REGISTER TRANSFER AND MICROOPERATIONS

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

SIMPLE DIGITAL SYSTEMS

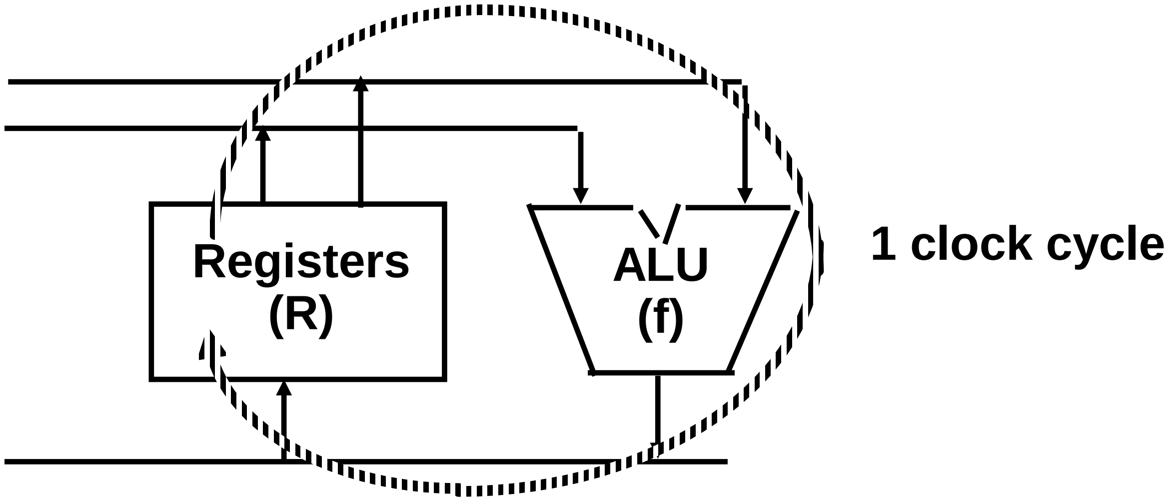
- **Combinational and sequential circuits (learned in Chapters 1 and 2) can be used to create simple digital systems.**
- **These are the low-level building blocks of a digital computer.**
- **Simple digital systems are frequently characterized in terms of**
  - **the registers they contain, and**
  - **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



$R \leftarrow f(R, R)$

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:**

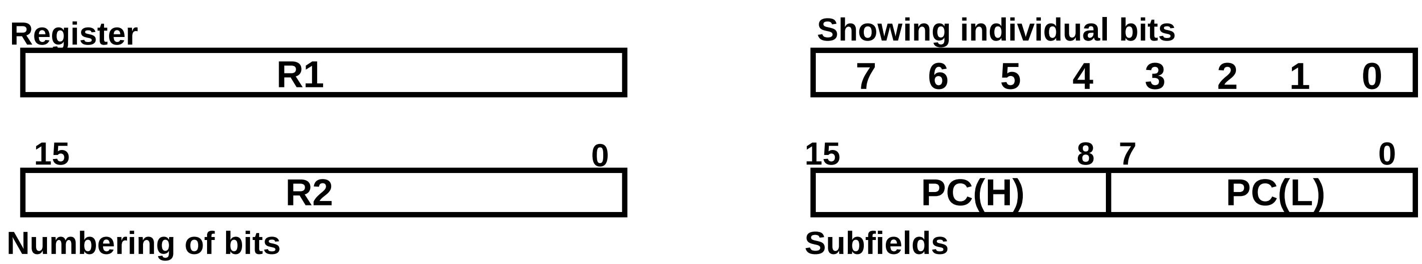
MAR

  - **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 R2 are copied (loaded) into register R1**
  - **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

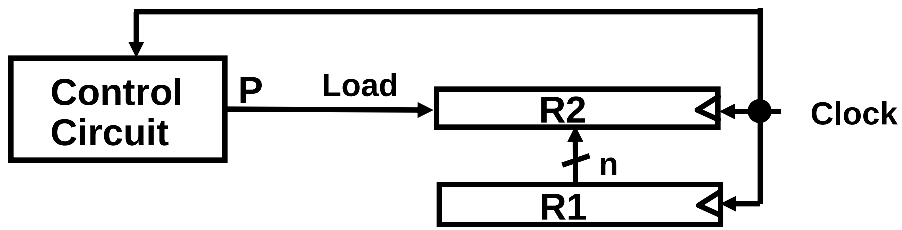
Which means "if P = 1, then load the contents of register R1 into register R2", i.e., if (P = 1) then (R2 $\leftarrow$ R1)

HARDWARE IMPLEMENTATION OF CONTROLLED TRANSFERS

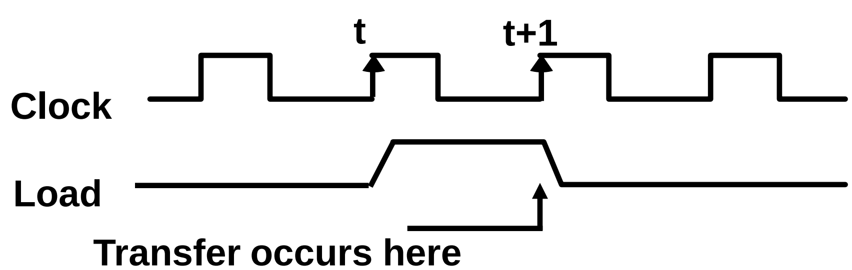
Implementation of controlled transfer

P: R2 $\leftarrow$ R1

Block diagram



Timing diagram



- The same clock controls the circuits that generate the control function and the destination register
- Registers are assumed to use *positive-edge-triggered* flip-flops

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

CONNECTING REGISTERS

- **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**

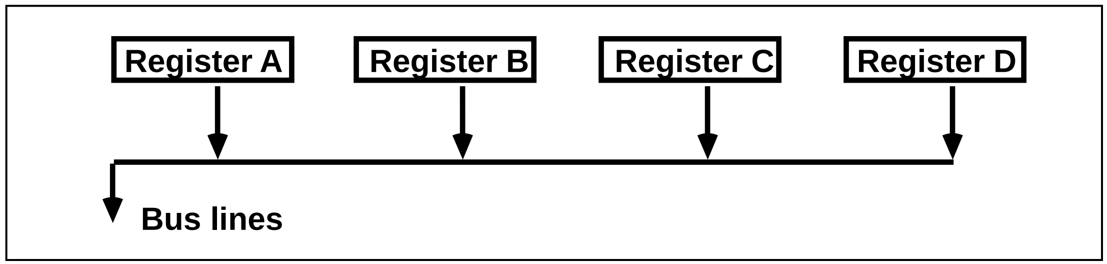
- **To completely connect n registers → n(n-1) lines**
- **$O(n^2)$ cost**
  - **This is not a realistic approach to use in a large digital system**

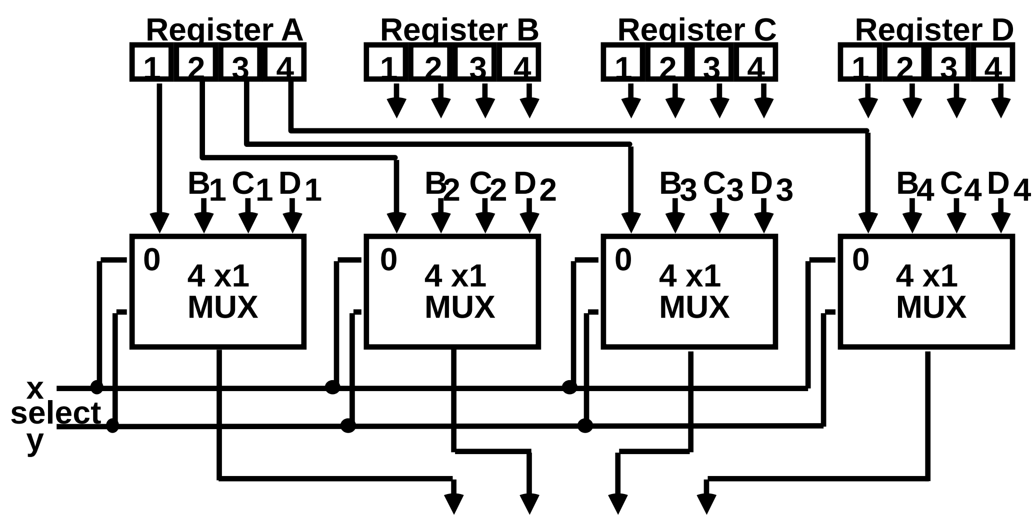
- **Instead, take a different approach**
- **Have one centralized set of circuits for data transfer – the bus**
- **Have control circuits to select which register is the source, and which is the destination**

BUS AND BUS TRANSFER

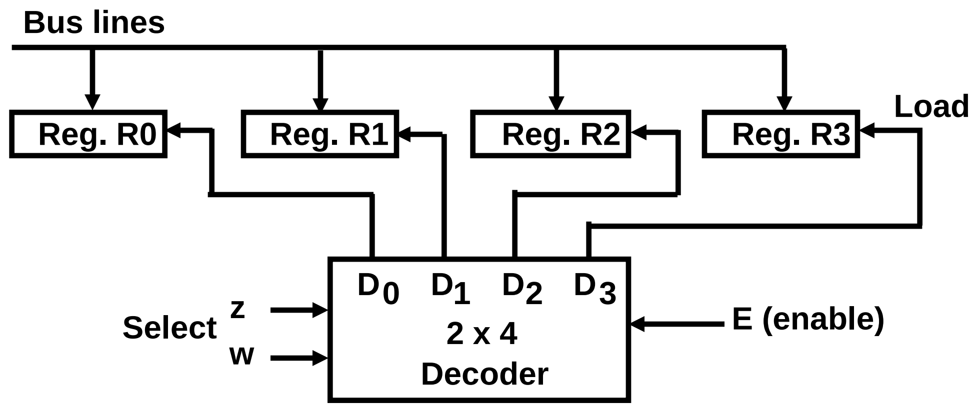
Bus is a path(of a group of wires) over which information is transferred, from any of several sources to any of several destinations.

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

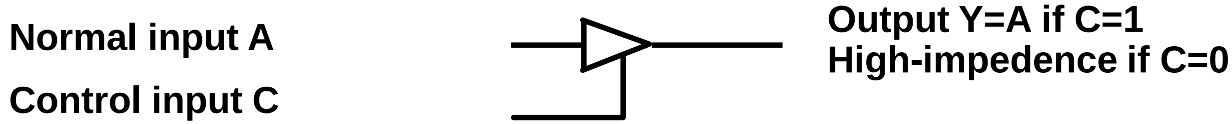




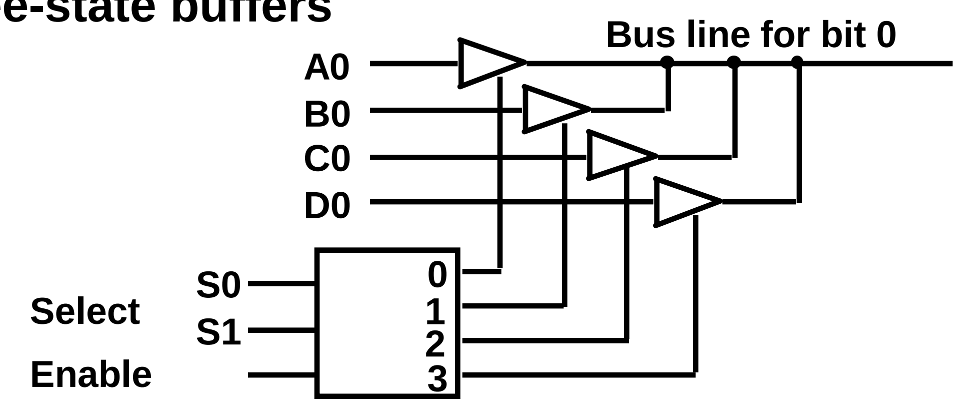
TRANSFER FROM BUS TO A DESTINATION REGISTER



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 $\leftarrow$ R1

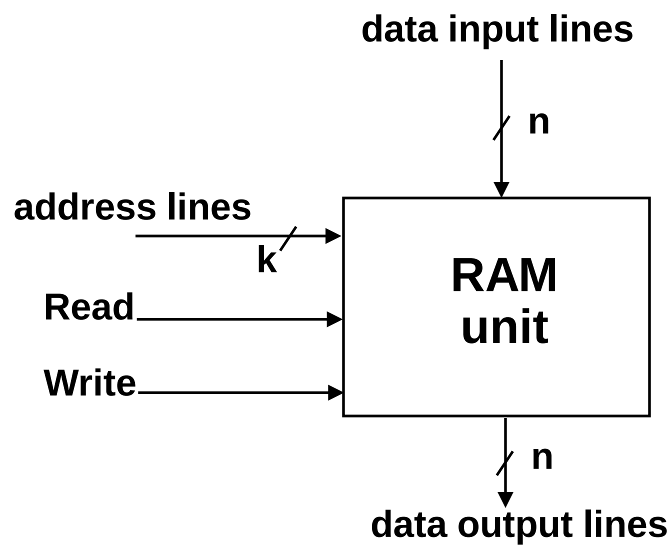
  or

  BUS $\leftarrow$ R1, R2 $\leftarrow$ BUS

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

MEMORY (RAM)

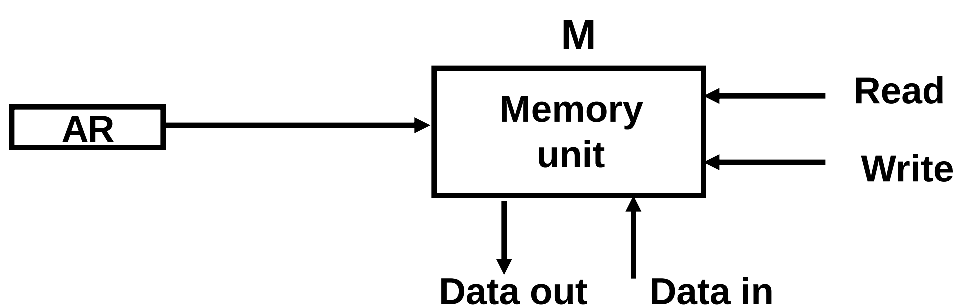
- Memory (RAM) can be thought as a sequential circuits containing some number of registers
- These registers hold the *words* of memory
- Each of the r registers is indicated by an *address*
- These addresses range from 0 to r-1
- Each register (word) can hold n bits of data
- Assume the RAM contains $r = 2^k$ words. It needs the following
  - n data input lines
  - n data output lines
  - k address lines
  - A Read control line
  - A Write control line



MEMORY TRANSFER

- **Collectively, the memory is viewed at the register level as a device, M.**
- **Since it contains multiple locations, we must specify which address in memory we will be using**
- **This is done by indexing memory references**

- **Memory is usually accessed in computer systems by putting the desired address in a special register, the *Memory Address Register* (*MAR*, or *AR*)**
- **When memory is accessed, the contents of the MAR get sent to the memory unit's address lines**



MEMORY READ

- To read a value from a location in memory and load it into a register, the register transfer language notation looks like this:

$$R1 \leftarrow M[MAR]$$

- This causes the following to occur
  - The contents of the MAR get sent to the memory address lines
  - A Read (= 1) gets sent to the memory unit
  - The contents of the specified address are put on the memory's output data lines
  - These get sent over the bus to be loaded into register R1

MEMORY WRITE

- **To write a value from a register to a location in memory looks like this in register transfer language:**

$$M[MAR] \leftarrow R1$$

- **This causes the following to occur**
  - **The contents of the MAR get sent to the memory address lines**
  - **A Write (= 1) gets sent to the memory unit**
  - **The values in register R1 get sent over the bus to the data input lines of the memory**
  - **The values get loaded into the specified address in the memory**

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**
$ABUS \leftarrow R1$, $R2 \leftarrow ABUS$	**Transfer content of R1 into bus A and, at the same time, 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

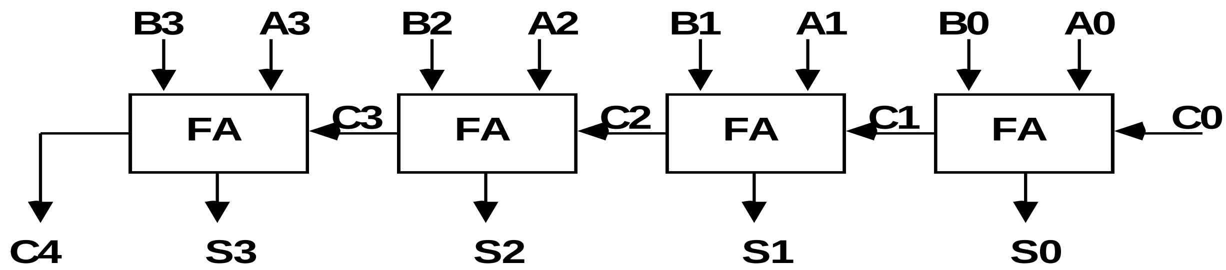
- **The additional arithmetic microoperations are**
  - Add with carry
  - Subtract with borrow
  - Transfer/Load
  - etc. …

Summary of Typical Arithmetic Micro-Operations

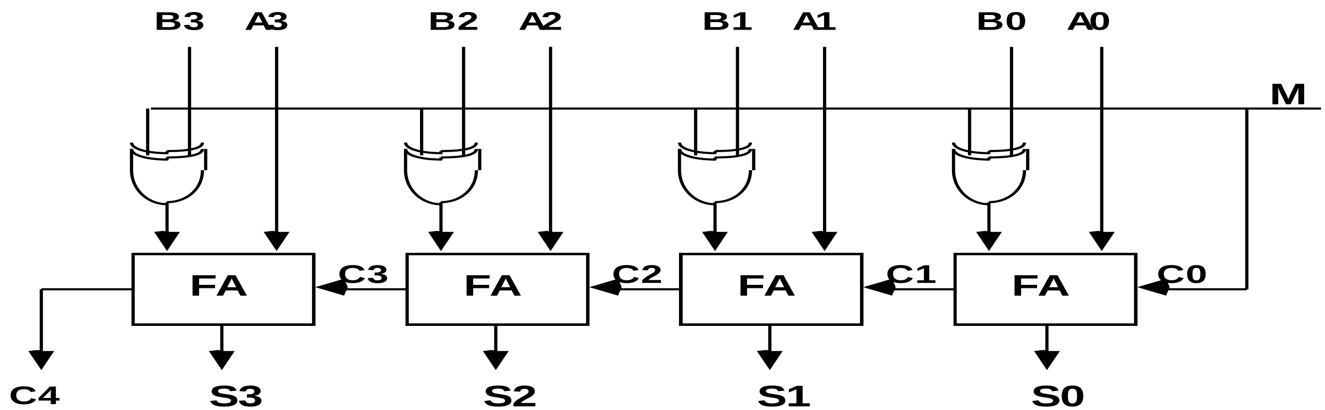
$R3 \leftarrow R1 + R2$	Contents of R1 plus R2 transferred to R3
$R3 \leftarrow R1 - R2$	Contents of R1 minus R2 transferred to R3
$R2 \leftarrow R2'$	Complement the contents of R2
$R2 \leftarrow R2' + 1$	2's complement the contents of R2 (negate)
$R3 \leftarrow R1 + R2' + 1$	subtraction
$R1 \leftarrow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

BINARY ADDER / SUBTRACTOR / INCREMENTER

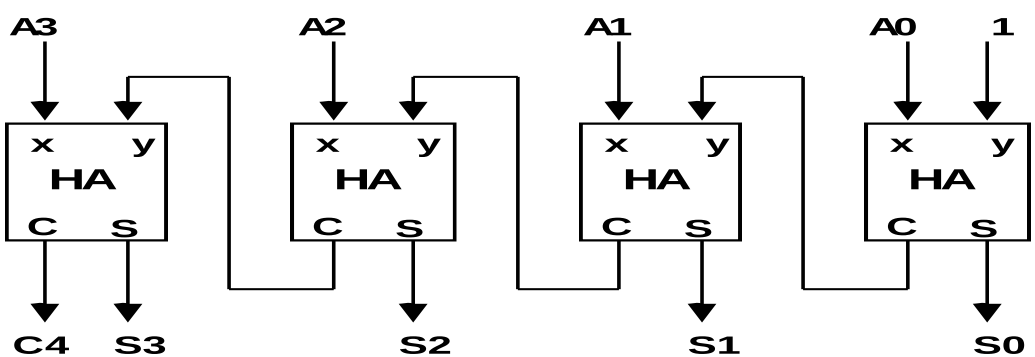
Binary Adder



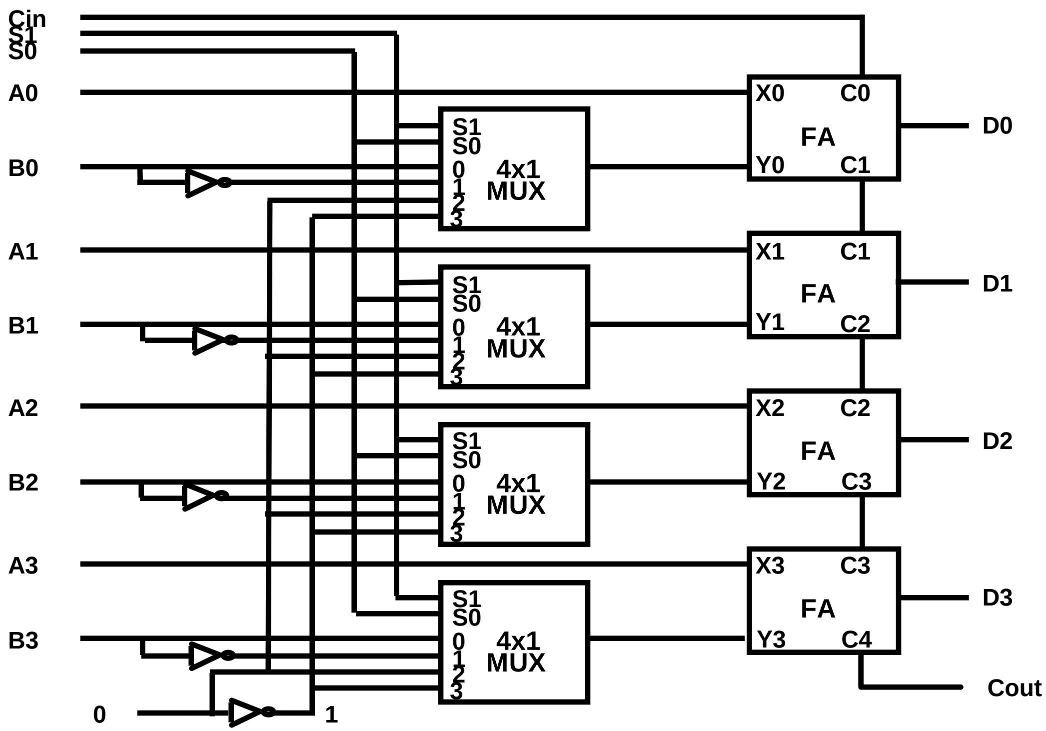
Binary Adder-Subtractor



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**

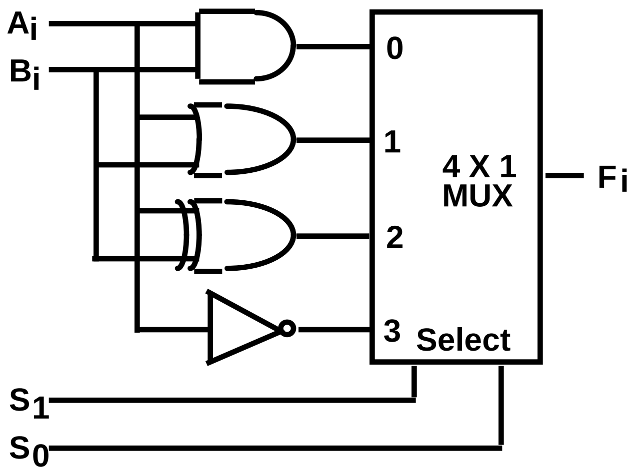
LIST OF LOGIC MICROOPERATIONS

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

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

x y	0 0 1 1 0 1 0 1	*Boolean Function*	*Micro-Operations*	*Name*
	0 0 0 0	F0 = 0	$F \leftarrow 0$	Clear
	0 0 0 1	F1 = xy	$F \leftarrow A \wedge B$	AND
	0 0 1 0	F2 = xy'	$F \leftarrow A \wedge B'$	
	0 0 1 1	F3 = x	$F \leftarrow A$	Transfer A
	0 1 0 0	F4 = x'y	$F \leftarrow A' \wedge B$	
	0 1 0 1	F5 = y	$F \leftarrow B$	Transfer B
	0 1 1 0	F6 = $x \oplus y$	$F \leftarrow A \oplus B$	Exclusive-OR
	0 1 1 1	F7 = x + y	$F \leftarrow A \vee B$	OR
	1 0 0 0	F8 = (x + y)'	$F \leftarrow (A \vee B)'$	NOR
	1 0 0 1	F9 = $(x \oplus y)'$	$F \leftarrow (A \oplus B)'$	Exclusive-NOR
	1 0 1 0	F10 = y'	$F \leftarrow B'$	Complement B
	1 0 1 1	F11 = x + y'	$F \leftarrow A \vee B'$	
	1 1 0 0	F12 = x'	$F \leftarrow A'$	Complement A
	1 1 0 1	F13 = x' + y	$F \leftarrow A' \vee B$	
	1 1 1 0	F14 = (xy)'	$F \leftarrow (A \wedge B)'$	NAND
	1 1 1 1	F15 = 1	$F \leftarrow$ 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

APPLICATIONS OF LOGIC MICROOPERATIONS

- Logic microoperations can be used to manipulate individual bits or a portions of a word in a register

- Consider the data in a register A. In another register, B, is bit data that will be used to modify the contents of A

– Selective-set	$A \leftarrow A + B$
– Selective-complement	$A \leftarrow A \oplus B$
– Selective-clear	$A \leftarrow A \bullet B'$
– Mask (Delete)	$A \leftarrow A \bullet B$
– Clear	$A \leftarrow A \oplus B$
– Insert	$A \leftarrow (A \bullet B) + C$
– Compare	$A \leftarrow A \oplus B$
– . . .	

SELECTIVE SET

- In a selective set operation, the bit pattern in B is used to *set* certain bits in A

1 1 0 0	A_t	
1 0 1 0	B	
1 1 1 0	A_{t+1}	$(A \leftarrow A + B)$

- If a bit in B is set to 1, that same position in A gets set to 1, otherwise that bit in A keeps its previous value

SELECTIVE COMPLEMENT

- **In a selective complement operation, the bit pattern in B is used to *complement* certain bits in A**

1 1 0 0	A_t	
1 0 1 0	B	
0 1 1 0	A_{t+1}	$(A \leftarrow A \oplus B)$

- **If a bit in B is set to 1, that same position in A gets complemented from its original value, otherwise it is unchanged**

SELECTIVE CLEAR

- In a selective clear operation, the bit pattern in B is used to *clear* certain bits in A

$$\begin{array}{ll} 1\,1\,0\,0 & A_t \\ 1\,0\,1\,0 & B \\ \hline 0\,1\,0\,0 & A_{t+1} \quad (A \leftarrow A \cdot B') \end{array}$$

- If a bit in B is set to 1, that same position in A gets set to 0, otherwise it is unchanged

MASK OPERATION

- In a mask operation, the bit pattern in B is used to *clear* certain bits in A

1 1 0 0	A_t	
1 0 1 0	B	
1 0 0 0	A_{t+1}	$(A \leftarrow A \cdot B)$

- If a bit in B is set to 0, that same position in A gets set to 0, otherwise it is unchanged

CLEAR OPERATION

- In a clear operation, if the bits in the same position in A and B are the same, they are cleared in A, otherwise they are set in A

$$
\begin{array}{ll}
1\ 1\ 0\ 0 & A_t \\
1\ 0\ 1\ 0 & B \\
\hline
0\ 1\ 1\ 0 & A_{t+1} \quad (A \leftarrow A \oplus B)
\end{array}
$$

Organization

INSERT OPERATION

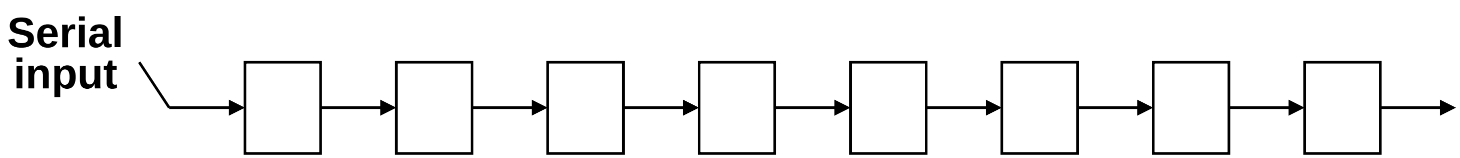
- An insert operation is used to introduce a specific bit pattern into A register, leaving the other bit positions unchanged
- This is done as
  - A mask operation to clear the desired bit positions, followed by
  - An OR operation to introduce the new bits into the desired positions
  - Example
    - » Suppose you wanted to introduce 1010 into the low order four bits of A: 1101 1000 1011 0001 A (Original)
      1101 1000 1011 1010 A (Desired)

```
» 1101 1000 1011 0001        A (Original)
  1111 1111 1111 0000        Mask
  ------------------------------------------
  1101 1000 1011 0000        A (Intermediate)
  0000 0000 0000 1010        Added bits
  ------------------------------------------
  1101 1000 1011 1010        A (Desired)
```

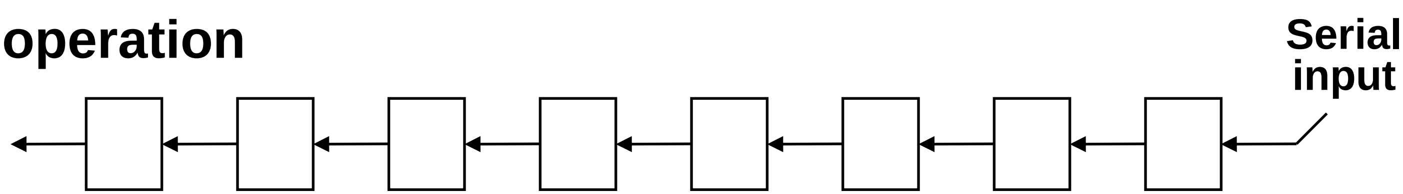
SHIFT MICROOPERATIONS

- 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



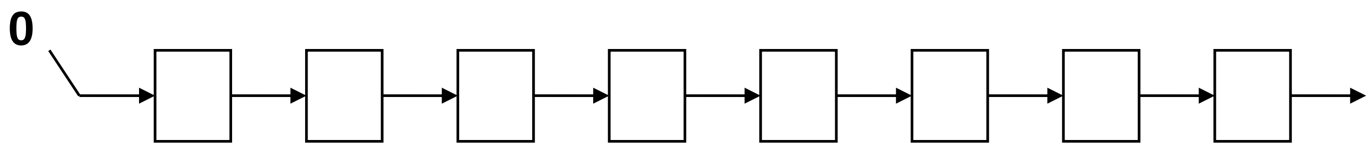
- A left shift operation



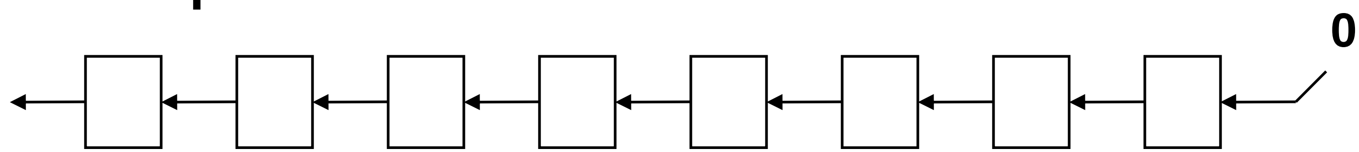
LOGICAL SHIFT

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

- A right logical shift operation:



- A left logical shift operation:

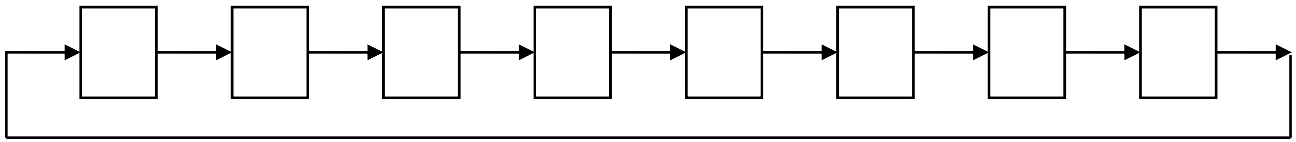


- In a Register Transfer Language, the following notation is used
  - *shl* for a logical shift left
  - *shr* for a logical shift right
  - Examples:
    - » R2 $\leftarrow$ *shr* R2
    - » R3 $\leftarrow$ *shl* R3

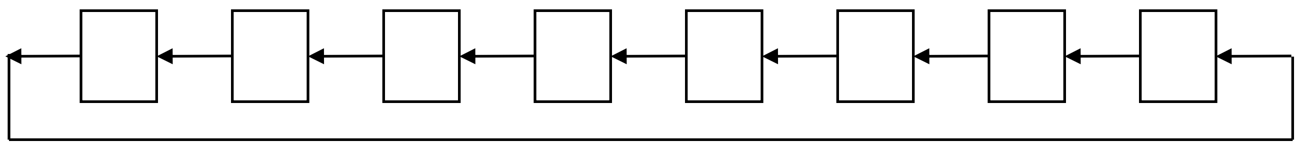
CIRCULAR SHIFT

- **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:**

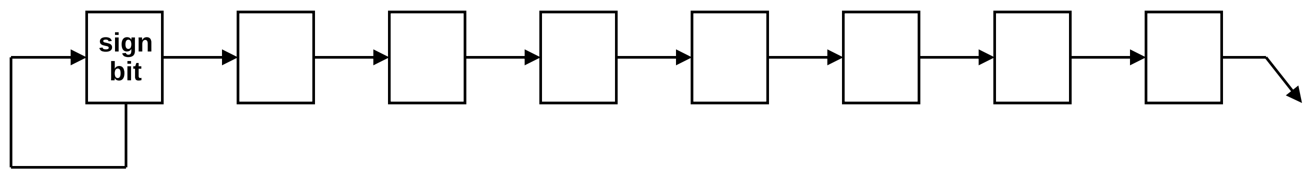


- **In a RTL, the following notation is used**
  - ***cil*   for a circular shift left**
  - ***cir*   for a circular shift right**
  - **Examples:**
    - » **R2 ← *cir* R2**
    - » **R3 ← *cil* R3**

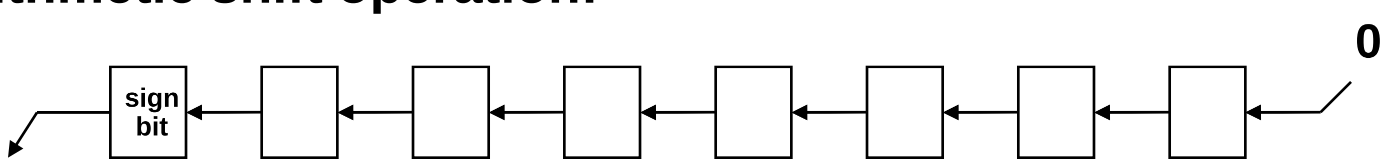
ARITHMETIC SHIFT

- 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:

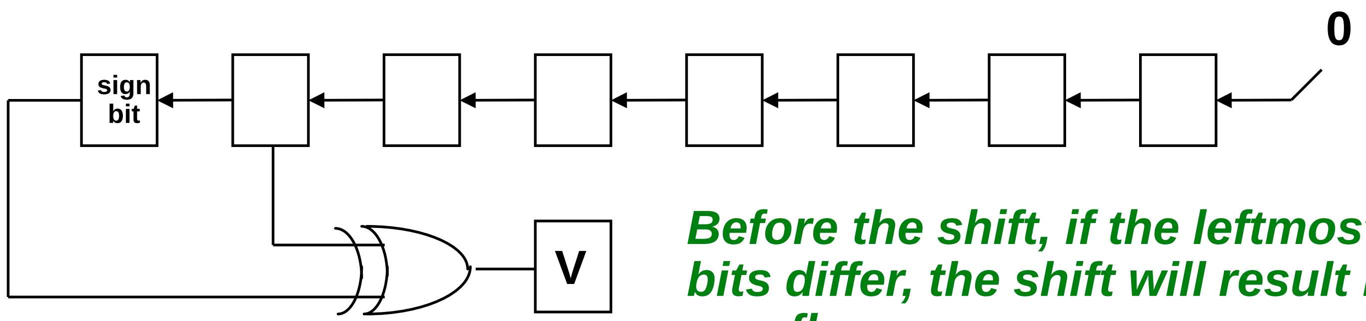


- A left arithmetic shift operation:



ARITHMETIC SHIFT

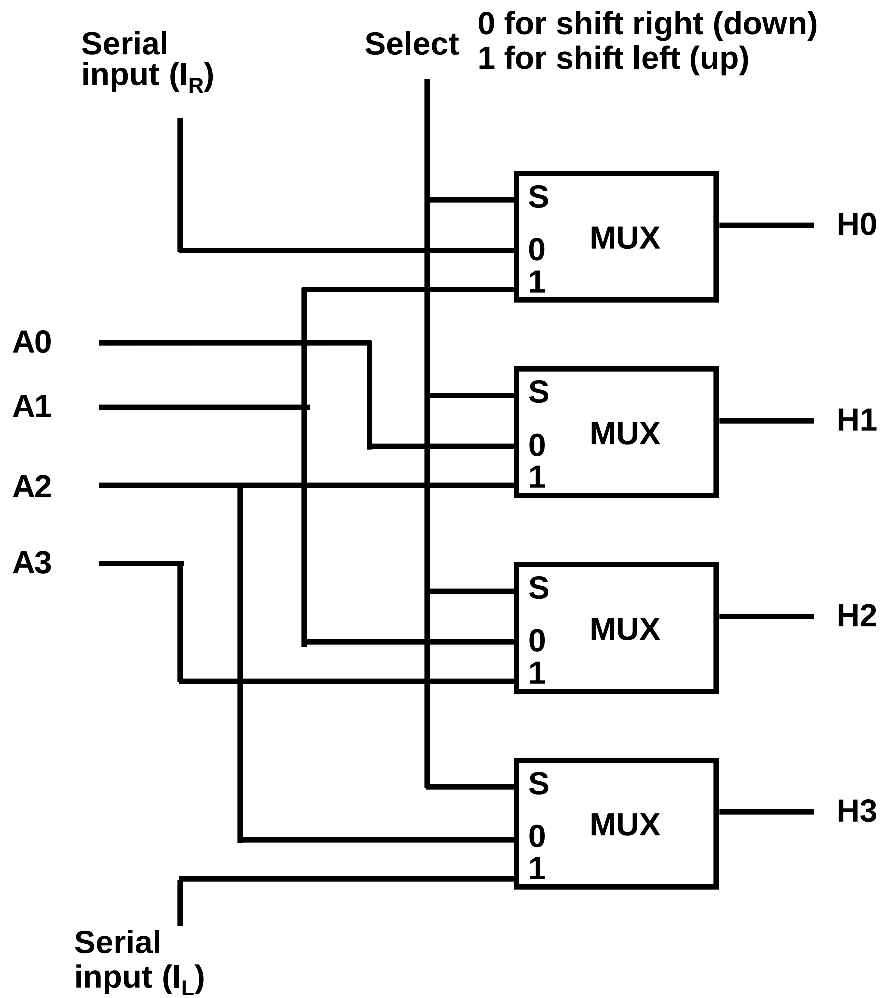
- An left arithmetic shift operation must be checked for the overflow



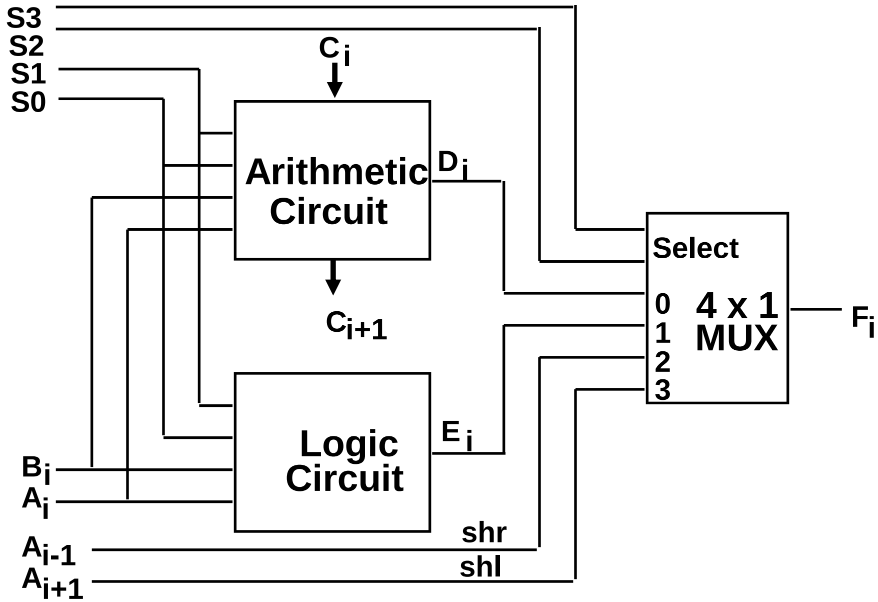
Before the shift, if the leftmost two bits differ, the shift will result in an overflow

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

HARDWARE IMPLEMENTATION OF SHIFT MICROOPERATIONS



ARITHMETIC LOGIC SHIFT UNIT



S3	S2	S1	S0	Cin	Operation	Function
0	0	0	0	0	F = A+B	Addition
0	0	0	0	1	F = A +B+1	Add with carry
0	0	0	1	0	F = A + B’	Subtract with borrow
0	0	0	1	1	F = A + B + 1	Subtraction
0	0	1	0	0	F = A	Transfer A
0	0	1	0	1	F = A + 1	Increment A
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 $\wedge$ B	AND
0	1	0	1	X	F = A $\vee$ B	OR
0	1	1	0	X	F = A $\oplus$ 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