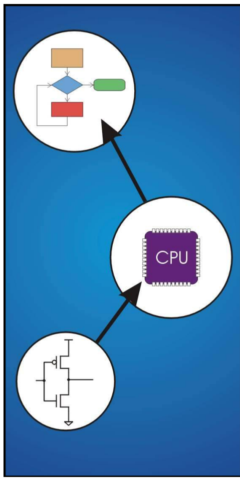

Chapter 3
Digital Logic Structures

Original slides from Gregory Byrd, North Carolina State University

Modified slides by Chris Wilcox, Colorado State University

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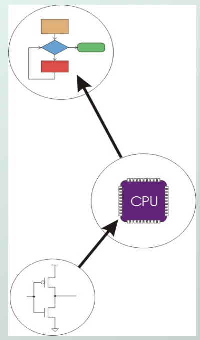
Computing Layers



- Problems
- Algorithms
- Language
- Instruction Set Architecture
- Microarchitecture
- Circuits ←
- Devices

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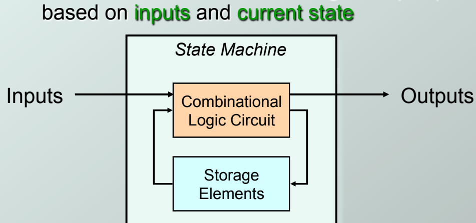
State Machine

- 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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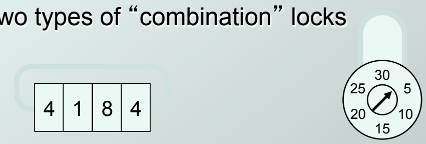
Combinational vs. Sequential

- Two types of "combination" locks



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.

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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.

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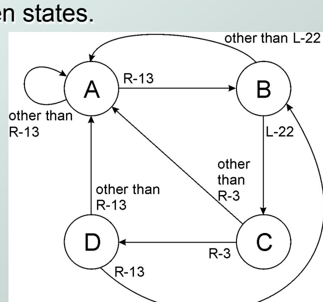
State Diagram

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



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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).

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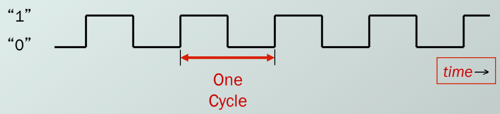
The Clock

- 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.**

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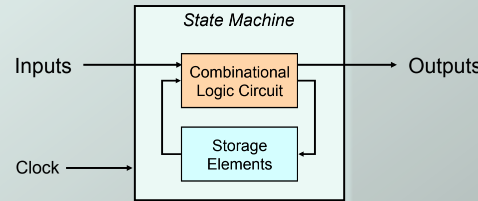
Implementing a Finite State Machine

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



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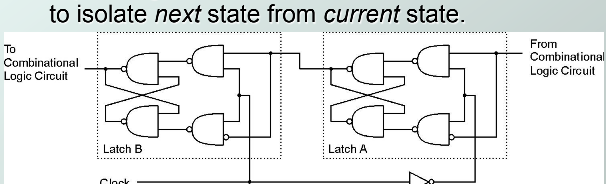
Storage: Master-Slave Flipflop

- 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.

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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, …

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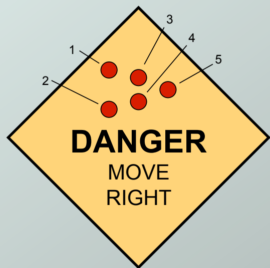
Complete Example

- 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)



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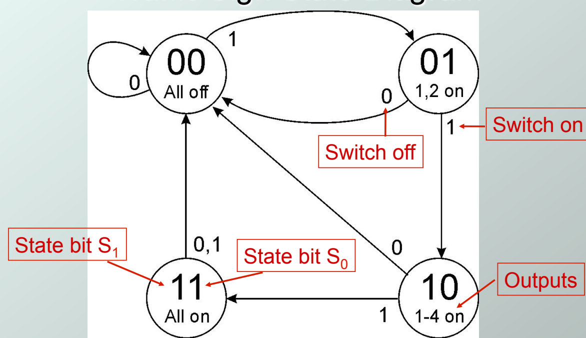
Traffic Sign State Diagram



Transition on each clock cycle.

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Traffic Sign Truth Tables

Outputs
(depend only on state: S_1S_0)

Lights 1 and 2 → Z; Lights 3 and 4 → Y; Light 5 → X

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)

Switch → In

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

Whenever In=0, next state is 00.

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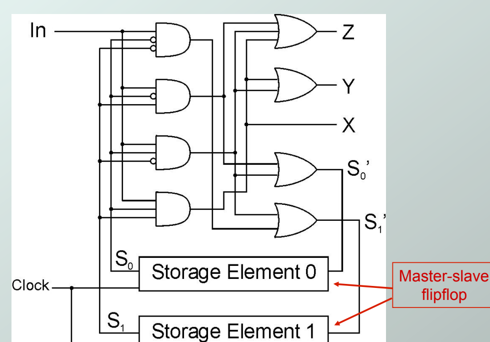
Traffic Sign Logic



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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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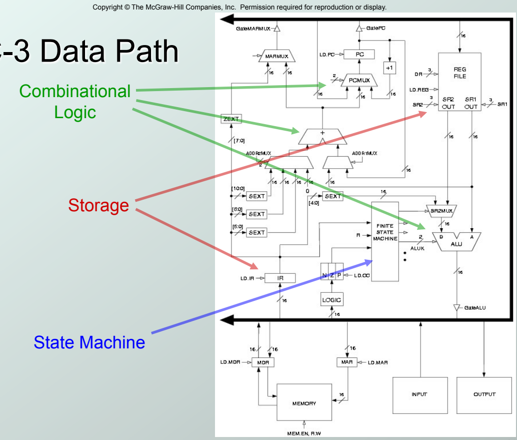
LC-3 Data Path



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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("&iArray[0]: %p", &iArray[0]);
printf("&iArray[1]: %p", &iArray[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("&iArray[0]: %p", &iArray[0]);
printf("&iArray[1]: %p", &iArray[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];
```


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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];
```


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Looking Ahead: C Structures

- Structures

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


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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';
```

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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 = c11
CC_FLAGS = -g -Wall -c
LD_FLAGS = -g -Wall
```


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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}
```


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Looking Ahead: Makefiles

- Build target (default)

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


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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
```