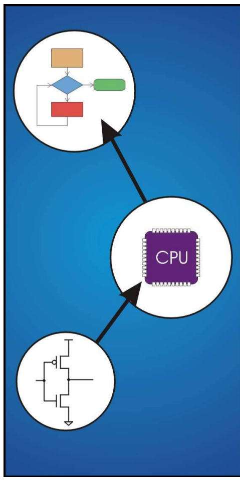
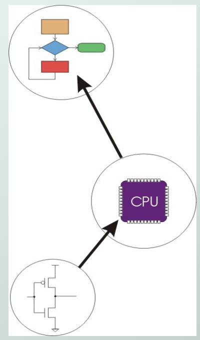


Chapter 3
Digital Logic Structures

Original slides from Gregory Byrd, North Carolina State University

Modified slides by Chris Wilcox, Colorado State University

Computing Layers



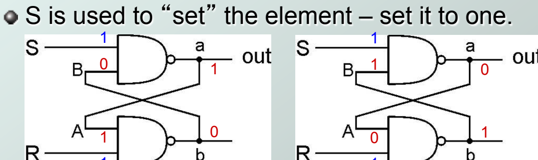
- Problems
- Algorithms
- Language
- Instruction Set Architecture
- Microarchitecture
- Circuits ←
- Devices

Combinational vs. Sequential

- **Combinational Circuit**
  - does not store information, always gives the same output for a given set of inputs
    - *example*: adder always generates sum and carry, regardless of previous inputs
- **Sequential Circuit**
  - stores information, output depends on stored info (state) plus input
  - so a given input might produce different outputs, depending on the stored information
  - useful for building "memory" elements and "state machines"
    - *example*: ticket counter

R-S Latch: Simple Storage Element

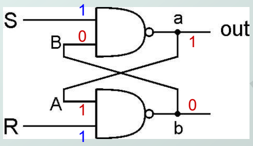
- R is used to "reset" or "clear" the element – set it to zero.
- S is used to "set" the element – set it to one.



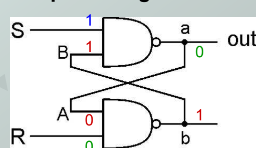
- If both R and S are one, output could be either zero or one.
  - "quiescent" state -- holds its previous value
  - if a is 1, b is 0, and vice versa

Clearing the R-S latch

- Suppose we start with output = 1, then change R to zero.



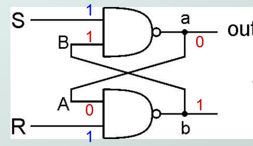
Output changes to zero.



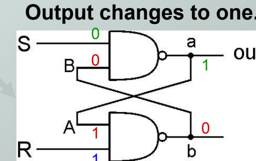
Then set R=1 to "store" value in quiescent state.

Setting the R-S Latch

- Suppose we start with output = 0, then change S to zero.



Output changes to one.



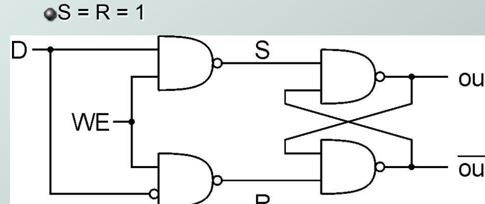
Then set S=1 to "store" value in quiescent state.

R-S Latch Summary

- **R = S = 1**
  - hold current value in latch
- **S = 0, R=1**
  - set value to 1
- **R = 0, S = 1**
  - set value to 0
- **R = S = 0**
  - both outputs equal one
  - final state determined by electrical properties of gates
  - ***Don't do it!***

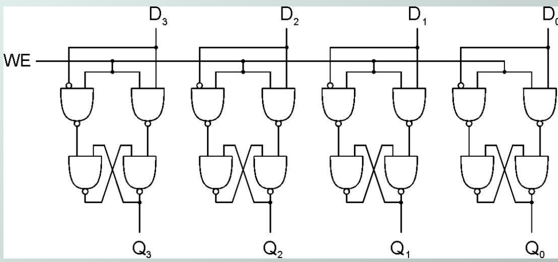
Gated D-Latch

- Two inputs: D (data) and WE (write enable)
  - when **WE = 1**, latch is set to **value of D**
    - S = NOT(D), R = D
  - when **WE = 0**, latch holds **previous value**
    - S = R = 1



Register

- A register stores a multi-bit value.
  - We use a collection of D-latches, all controlled by a common WE.



Representing Multi-bit Values

- Number bits from right (0) to left (n-1)
  - just a convention -- could be left to right, but must be *consistent*
- Use brackets to denote range:
  D[l:r] denotes bit **l** to bit **r**, from *left* to *right*

15 0

A = **0101001101010101**

A[14:9] = **101001**   A[2:0] = **101**

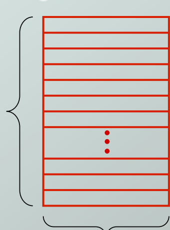
- May also see A**<14:9>**,
  especially in hardware block diagrams.

Memory

- Now that we know how to store bits, we can build a memory – a logical *k* × *m* array of stored bits.

Address Space:
number of locations
(usually a power of 2)

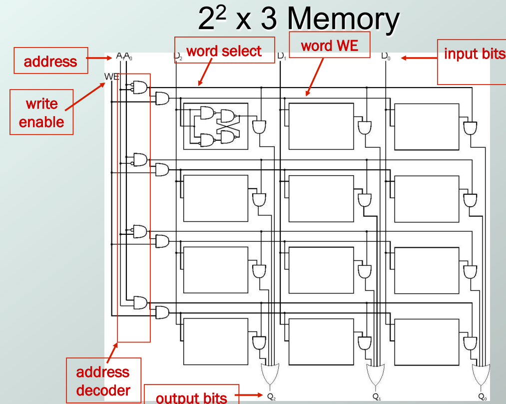
$k = 2^n$
locations



Addressability:
number of bits per location
(e.g., byte-addressable)

m bits

2^2 x 3 Memory



More Memory Details

- Not the way actual memory is implemented!
  - fewer transistors, denser, relies on electrical properties
- But the logical structure is very similar.
  - address decoder, word select line, word write enable
- Random Access Memory: 2 different types
  - Static RAM (SRAM)
    - fast, used for caches, maintains data when powered
  - Dynamic RAM (DRAM)
    - slower but denser, storage decays, must be refreshed
- Non-Volatile Memory: ROM, PROM, Flash

Memory Bandwidth

- Bandwidth is the rate at which memory can be read or written by the processor.
- Approximately equal to the memory bus size times the speed at which the memory is clocked.
- Examples of bandwidth (from Wikipedia):
  - Phone line, Modem, up to 5.6KB/s
  - Digital subscriber line, ADSL, up to 128KB/s
  - Wireless networking, 802.11g, up to 17.5MB/s
  - Peripheral connection, USB 2.0, 60MB/s
  - Digital video, HDMI, up to 1.275GB/s
  - Computer bus, PCI Express, up to 25.6GB/s
  - Memory chips, SDRAM, up to 52GB/s

Looking Ahead: C Arrays

- Similar to Java arrays

```
// integer array
int iArray[3] = {1,2,3};
printf("iArray[2]: %d", iArray[2]);
// float array
float fArray[2] = {0.1f,0.2f};
printf("fArray[1]: %f", fArray[1]);
// character array
char cArray[4] = {'a','b','c','d'};
printf("cArray[3]: %c", cArray[3]);
```


Looking Ahead: C Strings

- Array of chars with null (not NULL) termination

```
// string: static allocation
char *string1 = "Hello World\n";
printf("string1: %s", string1);

// string: dynamic allocation
char *string2 = malloc(13);
strcpy(string2, "Hello World\n");
```

Note that the programmer is responsible for making sure string has enough memory!

Looking Ahead: C Arrays and C Pointers

- Array name is a pointer to array

```
int iArray[2] = {1234, 5678};

printf("iArray[0]: %d", iArray[0]);
printf("iArray[1]: %d", iArray[1]);
printf("&iArray[0]: %x", &iArray[0]);
printf("&iArray[1]: %x", &iArray[1]);
printf("iArray: %x", iArray);
iArray[2] = 0; // out of bounds!
```


Looking Ahead: C Functions

- Can pass by value or reference

```
// by value (copies value)
float f1(int i, float f);
// by reference (copies pointer)
float f2(float *f);
```

- Function cannot change values passed by value

```
f1: i = 10; // changes the copy
```

- Function can change values passed by reference

```
f2: *f = 1.2; // changes actual value
```