

Chapter 3 Digital Logic Structures

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Computing Layers

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- Problems
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- Algorithms
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- Language
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- Instruction Set Architecture
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State Machine

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- Another type of sequential circuit
 - Combines combinational logic with storage
 - “Remembers” state, and changes output (and state) based on **inputs** and **current state**

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Combinational vs. Sequential

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- Two types of “combination” locks

4 1 8 4

Combinational

Success depends only on the **values**, not the order in which they are set.

Sequential

Success depends on the **sequence** of values (e.g. R-13, L-22, R-3).

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State

- The **state** of a system is a **snapshot** of **all the relevant elements** of the system at the moment the snapshot is taken.

Examples:

- The state of a basketball game can be represented by the scoreboard: number of points, time remaining, possession, etc.
- The state of a tic-tac-toe game can be represented by the placement of X's and O's on the board.

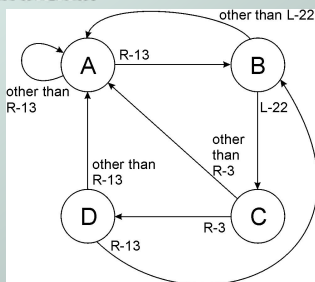
State of Sequential Lock

Our lock example has four different states, labelled A-D:

- A:** The lock is **not open**, and no relevant operations have been performed.
- B:** The lock is **not open**, and the user has completed the **R-13** operation.
- C:** The lock is **not open**, and the user has completed **R-13**, followed by **L-22**.
- D:** The lock is **open**.

State Diagram

- Shows **states** and **actions** that cause a **transition** between states.

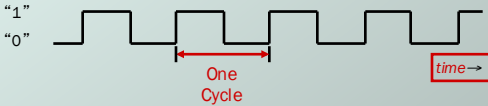


Finite State Machine

- A system with the following components:
 1. A finite number of **states**
 2. A finite number of external **inputs**
 3. A finite number of external **outputs**
 4. An explicit specification of all **state transitions**
 5. An explicit specification of what determines each external **output value**
- Often described by a state diagram.
 - Inputs trigger state transitions.
 - Outputs are associated with each state (or with each transition).

The Clock

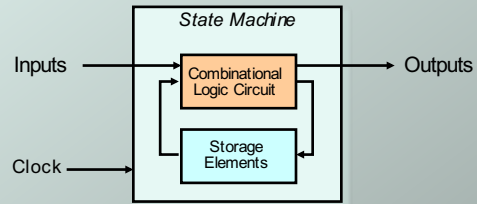
- Frequently, a **clock circuit** triggers transition from one state to the next.



- At the beginning of each clock cycle, state machine makes a transition, based on the current state and the external inputs.
 - Not always required. In lock example, the input itself triggers a transition.

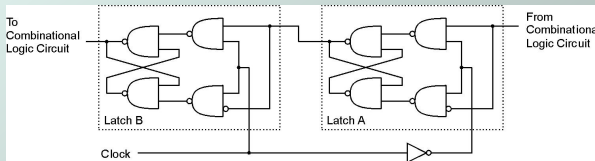
Implementing a Finite State Machine

- **Combinational logic**
 - Determine outputs and next state.
- **Storage elements**
 - Maintain state representation.



Storage: Master-Slave Flipflop

- A pair of gated D-latches, to isolate *next* state from *current* state.



During 1st phase (clock=1), previously-computed state becomes *current* state and is sent to the logic circuit.

During 2nd phase (clock=0), *next* state, computed by logic circuit, is stored in Latch A.

Storage

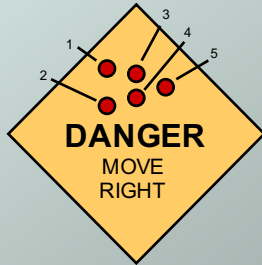
- Each master-slave flipflop stores one state bit.
- The number of storage elements (flipflops) needed is determined by the number of states (and the representation of each state).

- **Examples:**

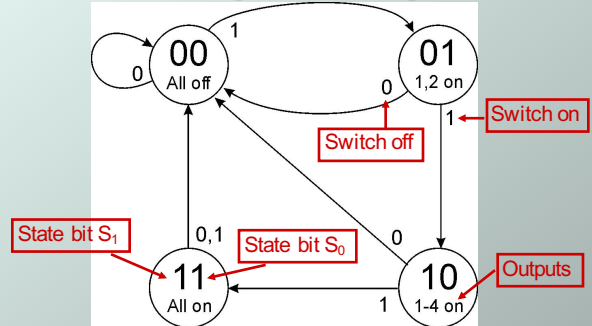
- Sequential lock
 - Four states – two bits
- Basketball scoreboard
 - 7 bits for each score, 5 bits for minutes, 6 bits for seconds, 1 bit for possession arrow, 1 bit for half, ...

Complete Example

- A blinking traffic sign
 - No lights on
 - 1 & 2 on
 - 1, 2, 3, & 4 on
 - 1, 2, 3, 4, & 5 on
 - (repeat as long as switch is turned on)



Traffic Sign State Diagram



Transition on each clock cycle.

Traffic Sign Truth Tables

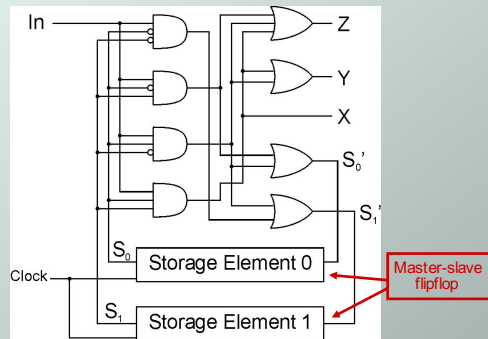
Outputs
(depend only on state: $S_1 S_0$)

S_1	S_0	Z	Y	X
0	0	0	0	0
0	1	1	0	0
1	0	1	1	0
1	1	1	1	1

Next State: $S_1' S_0'$
(depend on state and input)

In	S_1	S_0	S_1'	S_0'
0	X	X	0	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	1
1	1	1	0	0

Traffic Sign Logic



From Logic to Data Path

- The data path of a computer is all the logic used to process information.
 - See the data path of the LC-3 on next slide.
- **Combinational Logic**
 - Decoders -- convert instructions into control signals
 - Multiplexers -- select inputs and outputs
 - ALU (Arithmetic and Logic Unit) -- operations on data
- **Sequential Logic**
 - State machine -- coordinate control signals and data movement
 - Registers and latches -- storage elements

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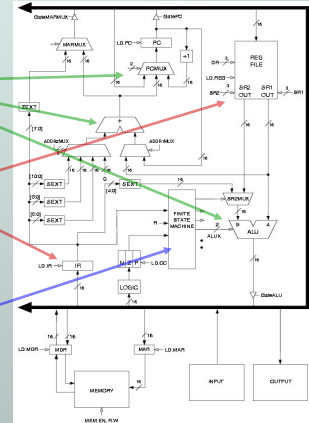
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LC-3 Data Path

Combinational Logic

Storage

State Machine



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Looking Ahead: C Arrays

- Array name can be used (and passed) as a pointer

```
// static allocation for array
int iArray[2] = {1234, 5678};
printf("iArray[0]: %d", iArray[0]);
printf("iArray[1]: %d", iArray[1]);
printf("siArray[0]: %p", siArray[0]);
printf("siArray[1]: %p", siArray[1]);
printf("iArray: %p", iArray);
```

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Looking Ahead: C Pointers

- Pointers can be used for array access

```
// dynamic allocation for array
int *iArray = malloc(2*sizeof(int));
iArray[0] = 1234; iArray[1] = 5678;
printf("iArray[0]: %d", iArray[0]);
printf("iArray[1]: %d", iArray[1]);
printf("siArray[0]: %p", siArray[0]);
printf("siArray[1]: %p", siArray[1]);
printf("iArray: %p", iArray);
```

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Looking Ahead: C Structures

◆ Structures

```
struct Student {
    char firstName[80];
    char lastName[80];
    int testScores[2];
    char letterGrade;
};
struct Student student;
struct Student students[10];
```

Looking Ahead: C Structures

◆ Structures

```
typedef struct _Student {
    char firstName[80];
    char lastName[80];
    int testScores[2];
    char letterGrade;
} Student;
Student student;
Student students[10];
```

Looking Ahead: C Structures

◆ Structures

```
typedef struct {
    char firstName[80];
    char lastName[80];
    int testScores[2];
    char letterGrade;
} Student;
Student student;
Student students[10];
```

Looking Ahead: C Structures

◆ Accessing structures

```
void func(Student student)
{
    strcpy(student.firstName, "John");
    student.letterGrade = 'A';
}

void func(Student *student)
{
    strcpy(student->firstName, "John");
    student->letterGrade = 'A';
}
```

Looking Ahead: Makefiles

- File list and compiler flags

```
C_SRCS = main.c example.c
C_OBJS = main.o example.o
C_HEADERS = example.h
EXE = example
```

```
CC = gcc
CC_FLAGS = -g -Wall -c
LD_FLAGS = -g -Wall
```

Looking Ahead: Makefiles

- File dependencies

```
# Compile .c source to .o objects
.c.o:
    @echo "Compiling C source files"
    $(CC) $(CC_FLAGS) $<
```

```
# Make .c files depend on .h files
$(C_OBJS): $(C_HEADERS)
```

Looking Ahead: Makefiles

- Build target (default)

```
# Target is the executable
default: $(C_OBJS)
    @echo "Linking object modules"
    $(CC) $(LD_FLAGS) $(C_OBJS) -o $(EXE)
```

Looking Ahead: Makefiles

- Miscellaneous targets

```
# Clean up the directory
clean:
    @echo "Cleaning up project directory"
    rm -f *.o *~ $(EXE)

# Package up the directory
package:
    @echo "Cleaning up project directory"
    tar cvf example.tar ../example
```