# REGISTER TRANSFER AND MICROOPERATIONS

- Register Transfer Language
- Register Transfer
- Bus Transfers
- Arithmetic Microoperations
- Logic Microoperations
- Shift Microoperations
- Arithmetic Logic Shift Unit

# SIMPLE DIGITAL SYSTEMS

- Combinational and sequential circuits can be used to create simple digital systems.

- These are  the low-level building blocks of a digital computer.

- Simple digital systems are frequently characterized in terms of
  - the registers they contain, and
  - the operations that they perform.

- Typically,
  - What operations are performed on the data in the registers
  - What information is passed between registers

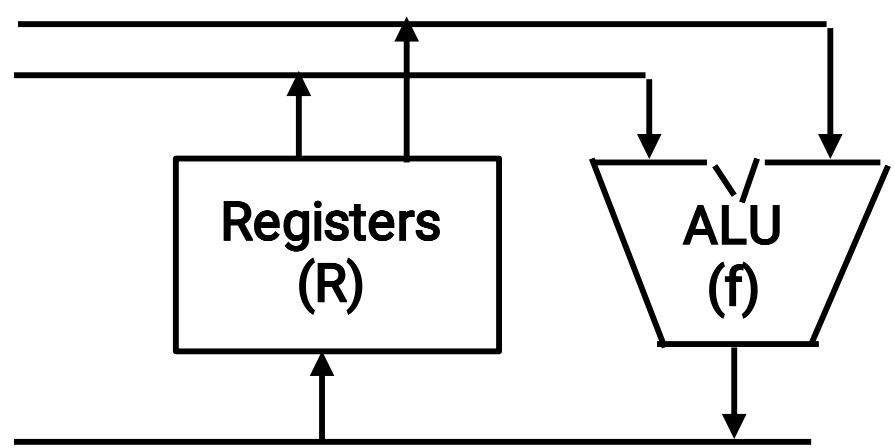
# MICROOPERATIONS (1)

- The operations on the data in registers are called microoperations.
- The functions built into registers are examples of microoperations
  - Shift
  - Load
  - Clear
  - Increment
  - …

# MICROOPERATION (2)

**An elementary operation performed (during one clock pulse), on the information stored in one or more registers**

*Clock Cycle* - A clock cycle is one operation done by a microprocessor in which electricity goes through a processor turning transistors on or off which is parallel to the binary code (1s and 0s) that make up any computer operation at the most simplified state. Hundreds of millions of clock cycles are performed every second in the most average of microprocessors today




1 clock cycle

R ← f(R, R)

f: shift, load, clear, increment, add, subtract, complement, and, or, xor, …

# ORGANIZATION OF A DIGITAL SYSTEM

- Definition of the (internal) organization of a computer

  - Set of registers and their functions

  - Microoperations set

    Set of allowable microoperations provided
    by the organization of the computer

  - Control signals that initiate the sequence of
    microoperations (to perform the functions)

# REGISTER TRANSFER LEVEL

- Viewing a computer, or any digital system, in this way is called the register transfer level

- This is because we're focusing on
  - The system's registers
  - The data transformations in them, and
  - The data transfers between them.

# REGISTER TRANSFER LANGUAGE

- Rather than specifying a digital system in words, a specific notation is used, *register transfer language*

- For any function of the computer, the register transfer language can be used to describe the (sequence of) microoperations

- Register transfer language
  - A symbolic language
  - A convenient tool for describing the internal organization of digital computers
  - Can also be used to facilitate the design process of digital systems.

# DESIGNATION OF REGISTERS

- Registers are designated by capital letters, sometimes followed by numbers (e.g., A, R13, IR)
- Often the names indicate function:
  - MAR - memory address register
  - PC - program counter
  - IR - instruction register

- Registers and their contents can be viewed and represented in *various ways*
  - A register can be viewed as a single entity:

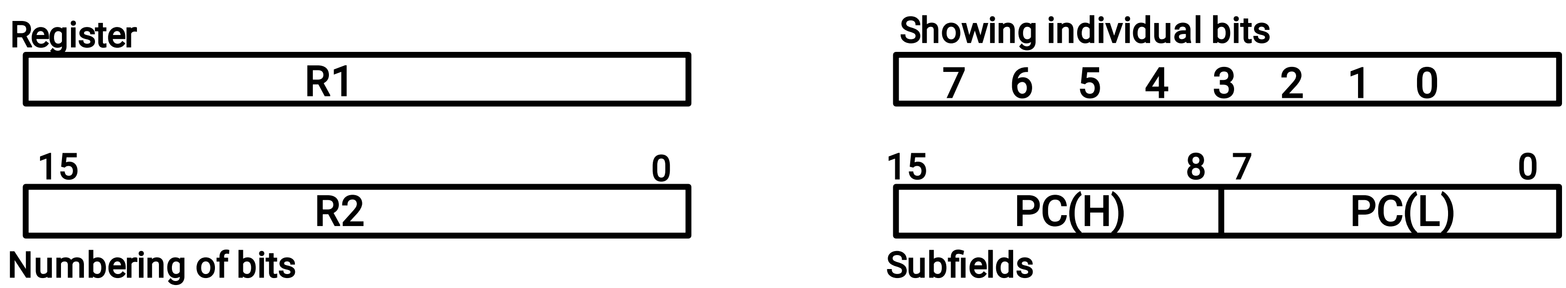
| MAR |
|---|

  - Registers may also be represented showing the bits of data they contain

# DESIGNATION OF REGISTERS

- Designation of a register
  - a register
  - portion of a register
  - a bit of a register

- Common ways of drawing the block diagram of a register



# REGISTER TRANSFER

- Copying the contents of one register to another is a register transfer

- A register transfer is indicated as

  $R2 \leftarrow R1$

  - In this case the contents of register R1 are copied (loaded) into register R2
  - A simultaneous transfer of all bits from the source R1 to the destination register R2, during one clock pulse
  - Note that this is a non-destructive; i.e. the contents of R1 are not altered by copying (loading) them to R2

# REGISTER TRANSFER

- A register transfer such as

  $R3 \leftarrow R5$

  Implies that the digital system has

  - the data lines from the source register (R5) to the destination register (R3)
  - Parallel load in the destination register (R3)
  - Control lines to perform the action

# CONTROL FUNCTIONS

- Often actions need to only occur if a certain condition is true
- This is similar to an "if" statement in a programming language
- In digital systems, this is often done via a *control signal*, called a *control function*
  - If the signal is 1, the action takes place
- This is represented as:

$P: R2 \leftarrow R1$

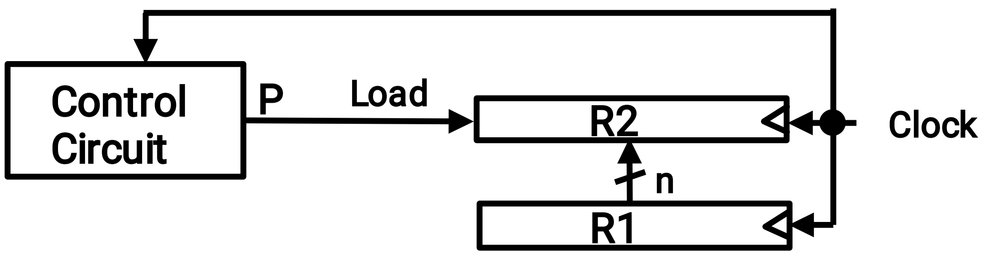
Which means "if $P = 1$, then load the contents of register R1 into register R2", i.e., if $(P = 1)$ then $(R2 \leftarrow R1)$

# HARDWARE IMPLEMENTATION OF CONTROLLED TRANSFERS

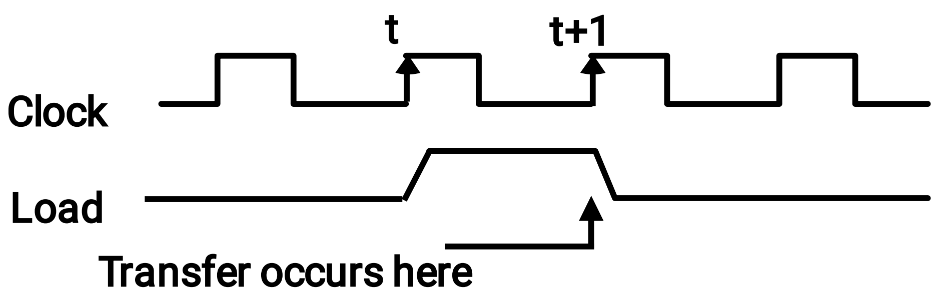
## Implementation of controlled transfer

P: R2 ← R1

## Block diagram




## Timing diagram




The same clock controls the circuits that generate the control function and the destination register

# SIMULTANEOUS OPERATIONS

- If two or more operations are to occur simultaneously, they are separated with commas

$$P: \; R3 \leftarrow R5, \; MAR \leftarrow IR$$

- Here, if the control function P = 1, load the contents of R5 into R3, and at the same time (clock), load the contents of register IR into register MAR

# BASIC SYMBOLS FOR REGISTER TRANSFERS

| Symbols | Description | Examples |
|---|---|---|
| Capital letters & numerals | Denotes a register | MAR, R2 |
| Parentheses () | Denotes a part of a register | R2(0-7), R2(L) |
| Arrow $\leftarrow$ | Denotes transfer of information | R2 $\leftarrow$ R1 |
| Colon : | Denotes termination of control function | P: |
| Comma , | Separates two micro-operations | A $\leftarrow$ B, B $\leftarrow$ A |

# CONNECTING REGISTRS

BUS

# CONNECTING REGISTRS

- In a digital system with many registers, it is impractical to have data and control lines to directly allow each register to be loaded with the contents of every possible other registers

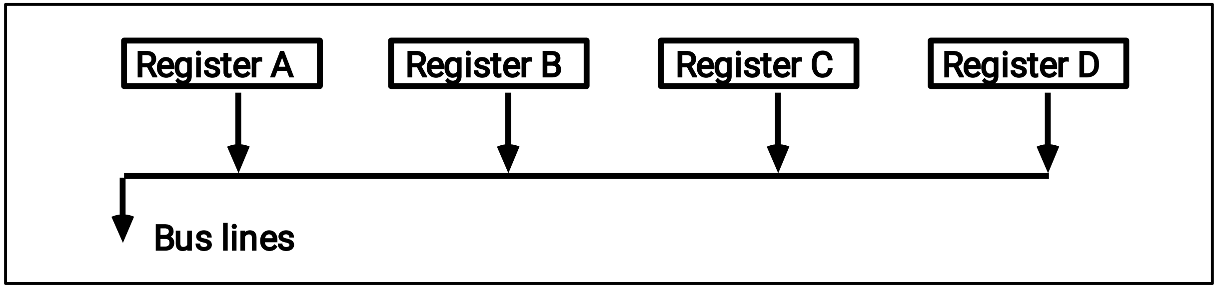
- To completely connect n registers → n(n-1) lines
- $O(n^2)$ cost
  - This is not a realistic approach to use in a large digital system

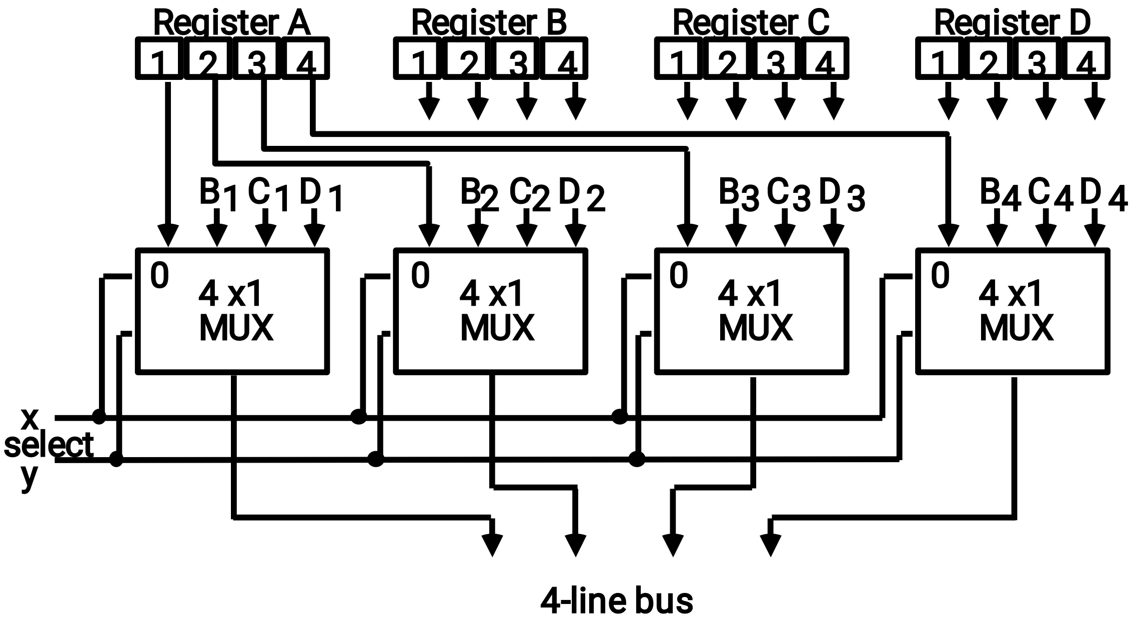
- Instead, take a different approach
- Have one centralized set of circuits for data transfer – the bus
- Have control circuits to select which register is the source, and which is the destination

# BUS AND BUS TRANSFER

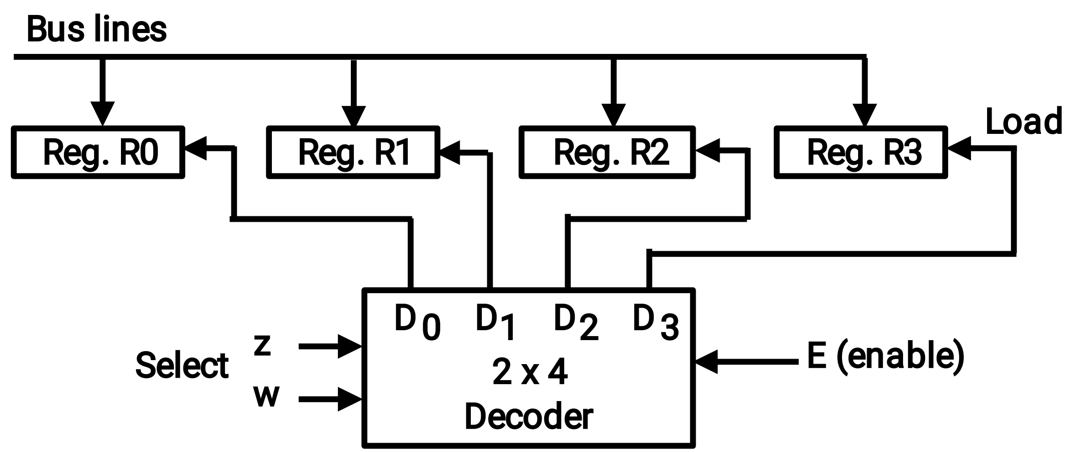
Bus is a path(of a group of wires) over which information is transferred, from any of several sources to any of several destinations.

From a register to bus: BUS $\leftarrow$ R

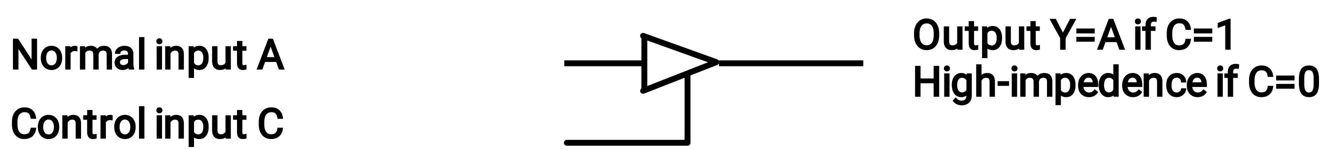


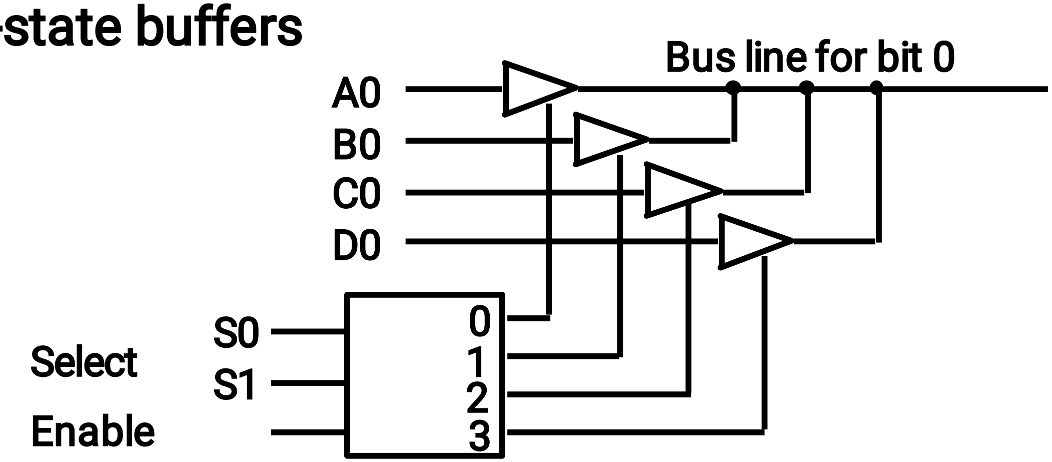
# TRANSFER FROM BUS TO A DESTINATION REGISTER




## Three-State Bus Buffers




## Bus line with three-state buffers



# BUS TRANSFER IN RTL

- Depending on whether the bus is to be mentioned explicitly or not, register transfer can be indicated as either

R2 ← R1

or

BUS ← R1, R2 ← BUS

- In the former case the bus is implicit, but in the latter, it is explicitly indicated

# SUMMARY OF R. TRANSFER MICROOPERATIONS

| | |
|---|---|
| $A \leftarrow B$ | Transfer content of reg. B into reg. A |
| $AR \leftarrow DR(AD)$ | Transfer content of AD portion of reg. DR into reg. AR |
| $A \leftarrow$ constant | Transfer a binary constant into reg. A |
| $ABUS \leftarrow R1$, | Transfer content of R1 into bus A and, at the same time, |
| $R2 \leftarrow ABUS$ | transfer content of bus A into R2 |
| AR | Address register |
| DR | Data register |
| M[R] | Memory word specified by reg. R |
| M | Equivalent to M[AR] |
| $DR \leftarrow M$ | Memory *read* operation: transfers content of memory word specified by AR into DR |
| $M \leftarrow DR$ | Memory *write* operation: transfers content of DR into memory word specified by AR |

# MICROOPERATIONS

- Computer system microoperations are of four types:

  - Register transfer microoperations
  - Arithmetic microoperations
  - Logic microoperations
  - Shift microoperations

# ARITHMETIC MICROOPERATIONS

- The basic arithmetic microoperations are
  - Addition
  - Subtraction
  - Increment
  - Decrement

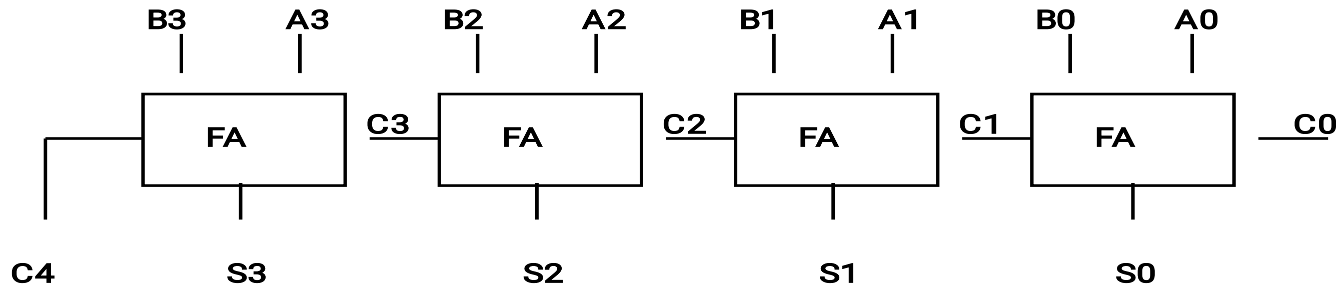
- The additional arithmetic microoperations are
  - Add with carry
  - Subtract with borrow
  - Transfer/Load
  - etc. …

## Summary of Typical Arithmetic Micro-Operations

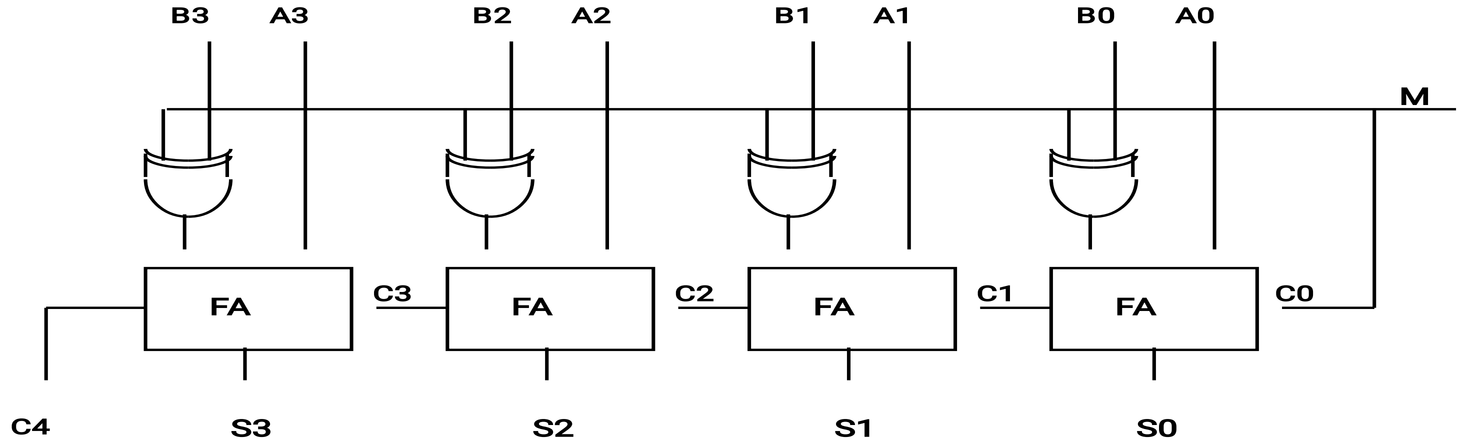
| | |
|---|---|
| R3 ← R1 + R2 | Contents of R1 plus R2 transferred to R3 |
| R3 ← R1 - R2 | Contents of R1 minus R2 transferred to R3 |
| R2 ← R2’ | Complement the contents of R2 |
| R2 ← R2’+ 1 | 2's complement the contents of R2 (negate) |
| R3 ← R1 + R2’+ 1 | subtraction |
| R1 ← R1 + 1 | Increment |
| R1 ← R1 - 1 | Decrement |

# BINARY ADDER / SUBTRACTOR / INCREMENTER

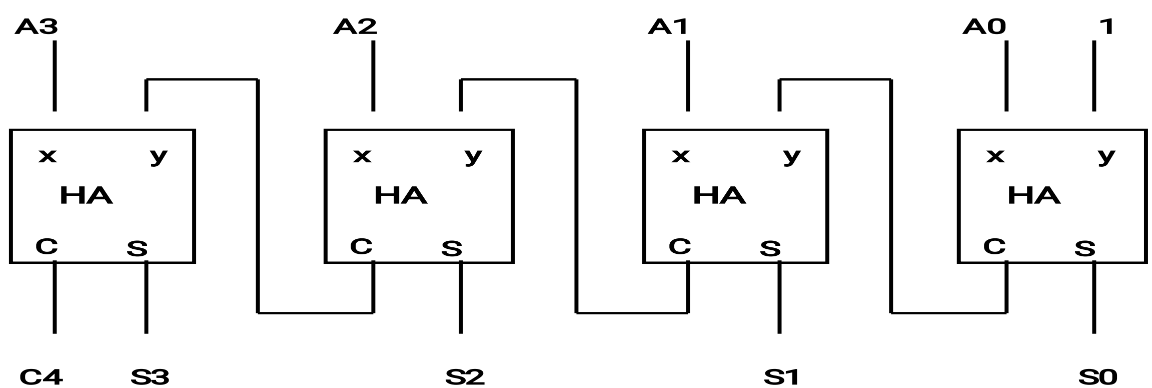
## Binary Adder



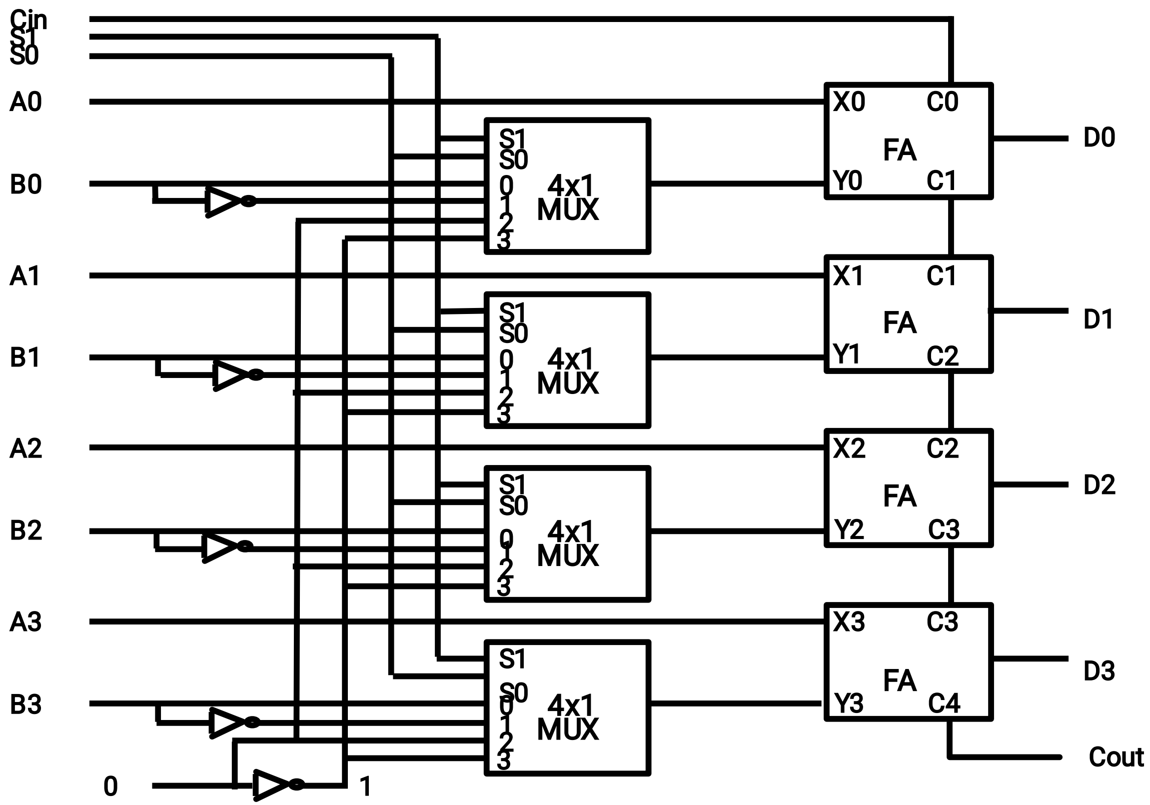

## Binary Adder-Subtractor




## Binary Incrementer



# ARITHMETIC CIRCUIT




| S1 | S0 | Cin | Y | Output | Microoperation |
|---|---|---|---|---|---|
| 0 | 0 | 0 | B | D = A + B | Add |
| 0 | 0 | 1 | B | D = A + B + 1 | Add with carry |
| 0 | 1 | 0 | B’ | D = A + B’ | Subtract with borrow |
| 0 | 1 | 1 | B’ | D = A + B’+ 1 | Subtract |
| 1 | 0 | 0 | 0 | D = A | Transfer A |
| 1 | 0 | 1 | 0 | D = A + 1 | Increment A |
| 1 | 1 | 0 | 1 | D = A - 1 | Decrement A |
| 1 | 1 | 1 | 1 | D = A | Transfer A |

# LOGIC MICROOPERATIONS

- Specify binary operations on the strings of bits in registers
  - Logic microoperations are bit-wise operations, i.e., they work on the individual bits of data
  - useful for bit manipulations on binary data
  - useful for making logical decisions based on the bit value
- There are, in principle, 16 different logic functions that can be defined over two binary input variables

| A | B | $F_0$ | $F_1$ | $F_2$ | … | $F_{13}$ | $F_{14}$ | $F_{15}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | … | 1 | 1 | 1 |
| 0 | 1 | 0 | 0 | 0 | … | 1 | 1 | 1 |
| 1 | 0 | 0 | 0 | 1 | … | 0 | 1 | 1 |
| 1 | 1 | 0 | 1 | 0 | … | 1 | 0 | 1 |

- However, most systems only implement four of these
  - AND ($\wedge$), OR ($\vee$), XOR ($\oplus$), Complement/NOT
- The others can be created from combination of these

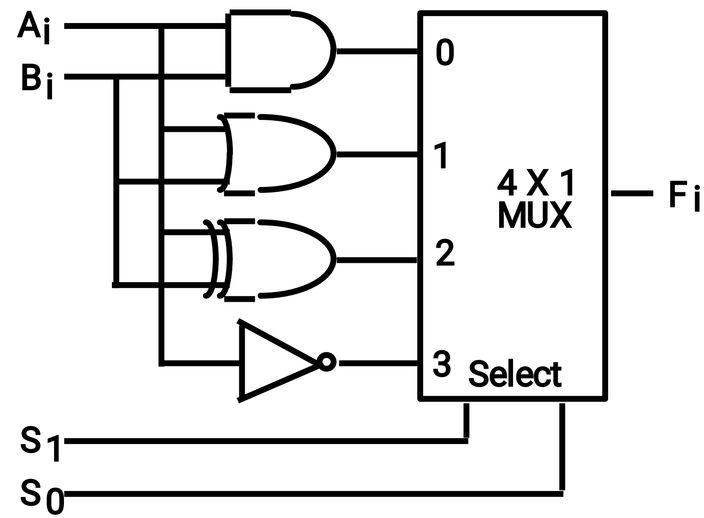
# LIST OF LOGIC MICROOPERATIONS

- List of Logic Microoperations
  - 16 different logic operations with 2 binary vars.
  - n binary vars → $2^{2^n}$ functions

- Truth tables for 16 functions of 2 variables and the corresponding 16 logic micro-operations

| x 0 0 1 1<br>y 0 1 0 1 | *Boolean Function* | *Micro-Operations* | *Name* |
|---|---|---|---|
| 0 0 0 0 | F0 = 0 | F ← 0 | Clear |
| 0 0 0 1 | F1 = xy | F ← A ∧ B | AND |
| 0 0 1 0 | F2 = xy' | F ← A ∧ B' | |
| 0 0 1 1 | F3 = x | F ← A | Transfer A |
| 0 1 0 0 | F4 = x'y | F ← A' ∧ B | |
| 0 1 0 1 | F5 = y | F ← B | Transfer B |
| 0 1 1 0 | F6 = x ⊕ y | F ← A ⊕ B | Exclusive-OR |
| 0 1 1 1 | F7 = x + y | F ← A ∨ B | OR |
| 1 0 0 0 | F8 = (x + y)' | F ← (A ∨ B)' | NOR |
| 1 0 0 1 | F9 = (x ⊕ y)' | F ← (A ⊕ B)' | Exclusive-NOR |
| 1 0 1 0 | F10 = y' | F ← B' | Complement B |
| 1 0 1 1 | F11 = x + y' | F ← A ∨ B | |
| 1 1 0 0 | F12 = x' | F ← A' | Complement A |
| 1 1 0 1 | F13 = x' + y | F ← A' ∨ B | |
| 1 1 1 0 | F14 = (xy)' | F ← (A ∧ B)' | NAND |
| 1 1 1 1 | F15 = 1 | F ← all 1's | Set to all 1's |

# HARDWARE IMPLEMENTATION OF LOGIC MICROOPERATIONS



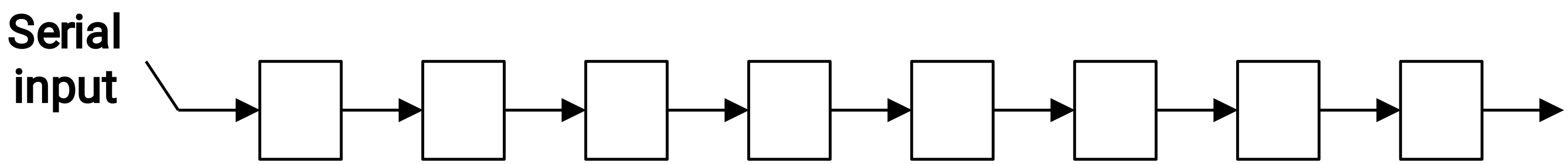

## Function table

| $S_1$ $S_0$ | Output | μ-operation |
|---|---|---|
| 0 0 | $F = A \wedge B$ | AND |
| 0 1 | $F = A \vee B$ | OR |
| 1 0 | $F = A \oplus B$ | XOR |
| 1 1 | $F = A'$ | Complement |

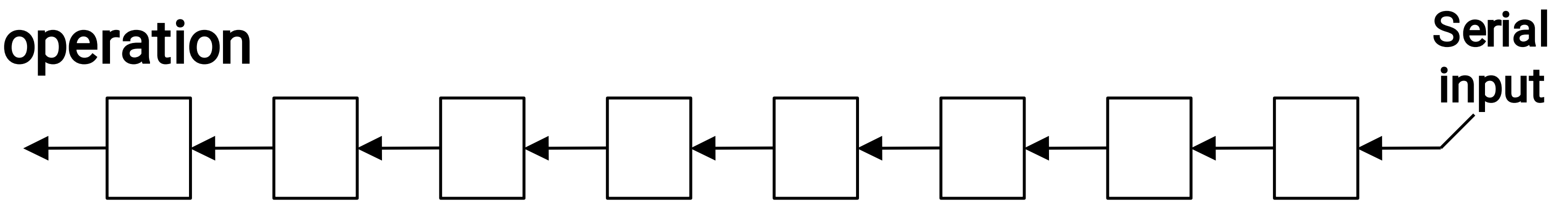
# SHIFT MICROOPERATIONS

- There are three types of shifts
  - *Logical shift*
  - *Circular shift*
  - *Arithmetic shift*
- What differentiates them is the information that goes into the serial input

- A right shift operation



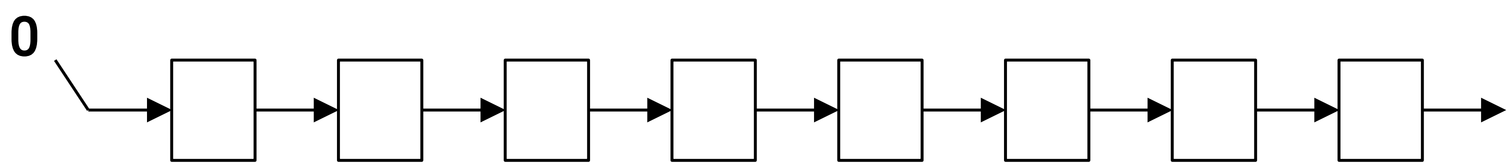

- A left shift operation



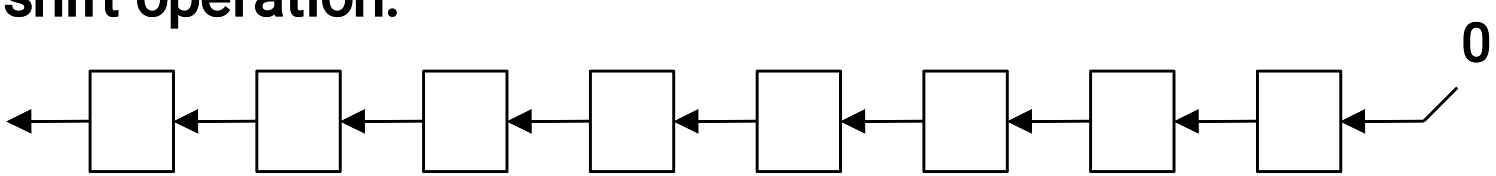
# LOGICAL SHIFT

- In a logical shift the serial input to the shift is a 0.

- A right logical shift operation:




- A left logical shift operation:

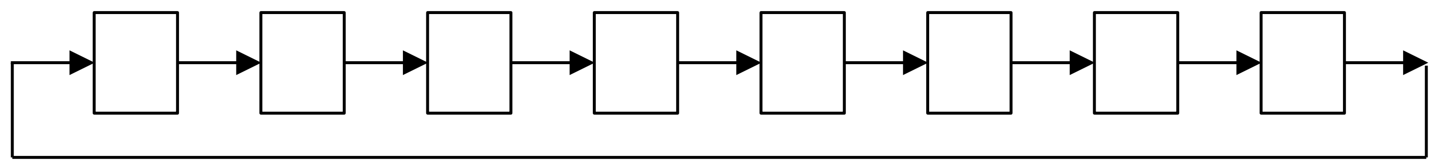



- In a Register Transfer Language, the following notation is used
  - *shl* for a logical shift left
  - *shr* for a logical shift right
  - Examples:
    - » R2 ← *shr* R2
    - » R3 ← *shl* R3

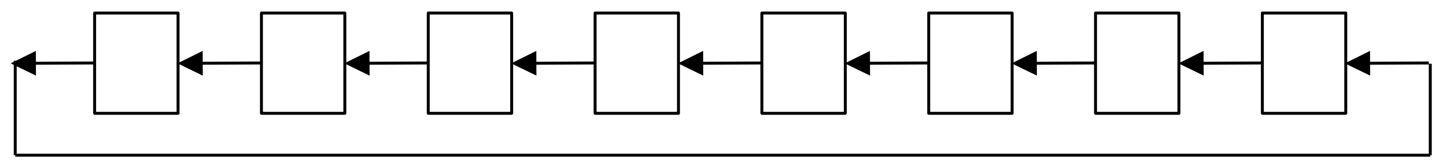
# CIRCULAR SHIFT

- In a circular shift the serial input is the bit that is shifted out of the other end of the register.

- A right circular shift operation:



- A left circular shift operation:

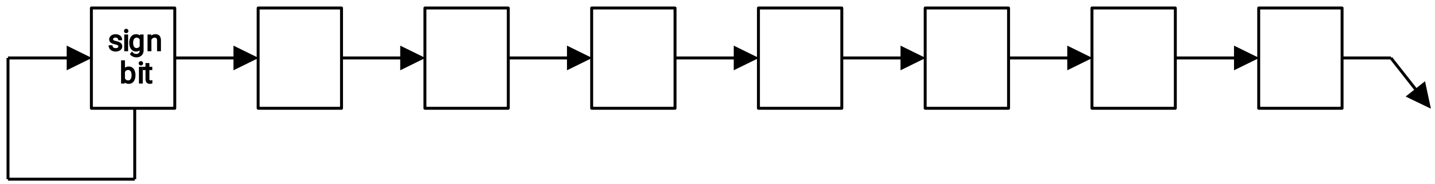


- In a RTL, the following notation is used
  - *cil* for a circular shift left
  - *cir* for a circular shift right
  - Examples:
    » R2 $\leftarrow$ *cir* R2
    » R3 $\leftarrow$ *cil* R3

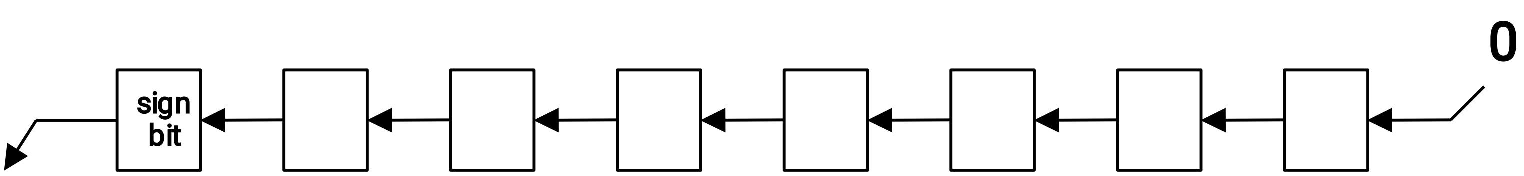
# ARITHMETIC SHIFT

- An arithmetic shift is meant for signed binary numbers (integer)
- An arithmetic left shift multiplies a signed number by two
- An arithmetic right shift divides a signed number by two
- The main distinction of an arithmetic shift is that it must keep the sign of the number the same as it performs the multiplication or division

- A right arithmetic shift operation:

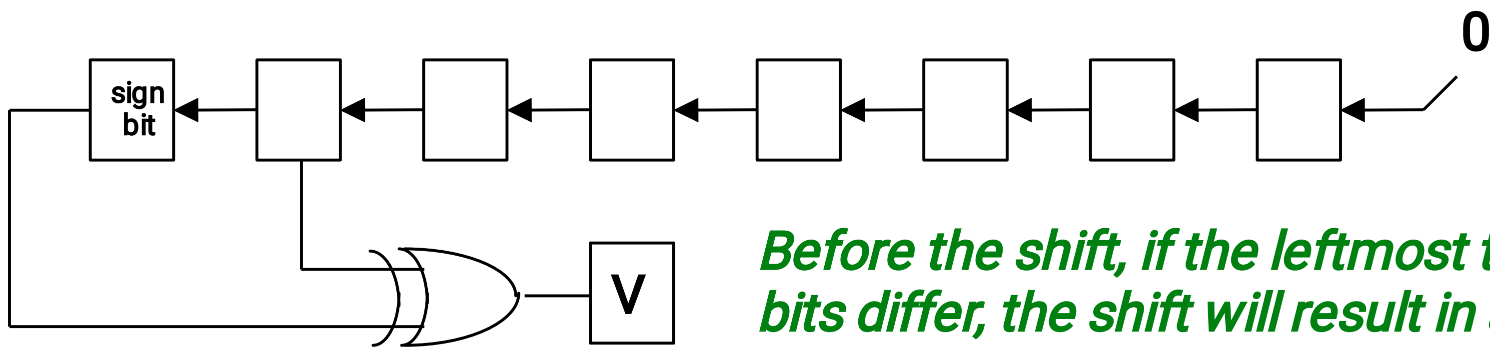



- A left arithmetic shift operation:



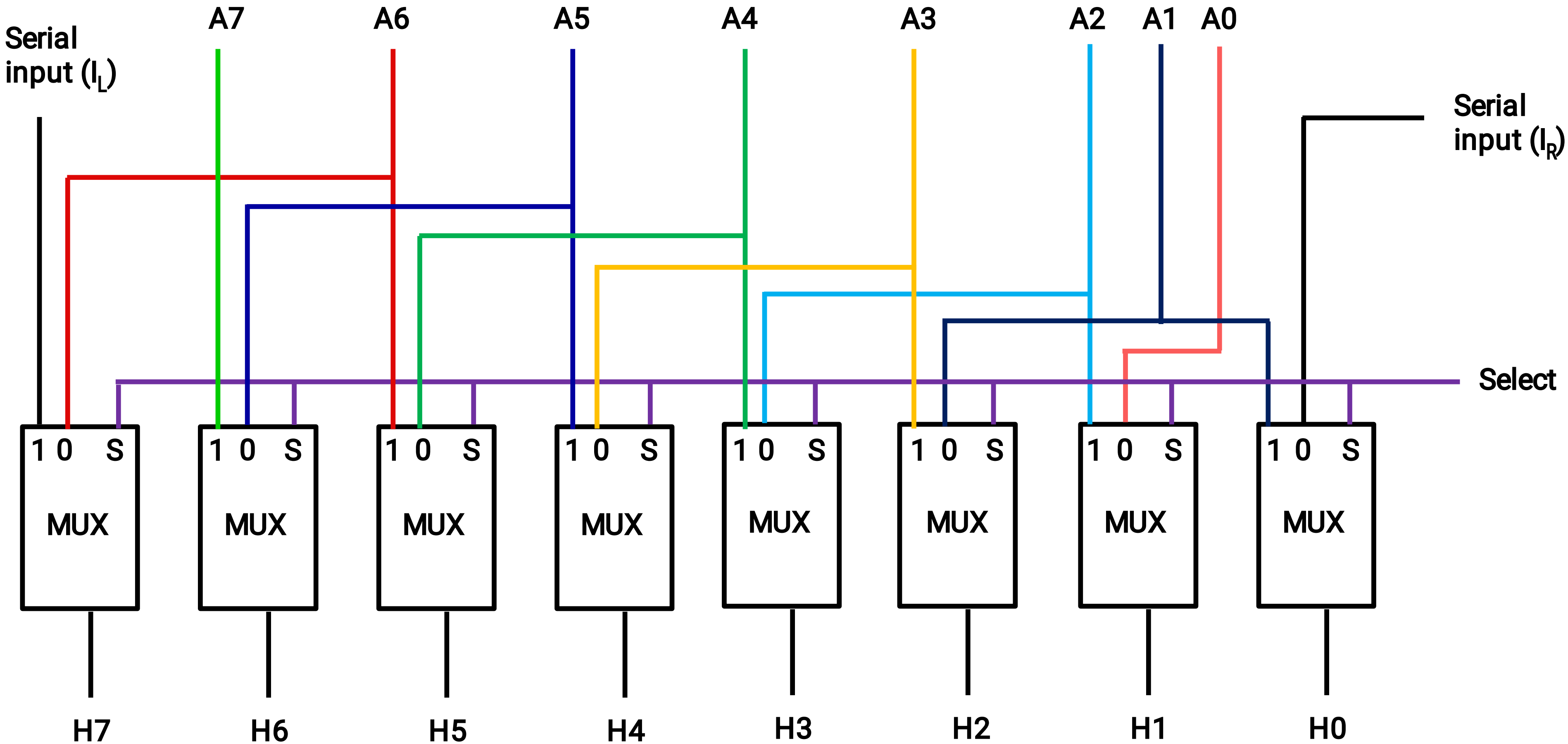
# ARITHMETIC SHIFT

- An left arithmetic shift operation must be checked for the overflow




*Before the shift, if the leftmost two bits differ, the shift will result in an overflow*

- In a RTL, the following notation is used
  - *ashl* for an arithmetic shift left
  - *ashr* for an arithmetic shift right
  - Examples:
    - » R2 ← *ashr* R2
    - » R3 ← *ashl* R3




**Operations**

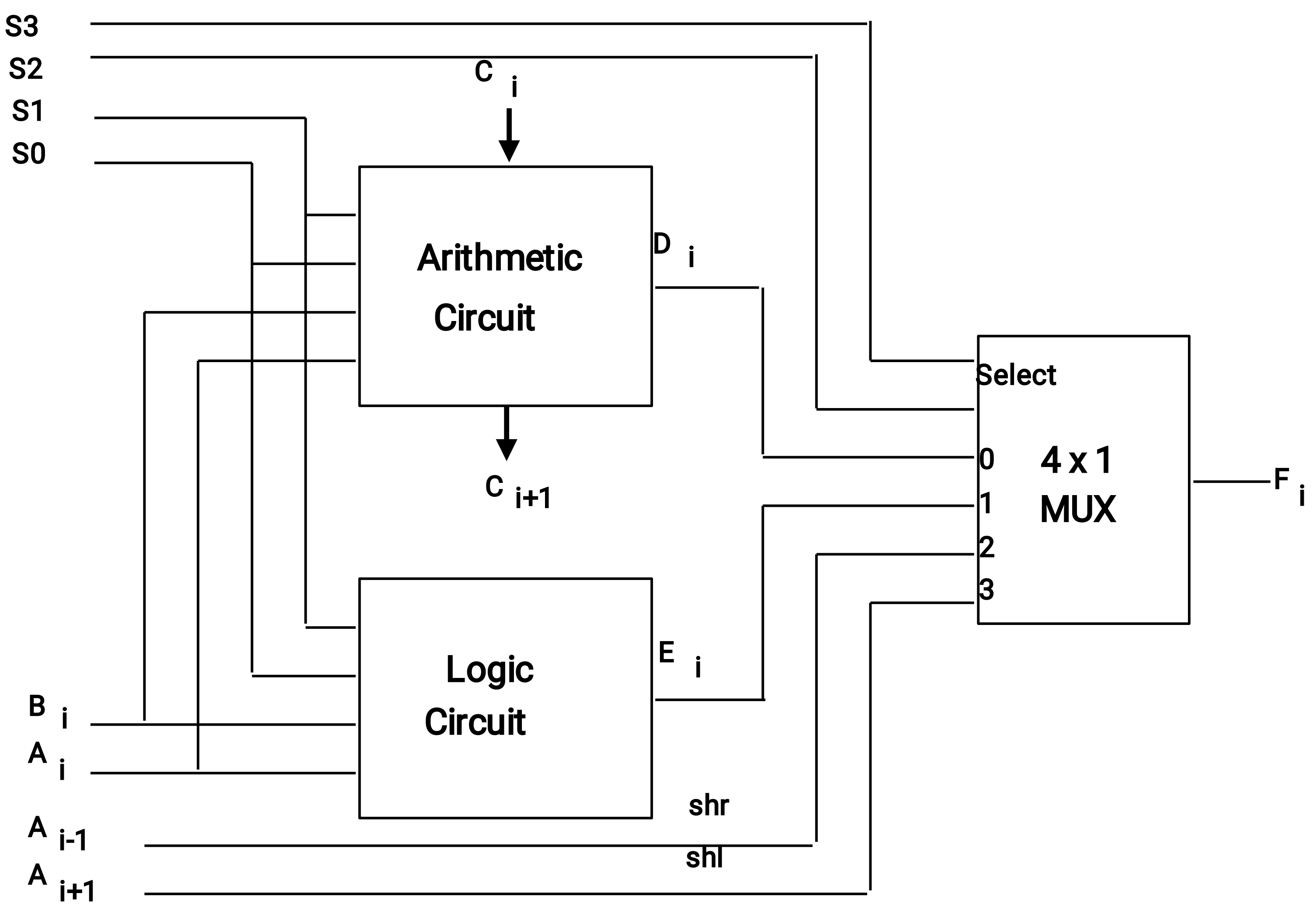
SHL – $I_R$=0 CIL – $I_R$= A7 ASHL – $I_R$=0

SHR – $I_L$= 0 CIR – $I_L$= A0 ASHR – $I_L$= A7

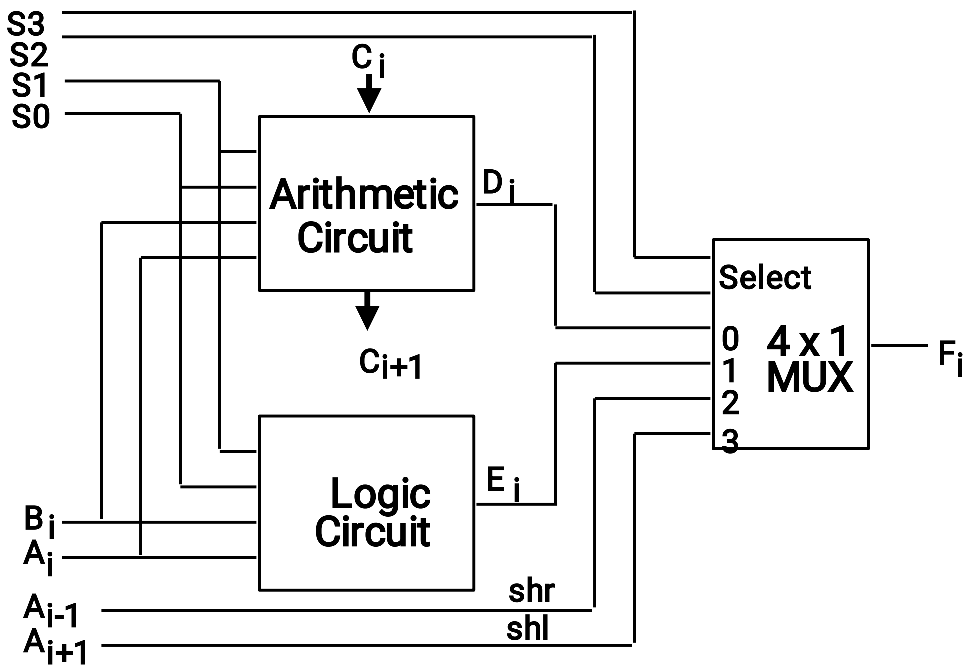
**0 - shift left**

**1 - shift right**

# ARITHMETIC LOGIC SHIFT UNIT



# ARITHMETIC LOGIC SHIFT UNIT




| S3 | S2 | S1 | S0 | Cin | Operation | Function |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | F = A | Transfer A |
| 0 | 0 | 0 | 0 | 1 | F = A + 1 | Increment A |
| 0 | 0 | 0 | 1 | 0 | F = A + B | Addition |
| 0 | 0 | 0 | 1 | 1 | F = A + B + 1 | Add with carry |
| 0 | 0 | 1 | 0 | 0 | F = A + B’ | Subtract with borrow |
| 0 | 0 | 1 | 0 | 1 | F = A + B’+ 1 | Subtraction |
| 0 | 0 | 1 | 1 | 0 | F = A - 1 | Decrement A |
| 0 | 0 | 1 | 1 | 1 | F = A | TransferA |
| 0 | 1 | 0 | 0 | X | F = A ⊠ B | AND |
| 0 | 1 | 0 | 1 | X | F = A⊠⊠ B | OR |
| 0 | 1 | 1 | 0 | X | F = A ⊠ B | XOR |
| 0 | 1 | 1 | 1 | X | F = A’ | Complement A |
| 1 | 0 | X | X | X | F = shr A | Shift right A into F |
| 1 | 1 | X | X | X | F = shl A | Shift left A into F |