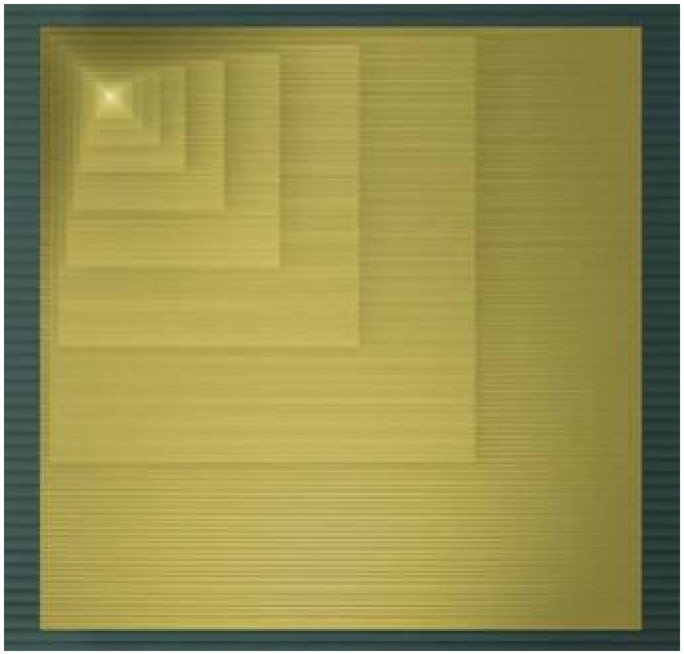


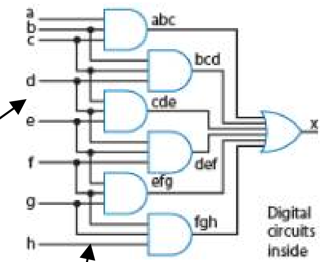
# Digital Design

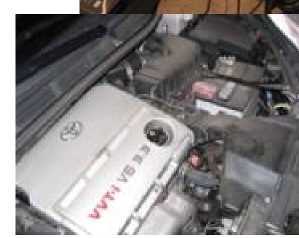
## Chapter 1: Introduction

Slides to accompany the textbook *Digital Design*, First Edition,
by Frank Vahid, John Wiley and Sons Publishers, 2007.
http://www.ddvahid.com

# Why Study Digital Design?

- Look "under the hood" of computers
  - Solid understanding --> confidence, insight, even better programmer when aware of hardware resource issues
- Electronic devices becoming digital
  - Enabled by shrinking and more capable chips
  - Enables:
    - Better devices: Better sound recorders, cameras, cars, cell phones, medical devices,...
    - New devices: Video games, PDAs, ...
  - Known as "embedded systems"
    - Thousands of new devices every year
    - Designers needed: Potential career direction



Portable music players (1995) · Satellites (1997) · Cell phones (1999) · DVD players (2001) · Cameras (2003) · Video recorders (2005) · TVs (2007) · Musical instruments · ???

1995 1997 1999 2001 2003 2005 2007

- Years shown above indicate when digital version began to *dominate*
  - (*Not* the first year that a digital version appeared)

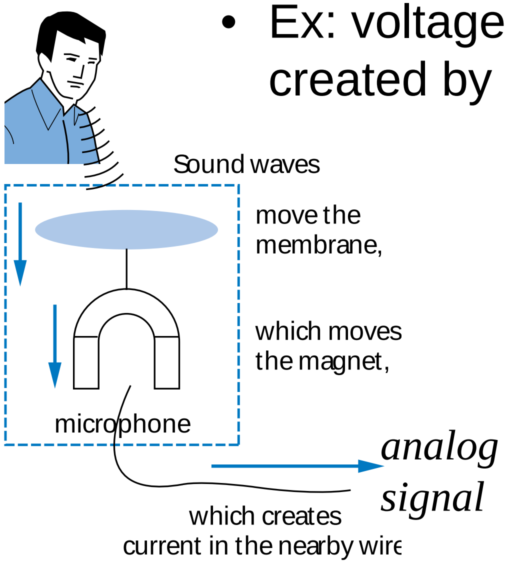




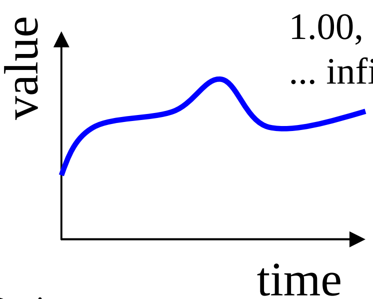
Note: Slides with animation are denoted with a small red "a" near the animated items

# What Does "Digital" Mean?

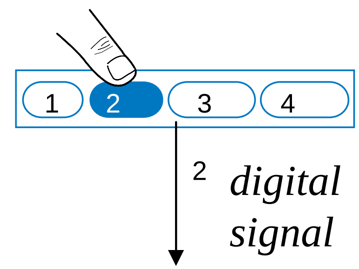
- Analog signal
  - Inifinite possible values
    - Ex: voltage on a wire created by microphone

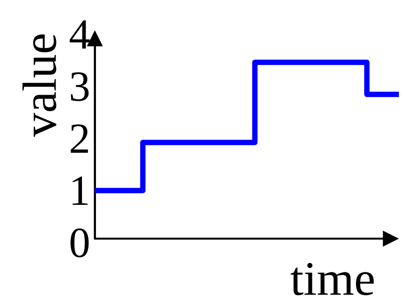



Possible values:
1.00, 1.01, 2.0000009,
... infinite possibilities




- Digital signal
  - Finite possible values
    - Ex: button pressed on a keypad

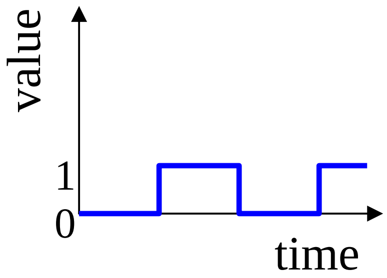



Possible values:
0, 1, 2, 3, or 4.
That's it.

# Digital Signals with Only Two Values: Binary

- ***Binary*** digital signal -- only *two* possible values
  - Typically represented as **0** and **1**
  - One *b*inary dig*it* is a ***bit***
  - We'll only consider *binary* digital signals
  - Binary is popular because
    - Transistors, the basic digital electric component, operate using *two* voltages (more in Chpt. 2)
    - Storing/transmitting one of *two* values is easier than three or more (e.g., loud beep or quiet beep, reflection or no reflection)

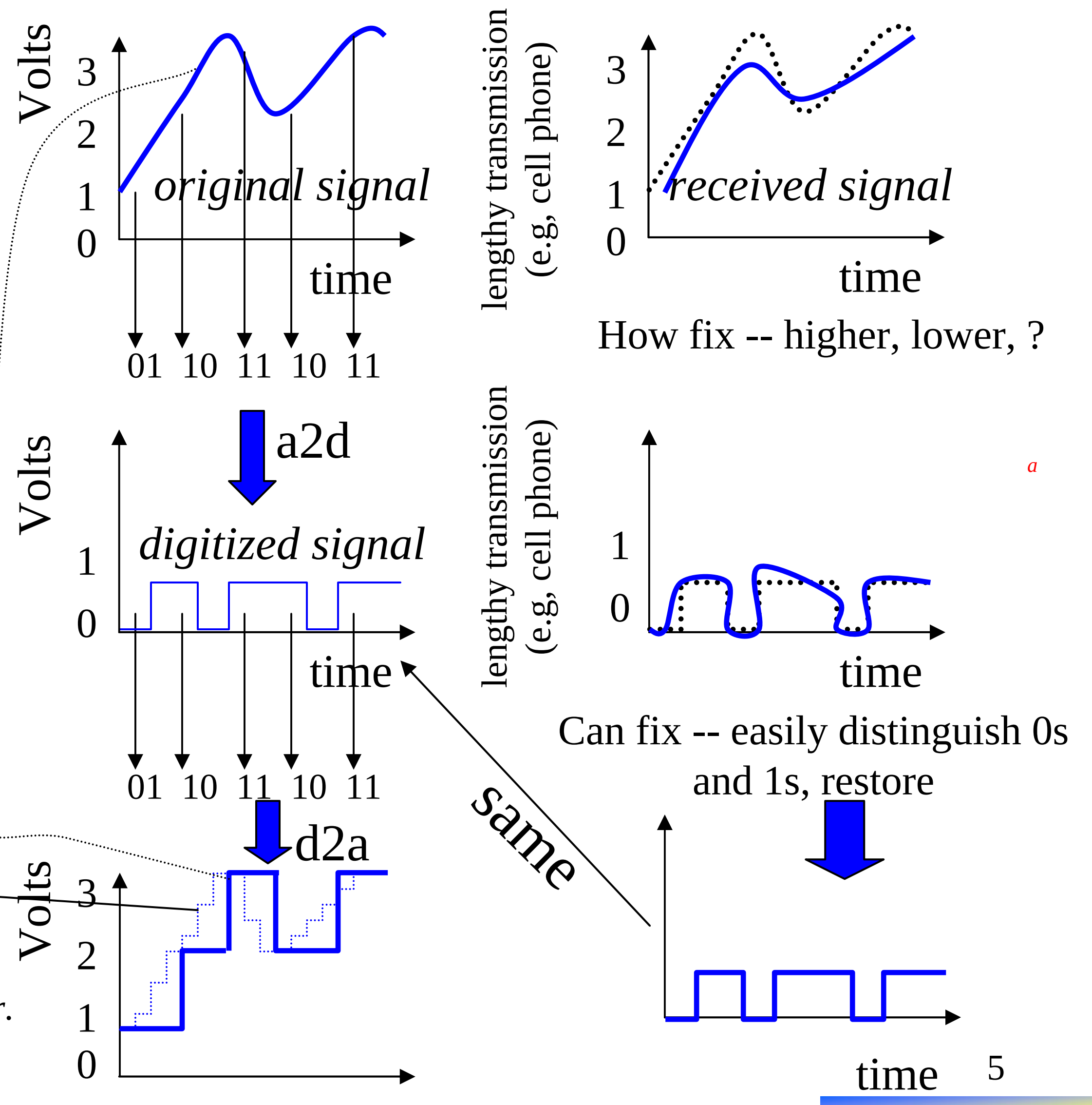


# Example of Digitization Benefit

- Analog signal (e.g., audio) may lose quality
  - Voltage levels not saved/copied/transmitted perfectly
- Digitized version enables near-perfect save/cpy/trn.
  - “Sample” voltage at particular rate, save sample using bit encoding
  - Voltage levels still not kept perfectly
  - But we can distinguish 0s from 1s

Let bit encoding be:
  1 V: “01”
  2 V: “10”
  3 V: “11”

*Digitized signal not perfect re-creation, but higher sampling rate and more bits per encoding brings closer.*



# Digitized Audio: Compression Benefit

- Digitized audio can be compressed
  - e.g., MP3s
  - A CD can hold about 20 songs uncompressed, but about 200 compressed
- Compression also done on digitized pictures (jpeg), movies (mpeg), and more
- Digitization has many other benefits too

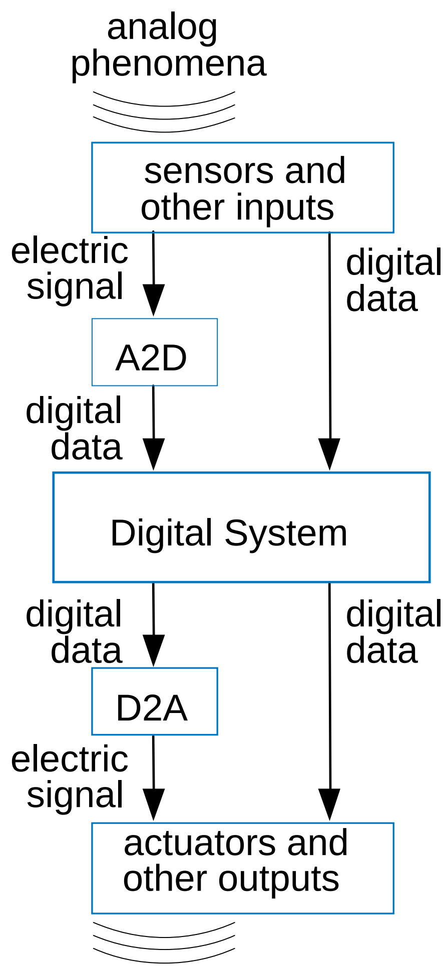
Example compression scheme:

00 --> 0000000000
01 --> 1111111111
1X --> X

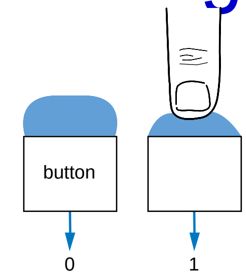
0000000000 0000000000 0000001111 111111111

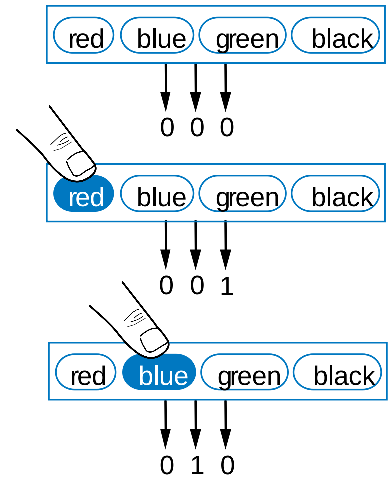
00 00 10000001111 01

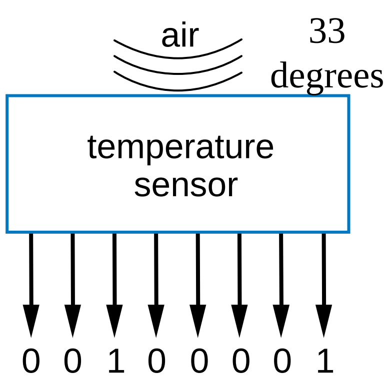
# How Do We Encode Data as Binary for Our Digital System?




- Some inputs inherently binary
  - Button: not pressed (0), pressed (1)
- Some inputs inherently digital
  - Just need encoding in binary
  - e.g., multi-button input: encode red=001, blue=010, ...
- Some inputs analog
  - Need analog-to-digital conversion
  - As done in earlier slide -- sample and encode with bits



# How to Encode Text: ASCII, Unicode

- ASCII: 7- (or 8-) bit encoding of each letter, number, or symbol
- Unicode: Increasingly popular 16-bit bit encoding
  - Encodes characters from various world languages

| Symbol | Encoding |
|---|---|
| R | 1010010 |
| S | 1010011 |
| T | 1010100 |
| L | 1001100 |
| N | 1001110 |
| E | 1000101 |
| 0 | 0110000 |
| . | 0101110 |
| <tab> | 0001001 |

| Symbol | Encoding |
|---|---|
| r | 1110010 |
| s | 1110011 |
| t | 1110100 |
| l | 1101100 |
| n | 1101110 |
| e | 1100101 |
| 9 | 0111001 |
| ! | 0100001 |
| <space> | 0100000 |

Question:
What does this ASCII bit sequence represent?

1010010 1000101 1010011 1010100

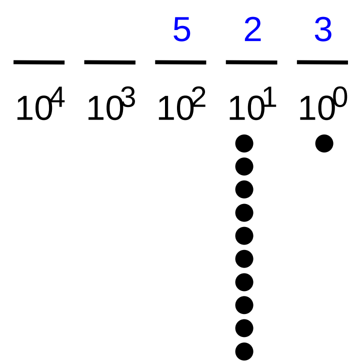
R E S T

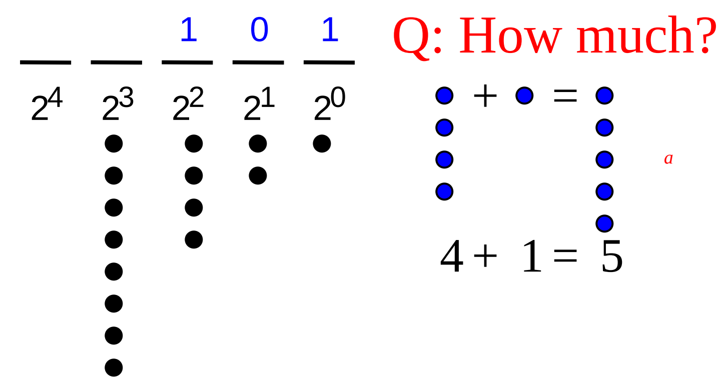
a

*Note: small red "a" (a) in a slide indicates animation*

# How to Encode Numbers: Binary Numbers

- Each position represents a quantity; symbol in position means how many of that quantity
  - Base ten (***decimal***)
    - Ten symbols: 0, 1, 2, ..., 8, and 9
    - More than 9 -- next position
      - So each position power of 10
    - Nothing special about base 10 -- used because we have 10 fingers
  - Base two (***binary***)
    - Two symbols: 0 and 1
    - More than 1 -- next position
      - So each position power of 2



# How to Encode Numbers: Binary Numbers

- Working with binary numbers
  - In base ten, helps to know powers of 10
    - one, ten, hundred, thousand, ten thousand, ...
  - In base two, helps to know powers of 2
    - one, two, four, eight, sixteen, thirty two, sixty four, one hundred twenty eight
      - (Note: unlike base ten, we don't have common names, like "thousand," for each position in base ten -- so we use the base ten name)
    - Q: count up by powers of two

| $2^9$ | $2^8$ | $2^7$ | $2^6$ | $2^5$ | $2^4$ | $2^3$ | $2^2$ | $2^1$ | $2^0$ |
|---|---|---|---|---|---|---|---|---|---|
| 512 | 256 | 128 | 64 | 32 | 16 | 8 | 4 | 2 | 1 |

512 256 128 64 32 16 8 4 2 1

a

# Converting from Decimal to Binary Numbers: Subtraction Method (Easy for Humans)

- Goal
  - Get the binary weights to add up to the decimal quantity
    - Work from left to right
    - (Right to left – may fill in 1s that shouldn't have been there – try it).

Desired decimal number: **12**

| 32 | 16 | 8 | 4 | 2 | 1 | |
|---|---|---|---|---|---|---|
| 1 | | | | | | =32 too much |
| 0 | 1 | | | | | =16 too much |
| 0 | 0 | 1 | | | | =8 ok, keep going |
| 0 | 0 | 1 | 1 | | | =8+4=12 DONE |
| **0** | **0** | **1** | **1** | **0** | **0** | answer |

# Converting from Decimal to Binary Numbers: Subtraction Method (Easy for Humans)

- Subtraction method
  - To make the job easier (especially for big numbers), we can just subtract a selected binary weight from the (remaining) quantity
    - Then, we have a new remaining quantity, and we start again (from the present binary position)
    - Stop when remaining quantity is 0

Remaining quantity: **12**

| _ | _ | _ | _ | _ | _ | |
|---|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 | |

| 1 | _ | _ | _ | _ | _ | 32 is too much |
|---|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 | |

| 0 | 1 | _ | _ | _ | _ | 16 is too much |
|---|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 | |

| 0 | 0 | 1 | _ | _ | _ | **12 – 8 = 4** |
|---|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 | |

| 0 | 0 | 1 | 1 | _ | _ | **4-4=0** DONE |
|---|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 | |

| **0** | **0** | **1** | **1** | **0** | **0** | answer |
|---|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 | |

# Converting from Decimal to Binary Numbers: Subtraction Method Example

- Q: Convert the number “23” from decimal to binary

A: Remaining quantity

23

Binary Number

| 0 | 0 | 0 | 0 | 0 | 0 |
|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 |

23
-16
7

a

| 0 | 1 | 0 | 0 | 0 | 0 |
|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 |

7
-4
3

| 0 | 1 | 0 | 1 | 0 | 0 |
|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 |

*8 is more than 7, can’t use*

4
-2
1

| 0 | 1 | 0 | 1 | 1 | 0 |
|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 |

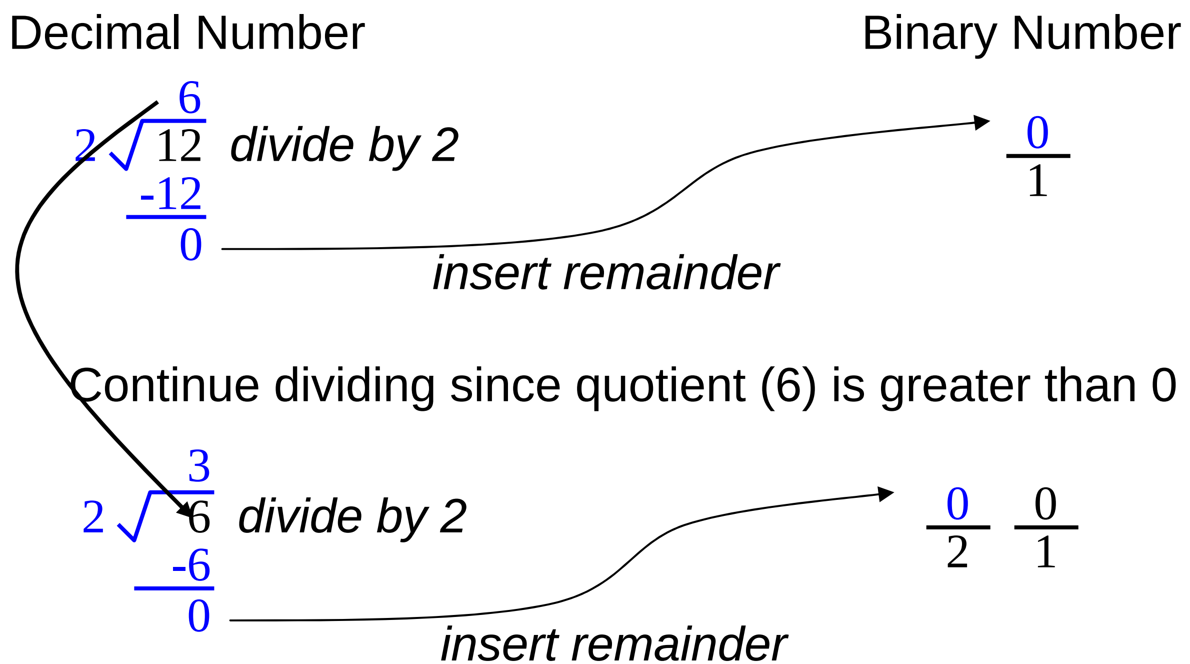
1
-1
0

| 0 | 1 | 0 | 1 | 1 | 1 |
|---|---|---|---|---|---|
| 32 | 16 | 8 | 4 | 2 | 1 |

Done! 23 in decimal is 10111 in binary.

# Converting from Decimal to Binary Numbers: Division Method (Good for Computers)

- Divide decimal number by 2 and insert remainder into new binary number.
  - Continue dividing quotient by 2 until the quotient is 0.
- Example: Convert decimal number 12 to binary




Continue dividing since quotient (3) is greater than 0

# Converting from Decimal to Binary Numbers: Division Method (Good for Computers)

- Example: Convert decimal number 12 to binary (continued)

Decimal Number

Binary Number

2 ⟌ 3 = 1, *divide by 2*

-2

1 *insert remainder*

| 1 | 0 | 0 |
|---|---|---|
| 4 | 2 | 1 |

Continue dividing since quotient (1) is greater than 0

2 ⟌ 1 = 0, *divide by 2*

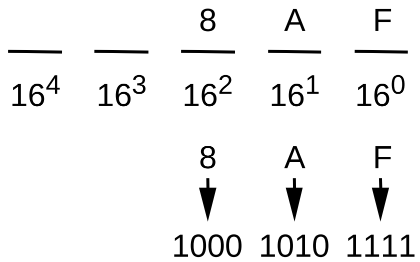
-0

1 *insert remainder*

| 1 | 1 | 0 | 0 |
|---|---|---|---|
| 8 | 4 | 2 | 1 |

Since quotient is 0, we can conclude that 12 is 1100 in binary

# Base Sixteen: Another Base Sometimes Used by Digital Designers

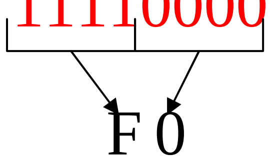



| hex | binary |
|---|---|
| 0 | 0000 |
| 1 | 0001 |
| 2 | 0010 |
| 3 | 0011 |
| 4 | 0100 |
| 5 | 0101 |
| 6 | 0110 |
| 7 | 0111 |

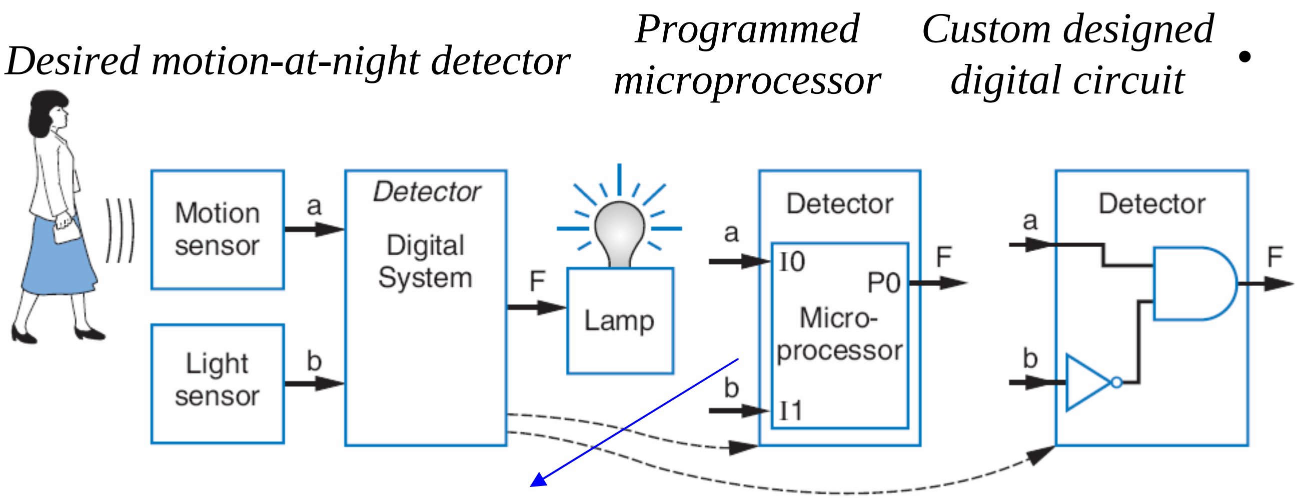
| hex | binary |
|---|---|
| 8 | 1000 |
| 9 | 1001 |
| A | 1010 |
| B | 1011 |
| C | 1100 |
| D | 1101 |
| E | 1110 |
| F | 1111 |

- Nice because each position represents four base two positions
  - Used as compact means to write binary numbers
- Known as ***hexadecimal***, or just ***hex***

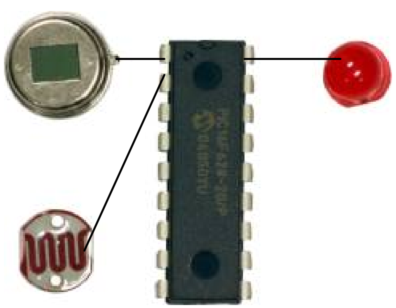
Q: Write 11110000 in hex

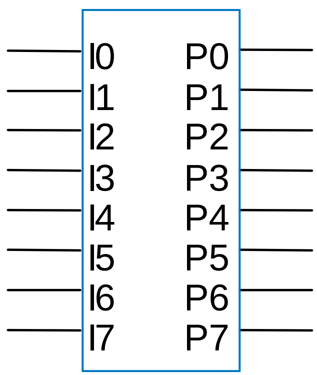


# Implementing Digital Systems: Programming Microprocessors Vs. Designing Digital Circuits

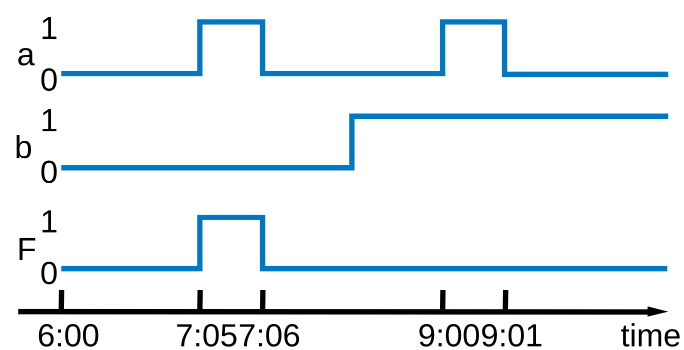



- Microprocessors a common choice to implement a digital system
  - Easy to program
  - Cheap (as low as $1)
  - Available now






```
void main()
{
  while (1) {
    P0 = I0 && !I1;
    // F = a and !b,
  }
}
```



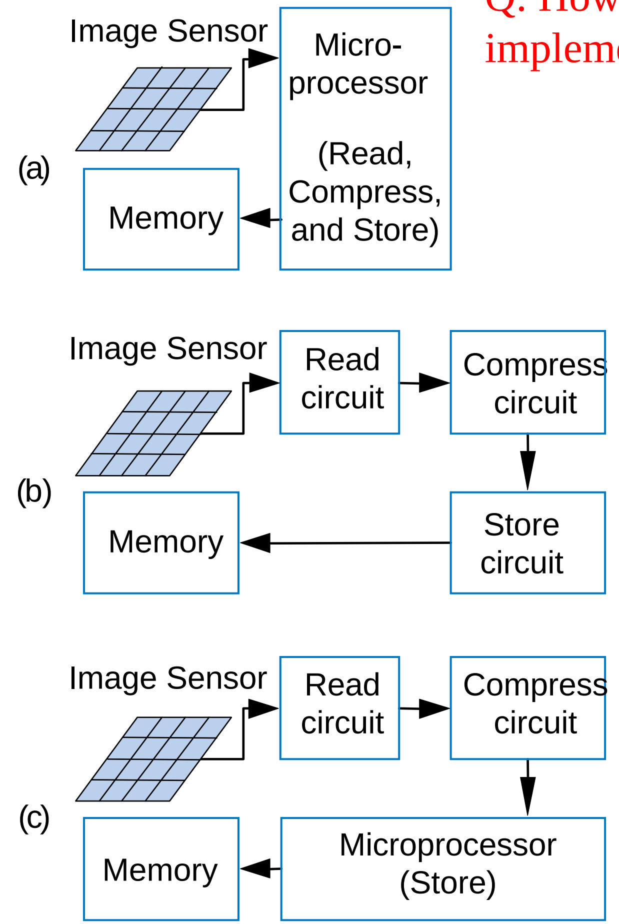
# Digital Design: When Microprocessors Aren't Good Enough

- With microprocessors so easy, cheap, and available, why design a digital circuit?
  - Microprocessor may be too slow
  - Or too big, power hungry, or costly

**Sample digital camera task execution times (in seconds) on a microprocessor versus a digital circuit:**

| **Task** | **Microprocessor** | **Custom Digital Circuit** |
|---|---|---|
| Read | 5 | 0.1 |
| Compress | 8 | 0.5 |
| Store | 1 | 0.8 |

Q: How long for each implementation option?




5+8+11
=24 sec

.1+.5+.8
=1.4 sec

.1+.5+1
=1.6 sec

Good compromise

# Chapter Summary

- Digital systems surround us
  - Inside computers
  - Inside huge variety of other electronic devices (embedded systems)
- Digital systems use 0s and 1s
  - Encoding analog signals to digital can provide many benefits
    - e.g., audio -- higher-quality storage/transmission, compression, etc.
  - Encoding integers as 0s and 1s: Binary numbers
- Microprocessors (themselves digital) can implement many digital systems easily and inexpensively
  - But often not good enough -- need custom digital circuits