2  ; add 2 to R1
```


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count the number of bits btw the first '1' and the last '1' and see if can divide by 2

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Summary

- Register direct is **efficient** as its execution involves no access to memory.
- Immediate addressing encode the operand **within the instruction**.
  - Like register direct, immediate addressing in the ARM is **efficient** as memory access is not incurred during execution, only when fetching the instruction.
  - Because data is encoded within fixed-length instruction, **only a subset** of immediate values are available.
- Immediate addressing is used when the operand **value is known** during the time of coding (e.g. loading known constants into registers).

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Chapter 4

Addressing Modes

Register Indirect with Base Register

Learning Objectives (4.3)

1. Describe what is register indirect and the ARM instructions that support this addressing mode.
2. Describe the variants and application of register indirect that uses base plus offset and index register.
3. Compare the relative pros and cons of register direct and register indirect addressing modes.

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Limitation of Register Direct and Immediate Addressing

- Register direct and immediate addressing **do not** allow CPU to access operands stored in **memory**.
  - C variables are usually allocated memory for storage (especially large arrays).
- How do you specific a 32-bit address in memory using a 32-bit long instruction?
  - The ARM specifies the 32-bit address of the operand in a 32-bit **register**.
  - The register with the memory address **points to the memory** location where the operand is stored.
  - Memory operand is fetched during instruction execution using **register indirect** addressing.
  - The ARM uses the `LDR` and `STR` mnemonics to access memory operands.

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load store

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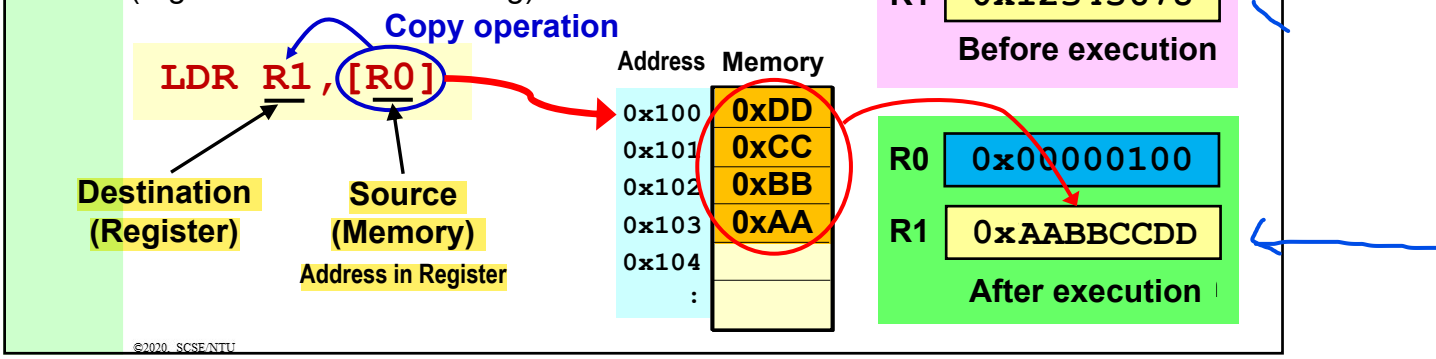
The LDR Instruction

- The LDR operator is used to copy **memory** content to a register.
  - The left operand the destination register.
  - The right source operand is a memory location whose address is contained in a register (register indirect addressing).



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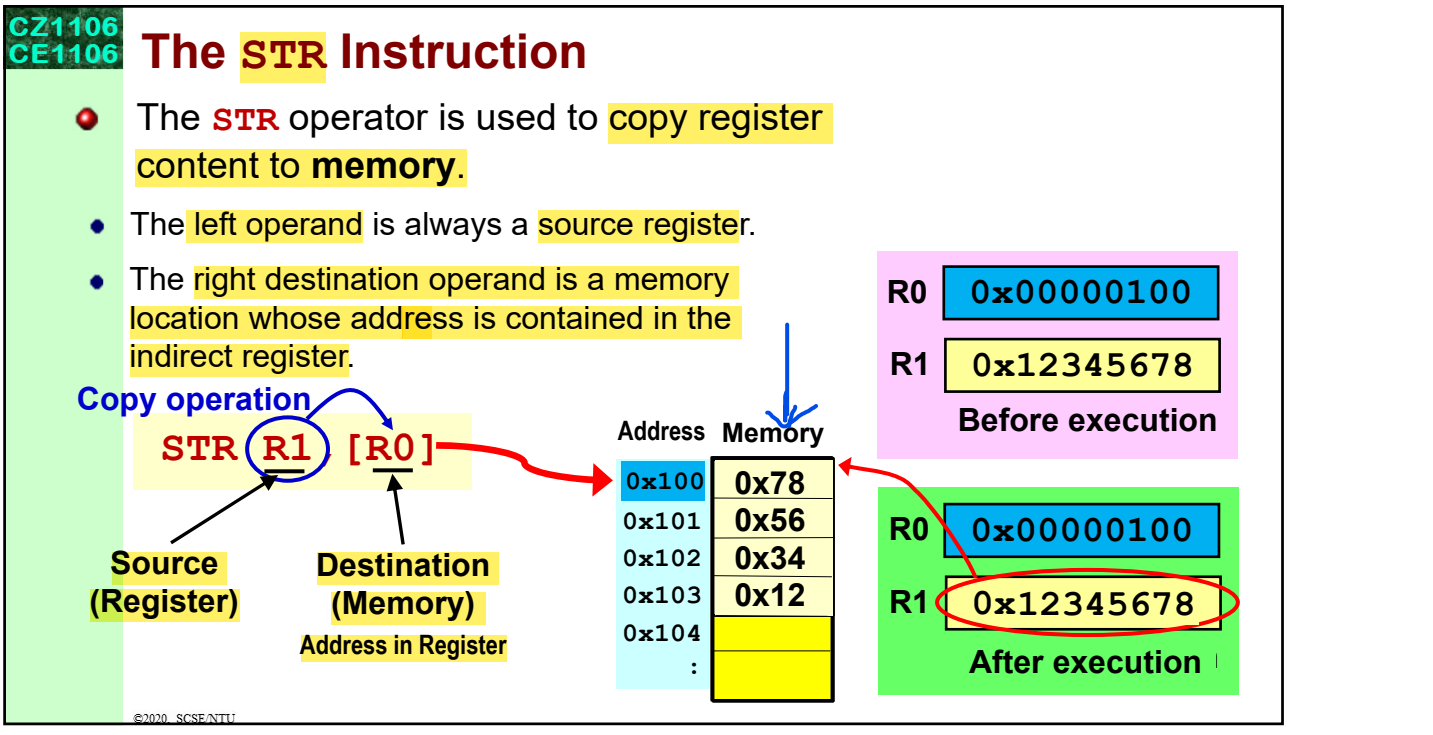
The STR Instruction

- The STR operator is used to copy register content to **memory**.
  - The left operand is always a source register.
  - The right destination operand is a memory location whose address is contained in the indirect register.



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operand with [ ] contains addresses

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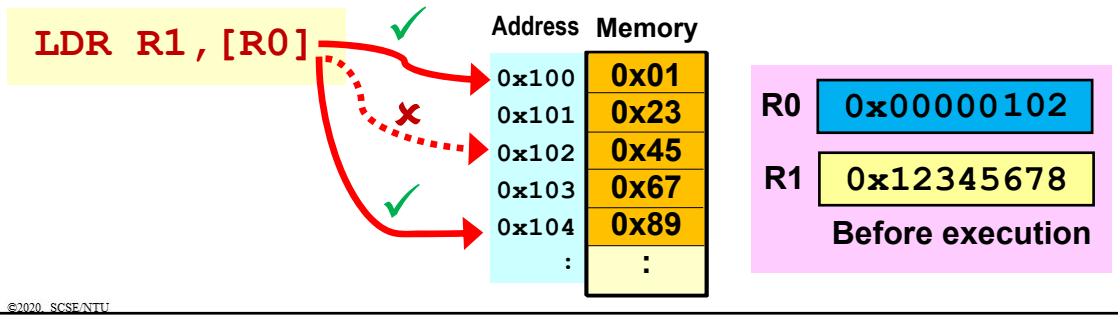
Data Alignment Constraints

- Access of 32-bit operand from memory must follow data alignment constraints.
  - The **4-byte data** read or written to memory must start at an address that is a **multiple of 4**.
  - The effects of an unaligned memory access depend on the ARM architecture but they invariably result in **performance degradation**.



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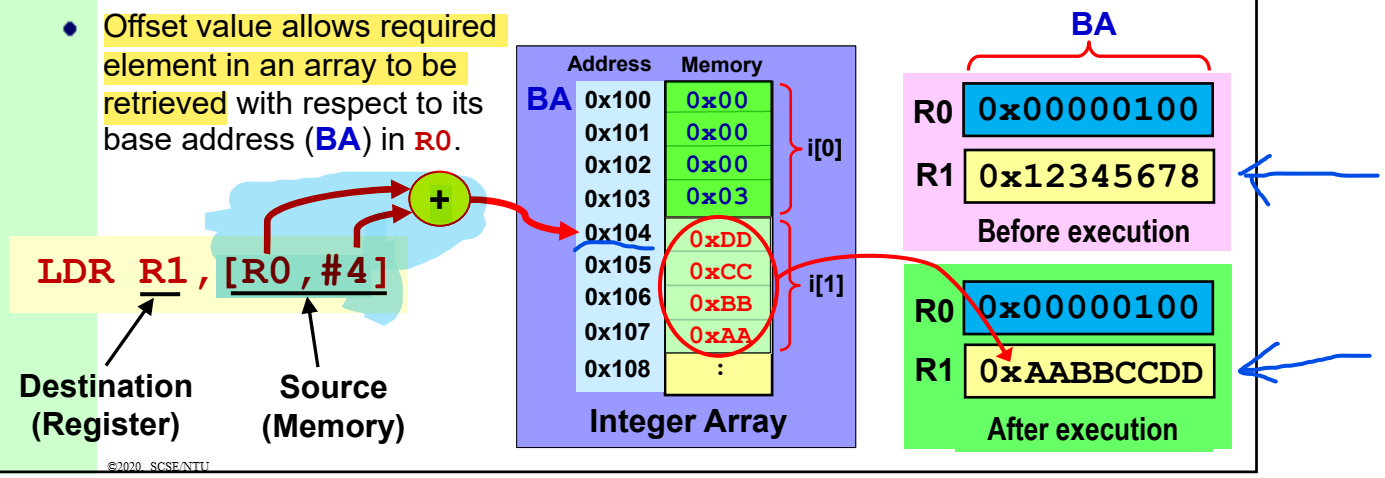
Register Indirect with Offset

- **Adds** a specific **offset value** to the indirect register to compute the effective address (EA) in memory.
  - **Base Plus Offset** addressing does not change indirect register's content.
  - Offset value allows required element in an array to be retrieved with respect to its base address (**BA**) in `R0`.



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Program Example

Accessing Array Elements

- Use base plus offset to access array element whose index is known during coding time.

```
main()
{
// assume base address
// of array i is 0x100
int i[5];

i[0]=7;
i[4]=7;
}
```

C program example
Assign first & last elements of array `i` with value of 7.

```
MOV   R2,#0x100      1
MOV   R1,#7          2
STR   R1,[R2,#0]     3
STR   R1,[R2,#16]    3
```

Using register indirect with base plus offset

1. Initialize base address of array `i` into register `R2`.
2. Load value of 7 into register `R1`.
3. Store the value of 7 into **i[0]** and **i[4]** using offsets of 0 and 16 of register **R2** respectively .
   - In computing offset, note that each integer element occupies 4 bytes in memory.

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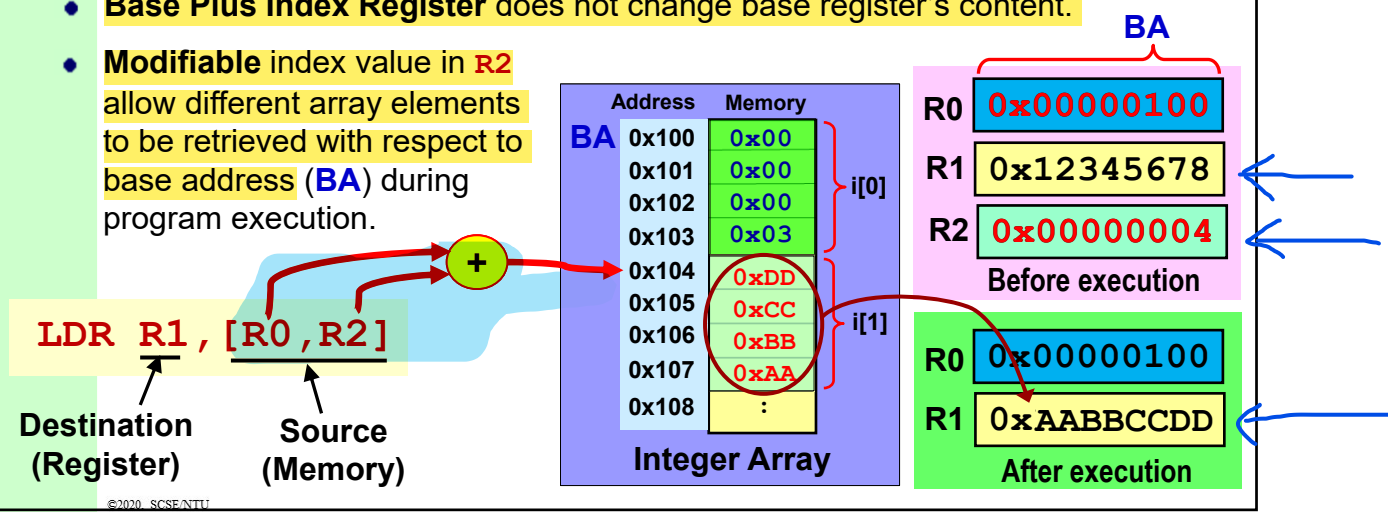
Register Indirect with Index Register

- This variant **adds** the content of the **index register** to the indirect register to compute EA. effective address
  - **Base Plus Index Register** does not change base register's content.
  - **Modifiable** index value in `R2` allow different array elements to be retrieved with respect to base address (**BA**) during program execution.



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R2 functions like #4 but is modifiable.

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Program Example

Clearing All Array Elements

- Use base plus index register to access each array element in turn.

```
main() {
// assume base address
// of array i is 0x100
int i[400];
int n=0;

while (n < 400) {
    i[n] = 0;
    n = n + 1;
    }
}
```

C program example
Initialise all 400 elements in array `i` with zero.

```
MOV   R2,#0x100   (1)
MOV   R0,#0       (2)
MOV   R1,#0
  :
STR   R0,[R2,R1]  (3)
ADD   R1,R1,#4    (4)
```

loop back 399 times

3 ×400 = 1200 cycles

Using register indirect with base plus index

1. Initialize base address of array `i` into register `R2`.
2. Load value of 0 into register `R0` and `R1` (index register).
3. Store 0 in `R0` into `i[n]` using current index value in `R1` plus base address in `R2`.
4. Increment index by 4, the size of each integer element in array.

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Summary

- Register indirect (with the `LDR` and `STR` operators) allows memory operands to be accessed.
- There are two variants of register indirect using base register.
  - Register indirect with **offset** (base plus offset)
  - Register indirect with **index** (base plus index register)
  - Contents in base register **do not change** after execution.
- Given the **base address** of an array, register indirect with base addressing is useful for accessing the contents of the array.
  - Use base plus offset if position of array element is known during coding time
  - Use base plus index if array element position is computed during run time.

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Chapter 4

Addressing Modes

Register Indirect with Autoindexing and Stacks

Learning Objectives (4.4)

1. Describe what is autoindexing feature of ARM's register indirect addressing mode.
2. Describe the differences between pre-index and post-index addressing modes.
3. Describe the various stack implementations and operations using the ARM addressing modes.

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Register Indirect with Autoindexing

- Recap – Register indirect with base register:
  - The base address in the indirect register can be added with an offset or the contents of index register to compute effective address of operand in memory.
  - Base address is **never modified** after execution as it is assumed to be the sole reference to the start of the array.
- What if we allow the indirect register to be modified before or after computing the effective address?
  - Keep a copy of the array's base address elsewhere.
  - **Autoindexing** allows the indirect register's content to be **modified** during execution.
  - Autoindexing provides an efficient way to access **consecutive** array elements.

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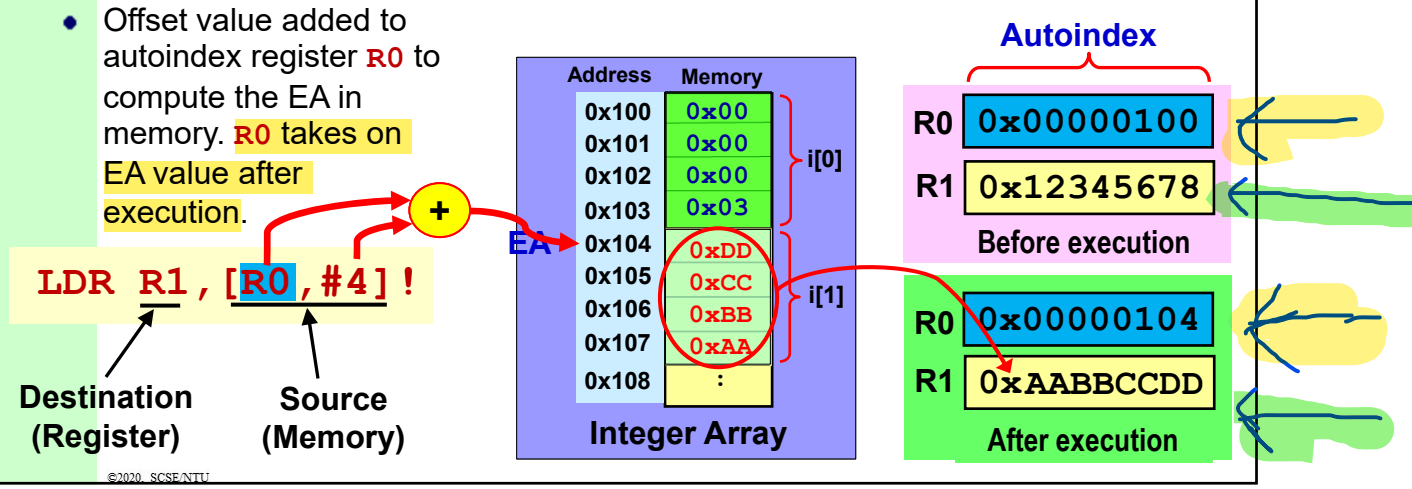
Offset with Autoindexing

- Adds offset value to the autoindex register (AR) to compute effective address (EA) and AR gets modified.
  - "!" in mnemonic causes autoindex register to be modified with the EA.
  - Offset value added to autoindex register R0 to compute the EA in memory. R0 takes on EA value after execution.



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Program Example (Optimised Version)

Clearing All Array Elements

- Use offset with autoindex to efficiently access each array element in turn.

```
main() {
// assume base address
// of array i is 0x100
int i[400];
int n=0;

while (n < 400) {
    i[n] = 0;
    n = n + 1;
    }
}
```

C program example
Initialise all 400 elements in array `i` with zero.

```
MOV R2,#0x100      1
MOV R1,#0          2
STR R1,[R2]        3
  :
STR R1,[R2,#4]!    4
```

loop back 398 times

2 ×400 = 800 cycles

Using register indirect plus offset with autoindex

1. Initialize base address of array `i` into register `R2`.
2. Load value of 0 into source register `R1`.
3. Store 0 in `R1` into first element of array `i[0]`.
4. Store 0 in `R1` into `i[n]` using current effective address (EA) of autoindex register `R2` plus offset `4`. Then put this EA into `R2`.

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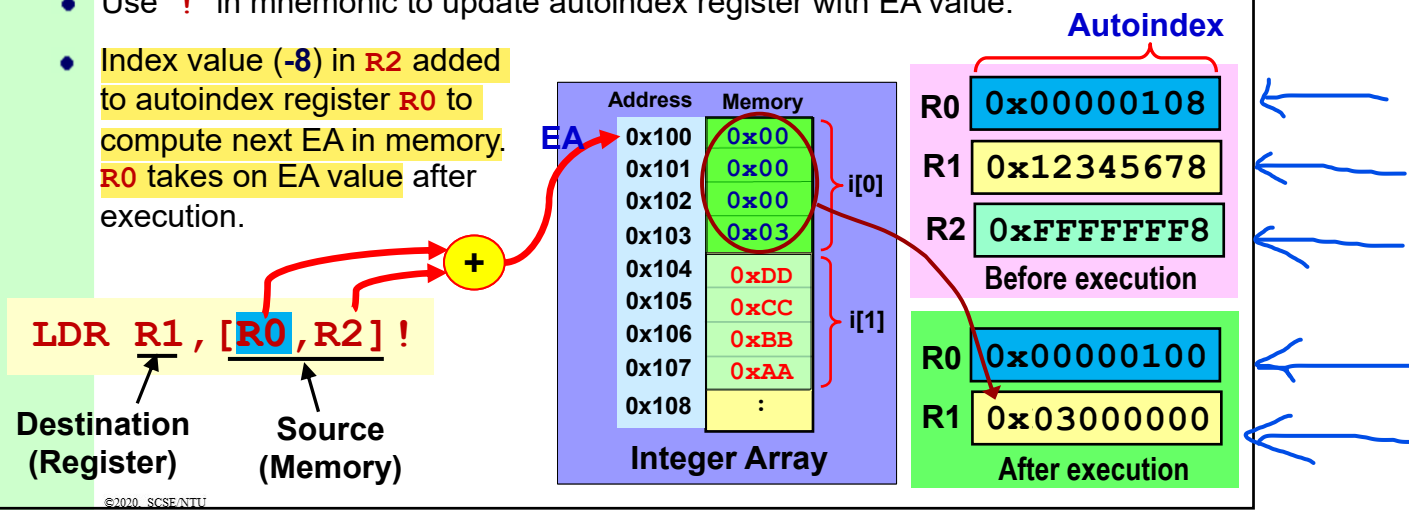
Index Register with Autoindex

- Adds index register value to autoindex register (AR) to compute effective address (EA) and AR gets modified.
  - Use "!" in mnemonic to update autoindex register with EA value.
  - Index value (-8) in R2 added to autoindex register R0 to compute next EA in memory. R0 takes on EA value after execution.



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Pre-index and Post-index

- In **pre-index**, the indirect register is **autoindex before** being used to compute effective address.

```
LDR R1,[R0,#4]!   ; R0 = R0+4
                  ; R1 = mem[R0]
```

Offset with Autoindexing (pre-index)

```
LDR R1,[R0,R2]!   ; R0 = R0+R2
                  ; R1 = mem[R0]
```

Index with Autoindexing (pre-index)

- In **post-index**, the indirect register is used to compute the effective address **before** it is **autoindexed**.

```
LDR R1,[R0],#4    ; R1 = mem[R0]
                  ; R0 = R0+4
```

Offset with Autoindexing (post-index)

```
LDR R1,[R0],R2    ; R1 = mem[R0]
                  ; R0 = R0+R2
```

Index with Autoindexing (post-index)

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Program Example (Alternative Version)

Clearing All Array Elements

- Use offset with **post-index autoindex** to keep all array access within loop.

```
main() {
// assume base address
// of array i is 0x100
int i[400];
int n=0;

while (n < 400) {
    i[n] = 0;
    n = n + 1;
    }
}
```

C program example
Initialise all 400 elements in array `i` with zero.

```
MOV R2,#0x100      (1)
MOV R1,#0          (2)

   :
STR R1,[R2],#4     (3)
```

loop back **399** times

(3) } 2 ×400 = 800 cycles

Using offset with post-index autoindexing

1. Initialize base address of array `i` into register `R2`.
2. Load value of 0 into source register `R1`.
3. Store 0 in `R1` into **i[n]** using current effective address (EA) in indirect register `R2`. Then add offset `4` to the current EA in `R2` so that `R2` is now pointing to the next array element.

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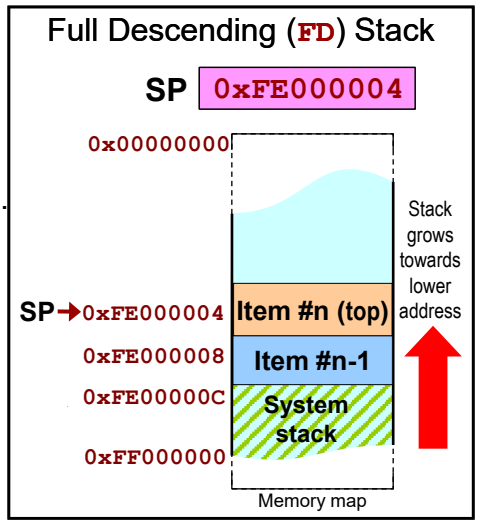
The System Stack

- A stack is a first-in, last-out linear data structure that is maintained in the memory's data area.
  - The system stack in the ARM is maintained by a dedicated stack pointer (**SP**) or **R13**.
  - The `FD` stack grows towards **lower memory** addresses.
    (e.g. by default, **SP** starts at **0xFF000000** in VisUAL ARM simulator).
  - In the `FD` stack, the **SP** points to the **top item (full)** on the stack (but SP can also point to the next **empty** space on the stack).
  - The 3 basic stack operations are **push**, **pop** and **access** items on the stack.

Learn More: Google "ARM stack implementation"



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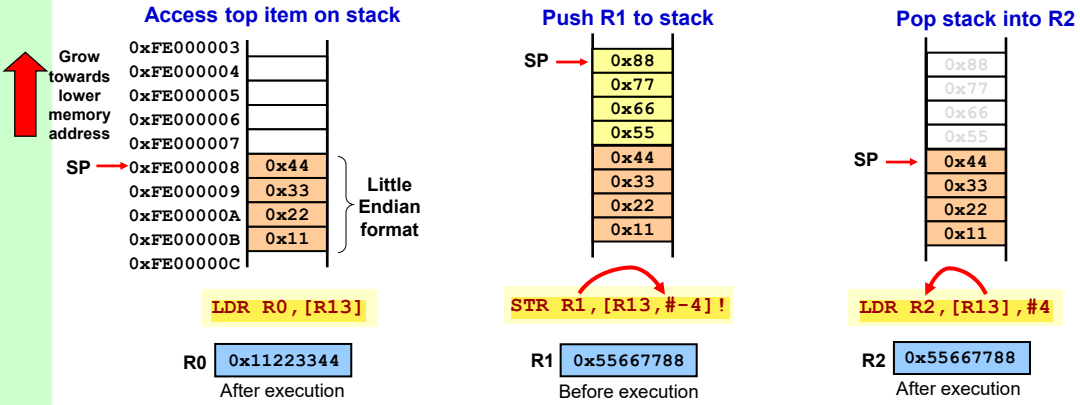
ARM Stack Implementation (FD)

- The are 4 possible stack implementations supported by the ARM instruction set.
  - Full Descending, Full Ascending, Empty Descending and Empty Ascending

Example of **Full Descending** (FD) stack implementation:



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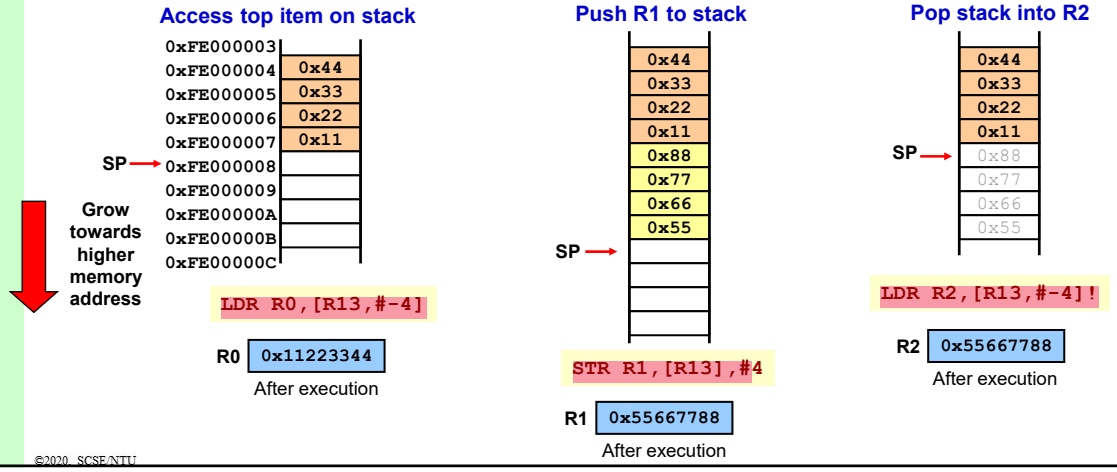
Empty Ascending Implementation (EA)

- EA is an alternative stack implementation.
  - **Empty** means **SP** points to an available **unoccupied** stack space.
  - **Ascending** means stack grows toward **higher** memory address.



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Summary

- Autoindexing modifies the indirect register besides just computing the effective address.
- The autoindexing can use either **offset** or **index register**.
- **Pre-index** does the autoindexing first before computing the effective address.
- **Post-index** computes the effective address first, then does the autoindexing.
- ARM's autoindexing feature can be used to implement stacks.
- There are **4** possible stack implementations (FD, FA, ED, EA).
- For a given stack implementation, the Push and Pop operation must complement each other to ensure the stack grows and collapses correctly.

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Chapter 4

Addressing Modes

PC-related Addressing Modes

Learning Objectives (4.5)

1. Describe difference between absolute & relative jump.
2. Describe the concept of position-independent code and how it is achieved.
3. Describe how data can be accessed using PC relative addressing

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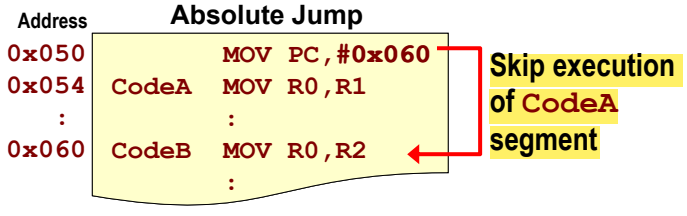
Absolute Jump

- A **new address** can be loaded into the **PC** to alter the sequential order of program execution.
  - An **absolute jump** to a new code position is done by loading the address to jump to into the **PC**.
  - Example: `MOV PC,#0x060 ;Jump to CodeB`



  - Absolute jump is not **position-independent**. This code can only execute correctly in this specific area of code memory.

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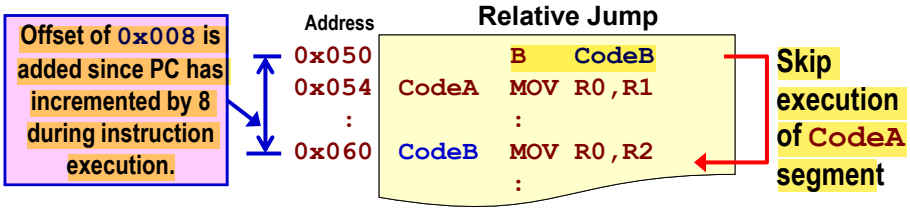
Relative Jump

- An **offset** can be added to the **PC** to alter the sequential order of program execution.
  - A **relative jump** is done using the branch instruction (e.g. `B`) with an appropriate **signed offset.** (Note: the range of this offset in ARM is **+/- 32 Mbytes**).
  - Example: `B CodeB ;Jump to CodeB`



  - Relative jump supports **position-independent** code.

Note: In the ARM processor the PC points 8 bytes ahead of the current executed instruction due to its pipeline architecture.

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count 8 bytes from 0x052

B CodeB itself takes up 2 bytes

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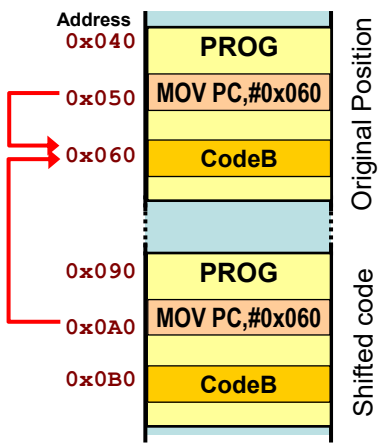
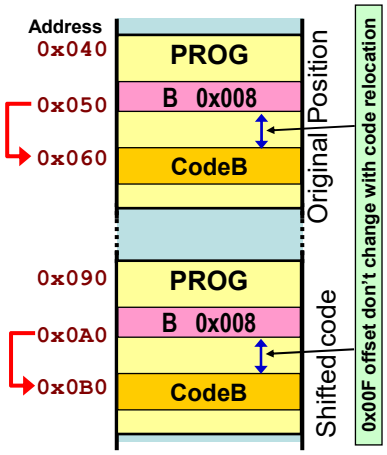
Position-Independent Code

- Such programs can be loaded anywhere in memory and still execute correctly (i.e. relocatable).



Does not jump to **CodeB** after **PROG** is shifted to `0x090`



`B` still branch to **CodeB** after **PROG** is shifted to `0x090`

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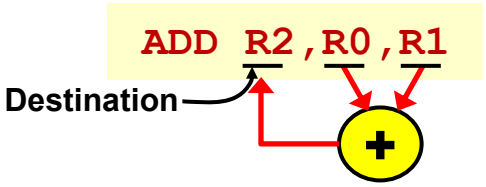
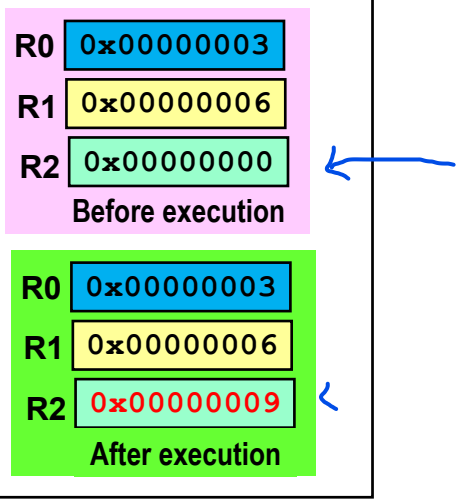
ADD Instruction (Introduction)

- This instruction does the **addition** operation.
  - The 3-operand `ADD` instruction adds 2 source operands and puts result into a 3rd destination operand.
  - The right and middle operands are added and the result is placed in the destination register.





  - Destination and middle operands must be registers but rightmost operand can be a **register** or an **immediate** value.

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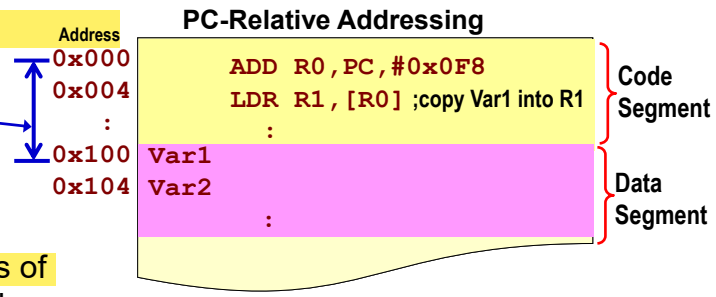
Accessing Data

- Position-independent (P-I) programs require data to be accessed relative to the **PC**.
  - **PC-relative addressing** is used to access variables in the data segment of program in memory.
  - E.g.: `ADD R0,PC,#0x0F8` ; **Get P-I address of Var1 in Data Seg into R0**

PC-relative offset of `0x0F8` is added since PC has incremented by `8` when executing `ADD` instruction.

PC-relative Offset:
Var address – (PC value + 8)



  - Referencing absolute address of variable in whatever ways will violate **P-I** requirements.

Note: In the ARM processor the **PC** points **8** bytes ahead of the current executed instruction.

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Summary

- Non-sequential execution of code can be achieved by modifying the PC contents directly.
  - The Branch instruction does this by **adding** a **signed offset**.
  - Such **relative** jumps create **position-independent** code.
- **PC-relative addressing** with **appropriate offsets** allows memory data to be accessed in a position-independent manner.

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