

# Welcome to EE130

- **Professor John G. Breslin**
- *Discipline of Electrical & Electronic Engineering*
- School of Engineering

# 1

Systems,  
Quantities, and  
Units



# Syllabus

- Introduction to electrical and electronic engineering. Overview of electronic system application areas (e.g. microprocessors, telecommunications, power systems, signal processing, electronic design processes). Elementary electrical concepts, including quantities and circuit elements. Basic circuit laws and DC analysis. Circuit simplification techniques. Voltage and current dividers. Analogue and digital signals. Introduction to digital electronics and logic gates. Boolean algebra. Basic logic circuits. Logic circuit representation and minimisation.



# Learning Outcomes

- On completion of this module, students should be able to:
  - Show an understanding of the basic concepts of electrical and electronic engineering and be able to describe a range of application areas;
  - Apply Kirchhoff's current and voltage laws in the analysis of simple electric circuits involving voltage sources, current sources, resistors, potentiometers, switches, etc.
  - Based on requirements for a logic system, derive an equivalent truth table and/or Boolean expression and equivalent digital logic representations.



# Assessment

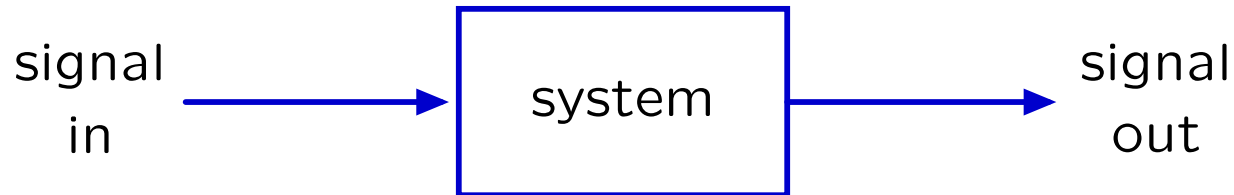
- All Continuous Assessment in 2021/2022
  - CircuitLab
  - Logisim
  - Blackboard MCQs
  - etc.



# The Signals and Systems Abstraction

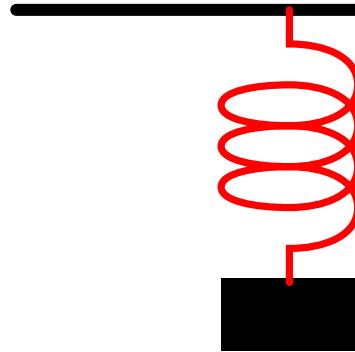
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Describe a **system** (physical, mathematical, or computational) by the way it transforms an **input signal** into an **output signal**.

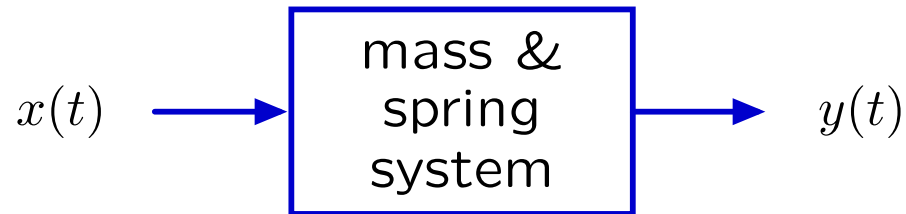
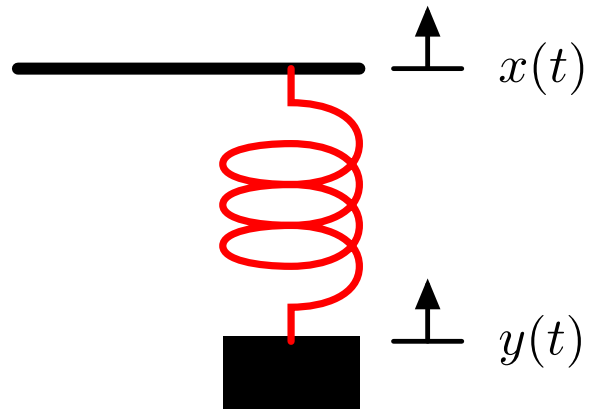


# Example: Mass and Spring

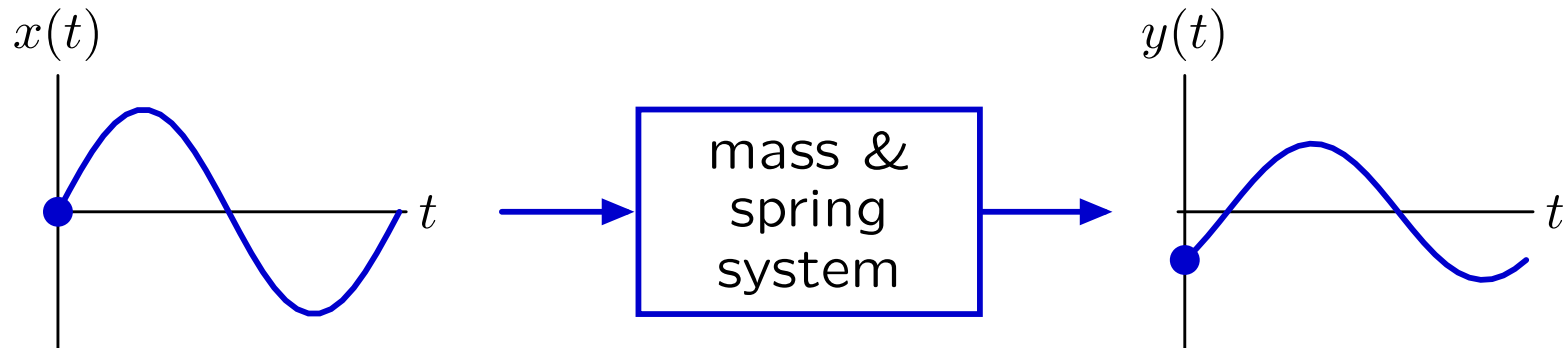
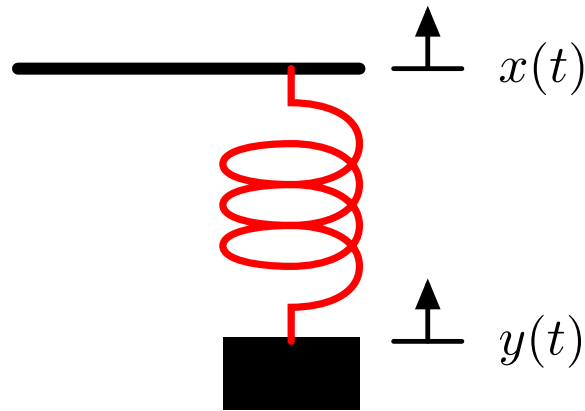
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# Example: Mass and Spring

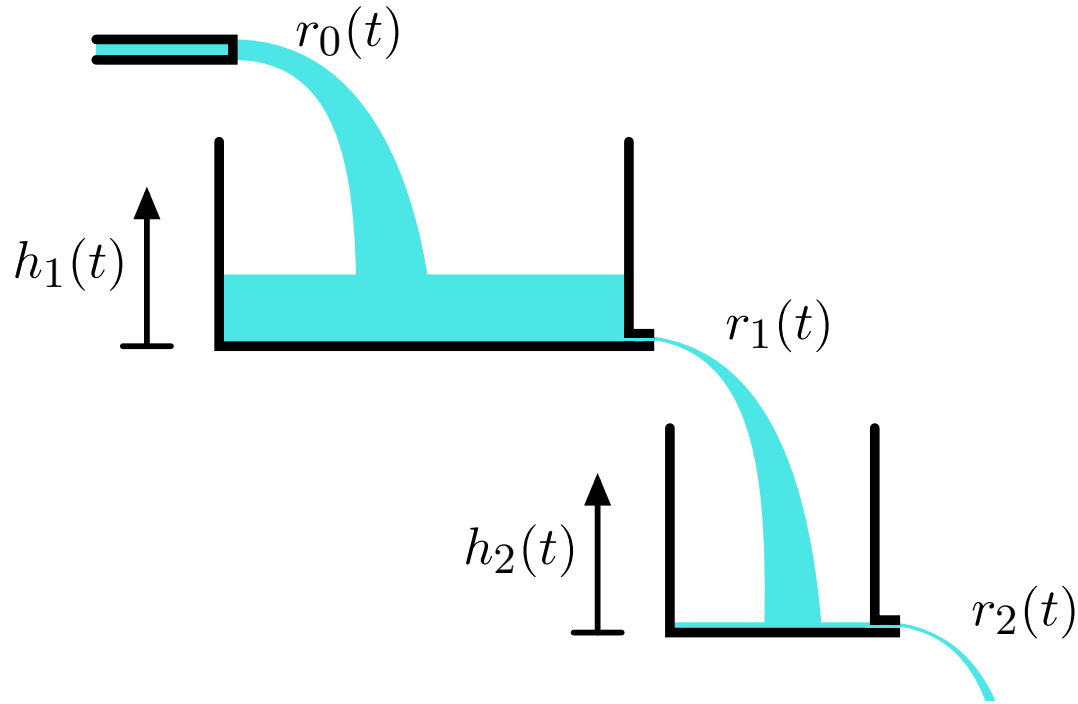


# Example: Mass and Spring

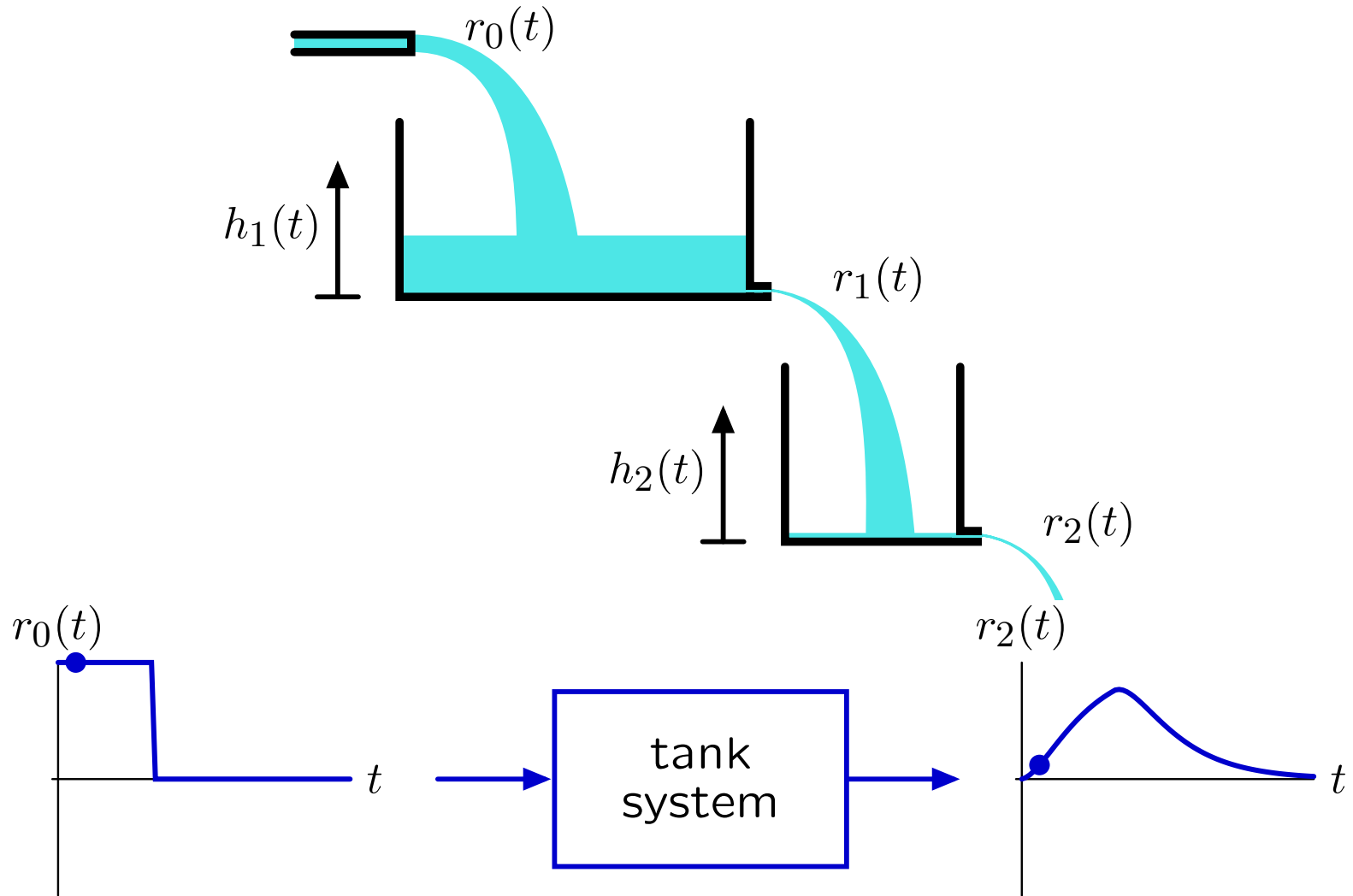




# Example: Tanks

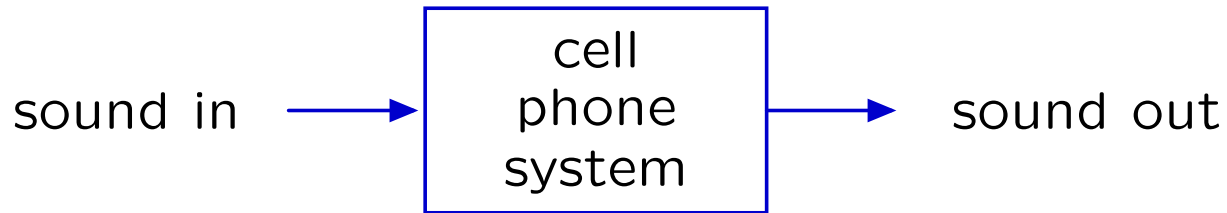
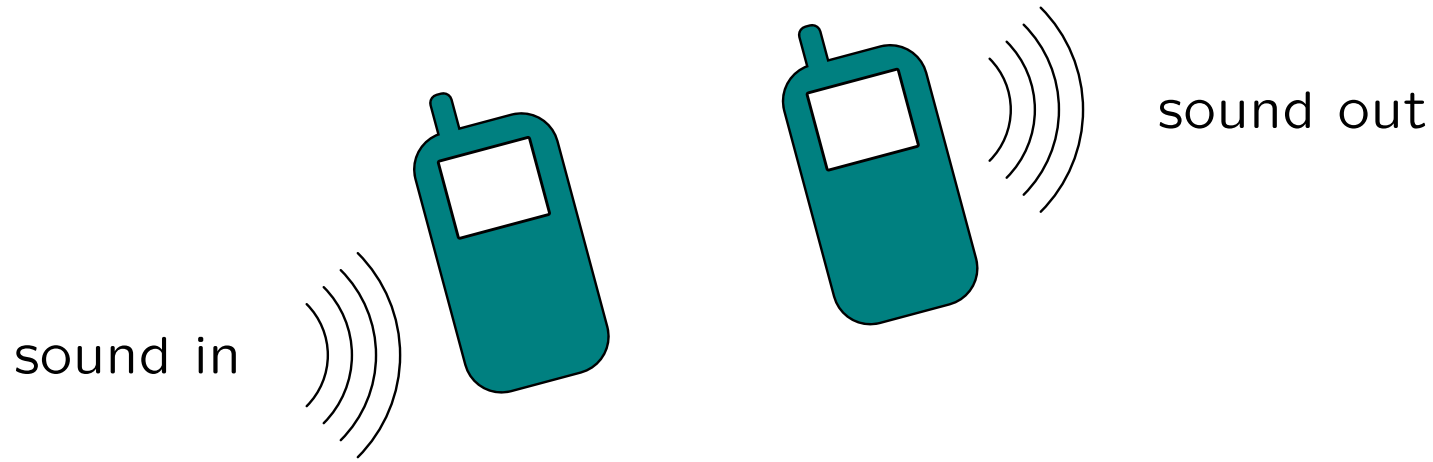


# Example: Tanks

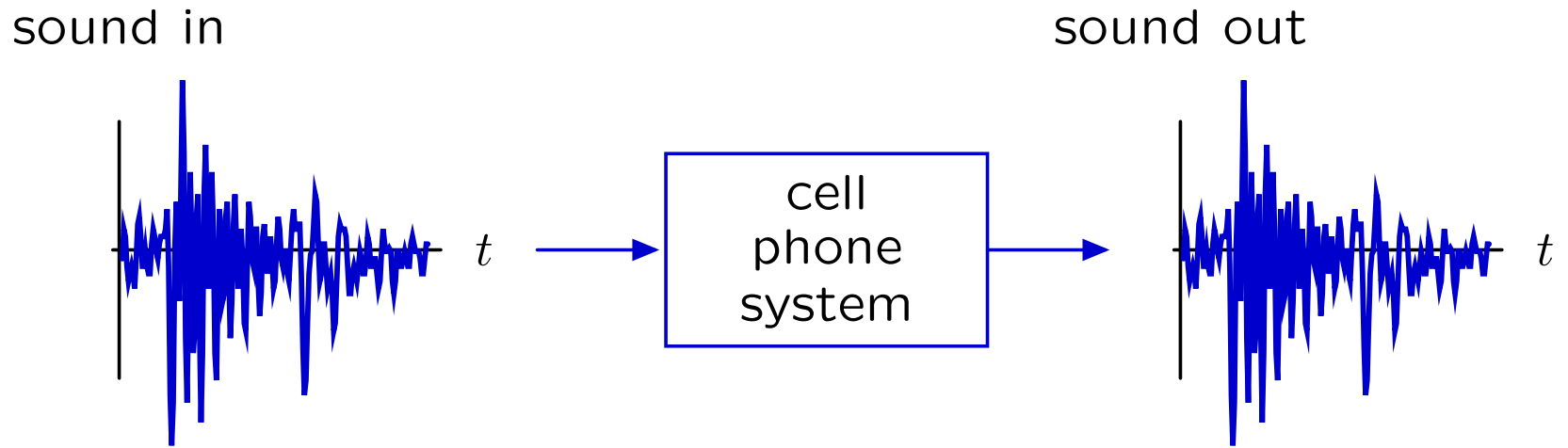
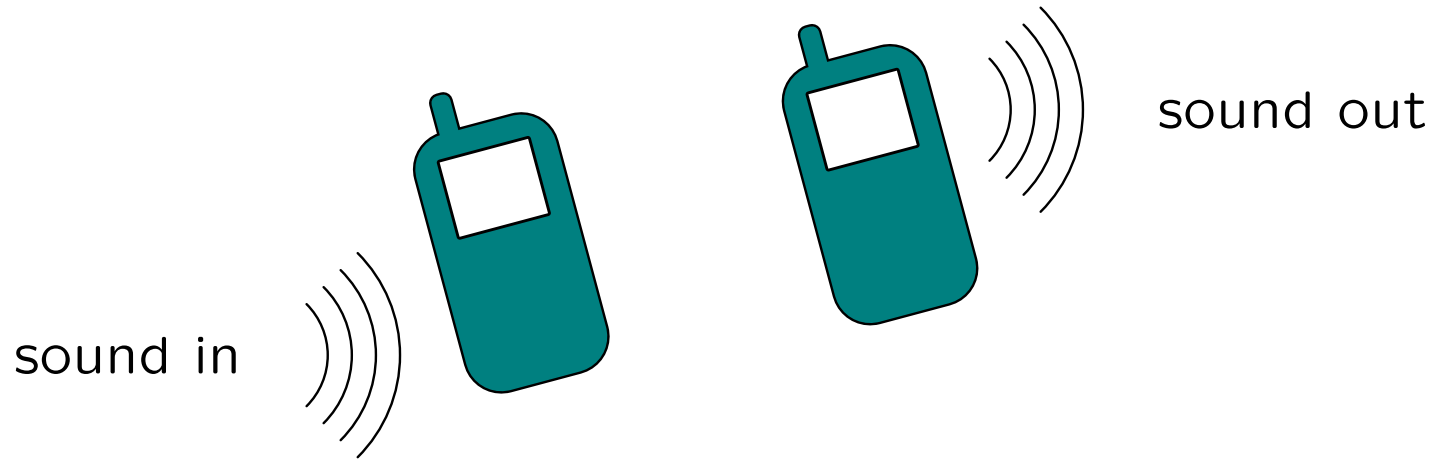


# Example: Cell Phone System

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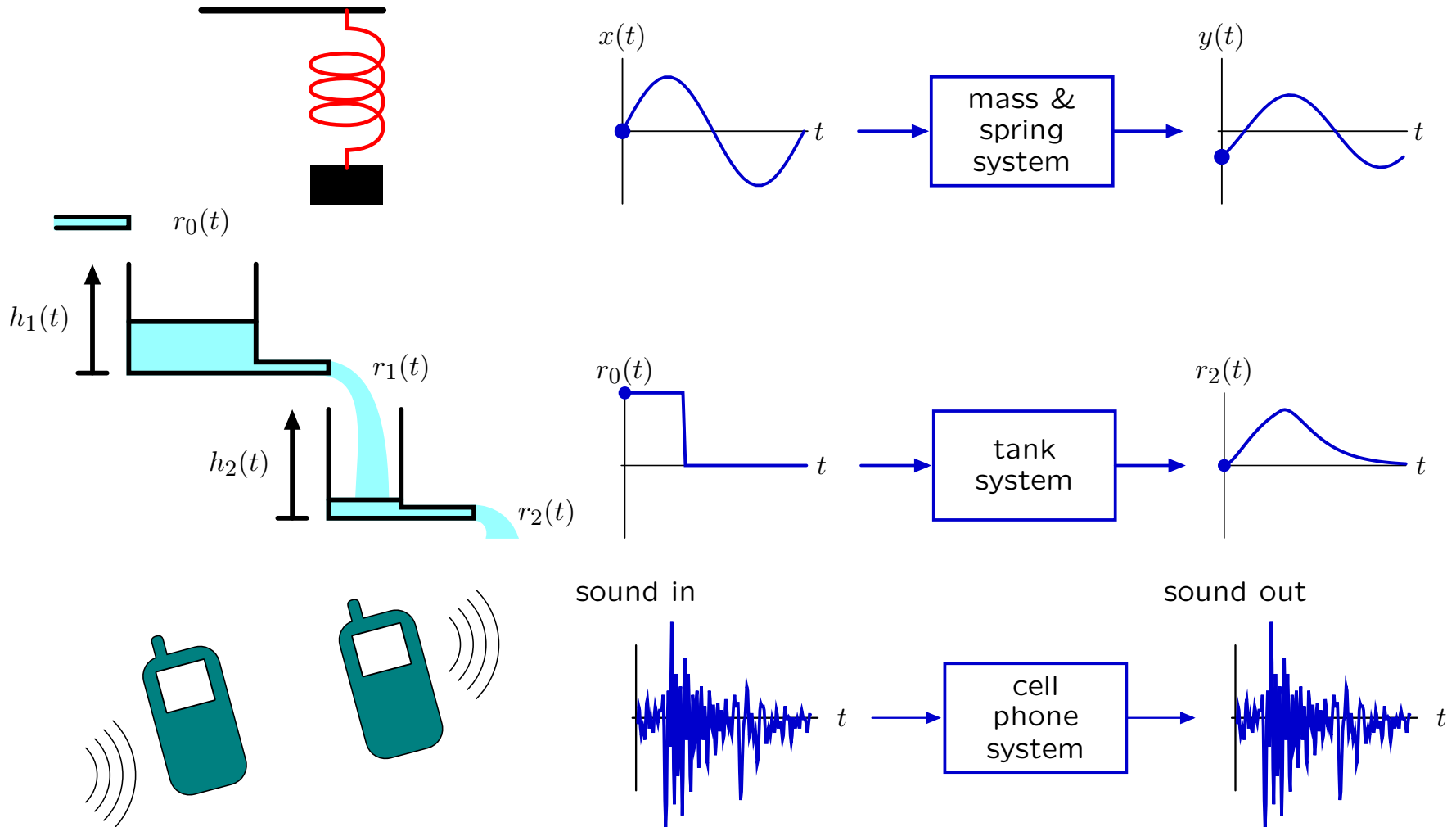


# Example: Cell Phone System



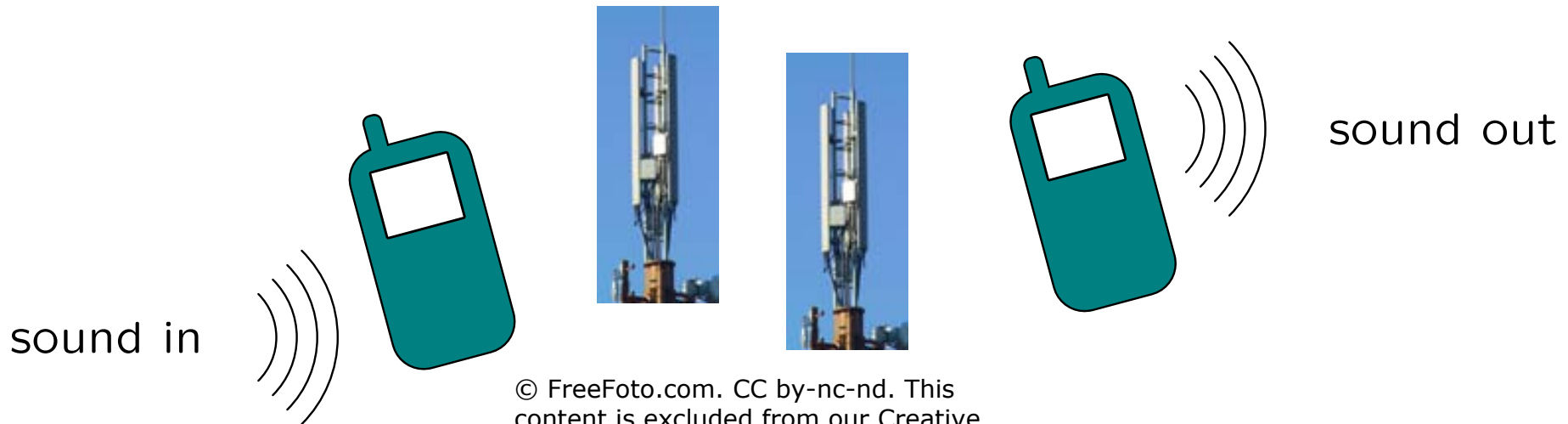
# Signals and Systems: Widely Applicable

The Signals and Systems approach has broad application: electrical, mechanical, optical, acoustic, biological, financial, ...

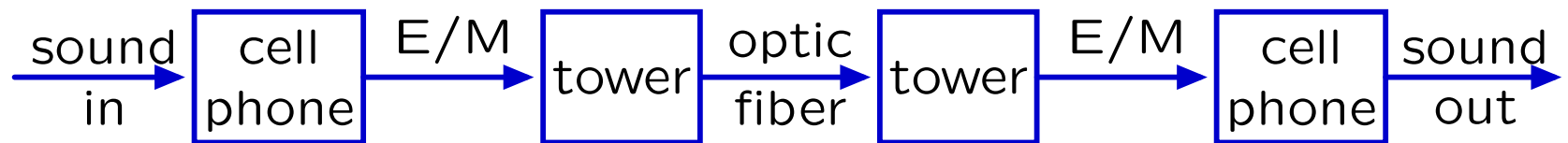


# Signals and Systems: Modular

The representation does not depend upon the physical substrate.



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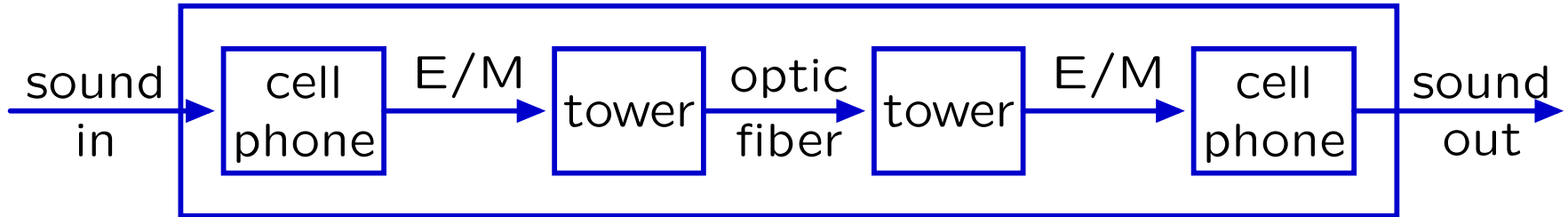
focuses on the flow of **information**, abstracts away everything else



# Signals and Systems: Hierarchical

Representations of component systems are easily combined.

Example: cascade of component systems



Composite system



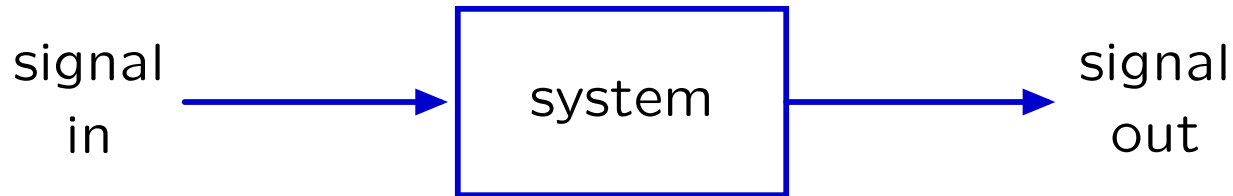
Component and composite systems have the same form, and are analyzed with same methods.



# The Signals and Systems Abstraction

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Our goal is to develop representations for systems that facilitate analysis.



Examples:

- Does the output signal overshoot? If so, how much?
- How long does it take for the output signal to reach its final value?





# Ch.1 Summary

## Systems

A **system** is a group of interrelated parts that perform a specific function.

A system communicates with the outside world via its *inputs* and *outputs*.

An **input** is the voltage, current or power that is applied to an electrical circuit to achieve a desired result.

An **output** is the result obtained from the system after processing its input(s).



# Ch.1 Summary

## Electrical and Electronic Systems

An **electrical system** deals with electric power.

Examples:

Residential wiring systems, heating, ventilation, and air-conditioning (HVAC) systems, EV charging, utility lighting systems.

An **electronic system** deals with **signals**; changing electrical or electromagnetic quantities that carry information.

Examples:

Personal computers, smart phones, television systems.

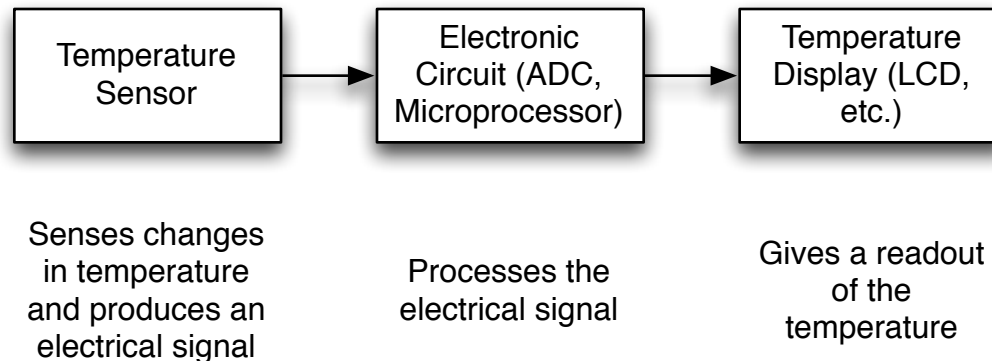


# Ch.1 Summary

## Block Diagrams

A **block diagram** is a model of a system that represents its structure in a graphical format using labeled blocks to represent functions and lines to represent the signal flow.

The signal through the *digital thermometer* represented below flows from left to right.



# Ch.1 Summary

## Types of Circuits

An **electrical circuit** must form a complete path from a power or signal source to a load, and back to the source.

A circuit that forms a complete loop (as described above) is called a **closed circuit**.

A circuit that does not form a complete loop is called an **open circuit**.

Circuits contain **components**; devices that alter one or more electrical characteristics of the power or signal input.



# Ch.1 Summary

## Types of Components

Resistors

Capacitors

Inductors

Transistors (switches)

etc.



# Ch.1 Summary

## Scientific and Engineering Notation

Very large and very small numbers are represented in scientific ( $1-10 \times 10^x$ ) or eng. notation ( $1-1000 \times 10^x$ ).

*For example, the number forty-seven million can be written as*

**47,000,000**

**Scientific Notation**

---

**$4.7 \times 10^7$**

**Engineering Notation**

---

**$47 \times 10^6$**



# Ch.1 Summary

## Scientific and Engineering Notation

Example	Scientific Notation	Engineering Notation
0.000027 =	$2.7 \times 10^{-5}$	$27 \times 10^{-6}$
0.605 =	$6.05 \times 10^{-1}$	$605 \times 10^{-3}$
32600 =	$3.26 \times 10^4$	$32.6 \times 10^3$
892,000 =	$8.92 \times 10^5$	$892 \times 10^3$
0.377 =	$3.77 \times 10^{-1}$	$377 \times 10^{-3}$



# Ch.1 Summary

## Fundamental Units

Quantity	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric Current	Ampere	A
Temperature	Kelvin	K
Luminous intensity	Candela	cd
Amount of substance	Mole	mol





# Ch.1 Summary

## Some Important Electrical Units

Except for current, all electrical and magnetic units are derived from the fundamental units. Current is a fundamental unit.

Quantity	Unit	Symbol
Current	Ampere	A
Charge	Coulomb	C
Voltage	Volt	V
Resistance	Ohm	$\Omega$
Power	Watt	W

These derived units are based on fundamental units from the meter-kilogram-second system and are called **mks units**.



# Ch.1 Summary

## Engineering Metric Prefixes

### Large numbers (>1)

*Can you name these engineering metric prefixes and their meaning?*

P	peta	$10^{15}$
T	tera	$10^{12}$
G	giga	$10^9$
M	mega	$10^6$
k	kilo	$10^3$



# Ch.1 Summary

## Engineering Metric Prefixes

### Small numbers (<1)

*Can you name these engineering metric prefixes and their meaning?*

<b>m</b>	<b>milli</b>	<b><math>10^{-3}</math></b>
<b><math>\mu</math></b>	<b>micro</b>	<b><math>10^{-6}</math></b>
<b>n</b>	<b>nano</b>	<b><math>10^{-9}</math></b>
<b>p</b>	<b>pico</b>	<b><math>10^{-12}</math></b>
<b>f</b>	<b>femto</b>	<b><math>10^{-15}</math></b>



# Ch.1 Summary

## Metric Conversions

When converting from one unit to a smaller unit, move the decimal point to the right. Remember, a smaller unit means the number must be larger.

$$0.47 \text{ M}\Omega = 470 \text{ k}\Omega$$

*Smaller unit*

*Larger number*



# Ch.1 Summary

## Metric Conversions

When converting from one unit to a larger unit, move the decimal point to the left.  
Remember, a larger unit means the number must be smaller.

$$10,000 \text{ pF} = 0.01 \text{ } \mu\text{F}$$

*Larger unit*

*Smaller number*



# Ch.1 Summary

## Metric Arithmetic

When adding or subtracting numbers with a metric prefix, convert them to the same prefix first.

$$10,000 \Omega + 22 \text{ k}\Omega =$$

$$10,000 \Omega + 22,000 \Omega = 32,000 \Omega$$

***Alternatively:***  $10 \text{ k}\Omega + 22 \text{ k}\Omega = 32 \text{ k}\Omega$



# Ch.1 Summary

## Metric Arithmetic

When adding or subtracting numbers with different metric prefixes, convert them to the same prefix first.

$$200 \mu\text{A} + 1.0 \text{ mA} =$$

$$200 \mu\text{A} + 1,000 \mu\text{A} = 1200 \mu\text{A}$$

***Alternatively:***  $0.200 \text{ mA} + 1.0 \text{ mA} = 1.2 \text{ mA}$



# Ch.1 Summary

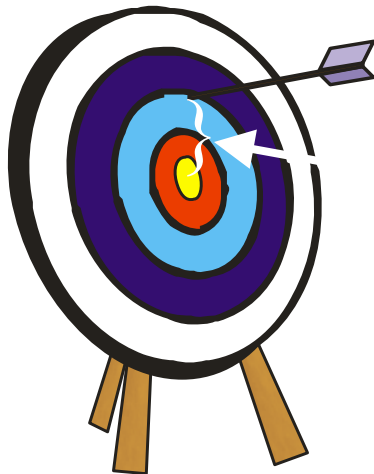
## Error, Accuracy and Precision

*Experimental uncertainty is part of all measurements.*

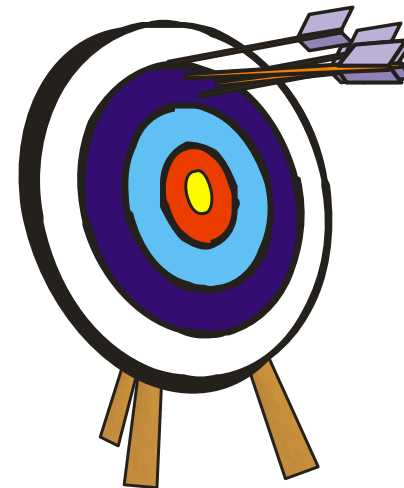
**Error** is the difference between the true or best accepted value and the measured value.

**Accuracy** is an indication of the range of error in a measurement.

**Precision** is a measure of repeatability



*Error*



*Precise,  
but not  
accurate.*





# Ch.1 Summary

## Error, Accuracy and Precision

When reporting a measured value, one uncertain digit may be retained, but other uncertain digits should be discarded. Normally this is the same number of digits as in the original measurement.

*Assume two measured quantities are 10.54 and 3.92. If the larger is divided by the smaller, the answer is ...*

**2.69**

*Why? Because the answer has the same uncertainty as the original measurement.*



# Ch.1 Summary

## When Is A Digit Considered Significant?

The rules for determining if a specified digit is significant are:

1. Nonzero digits are always considered to be significant.
2. Zeros to the left of the first nonzero digit are never significant.
3. Zeros between nonzero digits are always significant.
4. Zeros to the right of the decimal point for a decimal number are significant.
5. Zeros to the left of the decimal point with a whole number may or may not be significant, depending on the measurement.



# Ch.1 Summary

## Examples

1. Non-zero digits are always considered to be significant.  
*23.92 has four non-zero digits – they are all significant.*
2. Zeros to the left of the first non-zero digit are never significant.  
*0.00276 has three zeros to the left of the first non-zero digit. There are only three significant digits.*
3. Zeros between nonzero digits are always significant.  
*806 has three significant digits.*
4. Zeros to the right of the decimal point for a decimal number are significant.  
*9.00 has three significant digits.*
5. Zeros to the left of the decimal point with a whole number may or may not be significant depending on the measurement.  
*4000 does not have a clear number of significant digits.*



# Ch.1 Summary

## Rounding Numbers

**Rounding** is the process of discarding meaningless digits.  
The rules for rounding are:

1. *If the dropped digit is greater than 5, increase the last retained digit by 1.*
2. *If the dropped digit is less than 5, do not change the last retained digit.*
3. *If the dropped digit is 5, increase the last retained digit if it makes it even, otherwise do not. This is called the "round-to-even" rule.*



# Ch.1 Summary

## Key Terms

### ***Engineering notation***

A system for representing any number as a one-, two-, or three-digit number times a power of ten with an exponent that is a multiple of three.

### ***Exponent***

The number to which a base is raised.

### ***Metric prefix***

A symbol that is used to replace the power of ten in numbers expressed in scientific or engineering notation.

### ***Power of ten***

A numerical representation consisting of a base of 10 and an exponent; the number 10 raised to a power.



# Ch.1 Summary

## Key Terms

***Scientific notation*** A system for representing any number as a number between 1 and 10 times a power of ten.

***Accuracy*** An indication of the range of error in a measurement.

***Precision*** A measure of the repeatability (consistency) of a series of measurements.

***Significant digit*** A digit known to be correct in a number.



# Ch.1 Summary

## Quiz

1. The number  $2.59 \times 10^7$  is expressed in
  - a. scientific notation
  - b. engineering notation
  - c. both of the above
  - d. none of the above



# Ch.1 Summary

## Quiz

2. The electrical unit that is fundamental is the
- a. volt
  - b. ohm
  - c. coulomb
  - d. ampere





# Ch.1 Summary

## Quiz

3. In scientific notation, the number 0.00056 is expressed as

- a.  $5.6 \times 10^4$
- b.  $5.6 \times 10^{-4}$
- c.  $56 \times 10^{-5}$
- d.  $560 \times 10^{-6}$



# Ch.1 Summary

## Quiz

4. In engineering notation, the number 0.000 56 is expressed as

- a.  $5.6 \times 10^4$
- b.  $5.6 \times 10^{-4}$
- c.  $56 \times 10^{-5}$
- d.  $560 \times 10^{-6}$



# Ch.1 Summary

## Quiz

5. The metric prefix *nano* means

- a.  $10^{-3}$
- b.  $10^{-6}$
- c.  $10^{-9}$
- d.  $10^{-12}$



# Ch.1 Summary

## Quiz

6. The metric prefix *pico* means

- a.  $10^{-3}$
- b.  $10^{-6}$
- c.  $10^{-9}$
- d.  $10^{-12}$



# Ch.1 Summary

## Quiz

7. The number 2700 MW equals

- a. 2.7 TW
- b. 2.7 GW
- c. 2.7 kW
- d. 2.7 mW



# Ch.1 Summary

## Quiz

8. The number  $68 \text{ k}\Omega$  equals

a.  $6.8 \times 10^4 \Omega$

b.  $68,000 \Omega$

c.  $0.068 \text{ M}\Omega$

d. All of the above



# Ch.1 Summary

## Quiz

9.  $330 \text{ mW} + 1.5 \text{ W} =$

a.  $331.5 \text{ mW}$

b.  $3.35 \text{ W}$

c.  $1.533 \text{ W}$

d.  $1.83 \text{ W}$



# Ch.1 Summary

## Quiz

10. Precision is a measurement of
- a. the total error in a series of measurements
  - b. the consistency of a series of measurements
  - c. both of the above
  - d. none of the above





# Ch.1 Summary

## Answers

- |      |       |
|------|-------|
| 1. a | 6. d  |
| 2. d | 7. b  |
| 3. b | 8. d  |
| 4. d | 9. d  |
| 5. c | 10. b |



# 2

## Voltage, Current, and Resistance

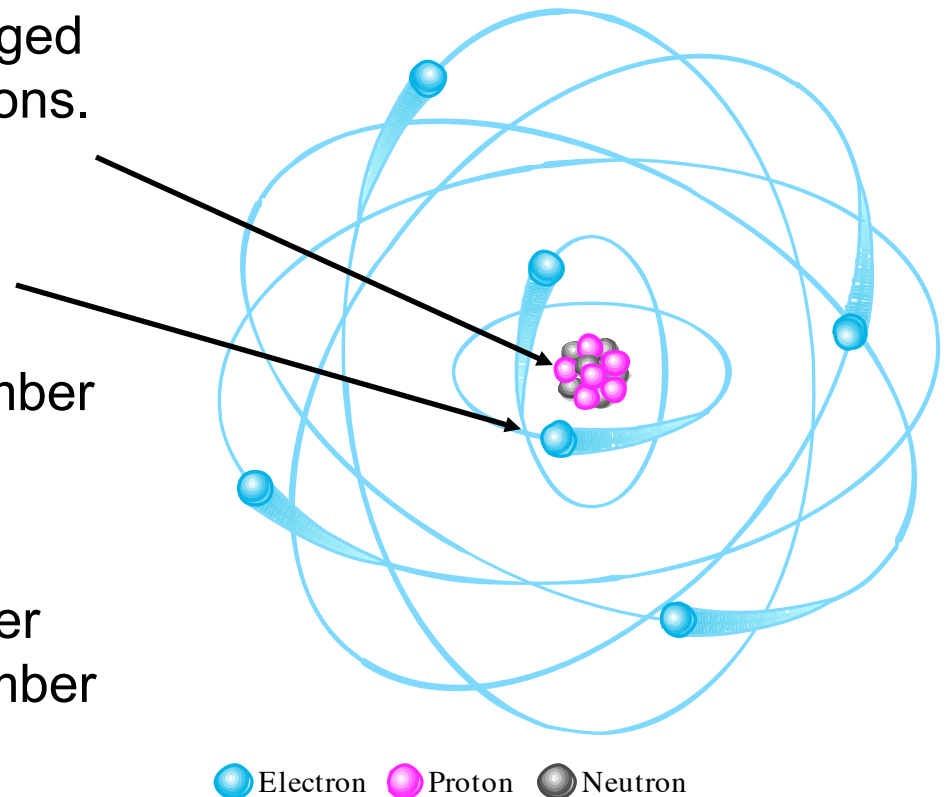


# Ch.2 Summary

## The Bohr Atom

**The Bohr atom is useful for visualizing atomic structure.**

- The nucleus is positively charged and has the protons and neutrons.
- Electrons are negatively charged and in discrete shells.
- The atomic number is the number of protons and determines the particular element.
- In the neutral atom, the number of electrons is equal to the number of protons.



# Ch.2 Summary

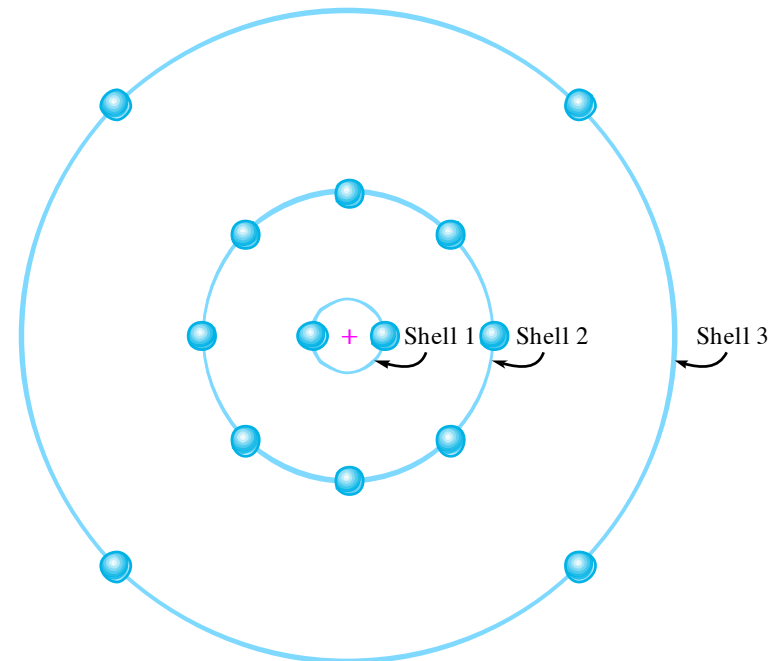
## The Valence Shell

The outer shell is called the **valence shell**. Electrons in this shell are involved in chemical reactions and they account for electrical and thermal conductivity in metals.

*A neutral silicon (Si) atom is shown. There are four electrons in the valence shell.*

*Is Si a conductor, insulator, or semiconductor?*

**Semiconductor**



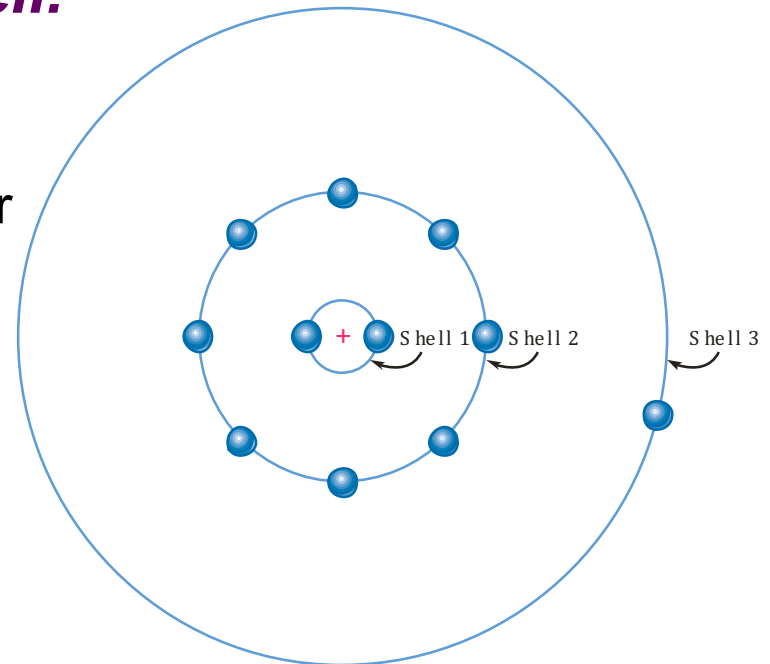
# Ch.2 Summary

## The Valence Shell

*Metals have one, two or three electrons in the valence shell. The atom illustrated here is a sodium (Na) atom with only one electron in its outer shell.*

Sodium is highly reactive, and easily gives up its single valence electron. For this reason, it is not used in electrical work.

Non-metals have either complete or nearly complete outer shells, so they make poor electrical conductors.



**Sodium atom**

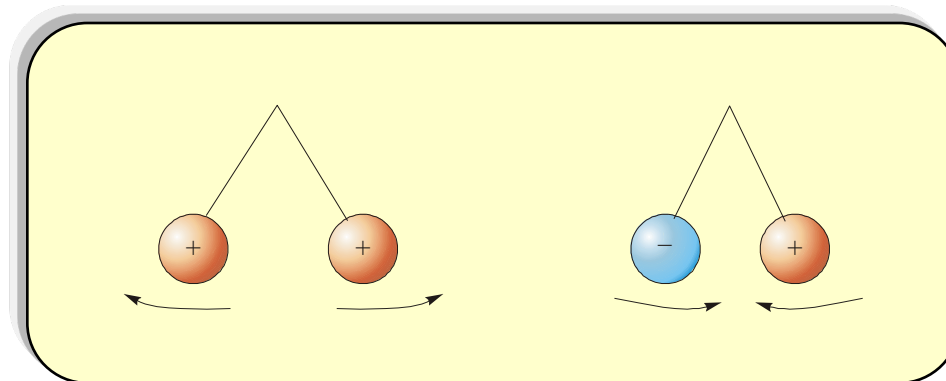


# Ch.2 Summary

## Electrical Charge

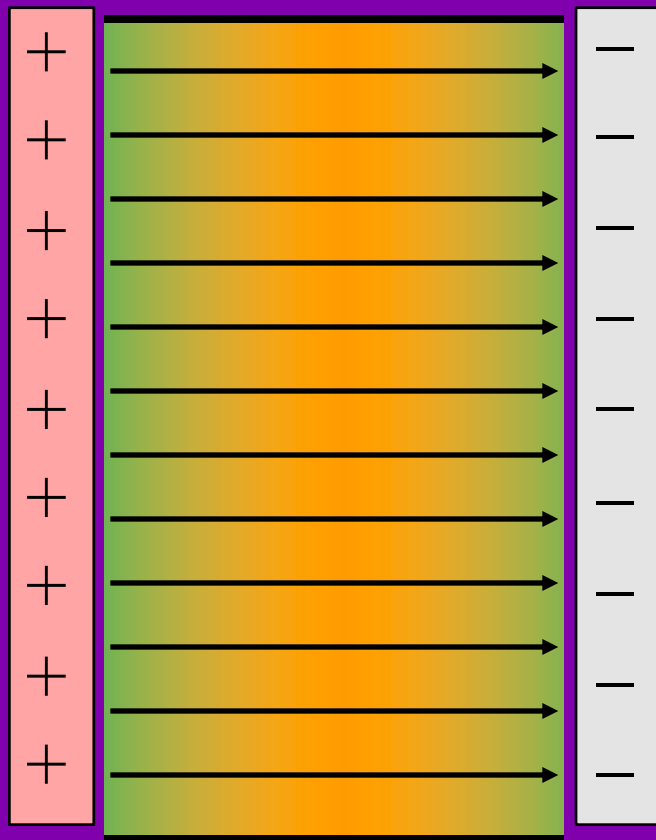
**There is a force ( $F$ ) between electrical charges.  
Like charges repel; unlike charges attract.**

- The force is directly proportional to charge.
- The force is inversely proportional to square of distance.



# Ch.2 Summary

## Voltage



Force is required to move a charge against an electric field.

When force is applied over a distance, work is done. Work done in moving a charge against the electric field leads to the definition of voltage:

*Voltage is the work per charge done against the electric field.*



# Ch.2 Summary

## Voltage

The defining equation for voltage is

$$V = \frac{W}{Q}$$

*One volt is the potential difference (voltage) between two points that uses one joule of energy to move one coulomb of charge from one point to the other.*





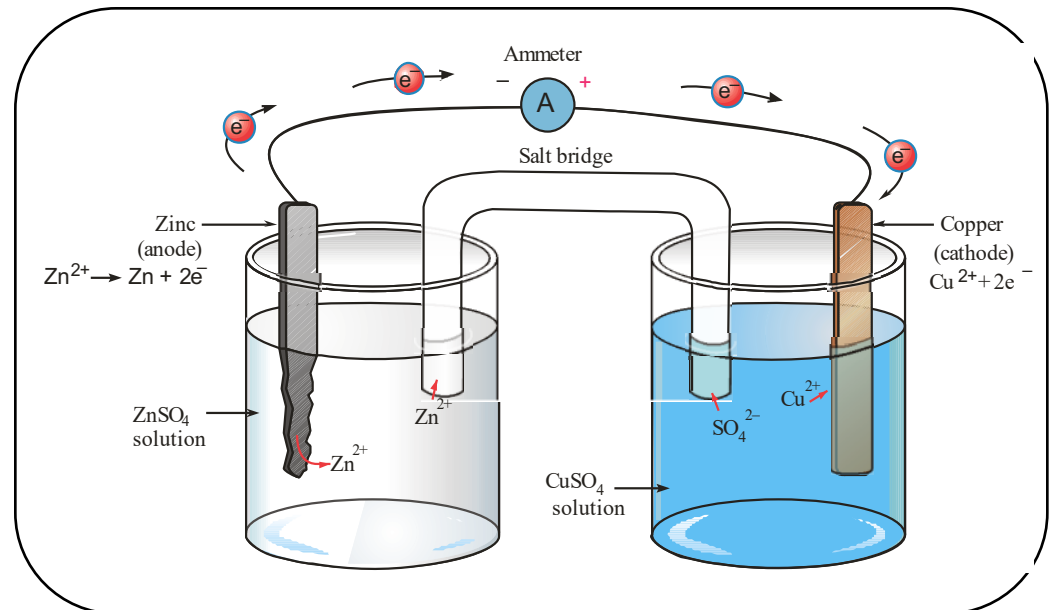
# Ch.2 Summary

## Voltage

**Voltage is responsible for establishing current.**

*This is an example of a single cell battery.*

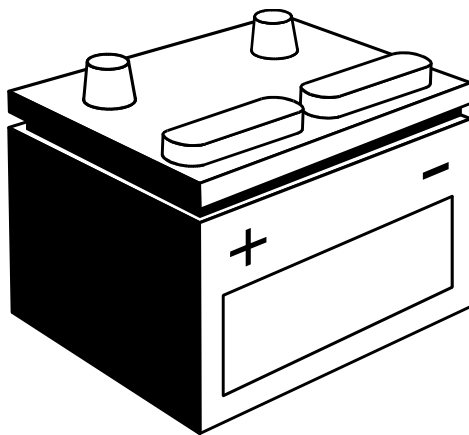
Sources of voltage include batteries, solar cells, fuel cells, and generators. A Cu-Zn battery, such as you might construct in a chemistry class, is shown.



# Ch.2 Summary

## Batteries

An automobile battery is an example of a multiple cell battery. Like all batteries, the automotive battery does *not* store charge – it stores chemical energy that can be used to generate current when an external path is provided to allow its chemical reaction to proceed.



*Rather than saying “charging” a battery, it is more accurate to say “reversing the chemical reaction” in a battery.*



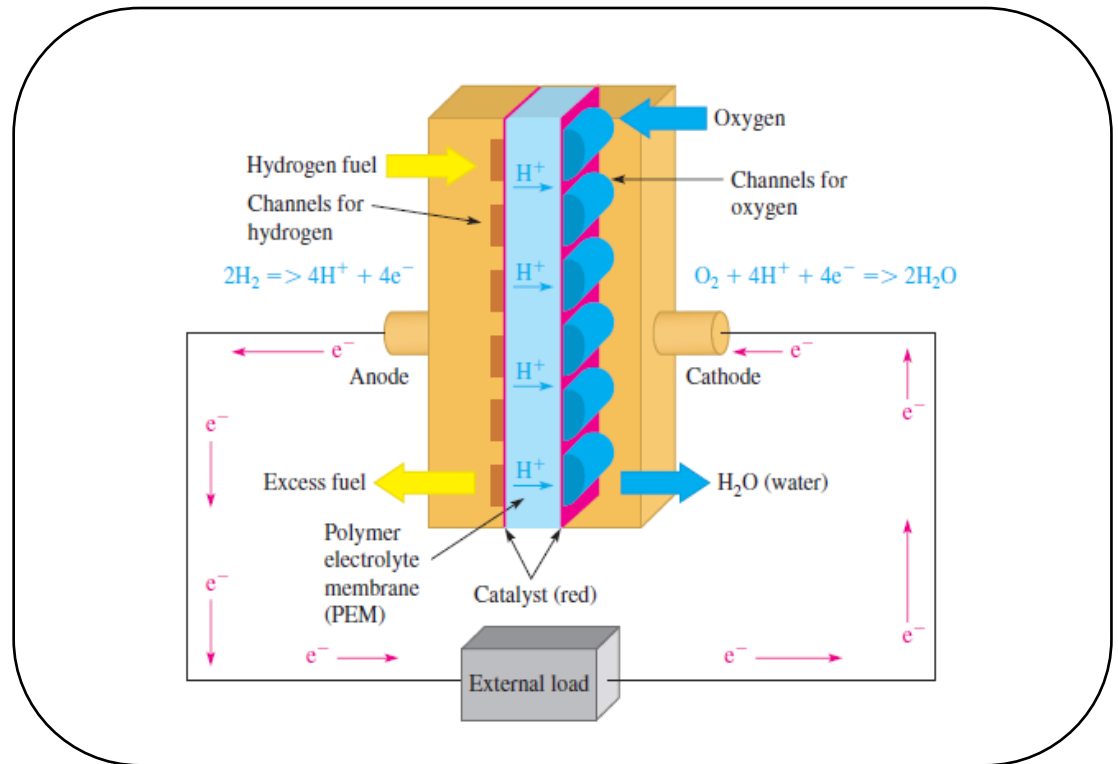
# Ch.2 Summary

## Fuel Cells

A fuel cell converts chemical energy into dc voltage by combining a fuel (usually hydrogen) with an oxidizing agent (usually oxygen).

*Hydrogen and oxygen react to form water.*

This process differs from batteries in that the reactants constantly flow into the cell where they combine and produce electricity.



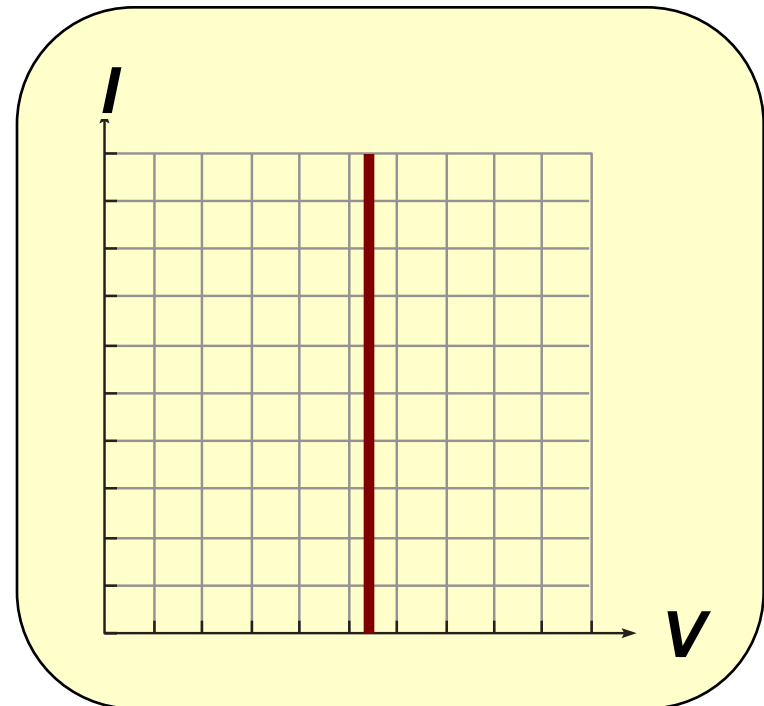
# Ch.2 Summary

## Voltage

**Ideally, a voltage source can provide a constant voltage for any current required by a circuit.**

The  $I/V$  curve for an ideal voltage source has a constant voltage for all current.

*In practice, ideal sources do not exist, but they can be closely approximated by actual sources.*



# Ch.2 Summary

## Current

Current ( $I$ ) is the amount of charge ( $Q$ ) that flows past a point per unit of time ( $t$ ). The defining equation is:

$$I = \frac{Q}{t}$$

One **ampere** is a number of electrons having a total charge of 1 C moving through a given cross section per second (s).

*What is the current if 2 C passes a point every 5 s?*

**0.4 A**

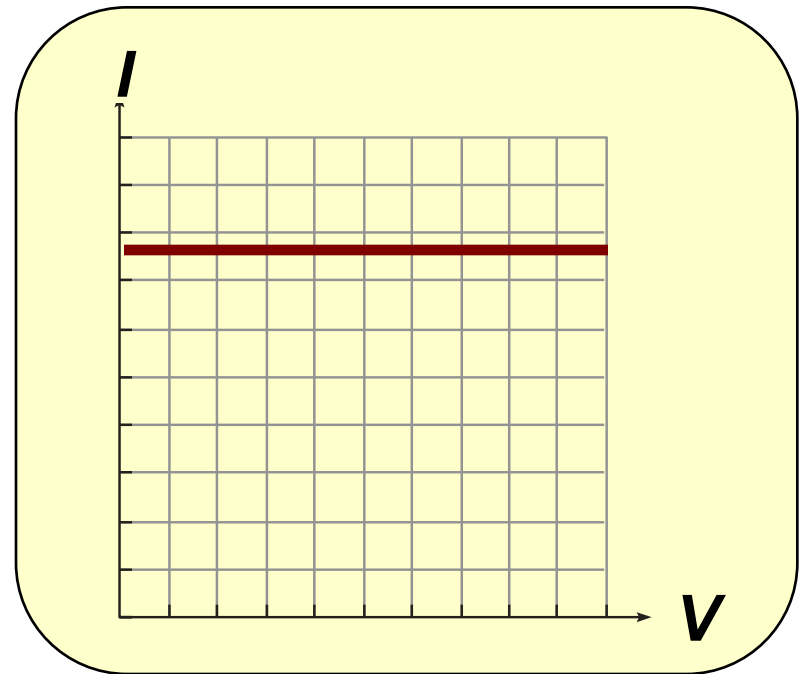


# Ch.2 Summary

## Current

Ideally, a current source can provide a constant current for any load.

The  $I/V$  curve for an ideal current source has a constant current as indicated by the straight line.



# Ch.2 Summary

## Current Sources

**Current sources are not as common as voltage sources, but they are useful for production testing.**

*The units shown here include current sources and built-in measurement instruments, and can operate using a built-in microprocessor to direct a test sequence.*



Courtesy of Keithley Instruments



# Ch.2 Summary

## Resistance

*Resistance (R) is the opposition to current.*

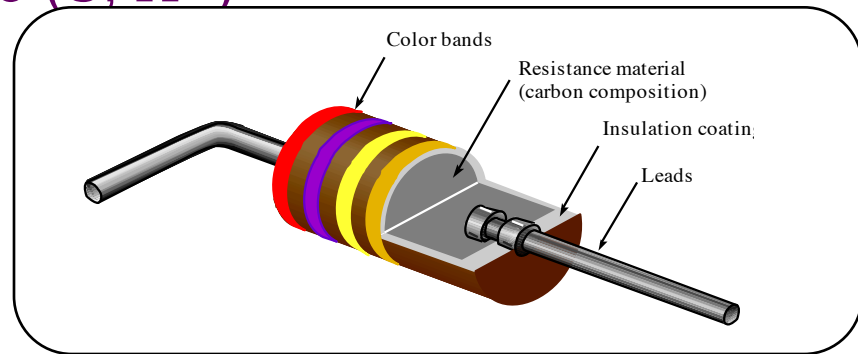
One ohm ( $1 \Omega$ ) is the resistance if one ampere (1 A) is in a material when one volt (1 V) is applied.

*Conductance (G) is the reciprocal of resistance.*

$$G = \frac{1}{R}$$

Measured in Siemens or Mho ( $S, \Omega^{-1}$ )

Components designed to have a specific amounts of resistance are called *resistors*.

















# Ch.2 Summary

## Resistance Color Code

### Resistance value, first three bands:

- First band – 1<sup>st</sup> digit
- Second band – 2<sup>nd</sup> digit
- Third band – Multiplier \*  
(number of zeros following second digit)
- Fourth band - tolerance

Color	Digit	Multiplier	Tolerance	
	Black	0	10 <sup>0</sup>	
	Brown	1	10 <sup>1</sup>	1% (five band)
	Red	2	10 <sup>2</sup>	2% (five band)
	Orange	3	10 <sup>3</sup>	
	Yellow	4	10 <sup>4</sup>	
	Green	5	10 <sup>5</sup>	
	Blue	6	10 <sup>6</sup>	
	Violet	7	10 <sup>7</sup>	
	Gray	8	10 <sup>8</sup>	
	White	9	10 <sup>9</sup>	
	Gold	5%	10 <sup>-1</sup>	5% (four band)
	Silver	10%	10 <sup>-2</sup>	10% (four band)
	No band	20%		





\* For resistance values less than 10  $\Omega$ , the third band is either gold or silver. Gold is for a multiplier of 0.1 and silver is for a multiplier of 0.01.



# Ch.2 Summary

## Question

*What is the resistance and tolerance of each of the four-band resistors?*

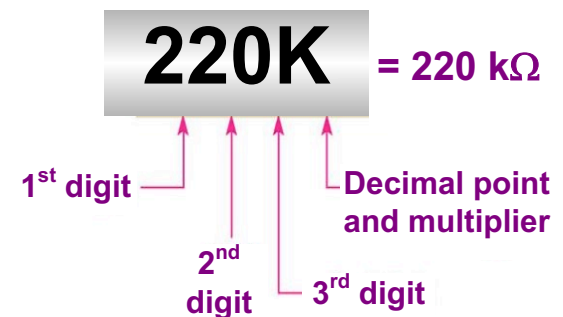
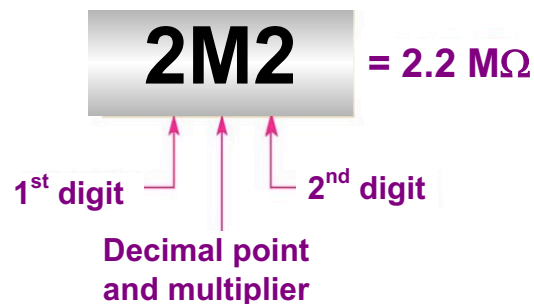
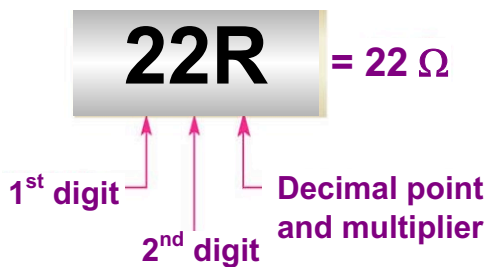
	$5.1 \text{ k}\Omega \pm 5\%$
	$820 \text{ k}\Omega \pm 10\%$
	$47 \Omega \pm 10\%$
	$1.0 \Omega \pm 5\%$



# Ch.2 Summary

## Alphanumeric Labeling

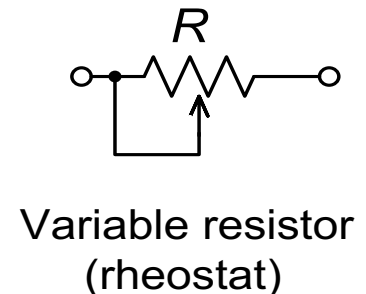
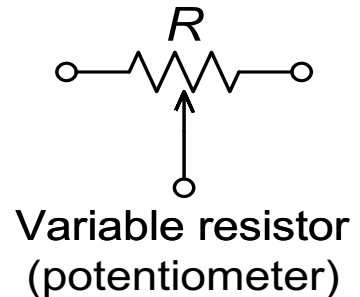
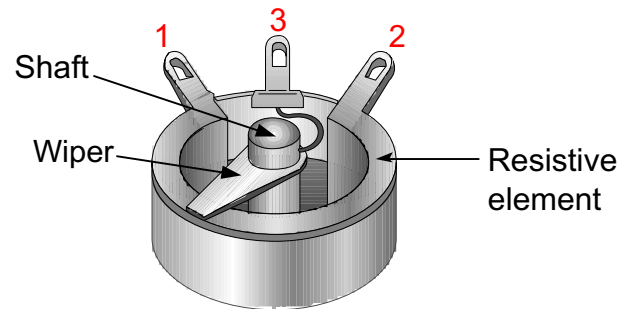
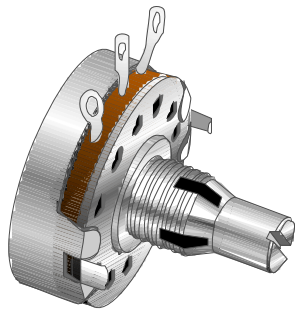
- Two or three digits, and one of the letters R, K, or M are used to identify a resistance value.
- The letter is used to indicate the multiplier, and its position is used to indicate decimal point position.
- W in picture below should be  $\Omega$



# Ch.2 Summary

## Variable Resistors

Variable resistors include the potentiometer and rheostat. The center terminal of a variable resistor is connected to the wiper.



*To connect a potentiometer as a rheostat, one of the outside terminals is connected to the wiper.*



# Ch.2 Summary

## Wire Resistance

Sometimes, the resistance of wires must be accounted for.  
The equation for wire resistance is:

$$R = \frac{\rho \times l}{A}$$

where  $\rho$  = resistivity in  $\Omega\text{m}$

$l$  = length in m

$A$  = cross sectional area in  $\text{m}^2$

*What is the resistance of 122 metres of 22 gauge copper wire? The area is  $0.326 \text{ mm}^2$  and the resistivity of copper is  $1.73 \times 10^{-8} \Omega\text{m}$ . The table value for resistance/metre of 22 gauge wire is  $52.96 \text{ m}\Omega/\text{m}$ .*

The resistance of 122m is  $122 \times 52.96 \times 10^{-3} \Omega = \mathbf{6.46 \Omega}$

$$\text{By the equation, } R = \frac{\rho \times l}{A} = \frac{1.73 \times 10^{-8} \Omega\text{m} \times 122\text{m}}{.326 \times 10^{-6} \text{ m}^2} = \mathbf{6.46 \Omega}$$



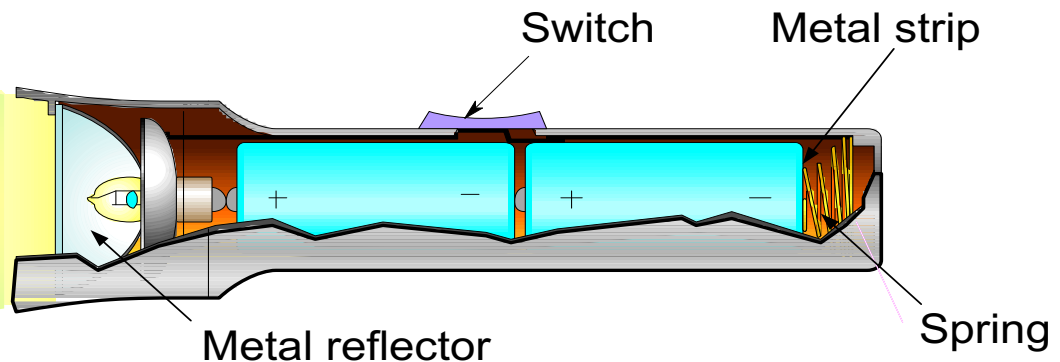
# Ch.2 Summary

## The Electric Circuit

**A basic electric circuit consists of**

- 1) a voltage source
- 2) a path
- 3) a load

*An example of a basic circuit is a flashlight, which has each of these plus a control element – the switch.*

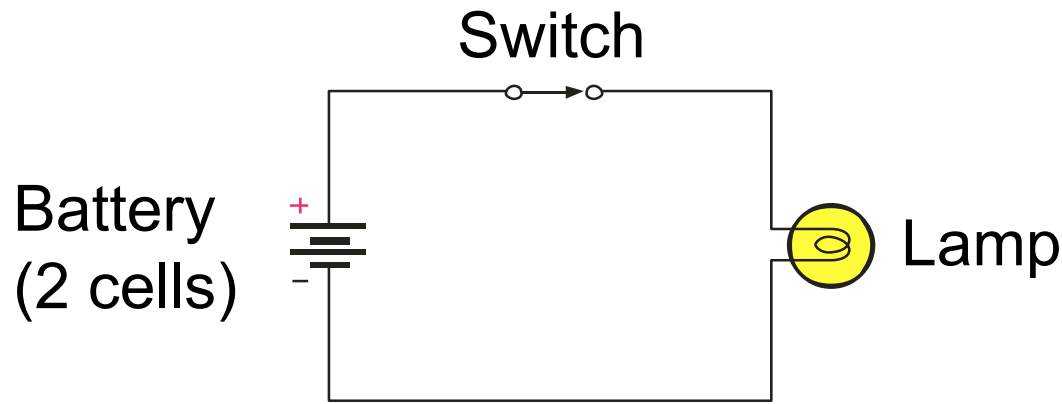


# Ch.2 Summary

## The Electric Circuit

**Circuits are represented pictorially with schematics.**

*For example, the flashlight can be represented as shown below.*

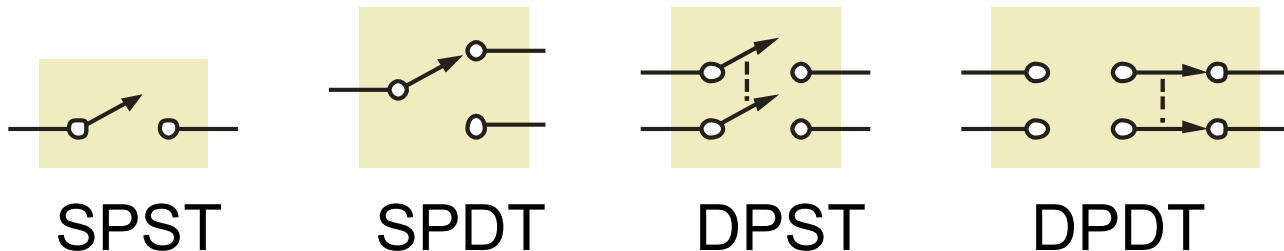


# Ch.2 Summary

## Switches

Switches are commonly used to control circuits by either mechanical or electronic means.

The ***pole*** refers to the movable arm of a switch.  
The ***throw*** refers to the number of contacts that are affected by a single switch action.



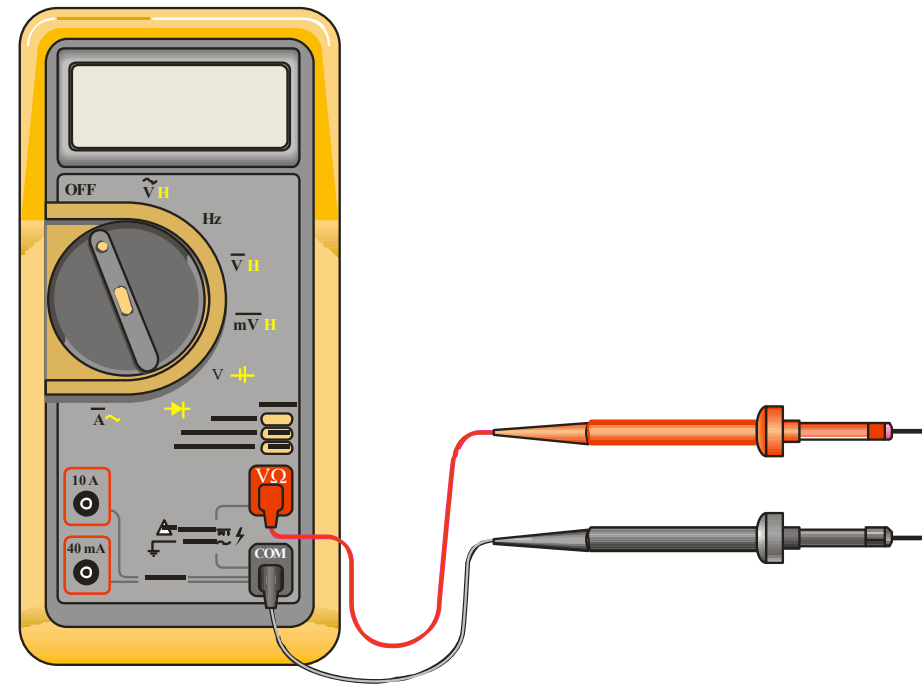


# Ch.2 Summary

## The DMM

The **digital multimeter**, or **DMM**, is an important multipurpose instrument which can measure voltage, current, and resistance.

*Many include other measurement options.*



# Ch.2 Summary

## Analog Meters

An **analog multimeter** is also called a **VOM** (volt-ohm-milliammeter). Analog meters measure voltage, current, and resistance. The user must choose the range and read the proper scale.



# Ch.2 Summary

## Selected Key Terms

### ***Ampere***

The unit of electrical current.

### ***AWG***

(American Wire Gauge) A standardization based on wire diameter.

### ***Charge***

An electrical property of matter that exists because of an excess or a deficiency of electrons. Charge can be either + or -.

### ***Circuit***

An interconnection of electronic components designed to produce a desired result. A basic circuit consists of a source, a load, and an interconnecting path.



# Ch.2 Summary

## Selected Key Terms

- Conductance** The ability of a circuit to allow current. The unit of conductance is the sieman (S).
- Coulomb** The unit of electrical charge.
- Current** The rate of flow of electrical charge.
- Electron** A basic particle of electrical charge in matter. The electron possesses a negative charge.
- Ground** The common or reference point in a circuit.
- Ohm ( $\Omega$ )** The unit of resistance.



# Ch.2 Summary

## Selected Key Terms

- Potentiometer** A three-terminal variable resistor.
- Resistance** The opposition to current. The unit is the ohm ( $\Omega$ ).
- Rheostat** A two-terminal variable resistor.
- Siemens** The unit of conductance.
- Volt** The unit of voltage or electromotive force.
- Voltage** The amount of energy per charge available to move electrons from one point to another in an electric circuit.



# Ch.2 Summary

## Quiz

1. The atomic number of an element is the number of
  - a. protons in the nucleus
  - b. neutrons in the nucleus
  - c. protons plus neutrons in the nucleus
  - d. electrons in the outer shell



# Ch.2 Summary

## Quiz

2. Valence electrons are
- a. in the outer shell
  - b. involved in chemical reactions
  - c. relatively loosely bound
  - d. all of the above



# Ch.2 Summary

## Quiz

3. The atomic particle responsible for electrical current in solid metallic conductors is the

- a. proton
- b. electron
- c. neutron
- d. all of the above





# Ch.2 Summary

## Quiz

4. The symbol for charge is

- a.  $C$
- b.  $\Omega$
- c.  $Q$
- d.  $W$



# Ch.2 Summary

## Quiz

5. The definition for voltage is

a.  $V = \frac{Q}{t}$

b.  $V = \frac{W}{t}$

c.  $V = \frac{W}{Q}$

d.  $V = I \times t$



# Ch.2 Summary

## Quiz

6. A battery stores

- a. electrons
- b. protons
- c. ions
- d. chemical energy



# Ch.2 Summary

## Quiz

7. The unit of conductance is the
- a. ohm
  - b. coulomb
  - c. siemens
  - d. ampere



# Ch.2 Summary

## Quiz

8. A four-color resistor with the color bands gray-red-black-gold is

- a.  $73 \Omega$
- b.  $82 \Omega$
- c.  $680 \Omega$
- d.  $820 \Omega$



# Ch.2 Summary

## Quiz

9. The color bands for a  $330\text{ k}\Omega \pm 5\%$  resistor are
- a. red-red-brown-gold
  - b. orange-orange-yellow-gold
  - c. yellow-yellow-red-gold
  - d. yellow-yellow-green-gold



# Ch.2 Summary

## Quiz

10. The circular mil is a unit of
- a. length
  - b. area
  - c. volume
  - d. resistance



# Ch.2 Summary

## Answers

- |      |       |
|------|-------|
| 1. a | 6. d  |
| 2. d | 7. c  |
| 3. b | 8. b  |
| 4. c | 9. b  |
| 5. c | 10. b |





# 3

## Ohm's Law, Energy, and Power



# Ch.3 Summary

## Review of $V$ , $I$ , and $R$

***Voltage*** is the amount of energy per charge available to move electrons from one point to another in a circuit, measured in **volts**.

***Current*** is the rate of charge flow, measured in **amperes**.

***Resistance*** is the opposition to current, measured in **ohms**.



# Ch.3 Summary

## Ohm's Law

The most important fundamental law in electronics is **Ohm's law**, which relates voltage, current, and resistance.

*Georg Simon Ohm (1787-1854) formulated the equation that bears his name:*

$$I = \frac{V}{R}$$

*What is the current in a circuit with a 12 V source if the resistance is 10  $\Omega$ ?*

**1.2 A**



# Ch.3 Summary

## Ohm's Law

If you need to solve for voltage, Ohm's law is:

$$V = I \times R$$

*What is the voltage across a 680  $\Omega$  resistor if the current is 26.5 mA?*

**18 V**



# Ch.3 Summary

## Ohm's Law

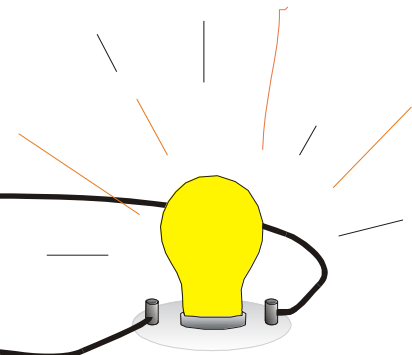
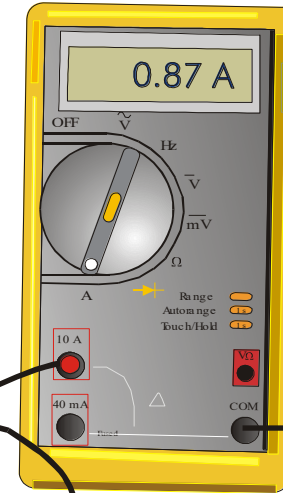
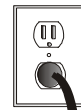
If you need to solve for resistance, Ohm's law is:

$$R = \frac{V}{I}$$

*What is the (hot) resistance of the bulb?*

**132  $\Omega$**

115 V



# Ch.3 Summary

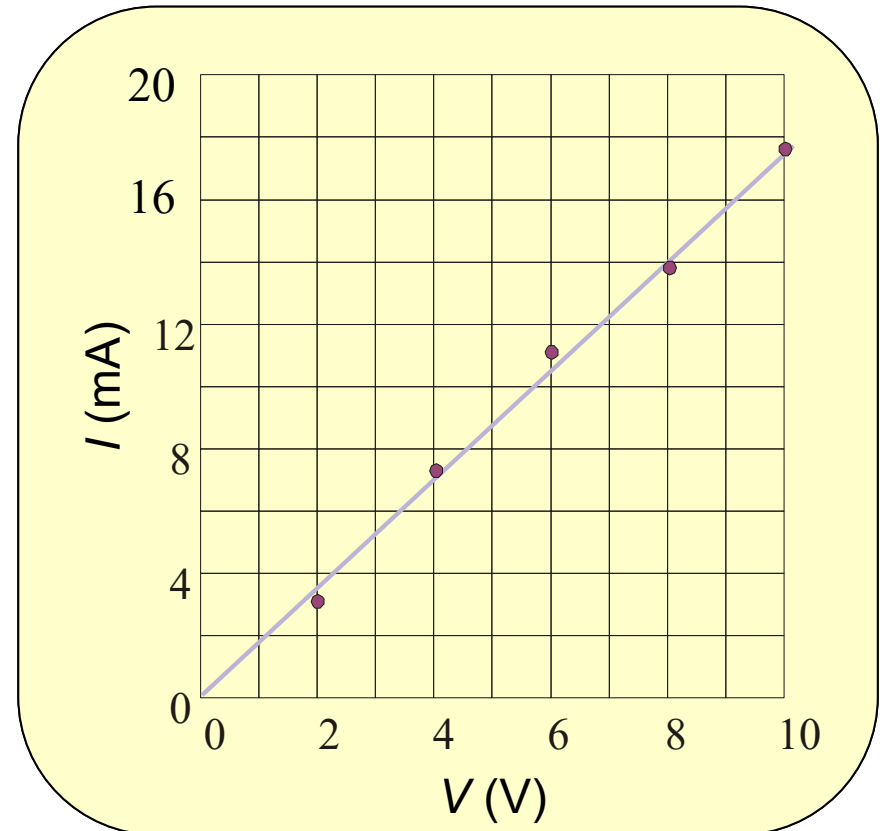
*A student takes data for a resistor and plots the data as shown. What is the conductance and the resistance of the resistor?*

The slope represents the conductance.

$$G = \frac{17.8 \text{ mA} - 0 \text{ mA}}{10.0 \text{ V} - 0 \text{ V}} = 1.78 \text{ mS}$$

The reciprocal of the conductance is the resistance.

$$R = \frac{1}{G} = \frac{1}{1.78 \text{ mS}} = 562 \text{ } \Omega$$



# Ch.3 Summary

## Graph of Current Versus Voltage

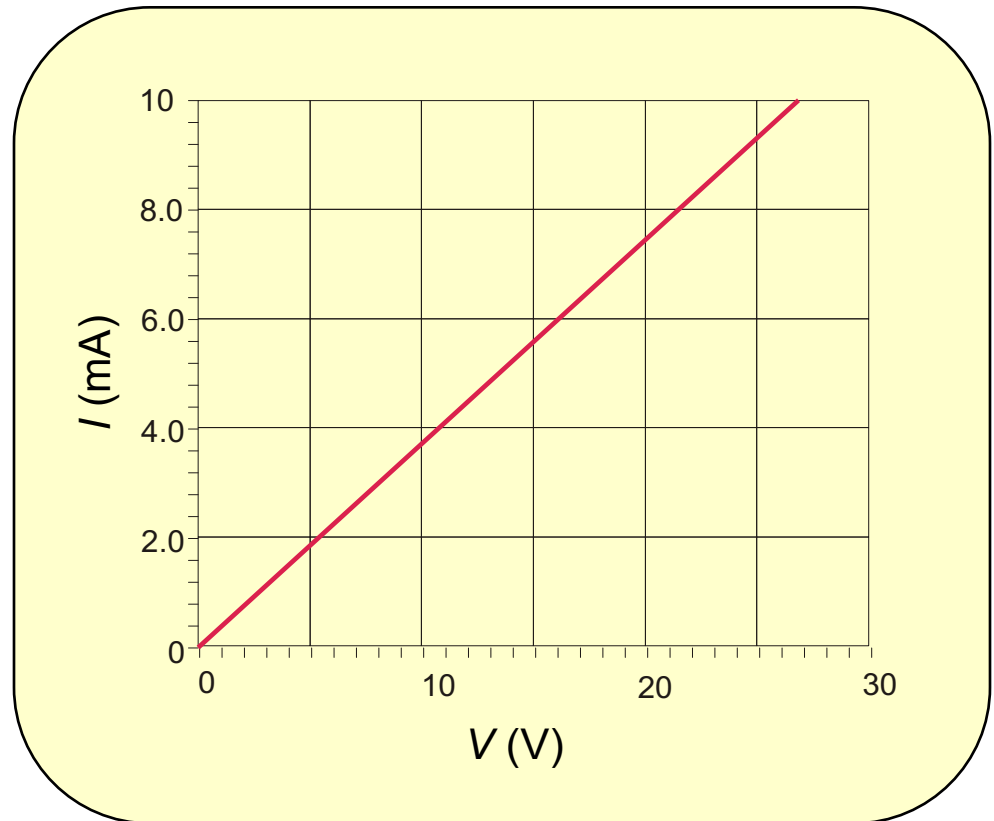
The plot of current versus voltage for a fixed resistor is a line with a positive slope.

*What is the resistance indicated by the graph?*

**2.7 k $\Omega$**

*What is its conductance?*

**0.37 mS**

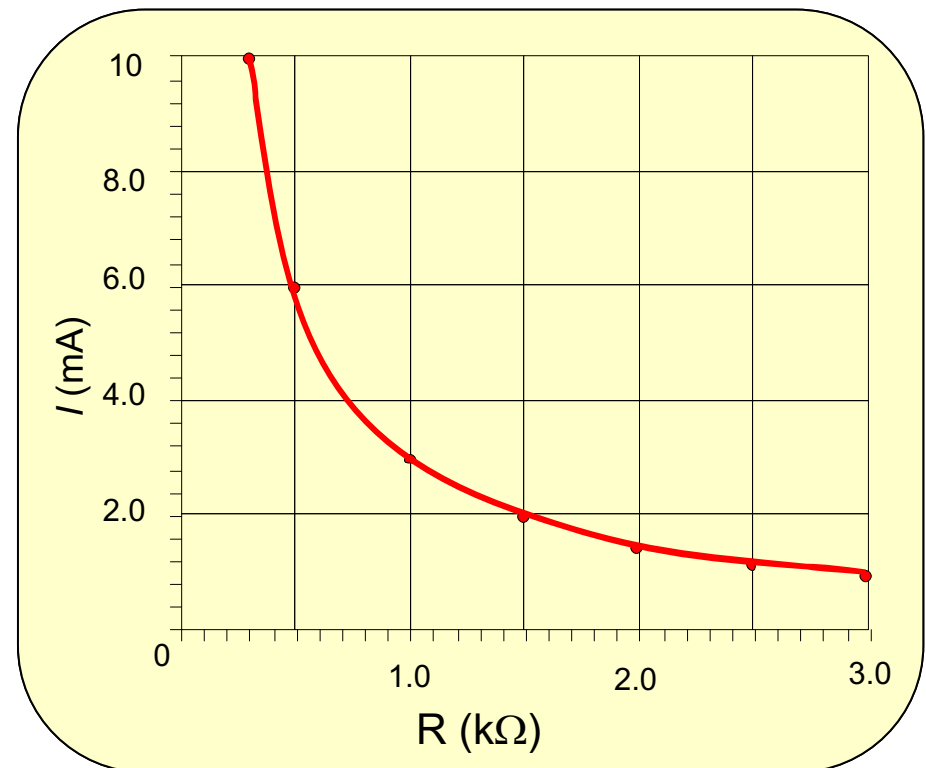


# Ch.3 Summary

## Graph of Current Versus Resistance

If resistance is varied for a constant voltage, the current versus resistance curve plots a hyperbola.

*What is the curve for a 3-V source?*





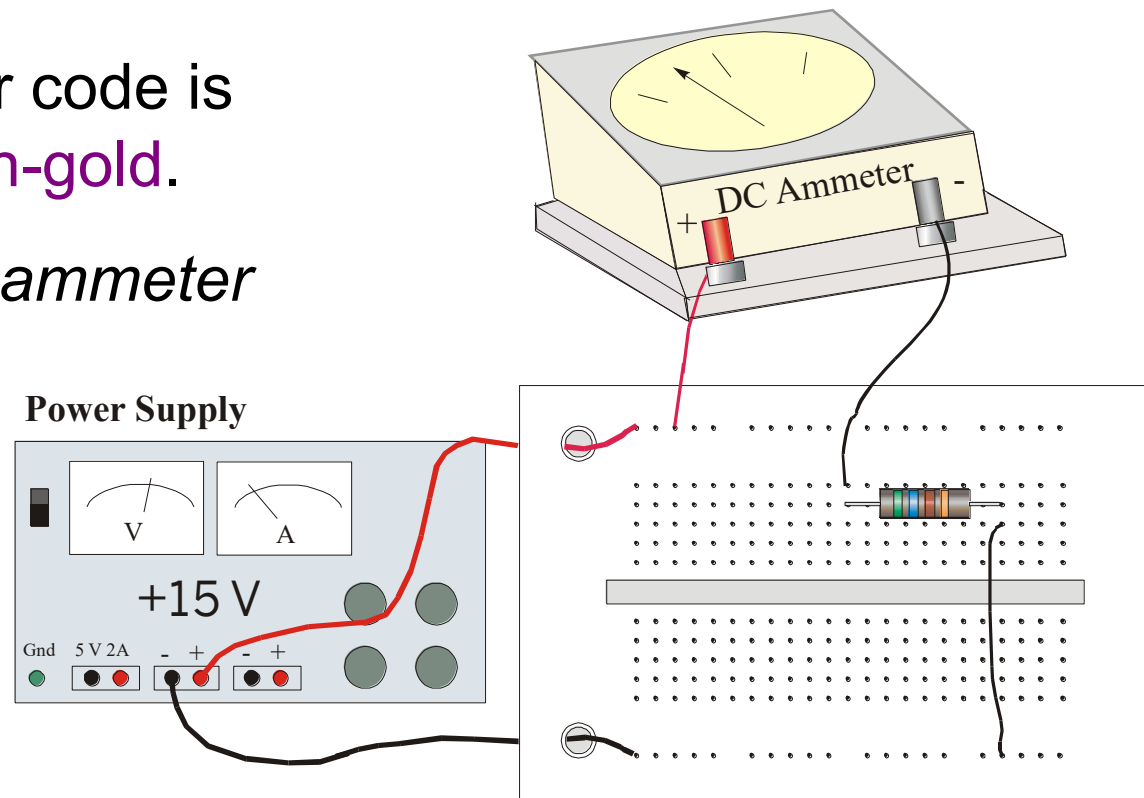
# Ch.3 Summary

## Application of Ohm's Law

The resistor color code is  
**green-blue-brown-gold.**

*What should the ammeter read?*

**26.8 mA**

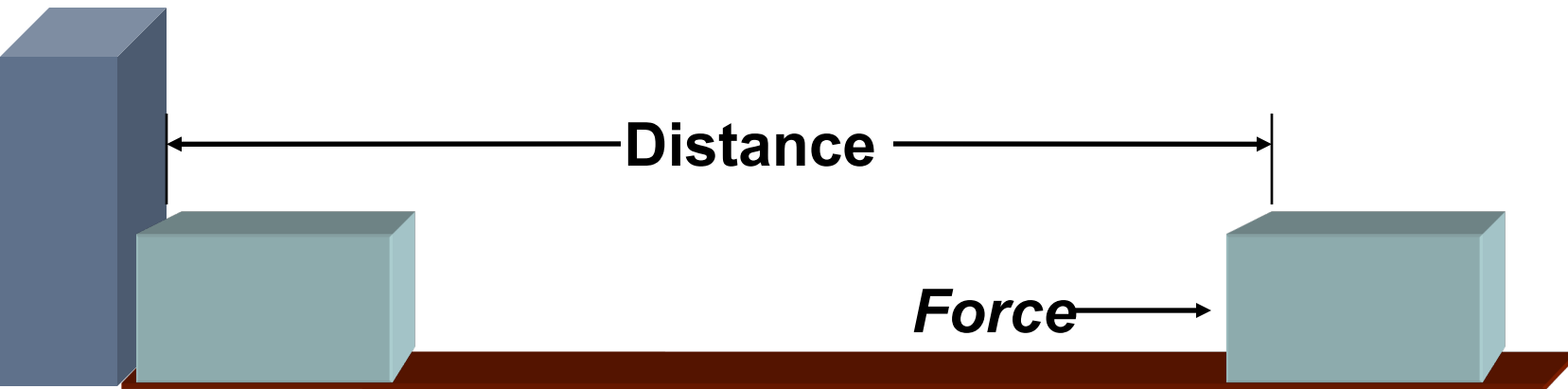


# Ch.3 Summary

## Energy and Power

When a constant force is applied to move an object over a distance, *the work is the force times the distance*. The force must be measured in the same direction as the distance.

The unit for work is the newton-meter (N-m) or joule (J).

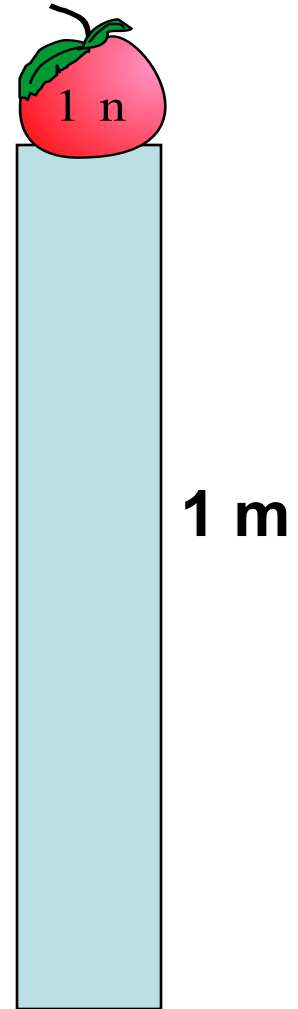


# Ch.3 Summary

## Energy and Power

One joule is the work done when a force of one newton is applied through a distance of one meter. A joule is a small amount of work approximately equal to the work done in raising an apple over a distance of 1 m.

The symbol for energy,  $W$ , represents work, but should not be confused with the unit for power, the watt,  $W$ .



# Ch.3 Summary

## Energy and Power

Energy is closely related to work. Energy is the ability to do work. As such, it is measured in the same units as work, namely the Newton-meter (N-m) or joule (J).

*What amount of energy is converted to heat in sliding a box along a floor for 5 meters if the force to move it is 400 n?*

$$W = Fd = (400 \text{ N})(5 \text{ m}) = 2000 \text{ N-m} = \mathbf{2000 \text{ J}}$$



# Ch.3 Summary

## Energy and Power

Power is the rate of doing work. Because it is a *rate*, a time unit is required. The unit is the joule per second (J/s), which defines a watt (W).

$$P = \frac{W}{t}$$

*What power is developed if the box in the previous example is moved in 10 s?*

$$P = \frac{W}{t} = \frac{2000 \text{ J}}{10 \text{ s}} = \mathbf{200 \text{ W}}$$



# Ch.3 Summary

## Energy and Power

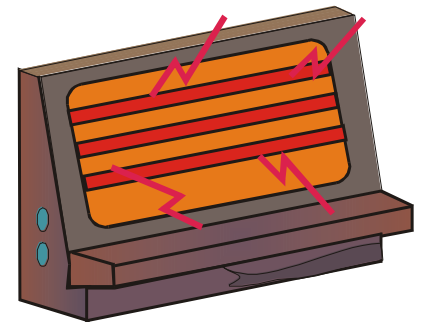
The kilowatt-hour (kWh) is a much larger unit of energy than the joule. There are  $3.6 \times 10^6$  J in a kWh. The kWh is convenient for electrical appliances.

*What is the energy used in operating a 1200 W heater for 20 minutes?*

$$1200 \text{ W} = 1.2 \text{ kW}$$

$$20 \text{ min} = 1/3 \text{ h}$$

$$1.2 \text{ kW} \times 1/3 \text{ h} = \mathbf{0.4 \text{ kWh}}$$



# Ch.3 Summary

## Energy and Power

In electrical work, the rate energy is dissipated can be determined from any of three forms of the power formula.

$$P = I^2 \times R$$

$$P = VI$$

$$P = \frac{V^2}{R}$$

Together, the three forms are called **Watt's law**.



# Ch.3 Summary

## Energy and Power

*What power is dissipated by a 27-Ω resistor if the current is 0.135 A?*

Given that you know the resistance and current, substitute the values into  $P = I^2 R$ .

$$\begin{aligned} P &= I^2 R \\ &= (0.135 \text{ A})^2 (27 \text{ } \Omega) \\ &= 0.49 \text{ W} \end{aligned}$$





# Ch.3 Summary

## Energy and Power

*What power is dissipated by a heater that draws 12 A of current from a 120 V supply?*

The most direct solution is to substitute into  $P = IV$ , as follows:

$$\begin{aligned} P &= VI \\ &= (120 \text{ V})(12 \text{ A}) \\ &= 1440 \text{ W} \end{aligned}$$



# Ch.3 Summary

## Energy and Power

*What power is dissipated by a 100-Ω resistor with 5 V across it?*

The most direct solution is to substitute into  $P = V^2 / R$ , as follows:

$$\begin{aligned} P &= \frac{V^2}{R} \\ &= \frac{(5 \text{ V})^2}{100 \Omega} \\ &= 0.25 \text{ W} \end{aligned}$$

It is important to remember that small resistors operating in low voltage systems need to be sized for the anticipated power.



# Ch.3 Summary

## Resistor Failures

Resistor failures are unusual except when they have been subjected to excessive heat. Look for discoloration (sometimes the color bands appear burned). Test with an ohmmeter by disconnecting one end from the circuit to isolate it and verify the resistance. Correct the cause of the heating problem (larger wattage resistor?, wrong value?).



**Normal**



**Overheated**



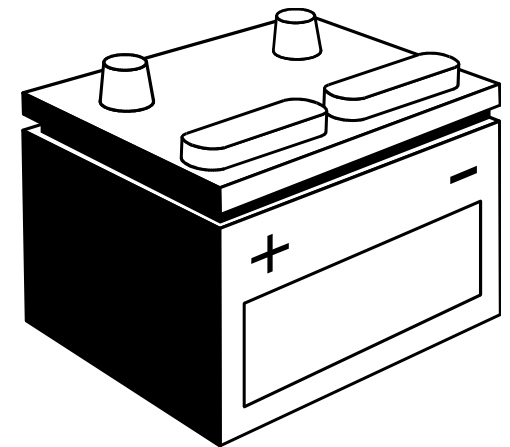
# Ch.3 Summary

## Ampere-hour Rating of Batteries

Expected battery life of batteries is given as the ampere-hours specification. Various factors affect this, so it is an approximation. (Factors include rate of current withdrawal, age of battery, temperature, etc.)

*How many hours can you expect to have a battery deliver 0.5 A if it is rated at 10 Ah?*

**20 h**



# Ch.3 Summary

## Troubleshooting

Some questions to ask before starting any troubleshooting are:

1. *Has the circuit ever worked?*
2. *If the circuit once worked, under what conditions did it fail?*
3. *What are the symptoms of the failure?*
4. *What are the possible causes of the failure?*



# Ch.3 Summary

## Troubleshooting

Plan the troubleshooting by reviewing pertinent information:

1. Schematics
2. Instruction manuals
3. Review when and how the failure occurred.



# Ch.3 Summary

## Troubleshooting

You may decide to start at the middle of a circuit and work in toward the failure. This approach is called *half-splitting*.

Based on the plan of attack, look over the circuit carefully and make measurements as needed to localize the problem. Modify the plan if necessary as you proceed.

*After solving the problem, it is useful to ask, “How can I prevent this failure in the future?”*



# Ch.3 Summary

## Selected Key Terms

- Ohm's law*** A law stating that current is directly proportional to voltage and inversely proportional to current.
- Linear*** Characterized by a straight-line relationship.
- Energy*** The ability to do work. The unit is the joule (J).
- Power*** The rate of energy usage.
- Joule*** The SI unit of energy.





# Ch.3 Summary

## Selected Key Terms

**Watt** The unit of power. One watt is the power when 1 J of energy is used in 1 s.

**Kilowatt-hour** A common unit of energy used mainly by utility companies.

**Ampere-hour rating** A number determined by multiplying the current (A) times the length of time (h) that a battery can deliver that current to a load.

**Efficiency** The ratio of output power to input power of a circuit, usually expressed as a percent.



# Ch.3 Summary

## Quiz

1. Holding the voltage constant, and plotting the current against the resistance as resistance is varied will form a

- a. straight line with a positive slope
- b. straight line with a negative slope
- c. parabola
- d. hyperbola



# Ch.3 Summary

## Quiz

2. When the current is plotted against the voltage for a fixed resistor, the plot is a
- a. straight line with a positive slope
  - b. straight line with a negative slope
  - c. parabola
  - d. hyperbola



# Ch.3 Summary

## Quiz

3. For constant voltage in a circuit, doubling the resistance means
- a. doubling the current
  - b. halving the current
  - c. there is no change in the current
  - d. depends on the amount of voltage



# Ch.3 Summary

## Quiz

4. A resistor is color-coded red-violet-orange-gold. If it is placed across a 12 V source, the expected current is

- a. 0.12 mA
- b. 0.44 mA
- c. 1.25 mA
- d. 4.44 mA



# Ch.3 Summary

## Quiz

5. If the current in a  $330\ \Omega$  resistor is  $15\ \text{mA}$ , the voltage across it is approximately

- a.  $5.0\ \text{V}$
- b.  $22\ \text{V}$
- c.  $46\ \text{V}$
- d.  $60\ \text{V}$



# Ch.3 Summary

## Quiz

6. A unit of power is the
- a. joule
  - b. kilowatt-hour
  - c. both of the above
  - d. none of the above



# Ch.3 Summary

## Quiz

7. The SI unit of energy is the

- a. volt
- b. watt
- c. joule
- d. kilowatt-hour





# Ch.3 Summary

## Quiz

8. If the voltage in a resistive circuit is doubled, the power will be

- a. halved
- b. unchanged
- c. doubled
- d. quadrupled



# Ch.3 Summary

## Quiz

9. The approximate power dissipated by a  $330\ \Omega$  resistor with  $9\ \text{V}$  across it is

- a.  $\frac{1}{4}\ \text{W}$
- b.  $\frac{1}{2}\ \text{W}$
- c.  $1\ \text{W}$
- d.  $2\ \text{W}$



# Ch.3 Summary

## Quiz

10. Before troubleshooting a faulty circuit you should find out

- a. If the circuit ever worked
- b. The conditions that existed when it failed
- c. The symptoms of the failure
- d. All of the above



# Ch.3 Summary

## Quiz Answers

- |      |       |
|------|-------|
| 1. d | 6. d  |
| 2. a | 7. c  |
| 3. b | 8. d  |
| 4. b | 9. a  |
| 5. a | 10. d |



# 4

## Series Circuits

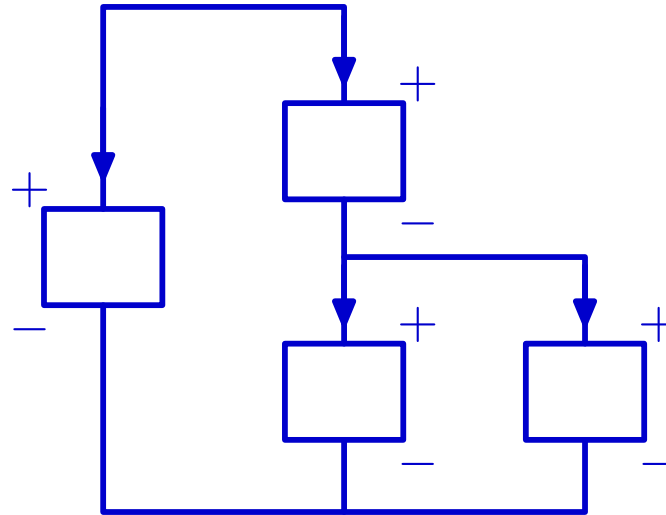


# The Circuit Abstraction

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**Circuits** represent systems as connections of elements

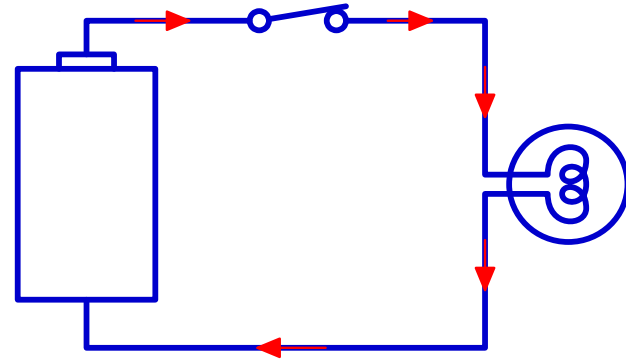
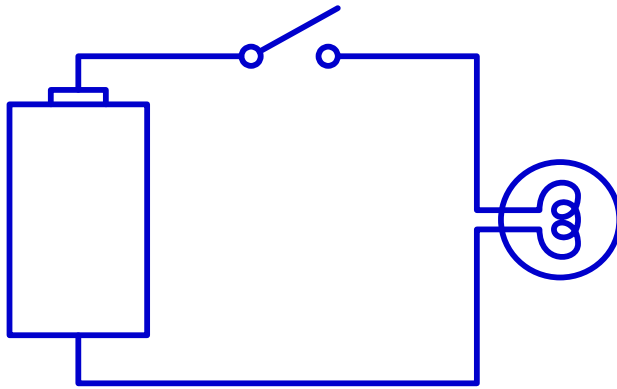
- through which currents (through variables) flow and
- across which voltages (across variables) develop.



# The Circuit Abstraction

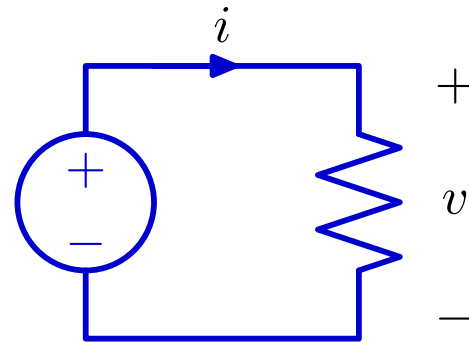
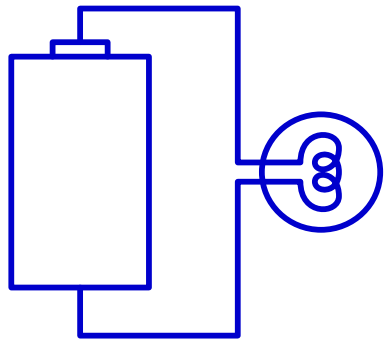
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Current flows through a flashlight when the switch is closed



# The Circuit Abstraction

We can represent the flashlight as a voltage source (battery) connected to a resistor (light bulb).



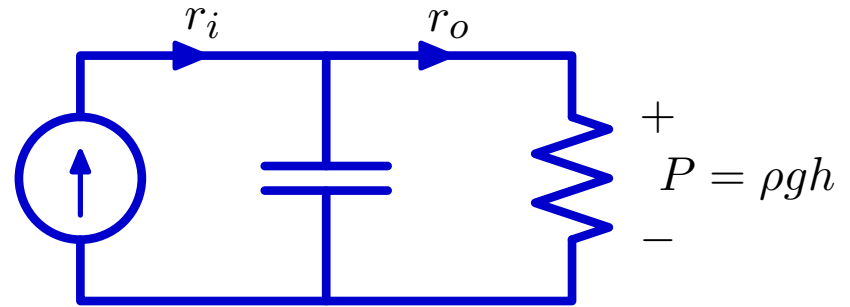
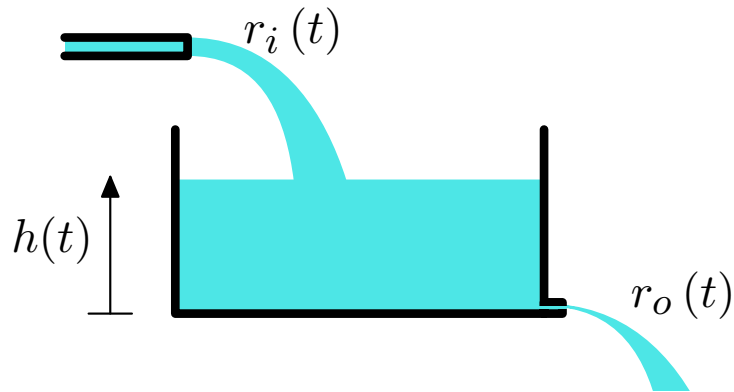
The voltage source generates a voltage  $v$  across the resistor and a current  $i$  through the resistor.





# The Circuit Abstraction

We can represent the flow of water by a circuit.



Flow of water into and out of tank are represented as “through” variables  $r_i$  and  $r_o$ , respectively. Hydraulic pressure at bottom of tank is represented by the “across” variable  $P = \rho gh$ .



# The Circuit Abstraction

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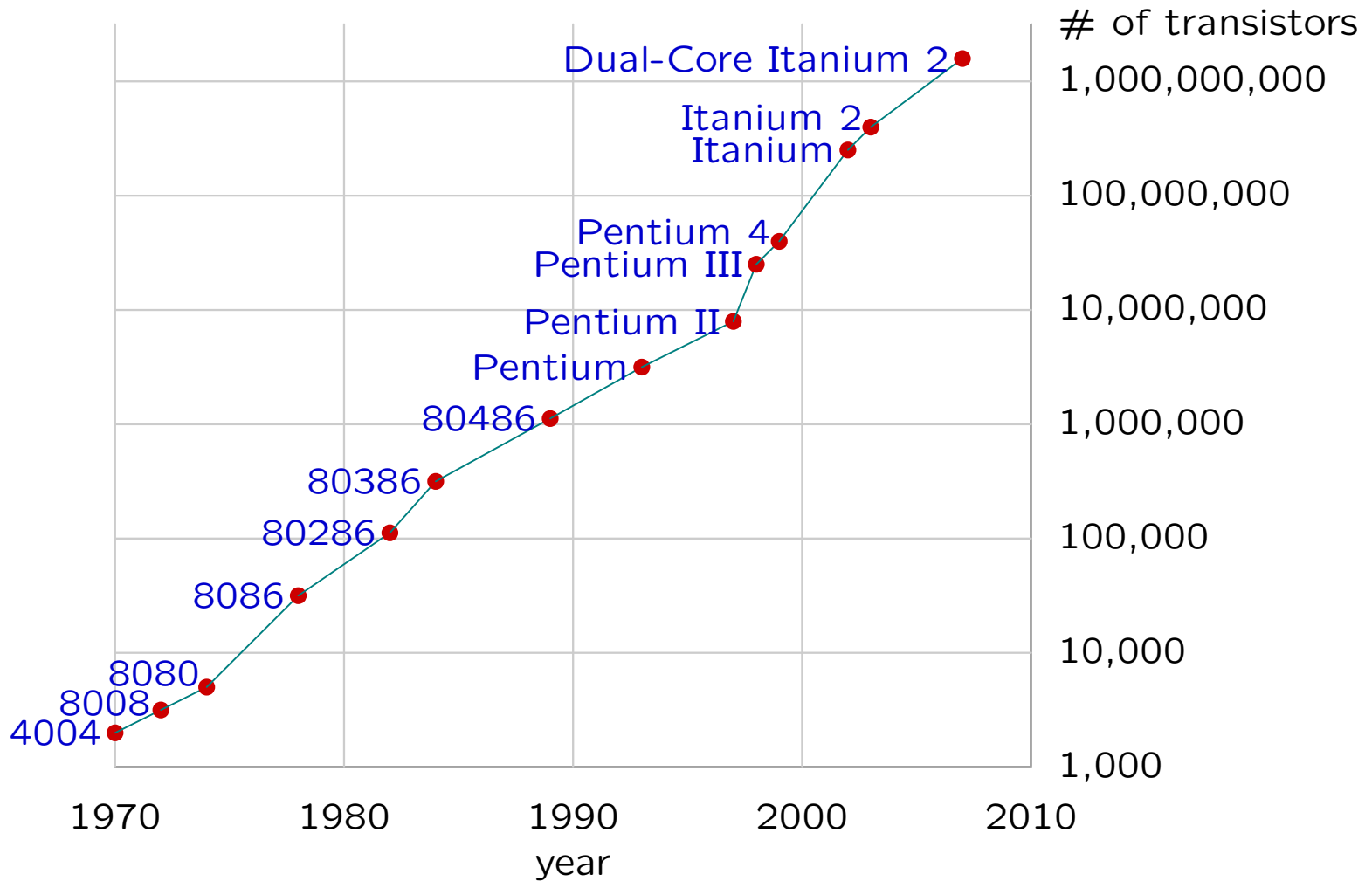
Circuits are important for two very different reasons:

- as **physical systems**
  - power (from generators and transformers to power lines)
  - electronics (from cell phones to computers)
- as **models** of complex systems
  - neurons
  - brain
  - cardiovascular system
  - hearing



# The Circuit Abstraction

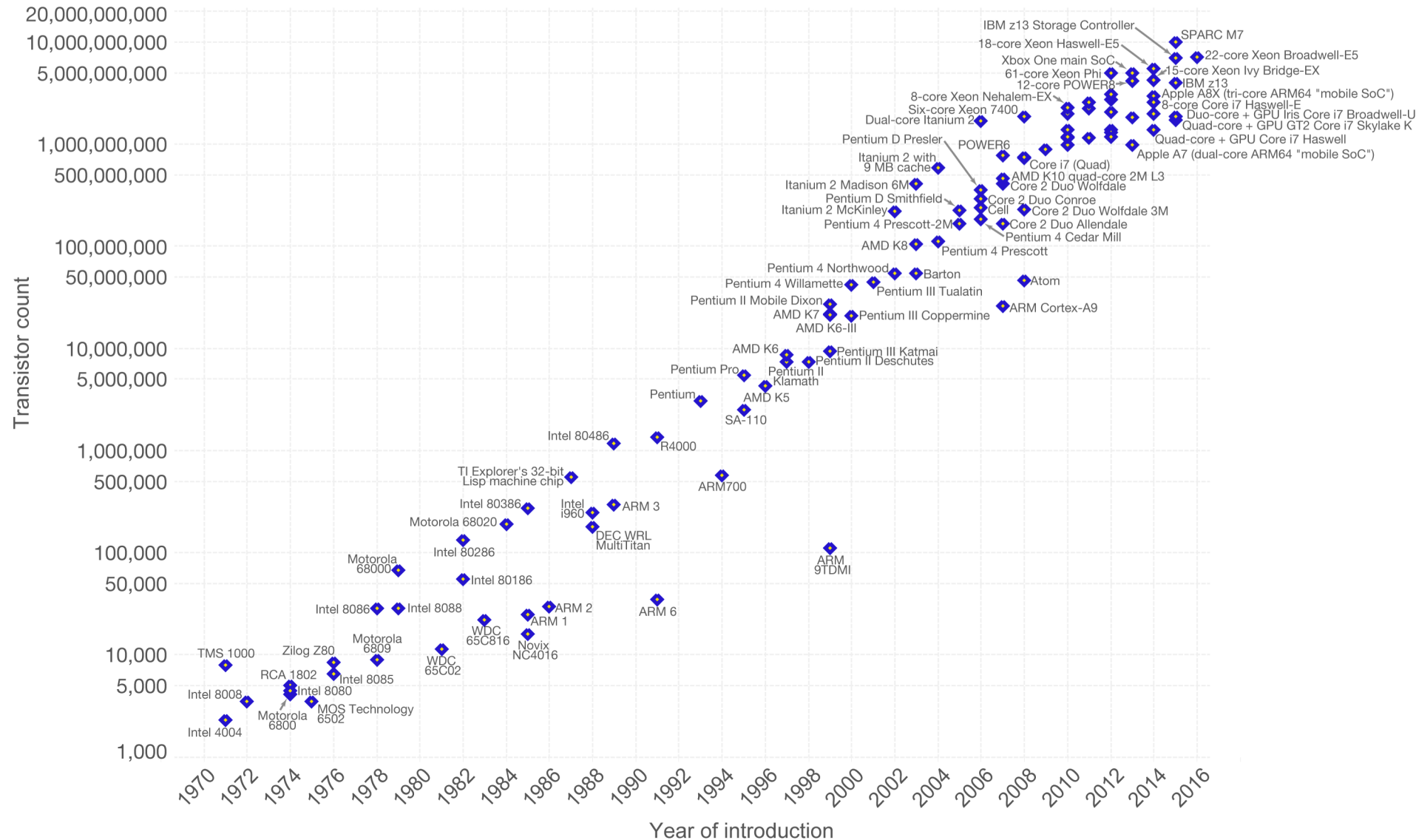
Circuits are basis of enormously successful semiconductor industry.



What design principles enable development of such complex systems?

# Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.



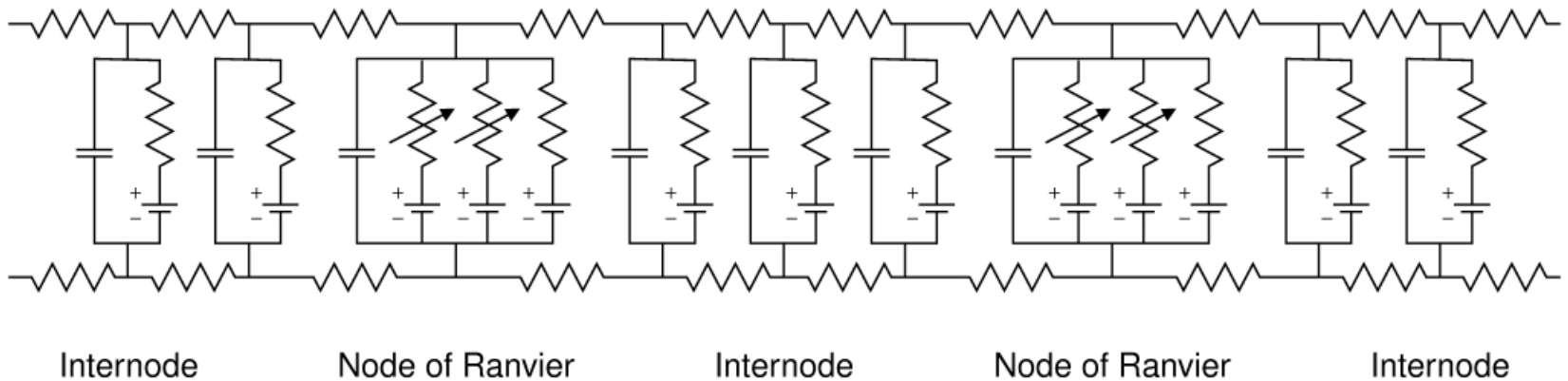
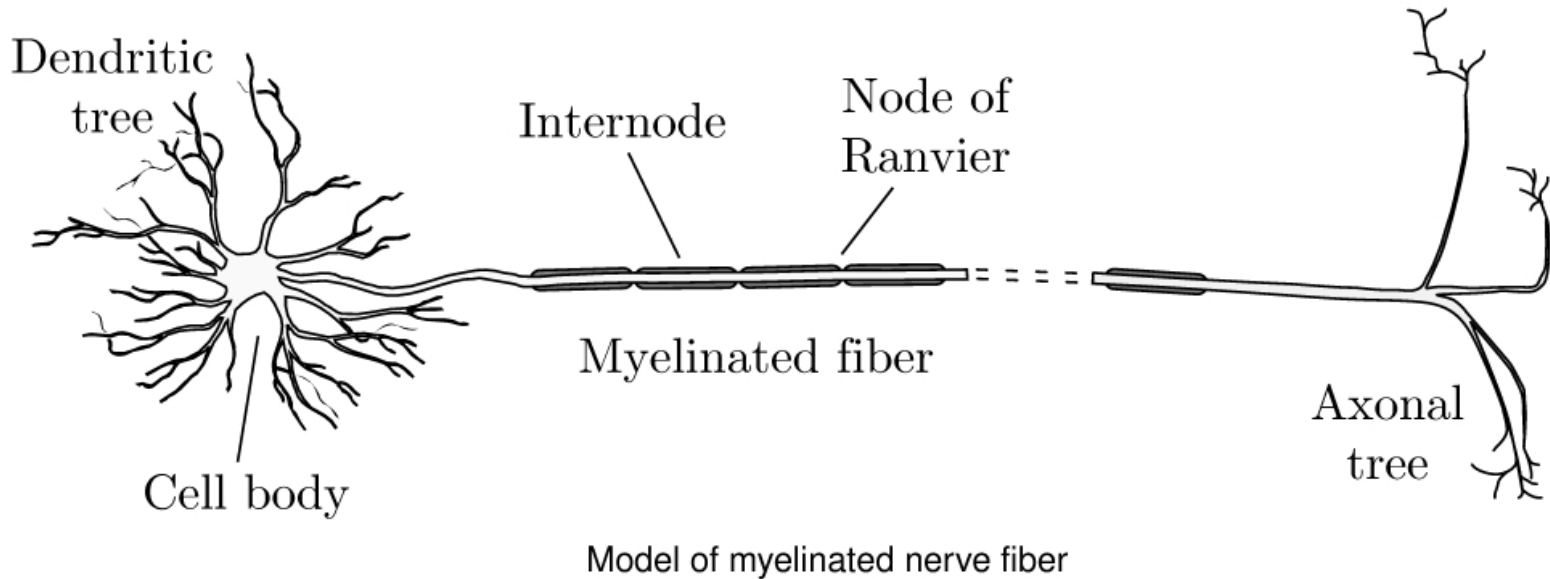
Data source: Wikipedia ([https://en.wikipedia.org/wiki/Transistor\\_count](https://en.wikipedia.org/wiki/Transistor_count))

The data visualization is available at [OurWorldinData.org](https://www.ourworldindata.org). There you find more visualizations and research on this topic.

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# The Circuit Abstraction

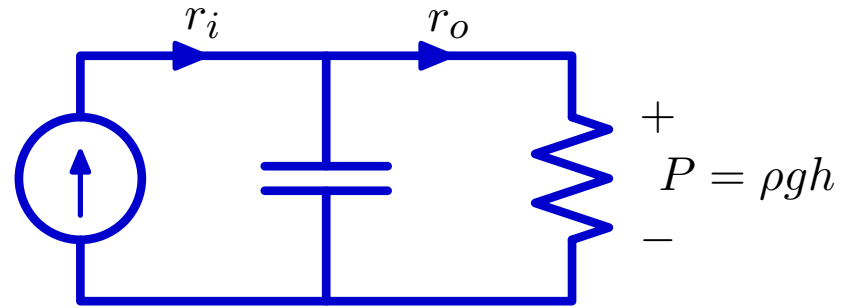
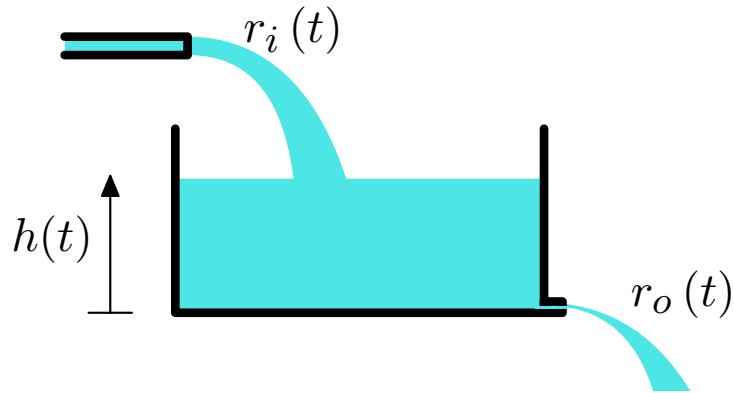
Circuits as models of complex systems: myelinated neuron.



# The Circuit Abstraction

**Circuits** represent systems as connections of elements

- through which currents (through variables) flow and
- across which voltages (across variables) develop.



The **primitives** are the elements:

- sources,
- capacitors, and
- resistors.

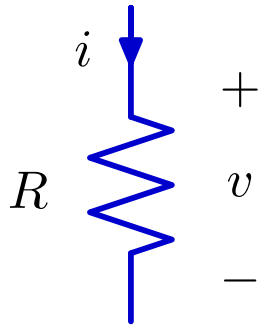
The **rules of combination** are the rules that govern

- flow of current (through variable) and
- development of voltage (across variable).

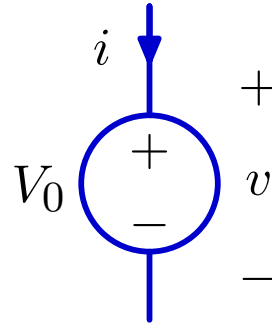


# Analyzing Circuits: Elements

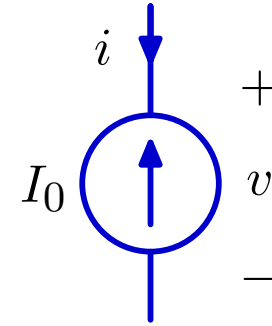
We will start with the simplest elements: resistors and sources



$$v = iR$$



$$v = V_0$$



$$i = -I_0$$

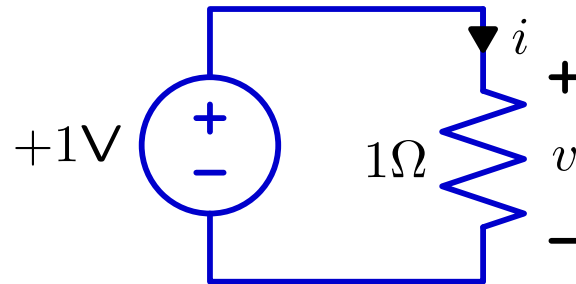


# Analyzing Simple Circuits

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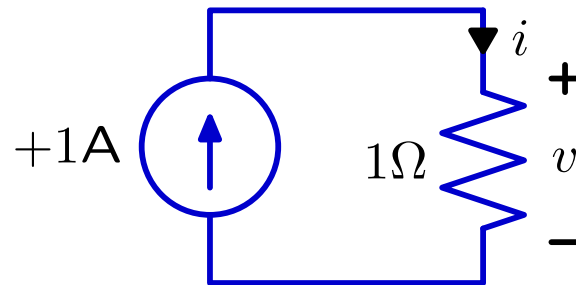
Analyzing simple circuits is straightforward.

Example 1:



The voltage source determines the voltage across the resistor,  $v = 1\text{V}$ , so the current through the resistor is  $i = v/R = 1/1 = 1\text{A}$ .

Example 2:

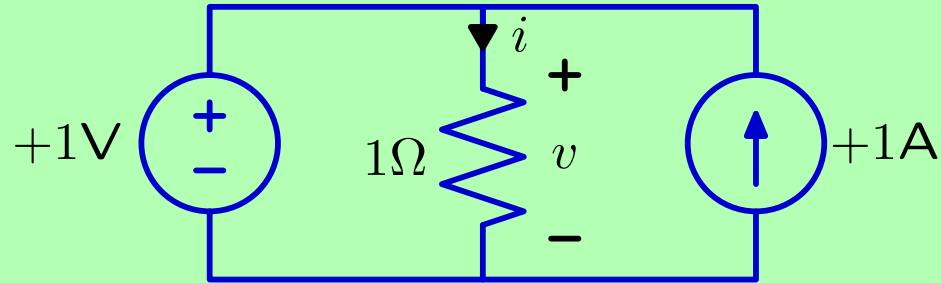


The current source determines the current through the resistor,  $i = 1\text{A}$ , so the voltage across the resistor is  $v = iR = 1 \times 1 = 1\text{V}$ .



# Check Yourself

What is the current through the resistor below?



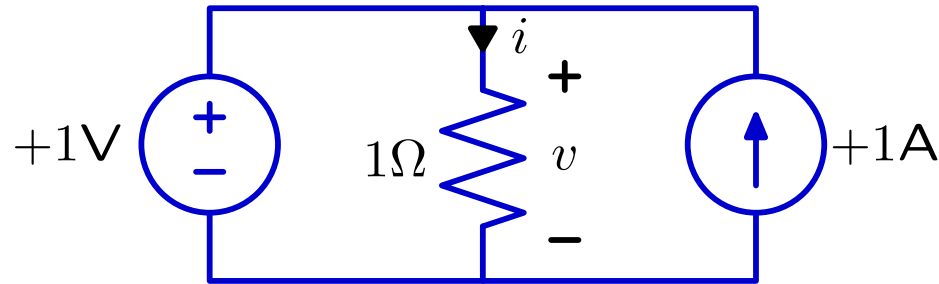
1. 1A
2. 2A
3. 0A
4. cannot determine
5. none of the above



## Check Yourself

---

What is the current through the resistor below?



The voltage source forces the voltage across the resistor to be 1V. Therefore, the current through the resistor is  $1\text{V}/1\Omega = 1\text{A}$ .

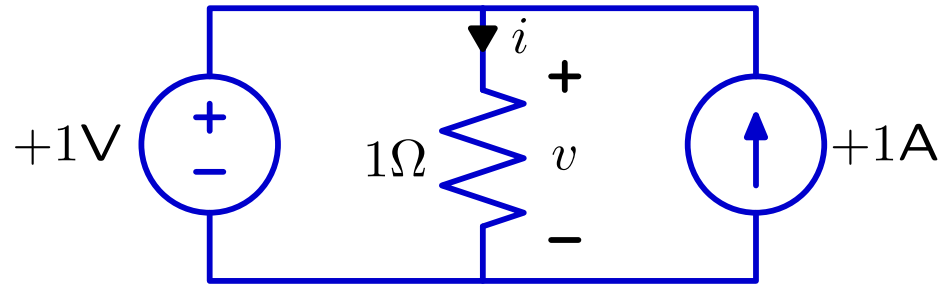
Does the current source do anything?



## Check Yourself

---

Does the current source do anything?



If all of the current from current source flowed through the resistor, then it would generate 1V across the resistor.

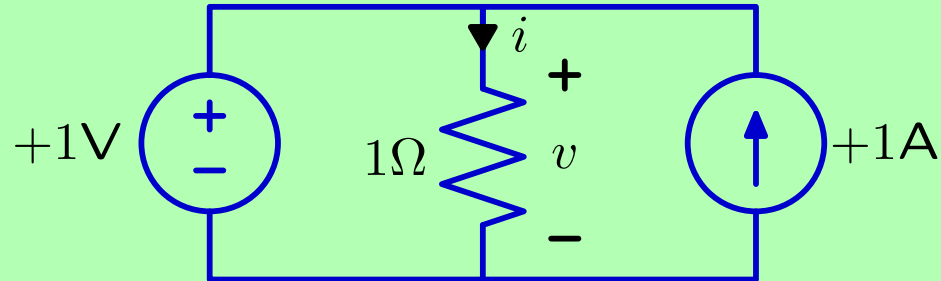
Since the voltage generated by the current source is equal to that across the voltage source, the voltage source provides zero current.

The current source supplies all of the current through the resistor!



# Check Yourself

What is the current through the resistor below?



1.  $1\text{A}$
2.  $2\text{A}$
3.  $0\text{A}$
4. cannot determine
5. none of the above

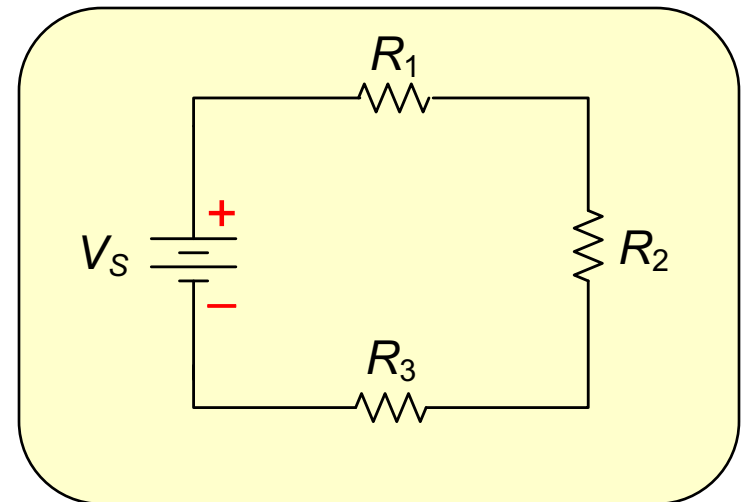


# Ch.4 Summary

## Series Circuits

All circuits have three common attributes.  
These are:

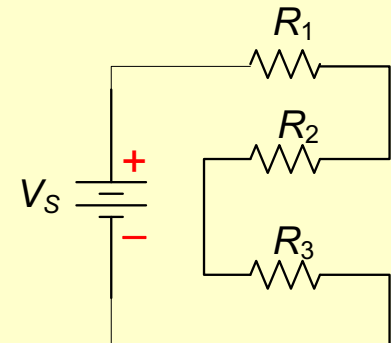
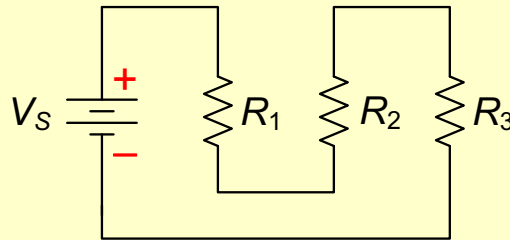
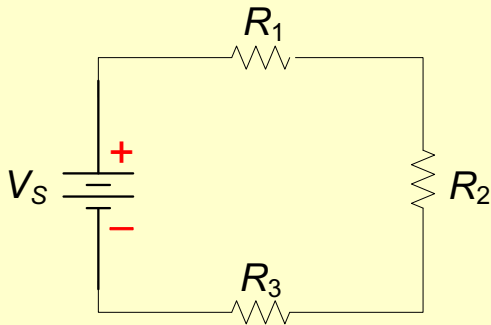
1. A source of voltage.
2. A load.
3. A complete path.



# Ch.4 Summary

## Series Circuits

A **series circuit** is one that has **only one current path**.

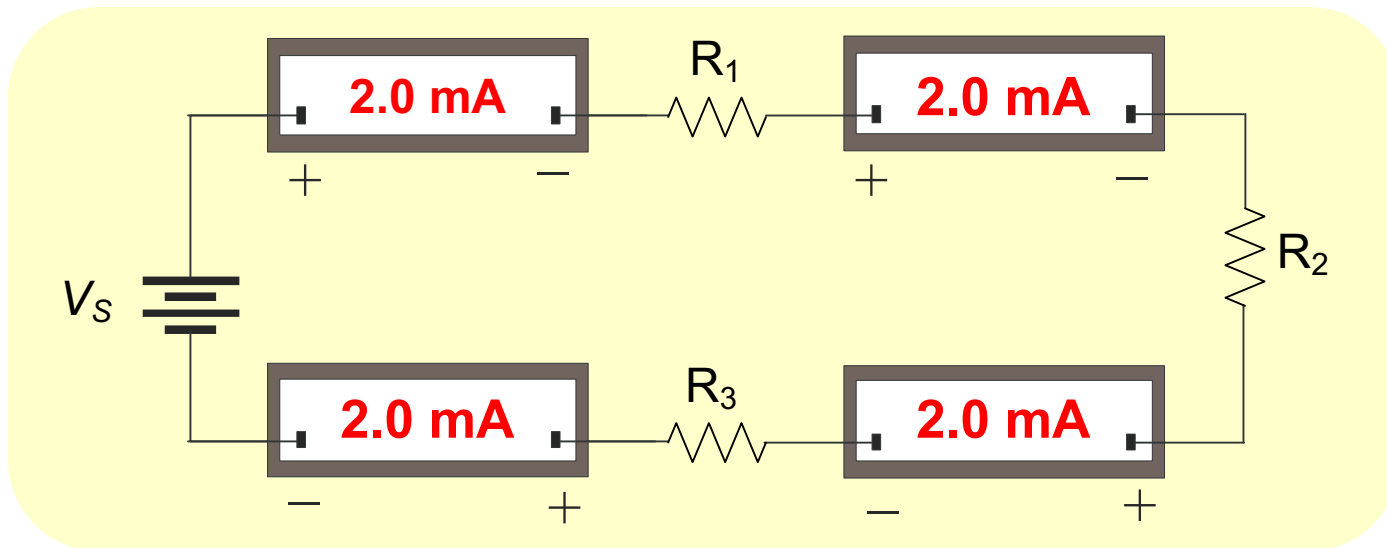


# Ch.4 Summary

## Series Circuit Rule for Current

Because there is only one path, the current everywhere is *the same*.

*For example, the reading on the first ammeter below is 2.0 mA, What do the other meters read?*

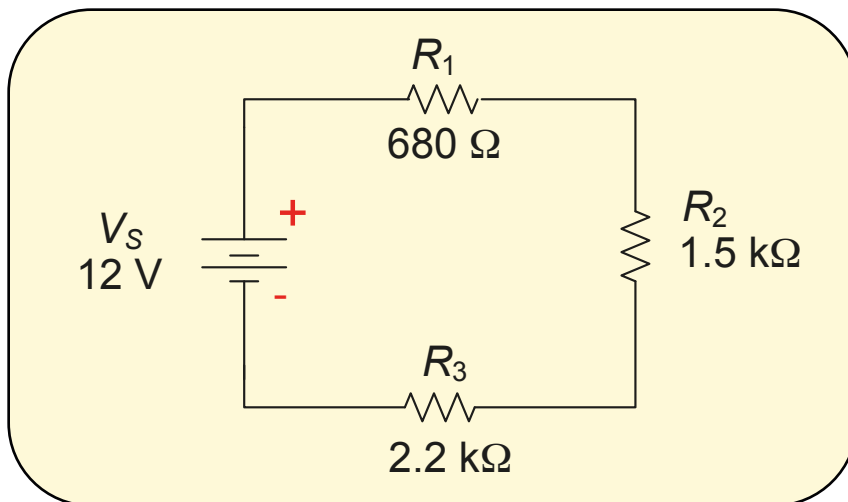


# Ch.4 Summary

## Series Circuits

The total resistance of resistors in series equals ***the sum of the individual resistors.***

*For example, the resistors in the series circuit below are  $680\ \Omega$ ,  $1.5\ \text{k}\Omega$ , and  $2.2\ \text{k}\Omega$ . What is the total resistance?*



**4.38 k $\Omega$**

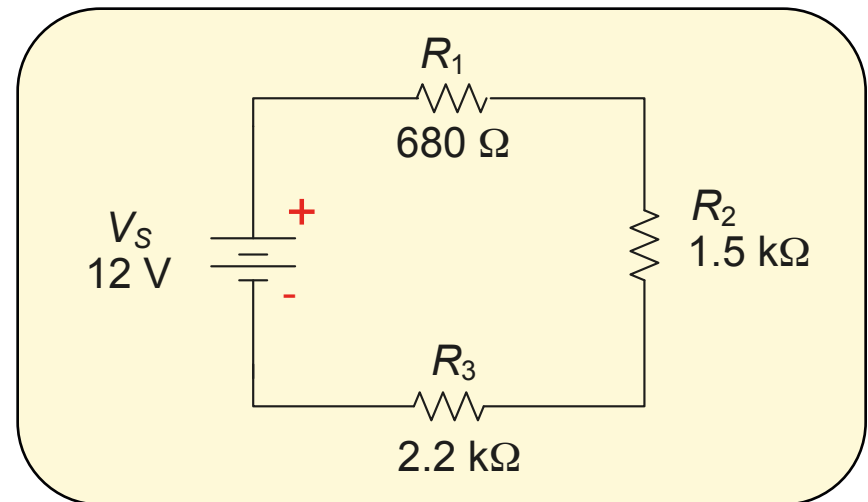




# Ch.4 Summary

## Series Circuits

Tabulating current, resistance, voltage and power is a useful way to summarize parameters in a series circuit.



$I_1 = 2.74 \text{ mA}$	$R_1 = 680 \Omega$	$V_1 = 1.86 \text{ V}$	$P_1 = 5.1 \text{ mW}$
$I_2 = 2.74 \text{ mA}$	$R_2 = 1.5 \text{ k}\Omega$	$V_2 = 4.11 \text{ V}$	$P_2 = 11.3 \text{ mW}$
$I_3 = 2.74 \text{ mA}$	$R_3 = 2.2 \text{ k}\Omega$	$V_3 = 6.03 \text{ V}$	$P_3 = 16.5 \text{ mW}$
$I_T = 2.74 \text{ mA}$	$R_T = 4.38 \text{ k}\Omega$	$V_T = 12 \text{ V}$	$P_T = 32.9 \text{ mW}$

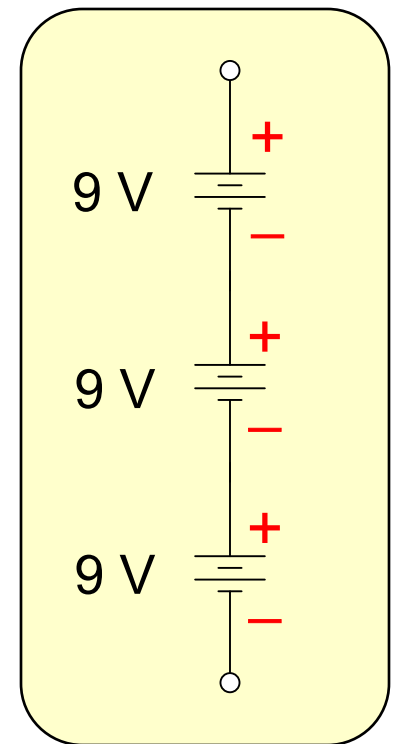


# Ch.4 Summary

## Voltage Sources in Series

Voltage sources in series add algebraically. For example, the total voltage of the sources shown is **27 V**

What is the total voltage if one battery is accidentally reversed?  
**9 V**



# Analyzing More Complex Circuits

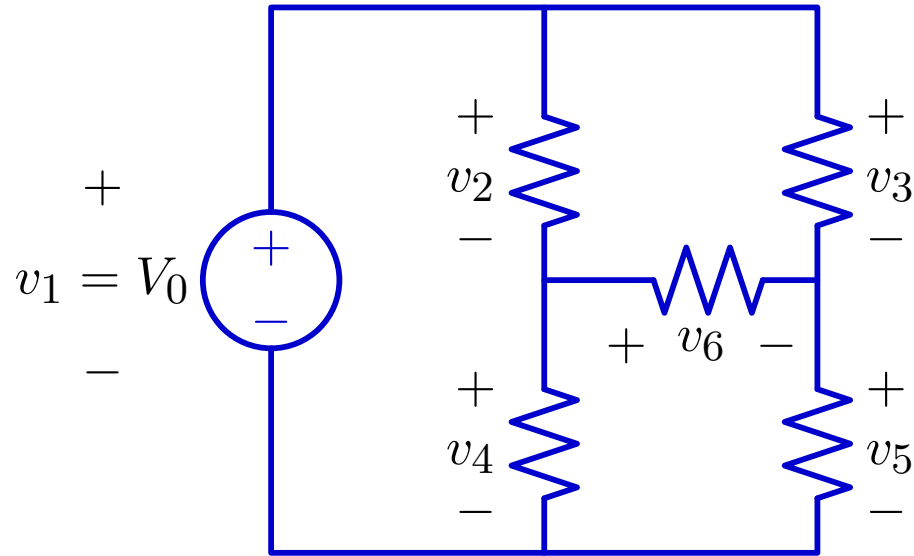
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More complex circuits can be analyzed by systematically applying Kirchhoff's voltage law (KVL) and Kirchhoff's current law (KCL).



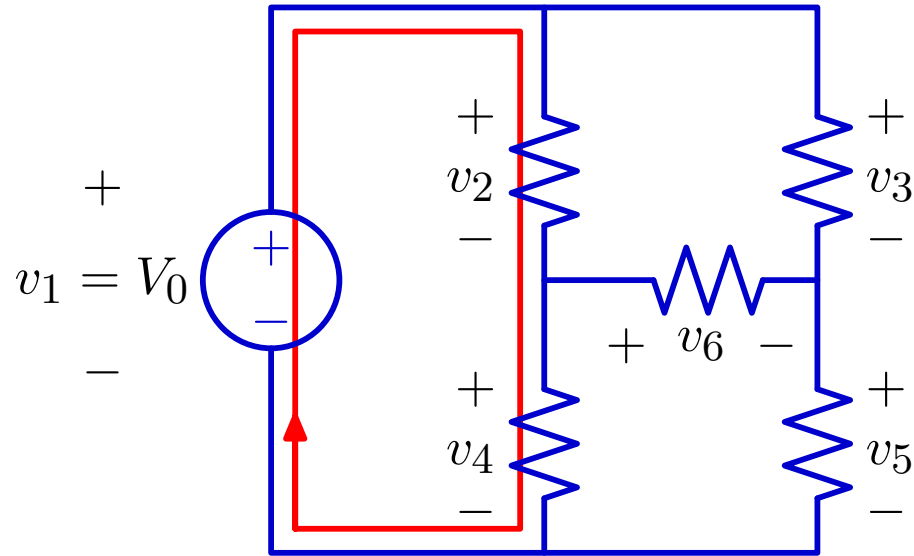
# Analyzing Circuits: KVL

KVL: The sum of the voltages around any closed path is zero.



# Analyzing Circuits: KVL

KVL: The sum of the voltages around any closed path is zero.



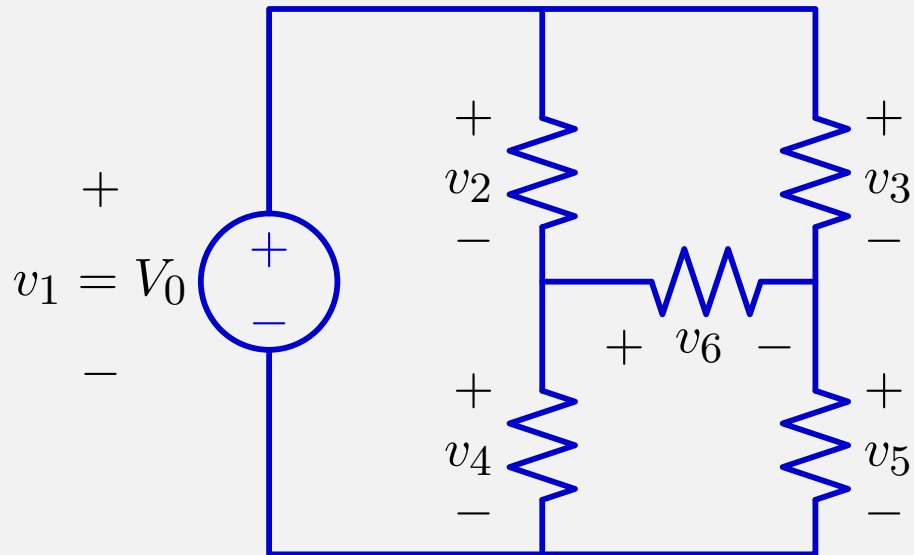
Example:  $-v_1 + v_2 + v_4 = 0$  or equivalently  $v_1 = v_2 + v_4$ .

How many other KVL relations are there?



# Check Yourself

How many KVL equations can be written for this circuit?



1. 3

2. 4

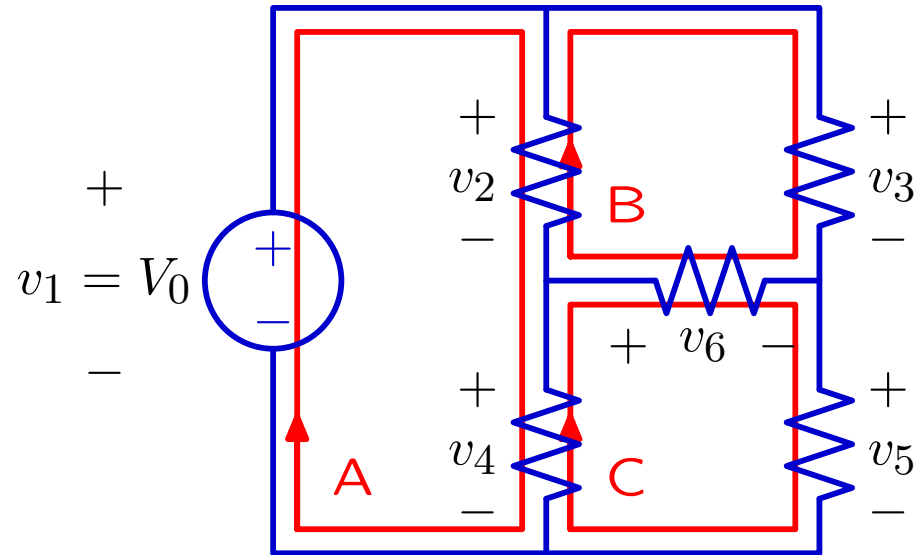
3. 5

4. 6

5. 7



# Check Yourself



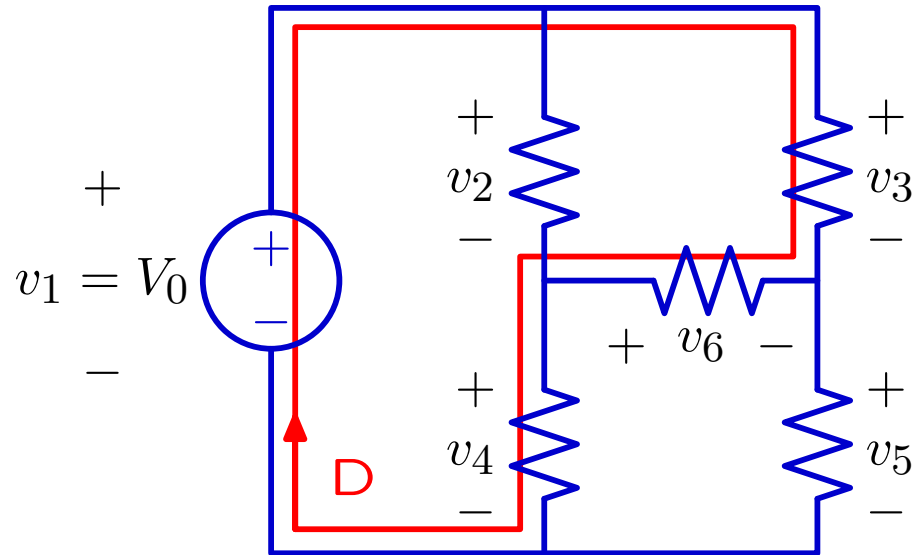
$$A : -v_1 + v_2 + v_4 = 0$$

$$B : -v_2 + v_3 - v_6 = 0$$

$$C : -v_4 + v_6 + v_5 = 0$$



# Check Yourself

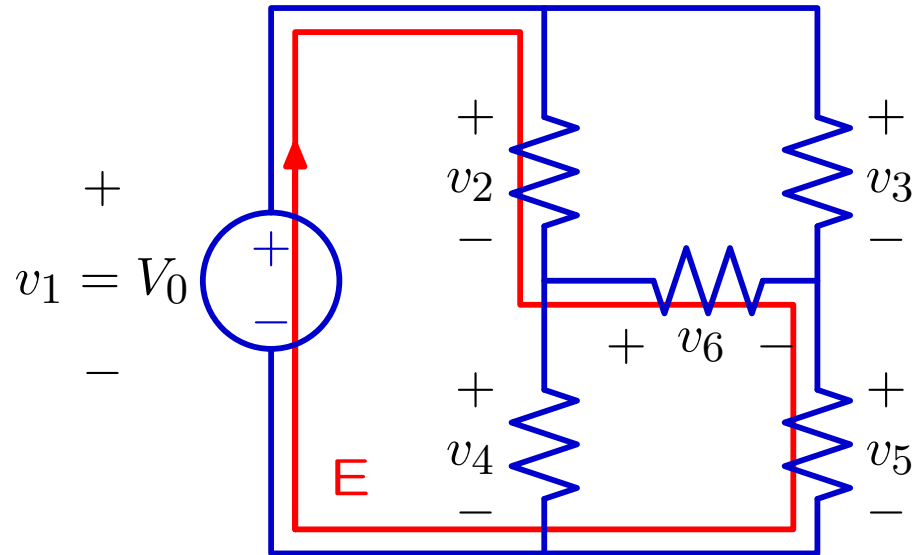


$$D : -v_1 + v_3 - v_6 + v_4 = 0$$





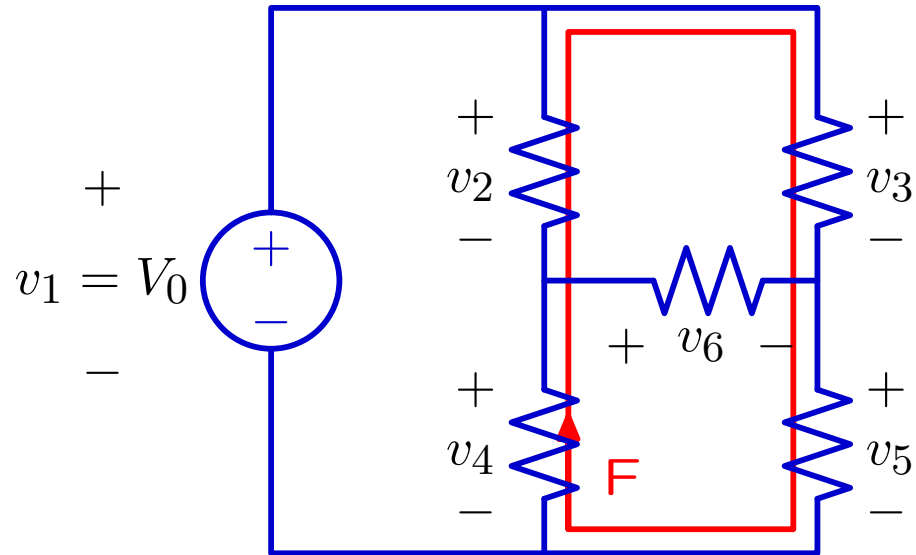
# Check Yourself



$$E : -v_1 + v_2 + v_6 + v_5 = 0$$



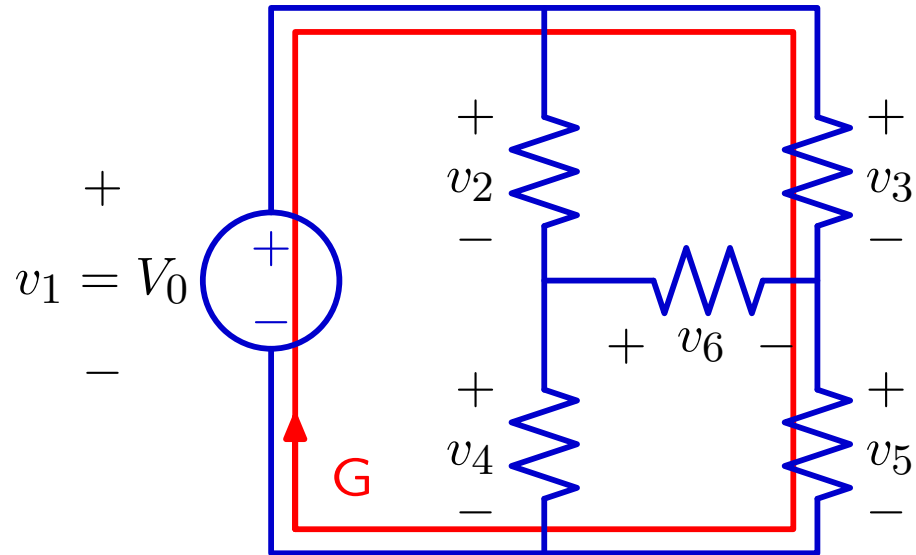
# Check Yourself



$$F : -v_4 - v_2 + v_3 + v_5 = 0$$



# Check Yourself



$$G : -v_1 + v_3 + v_5 = 0$$



## Check Yourself

---

There are 7 KVL equations for this circuit.

$$A : -v_1 + v_2 + v_4 = 0$$

$$B : -v_2 + v_3 - v_6 = 0$$

$$C : -v_4 + v_6 + v_5 = 0$$

$$D : -v_1 + v_3 - v_6 + v_4 = 0$$

$$E : -v_1 + v_2 + v_6 + v_5 = 0$$

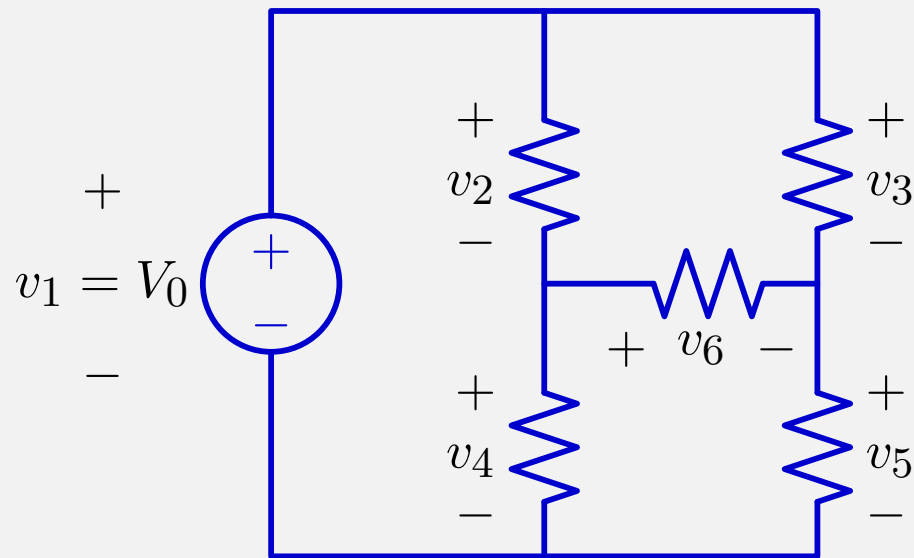
$$F : -v_4 - v_2 + v_3 + v_5 = 0$$

$$G : -v_1 + v_3 + v_5 = 0$$

Not all of these equations are linearly independent.



How many KVL equations can be written for this circuit?



1. 3

2. 4

3. 5

4. 6

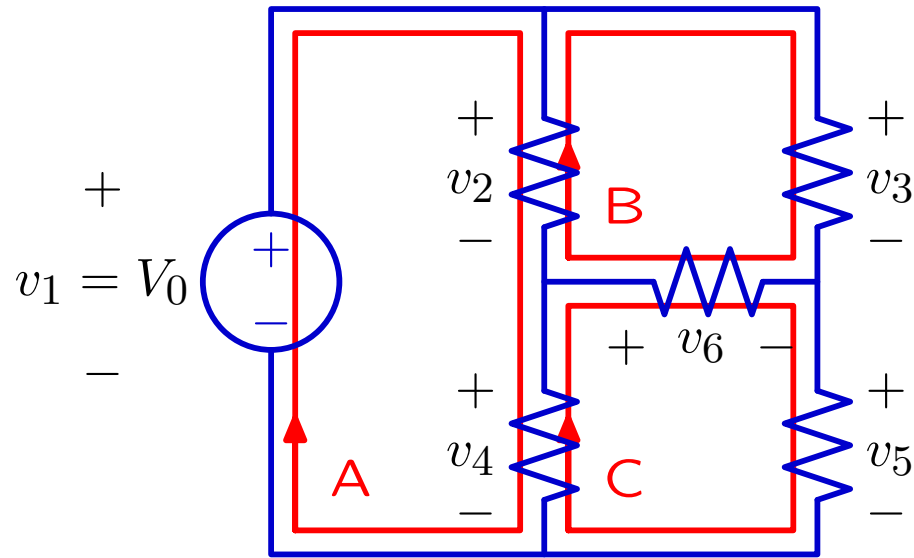
5. 7

But not all of these equations are linearly independent.



# Analyzing Circuits: KVL

Planar circuits can be characterized by their “inner” loops.  
KVL equations for the inner loops are independent.



$$A : -v_1 + v_2 + v_4 = 0$$

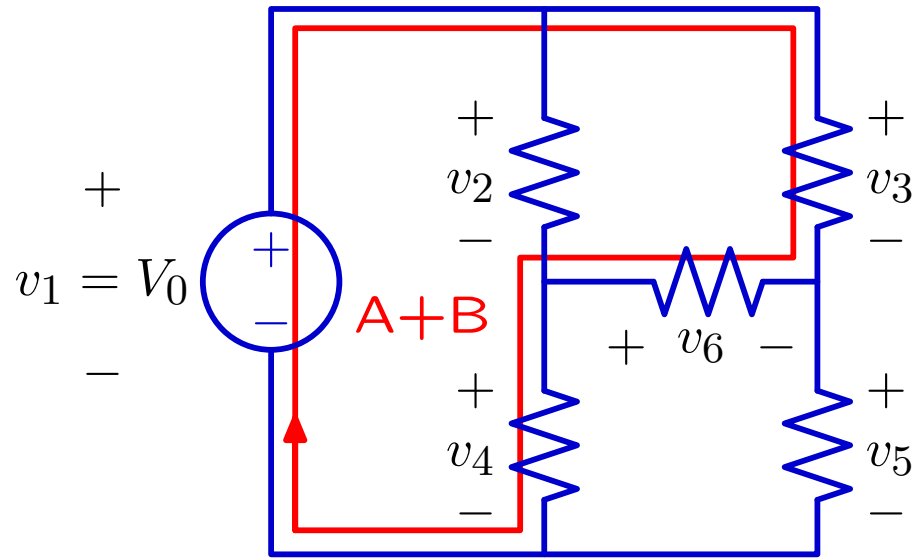
$$B : -v_2 + v_3 - v_6 = 0$$

$$C : -v_4 + v_6 + v_5 = 0$$



# Analyzing Circuits: KVL

All possible KVL equations for planar circuits can be generated by combinations of the “inner” loops.



$$A : -v_1 + v_2 + v_4 = 0$$

$$B : -v_2 + v_3 - v_6 = 0$$

$$A+B : -v_1 + v_2 + v_4 - v_2 + v_3 - v_6 = -v_1 + v_3 - v_6 + v_4 = 0$$



# KVL: Summary

---

The sum of the voltages around any closed path is zero.

One KVL equation can be written for every closed path in a circuit.

Sets of KVL equations are not necessarily linearly independent.

KVL equations for the “inner” loops of planar circuits are linearly independent.





# Ch.4 Summary

## Kirchhoff's Voltage Law

Kirchhoff's voltage law (KVL) is generally stated as:

*The sum of all the voltage drops around a closed path in a circuit is equal to the total source voltage in that closed path.*

KVL applies to all circuits, but you must apply it to only one closed path. In a series circuit, this is (of course) the entire circuit.

*A mathematical shorthand way of writing KVL is*

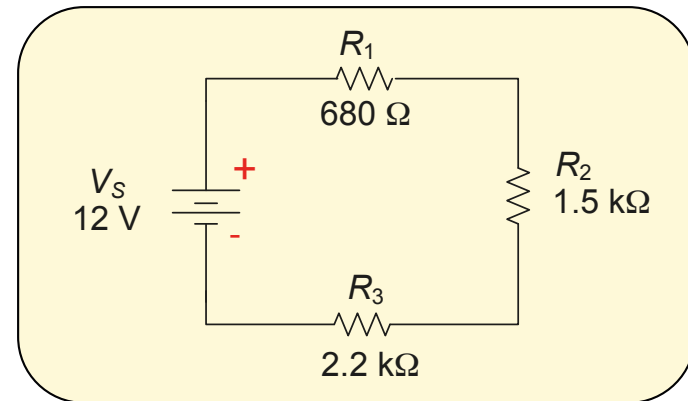
$$\sum_{i=1}^n V_i = 0$$



# Ch.4 Summary

## Kirchhoff's Voltage Law

Notice in the series example given earlier that the sum of the resistor voltages is equal to the source voltage.



$I_1 = 2.74 \text{ mA}$	$R_1 = 680 \text{ } \Omega$	$V_1 = 1.86 \text{ V}$	$P_1 = 5.1 \text{ mW}$
$I_2 = 2.74 \text{ mA}$	$R_2 = 1.5 \text{ k}\Omega$	$V_2 = 4.11 \text{ V}$	$P_2 = 11.3 \text{ mW}$
$I_3 = 2.74 \text{ mA}$	$R_3 = 2.2 \text{ k}\Omega$	$V_3 = 6.03 \text{ V}$	$P_3 = 16.5 \text{ mW}$
$I_T = 2.74 \text{ mA}$	$R_T = 4.38 \text{ k}\Omega$	$V_T = 12 \text{ V}$	$P_T = 32.9 \text{ mW}$



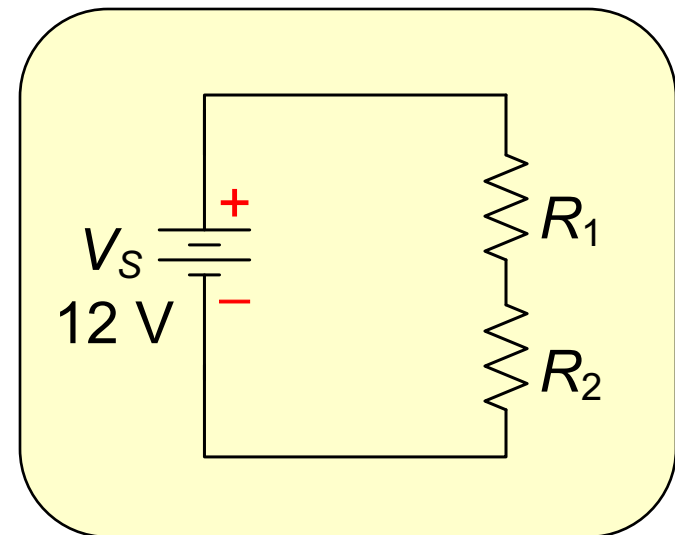
# Ch.4 Summary

## Voltage Divider Rule

*The voltage drop across any given resistor in a series circuit is equal to the ratio of that resistor to the total resistance, multiplied by source voltage.*

*Assume  $R_1$  has twice the value of  $R_2$ . What is the voltage across  $R_1$ ?*

**8 V**



# Ch.4 Summary

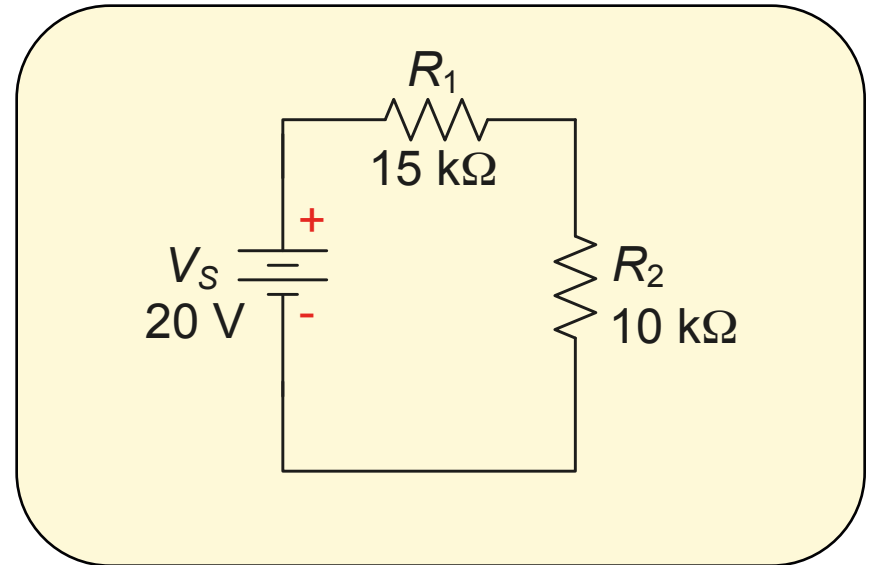
## Voltage Divider

*What is the voltage across  $R_2$  in the circuit shown?*

The total resistance is **25 k $\Omega$**

Applying the voltage divider formula:

$$V_2 = \left( \frac{R_2}{R_T} \right) \times V_S = \left( \frac{10 \text{ k}\Omega}{25 \text{ k}\Omega} \right) \times (20 \text{ V}) = \mathbf{8.0 \text{ V}}$$



*Notice that 40% of the source voltage is across  $R_2$ , which represents 40% of the total resistance.*



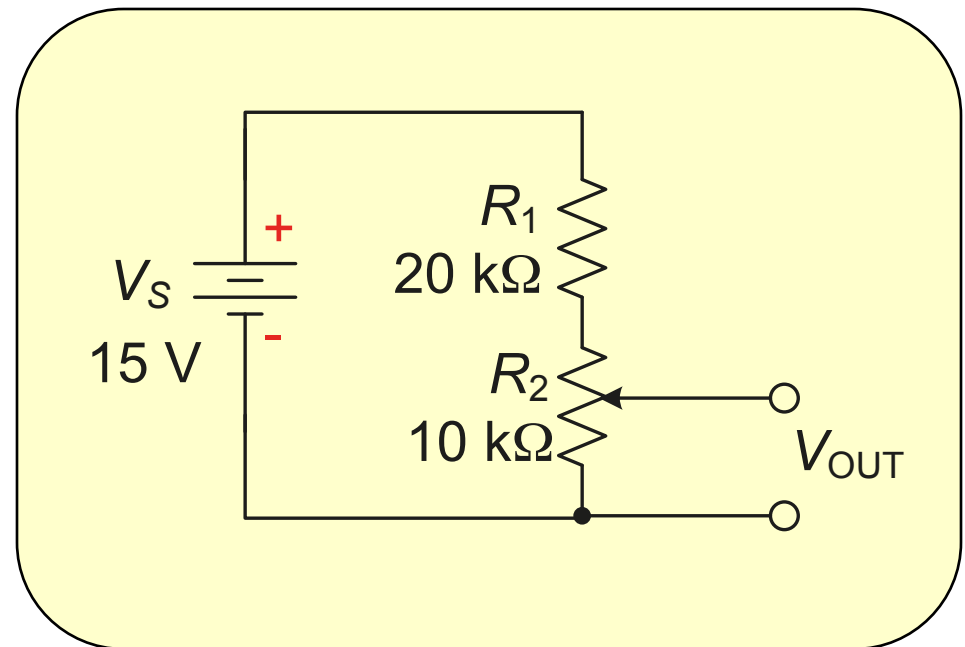
# Ch.4 Summary

## Voltage Divider

Voltage dividers can be set up for a variable output using a potentiometer. In the circuit shown, the output voltage is variable.

*What is the largest output voltage available?*

**5.0 V**



# Ch.4 Summary

## Power in Series Circuits

Applying the voltage divider rule:

$$V_1 = \left( \frac{470 \Omega}{800 \Omega} \right) \times (20 \text{ V}) = \mathbf{11.75 \text{ V}}$$

$$V_2 = \left( \frac{330 \Omega}{800 \Omega} \right) \times (20 \text{ V}) = \mathbf{8.25 \text{ V}}$$

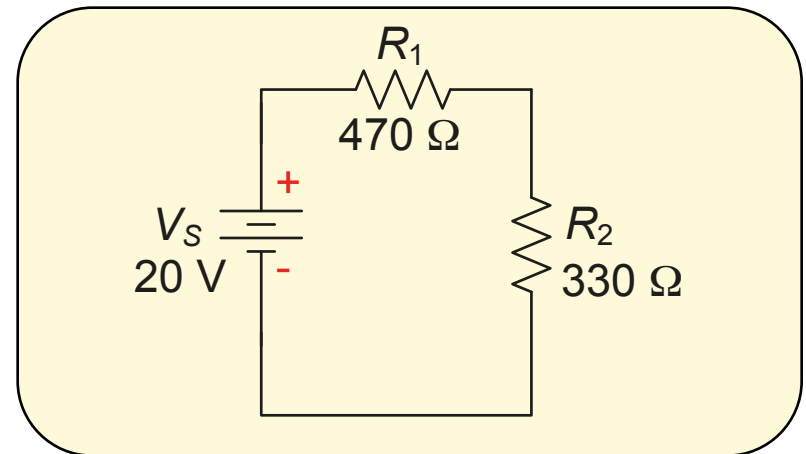
The power dissipated by each resistor is:

$$P_1 = \frac{(11.75 \text{ V})^2}{470 \Omega} = \mathbf{0.29 \text{ W}}$$

$$P_2 = \frac{(8.25 \text{ V})^2}{330 \Omega} = \mathbf{0.21 \text{ W}}$$

$$\mathbf{P_T = 0.5 \text{ W}}$$

*Use the voltage divider rule to find  $V_1$  and  $V_2$ . Then find the power in  $R_1$  and  $R_2$  and  $P_T$ .*

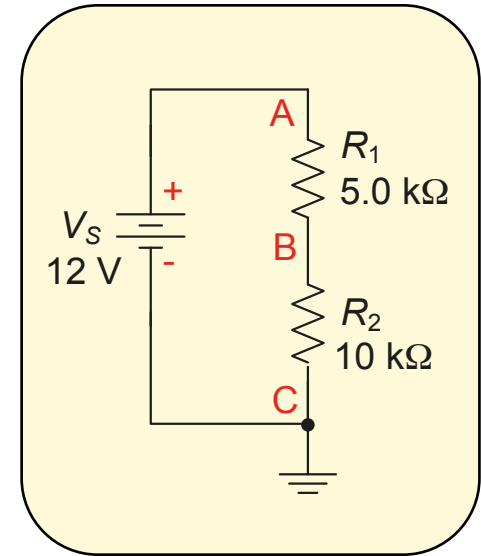


# Ch.4 Summary

## Voltage Measurements

Voltage is relative and is measured with respect to another point in the circuit.

Voltages that are given with respect to ground are shown with a single subscript. For example,  $V_A$  means the voltage at point A with respect to ground (called *reference ground*).  $V_B$  means the voltage at point B with respect to ground.  $V_{AB}$  means the voltage between points A and B.



*What are  $V_A$ ,  $V_B$ , and  $V_{AB}$  for the circuit shown?*

$$V_A = 12 \text{ V}$$

$$V_B = 8 \text{ V}$$

$$V_{AB} = 4 \text{ V}$$



# Ch.4 Summary

## Voltage Measurements

Ground reference is not always at the lowest point in a circuit schematic. Assume the ground is moved to point B as shown.

*What are  $V_A$ ,  $V_B$ , and  $V_C$  for the circuit?*

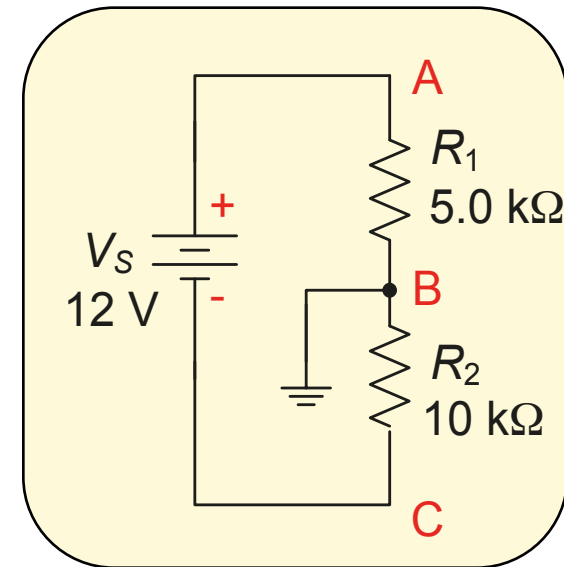
$$V_A = 4 \text{ V}$$

$$V_B = 0 \text{ V}$$

$$V_C = -8 \text{ V}$$

*Has  $V_{AB}$  changed from the previous circuit?*

***No, it is still 4 V***

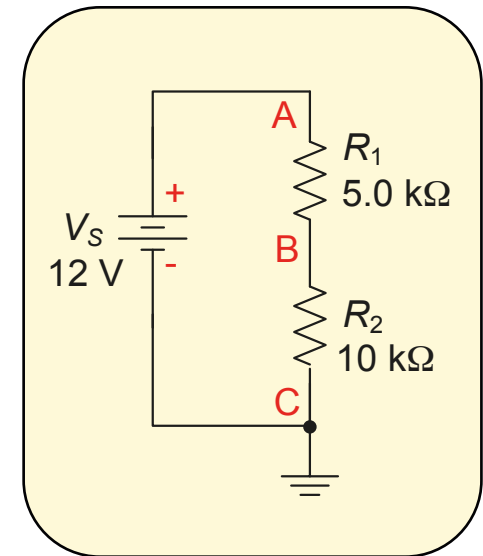




# Ch.4 Summary

## Voltage Measurements

*Assume that  $R_2$  is open.  $C$  is the reference ground. What are  $V_A$ ,  $V_B$ , and  $V_C$  for the circuit?*



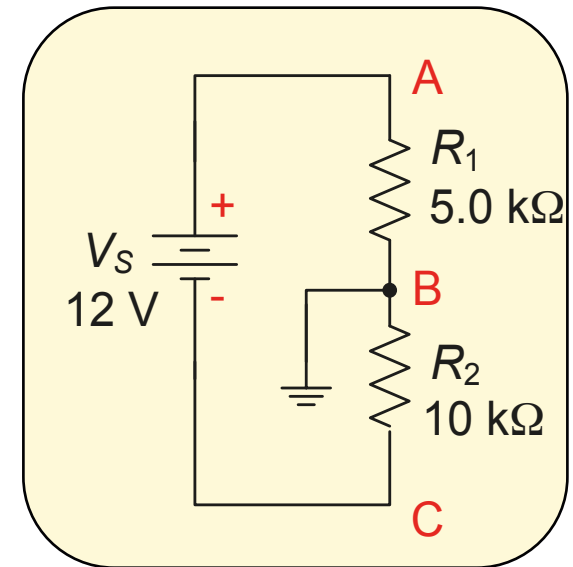
**If  $R_2$  is open, there is no current. Notice that  $V_C = 0$  V because it is ground and  $V_A = 12$  V because it has the same potential as  $V_S$ .  $V_B = 12$  V because there is no current through  $R_1$  ( $V_{AB} = V_A - V_B = 12 - V_B = 0$  V).**



# Ch.4 Summary

## Voltage Measurements

*Assume that  $R_2$  is open.  $B$  is the reference ground. What are  $V_A$ ,  $V_B$ , and  $V_C$  for the circuit?*



**If  $R_2$  is open, there is no current. Notice that  $V_B = 0$  V because it is ground and  $V_A = 0$  V because it has the same potential as  $V_B$ .  $V_C = -12$  V because the source voltage is across the open.**



# Ch.4 Summary

## Selected Key Terms

***Series*** In an electric circuit, a relationship of components in which the components are connected such that they provide a single path between two points.

***Kirchhoff's voltage law*** A law stating that (1) the sum of the voltage drops around a closed loop equals the source voltage in that loop or (2) the algebraic sum of all of the voltages (drops and source) is zero.

***Voltage divider*** A circuit consisting of series resistors across which one or more output voltages are taken.



# Ch.4 Summary

## Selected Key Terms

### **Reference ground**

The metal chassis that houses the assembly or a large conductive area on a printed circuit board is used as a common or reference point; also called common.

### **Open**

A circuit condition in which the current path is broken.

### **Short**

A circuit condition in which there is zero or an abnormally low resistance between two points; usually an inadvertent condition.



# Ch.4 Summary

## Quiz

1. In a series circuit with more than one resistor, the current is
  - a. larger in larger resistors
  - b. smaller in larger resistors
  - c. always the same in all resistors
  - d. there is not enough information to say



# Ch.4 Summary

## Quiz

2. In a series circuit with more than one resistor, the voltage is
- a. larger across larger resistors
  - b. smaller across larger resistors
  - c. always the same across all resistors
  - d. there is not enough information to say



# Ch.4 Summary

## Quiz

3. If three equal resistors are in series, the total resistance is
- a. one third the value of one resistor
  - b. the same as one resistor
  - c. three times the value of one resistor
  - d. there is not enough information to say



# Ch.4 Summary

## Quiz

4. A series circuit cannot have
- a. more than two resistors
  - b. more than one voltage source
  - c. more than one path
  - d. all of the above





# Ch.4 Summary

## Quiz

5. In a closed loop, the algebraic sum of all voltages (both sources and drops)
- a. is zero
  - b. is equal to the smallest voltage in the loop
  - c. is equal to the largest voltage in the loop
  - d. depends on the source voltage

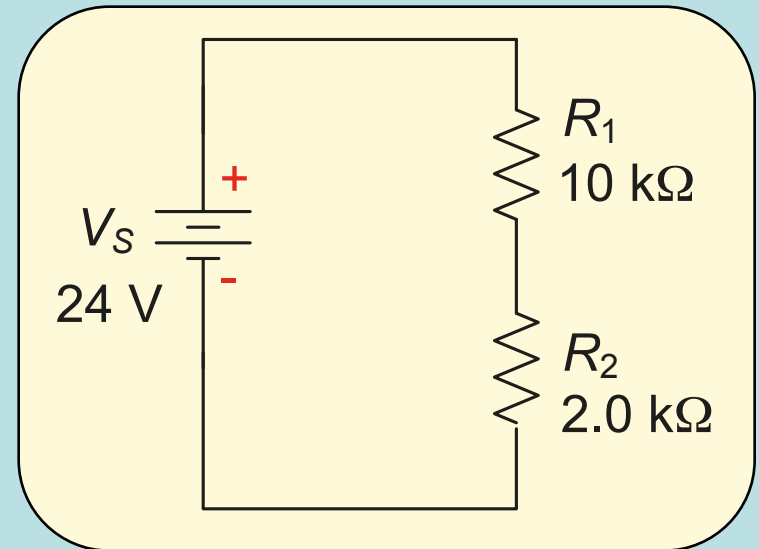


# Ch.4 Summary

## Quiz

6. The current in the  $10\text{ k}\Omega$  resistor is

- a.  $0.5\text{ mA}$
- b.  $2.0\text{ mA}$
- c.  $2.4\text{ mA}$
- d.  $10\text{ mA}$

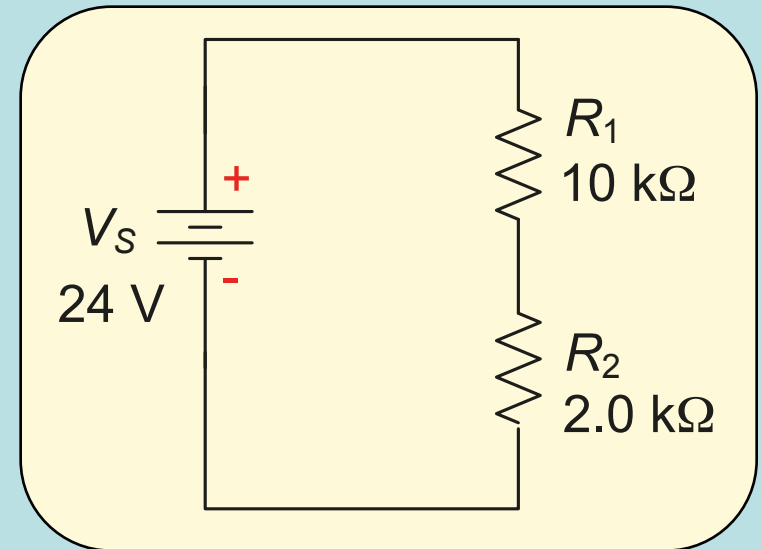


# Ch.4 Summary

## Quiz

7. The voltage across  $R_2$  equals

- a. 2.0 V
- b. 4.0 V
- c. 12 V
- d. 20 V

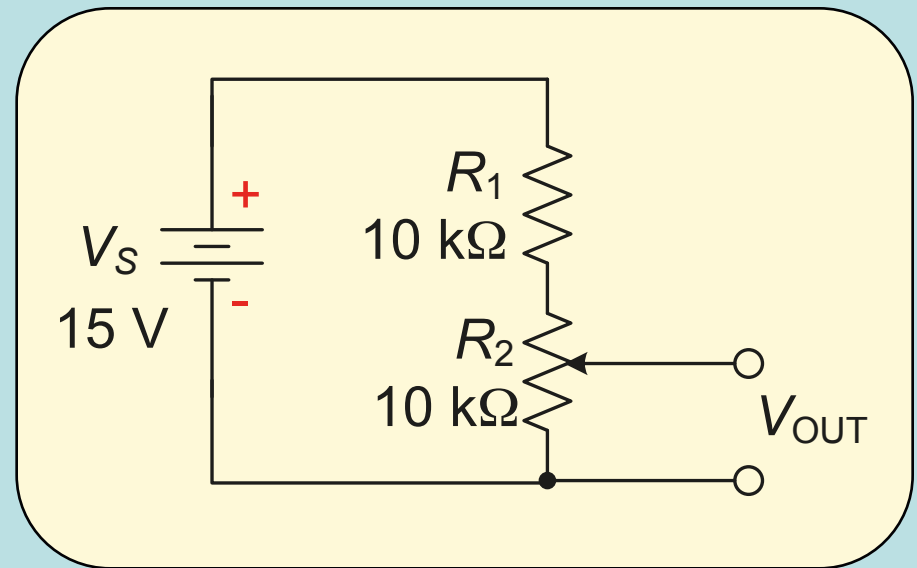


# Ch.4 Summary

## Quiz

8. The smallest output voltage available from the voltage divider is

- a. 0 V
- b. 1.5 V
- c. 5.0 V
- d. 7.5 V



# Ch.4 Summary

## Quiz

9. The total power dissipated in a series circuit is equal to the
- a. power in the largest resistor
  - b. power in the smallest resistor
  - c. average of the power in all resistors
  - d. sum of the power in all resistors



# Ch.4 Summary

## Quiz

10. The meaning of the voltage  $V_{AB}$  is the voltage at
- a. Point A with respect to ground
  - b. Point B with respect to ground
  - c. The average voltage between points A and B.
  - d. The voltage difference between points A and B.



# Ch.4 Summary

## Answers

- |      |       |
|------|-------|
| 1. c | 6. b  |
| 2. a | 7. b  |
| 3. c | 8. a  |
| 4. c | 9. d  |
| 5. a | 10. d |





5

Parallel Circuits

5

Parallel Circuits



NUI Galway  
OÉ Gaillimh

John Breslin  
Fundamentals of EEE

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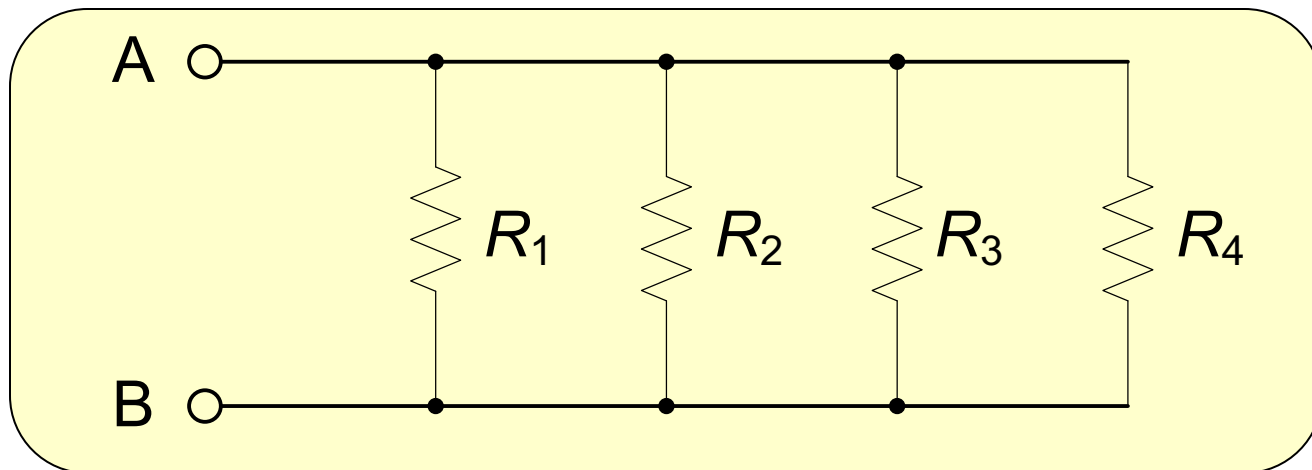
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# Ch.5 Summary

## Resistors in Parallel

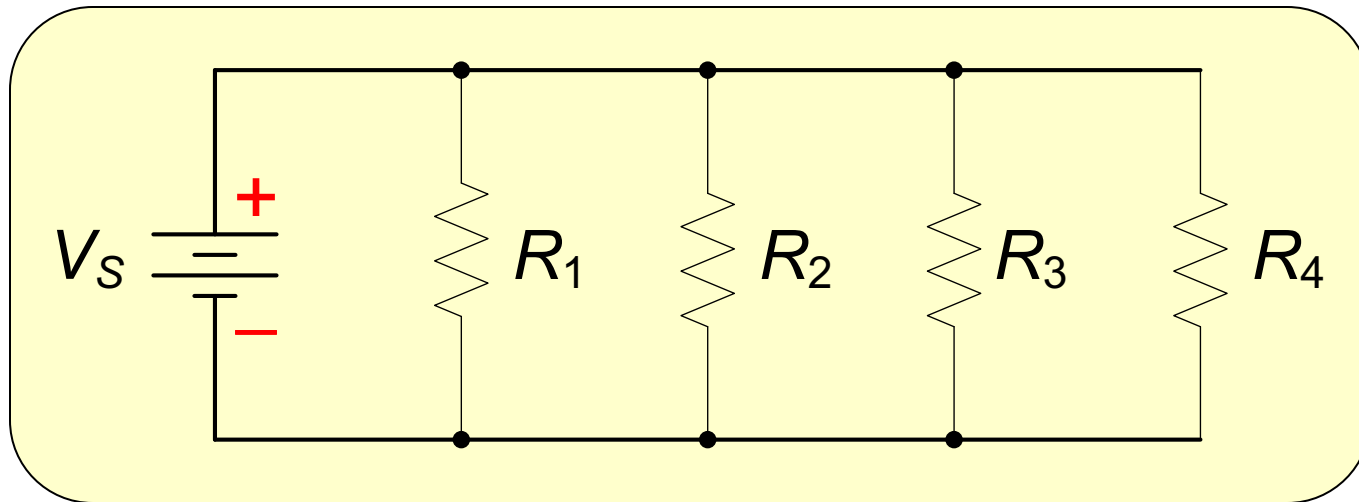
Resistors that are connected to the same two points are said to be in parallel. For example, the four resistors (below) are connected in parallel.



# Ch.5 Summary

## Parallel Circuits

A parallel circuit has *more than one current path (branch) connected to a common voltage source.*

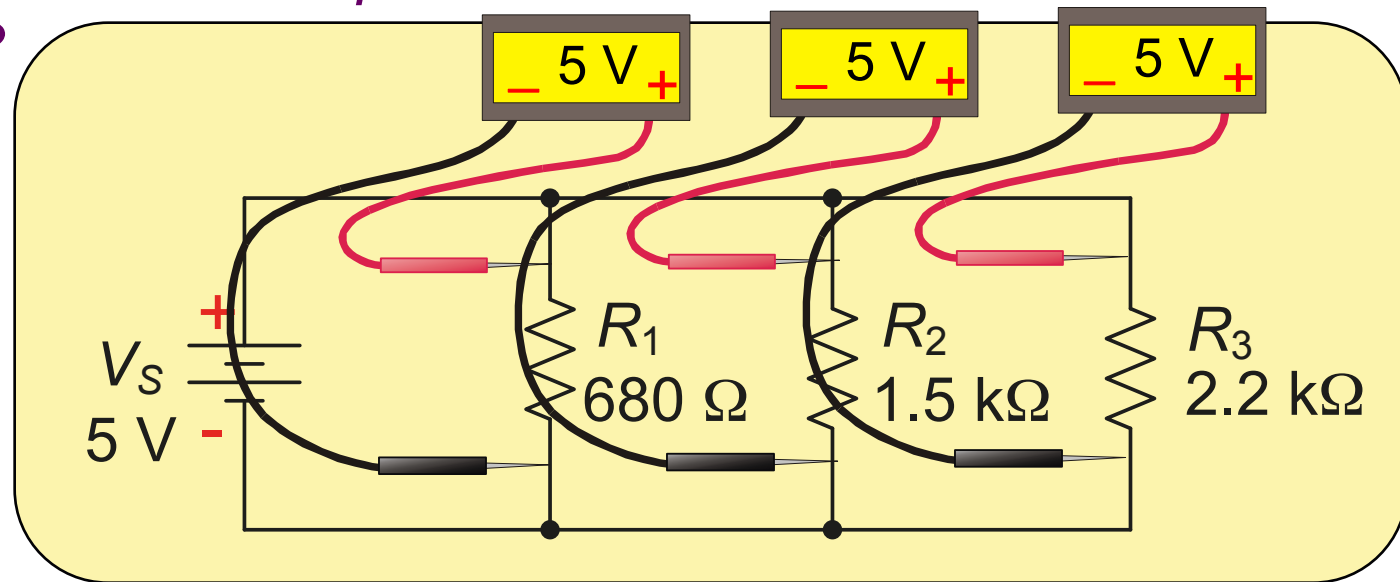


# Ch.5 Summary

## Parallel Circuit Rule for Voltage

Because all components are connected across the same voltage source, the voltage across each is the same.

*For example, the source voltage is 5.0 V. What will a volt-meter read if it is placed across each of the resistors?*

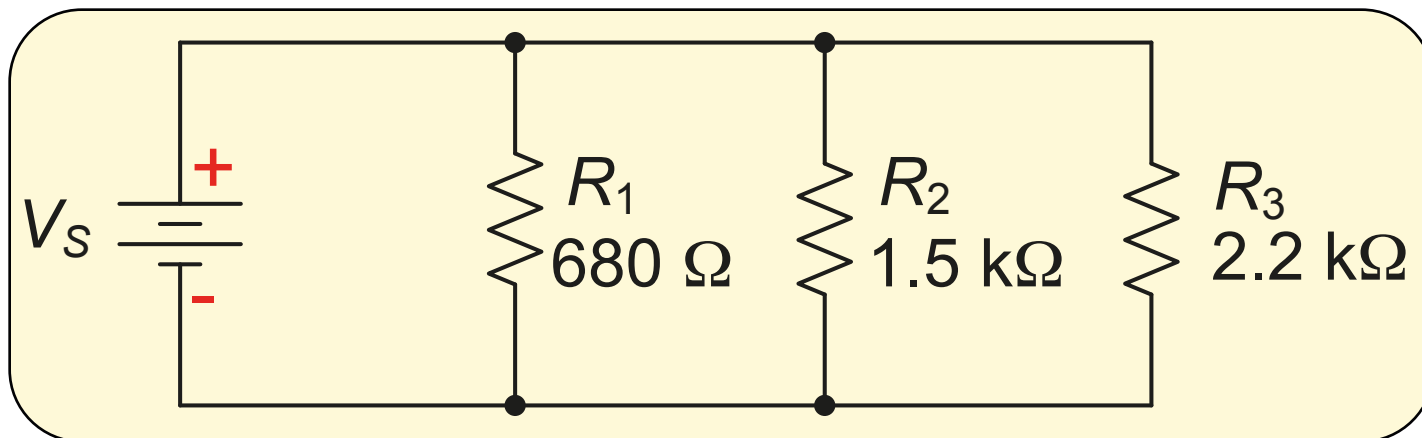


# Ch.5 Summary

## Parallel Circuit Rule for Resistance

The total resistance of resistors in parallel is ***the reciprocal of the sum of the reciprocals of the individual resistors.***

For example, the resistors in a parallel circuit are  $680\ \Omega$ ,  $1.5\ \text{k}\Omega$ , and  $2.2\ \text{k}\Omega$ . What is the total resistance?  **$386\ \Omega$**



# Ch.5 Summary

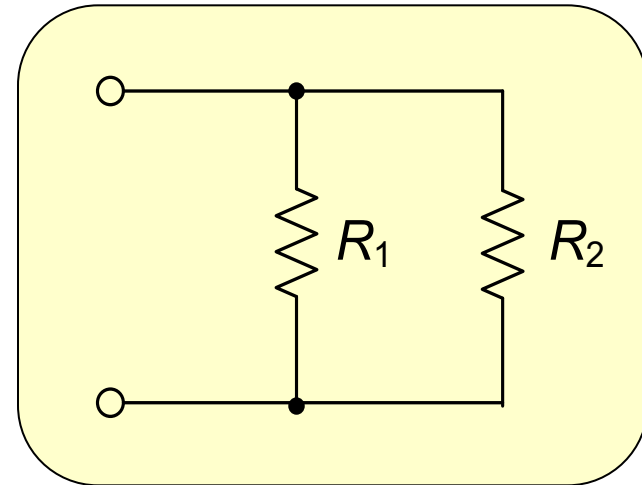
## Special Case for Resistance of Two Parallel Resistors

The resistance of two parallel resistors can be found using either:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} \quad \text{or} \quad R_T = \frac{R_1 R_2}{R_1 + R_2}$$

*What is the total resistance if  $R_1 = 27 \text{ k}\Omega$  and  $R_2 = 56 \text{ k}\Omega$ ?*

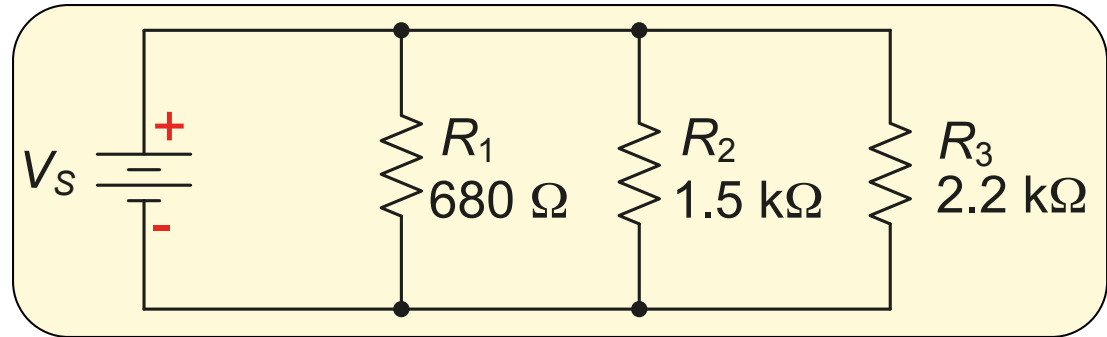
**18.2 k $\Omega$**



# Ch.5 Summary

## Parallel Circuit

Tabulating current, resistance, voltage and power is a useful way to summarize parameters in a parallel circuit.



*Continuing with the previous example, complete the parameters listed in the Table.*

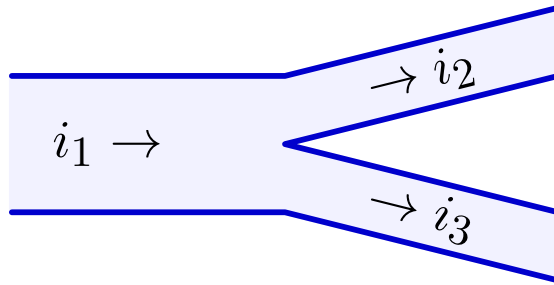
$I_1 = 7.4 \text{ mA}$	$R_1 = 0.68 \text{ k}\Omega$	$V_1 = 5.0 \text{ V}$	$P_1 = 36.8 \text{ mW}$
$I_2 = 3.3 \text{ mA}$	$R_2 = 1.50 \text{ k}\Omega$	$V_2 = 5.0 \text{ V}$	$P_2 = 16.7 \text{ mW}$
$I_3 = 2.3 \text{ mA}$	$R_3 = 2.20 \text{ k}\Omega$	$V_3 = 5.0 \text{ V}$	$P_3 = 11.4 \text{ mW}$
$I_T = 13.0 \text{ mA}$	$R_T = 386 \Omega$	$V_T = 5.0 \text{ V}$	$P_T = 64.8 \text{ mW}$



# Kirchhoff's Current Law

---

The flow of electrical current is analogous to the flow of incompressible fluid (e.g., water).



Current  $i_1$  flows into a **node** and two currents  $i_2$  and  $i_3$  flow out:

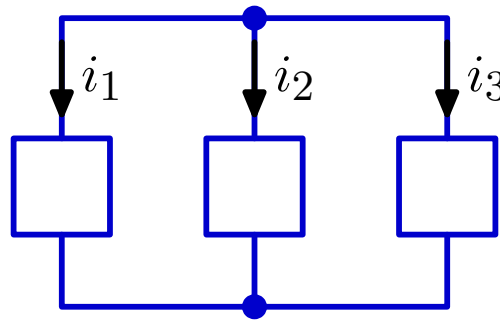
$$i_1 = i_2 + i_3$$



# Kirchhoff's Current Law

---

The net flow of electrical current into (or out of) a **node** is zero.



Here, there are two nodes, each indicated by a dot.

The net current out of the top node must be zero:

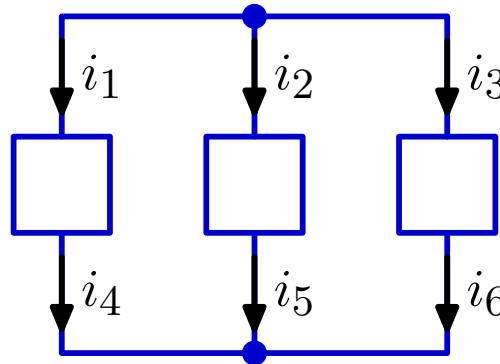
$$i_1 + i_2 + i_3 = 0.$$





# Kirchhoff's Current Law

Electrical currents cannot accumulate in elements, so current that flows into a circuit element must also flow out.



$$i_1 = i_4$$

$$i_2 = i_5$$

$$i_3 = i_6$$

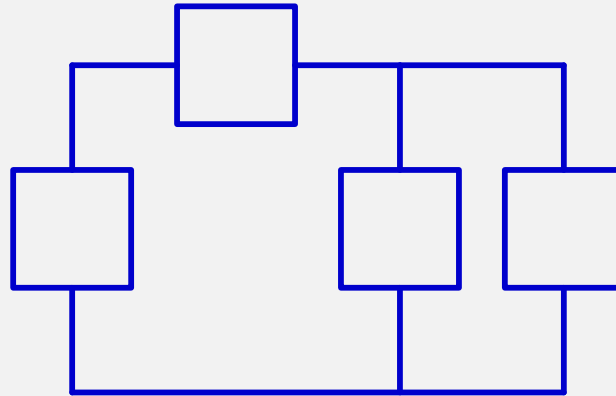
Since  $i_1 + i_2 + i_3 = 0$  it follows that

$$i_4 + i_5 + i_6 = 0.$$



# Check Yourself

How many linearly independent KCL equations can be written for the following circuit?



1. 1

2. 2

3. 3

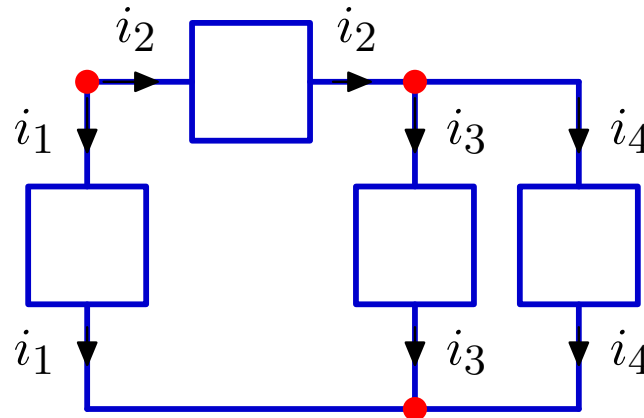
4. 4

5. 5



# Check Yourself

How many linearly independent KCL equations can be written for the following circuit?



There are four **element currents**:  $i_1$ ,  $i_2$ ,  $i_3$ , and  $i_4$ .

We can write a KCL equation at each of the three **nodes**:

$$i_1 + i_2 = 0$$

$$i_2 = i_3 + i_4$$

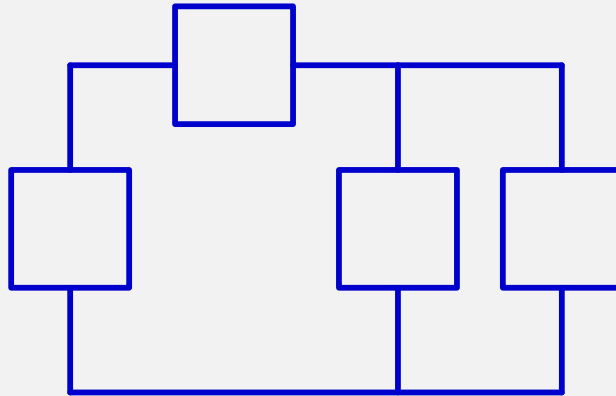
$$i_1 + i_3 + i_4 = 0$$

Substituting  $i_2$  from the second equation into the first yields the third equation. Only two of these equations are linearly independent.



# Check Yourself

How many linearly independent KCL equations can be written for the following circuit? **2**



1. 1

**2. 2**

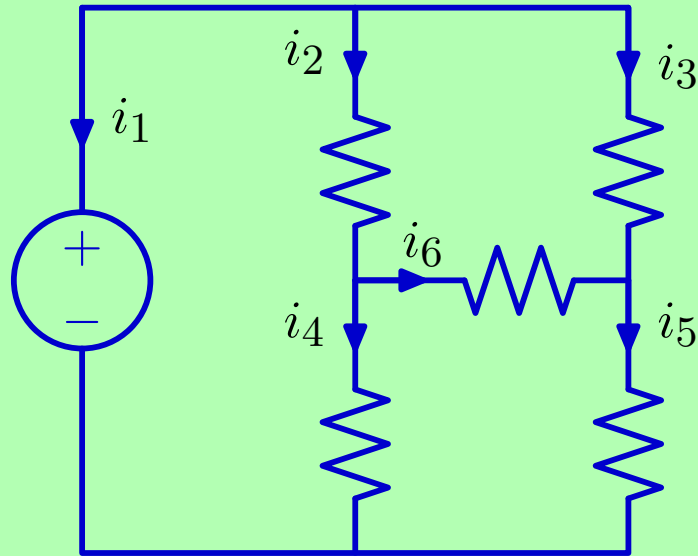
3. 3

4. 4

5. 5



How many distinct KCL relations can be written for this circuit?



1. 3

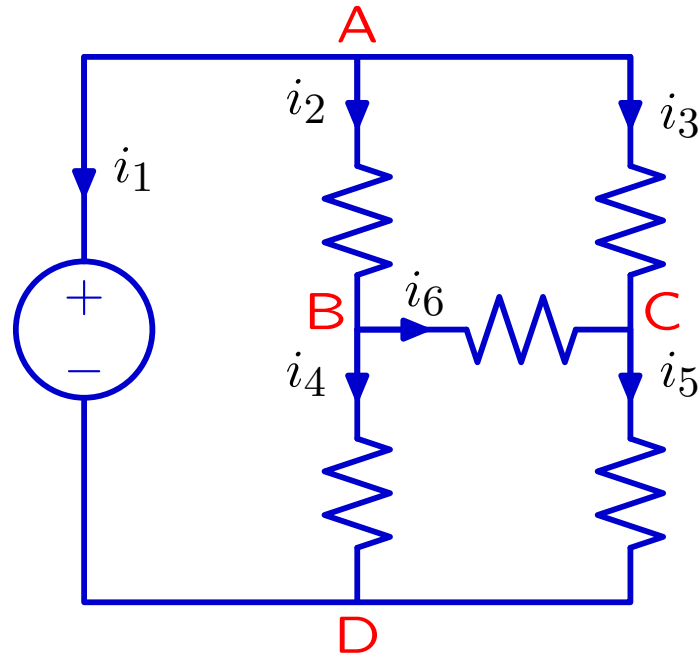
2. 4

3. 5

4. 6

5. 7

# Check Yourself



$$A: \quad i_1 + i_2 + i_3 = 0$$

$$B: \quad -i_2 + i_4 + i_6 = 0$$

$$C: \quad -i_6 - i_3 + i_5 = 0$$

$$D: \quad i_1 + i_4 + i_5 = 0$$



## Check Yourself

---

These equations are not linearly independent.

$$1: \quad i_1 + i_2 + i_3 = 0$$

$$2: \quad -i_2 + i_4 + i_6 = 0$$

$$3: \quad -i_6 - i_3 + i_5 = 0$$

$$4: \quad i_1 + i_4 + i_5 = 0$$

Substitute  $i_2$  from 2 and  $i_3$  from 3 into 1.

$$i_1 + (i_4 + i_6) + (i_5 - i_6) = i_1 + i_4 + i_5$$

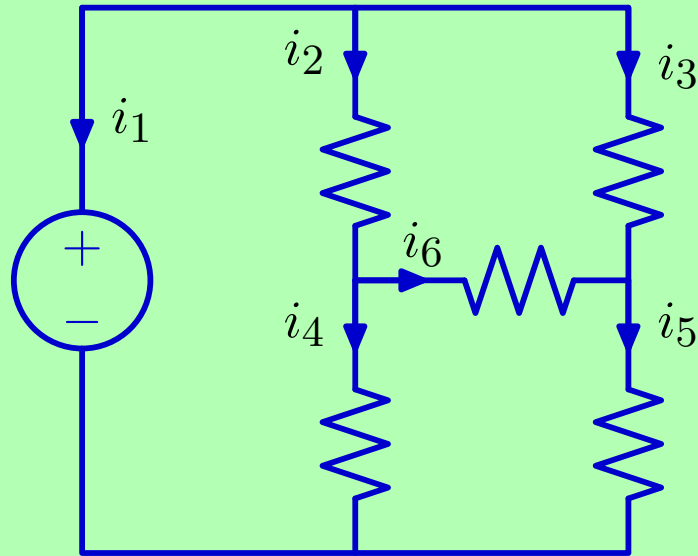
This is equation 4!

There are only 3 linearly independent KCL equations.



# Check Yourself

How many distinct KCL relations can be written for this circuit?



1. 3

2. 4

3. 5

4. 6

5. 7

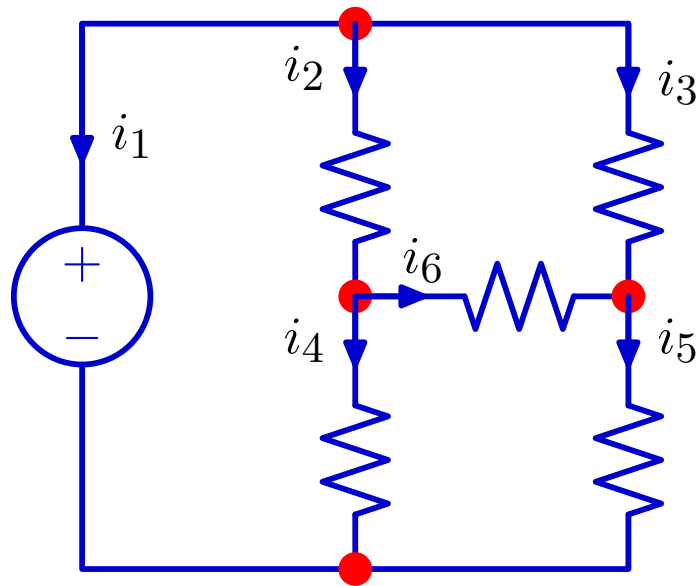




# Analyzing Circuits: KCL

The number of independent KCL equations is one less than the number of nodes.

Previous circuit: four nodes and three independent KCL equations.

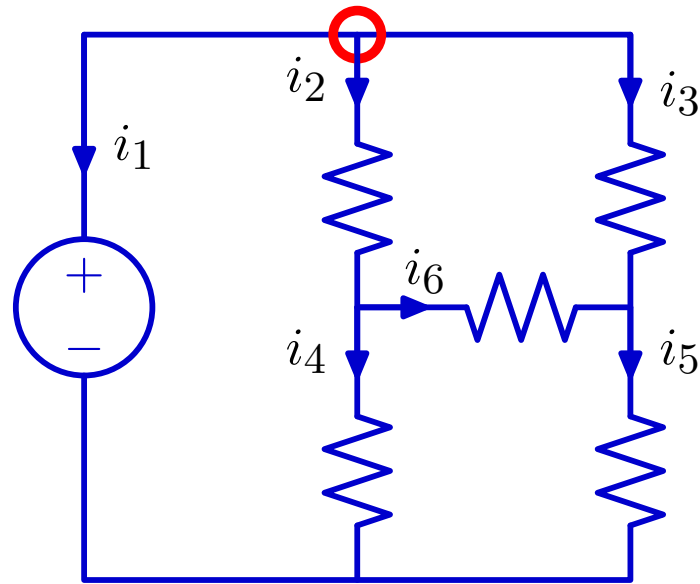


This relation follows from a generalization of KCL, as follows.



# Analyzing Circuits: KCL

The net current out of any closed surface (which can contain multiple nodes) is zero.



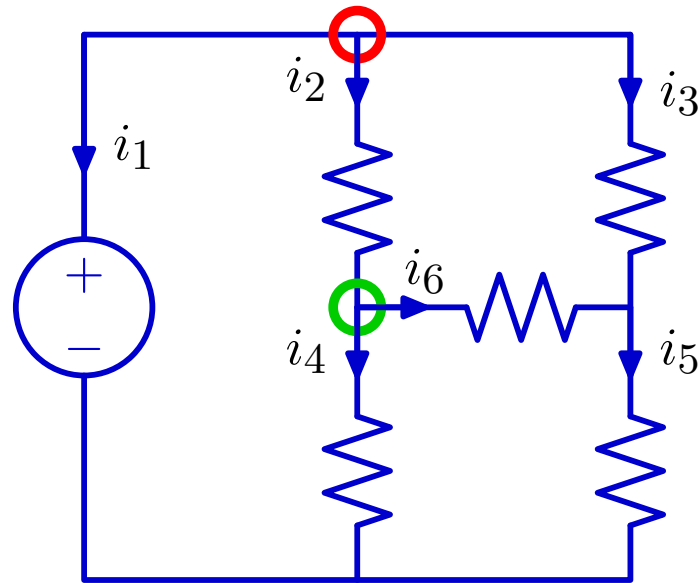
node 1:  $i_1 + i_2 + i_3 = 0$

Such a closed surface with multiple nodes is sometimes referred to as a "supernode"



# Analyzing Circuits: KCL

The net current out of any closed surface (which can contain multiple nodes) is zero.



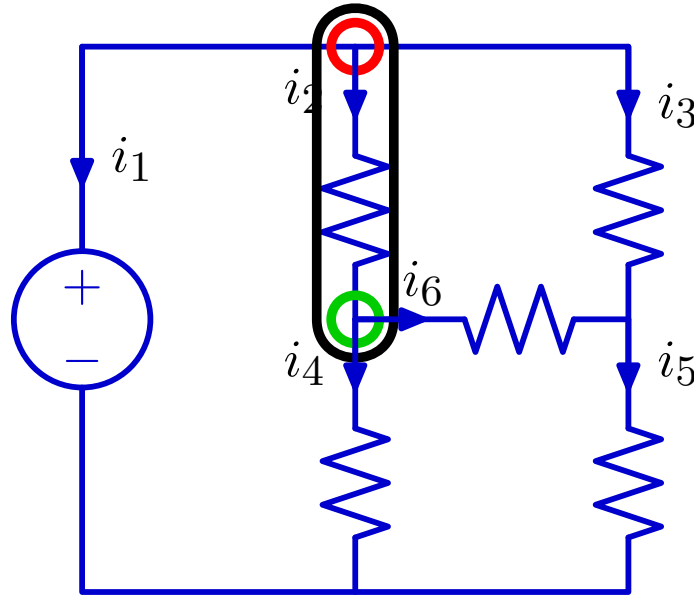
node 1:  $i_1 + i_2 + i_3 = 0$

node 2:  $-i_2 + i_4 + i_6 = 0$



# Analyzing Circuits: KCL

The net current out of any closed surface (which can contain multiple nodes) is zero.



$$\text{node 1: } i_1 + i_2 + i_3 = 0$$

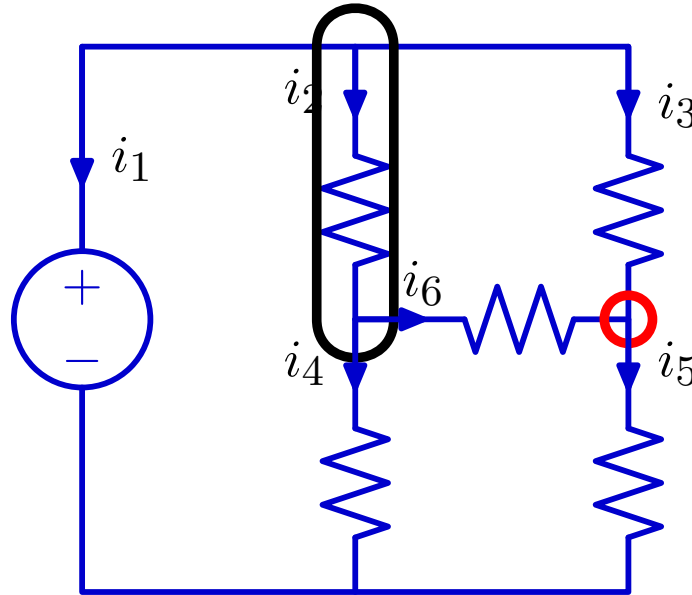
$$\text{node 2: } -i_2 + i_4 + i_6 = 0$$

$$\text{nodes 1+2: } i_1 + i_2 + i_3 - i_2 + i_4 + i_6 = i_1 + i_3 + i_4 + i_6 = 0$$



# Analyzing Circuits: KCL

The net current out of any closed surface (which can contain multiple nodes) is zero.



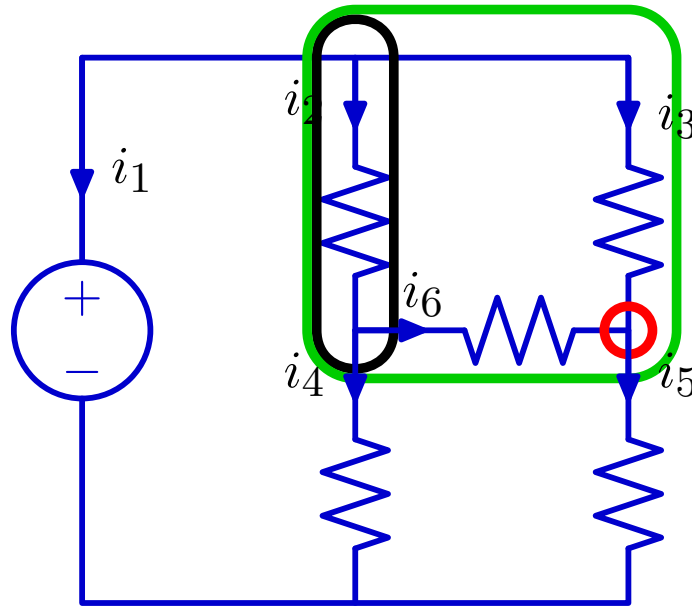
$$\text{nodes 1+2: } i_1 + i_2 + i_3 - i_2 + i_4 + i_6 = i_1 + i_3 + i_4 + i_6 = 0$$

$$\text{node 3: } -i_3 - i_6 + i_5 = 0$$



# Analyzing Circuits: KCL

The net current out of any closed surface (which can contain multiple nodes) is zero.



$$\text{nodes 1+2: } i_1 + i_3 + i_4 + i_6 = 0$$

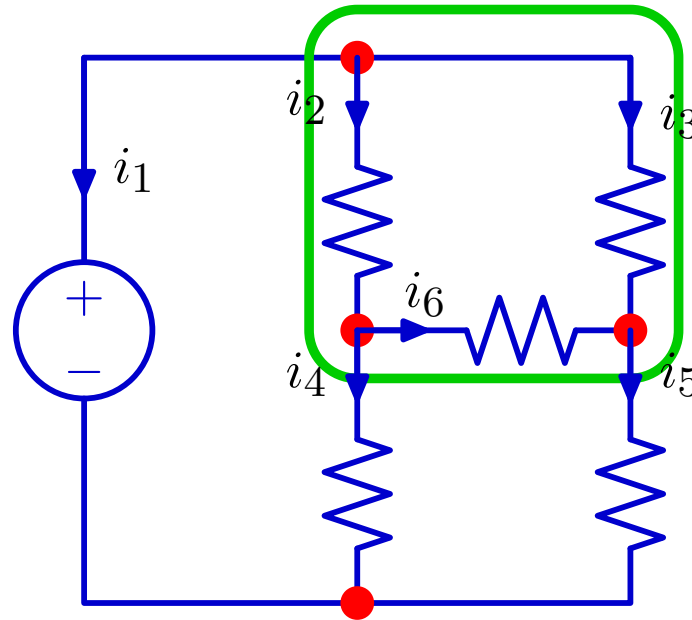
$$\text{node 3: } -i_3 - i_6 + i_5 = 0$$

$$\text{nodes 1+2+3: } i_1 + i_3 + i_4 + i_6 - i_3 - i_6 + i_5 = i_1 + i_4 + i_5 = 0$$



# Analyzing Circuits: KCL

The net current out of any closed surface (which can contain multiple nodes) is zero.



$$\text{nodes 1+2: } i_1 + i_3 + i_4 + i_6 = 0$$

$$\text{node 3: } -i_3 - i_6 + i_5 = 0$$

$$\text{nodes 1+2+3: } i_1 + i_3 + i_4 + i_6 - i_3 - i_6 + i_5 = i_1 + i_4 + i_5 = 0$$

Net current out of nodes 1+2+3 = net current into bottom node!



# KCL: Summary

---

The sum of the currents out of any node is zero.

One KCL equation can be written for every closed surface (which contain one or more nodes) in a circuit.

Sets of KCL equations are not necessarily linearly independent.

KCL equations for every primitive node except one (ground) are linearly independent.





# Ch.5 Summary

## Kirchhoff's Current Law

Kirchhoff's current law (KCL) is generally stated as:

*The sum of the currents entering a node is equal to the sum of the currents leaving the node.*

Notice in the previous example that the current from the source is equal to the sum of the branch currents.

$I_1 = 7.4 \text{ mA}$	$R_1 = 0.68 \text{ k}\Omega$	$V_1 = 5.0 \text{ V}$	$P_1 = 36.8 \text{ mW}$
$I_2 = 3.3 \text{ mA}$	$R_2 = 1.50 \text{ k}\Omega$	$V_2 = 5.0 \text{ V}$	$P_2 = 16.7 \text{ mW}$
$I_3 = 2.3 \text{ mA}$	$R_3 = 2.20 \text{ k}\Omega$	$V_3 = 5.0 \text{ V}$	$P_3 = 11.4 \text{ mW}$
$I_T = 13.0 \text{ mA}$	$R_T = 386 \text{ }\Omega$	$V_T = 5.0 \text{ V}$	$P_T = 64.8 \text{ mW}$



# Ch.5 Summary

## Current Divider

When current enters a node (junction) it divides into currents with values that are inversely proportional to the resistance values.

*The most widely used formula for the current divider is the two-resistor equation. For resistors  $R_1$  and  $R_2$ ,*

$$I_1 = \left( \frac{R_2}{R_1 + R_2} \right) \times I_T \quad \text{and} \quad I_2 = \left( \frac{R_1}{R_1 + R_2} \right) \times I_T$$

*Notice the subscripts. The resistor in the numerator is not the same as the one for which current is found.*



# Ch.5 Summary

## Current Divider

Assume that  $R_1$  is a 2.2 k $\Omega$  resistor that is in parallel with a 4.7 k $\Omega$  resistor ( $R_2$ ). If the total circuit current is 8.0 mA, what is the current through each resistor?

$$I_1 = \left( \frac{R_2}{R_1 + R_2} \right) \times I_T = \left( \frac{4.7 \text{ k}\Omega}{6.9 \text{ k}\Omega} \right) (8.0 \text{ mA}) = \mathbf{5.45 \text{ mA}}$$

$$I_2 = \left( \frac{R_1}{R_1 + R_2} \right) \times I_T = \left( \frac{2.2 \text{ k}\Omega}{6.9 \text{ k}\Omega} \right) (8.0 \text{ mA}) = \mathbf{2.55 \text{ mA}}$$

*Notice that the higher-value resistor has the lower current.*



# Ch.5 Summary

## Power in Parallel Circuits

The power dissipated by a resistor can be calculated with any of the standard power formulas. Most of the time, the voltage is known, so the most convenient equation is:

$$P = \frac{V^2}{R}$$

As with series circuits, the total power is the sum of the power dissipated by each resistor.

*What is the total power if 10 V is applied to the parallel combination of  $R_1 = 270 \Omega$  and  $R_2 = 150 \Omega$ ?*

**1.04 W**



# Ch.5 Summary

## Application

Assume there are 8 resistive wires in parallel that form a rear window defroster for an automobile.

*(a) If the defroster dissipates 90 W when connected to a 12.6 V source, what power is dissipated by each resistive wire?*

*(b) What is the total resistance of the defroster?*

**(a) Each of the 8 wires will dissipate 1/8 of the total power or**

$$\frac{90 \text{ W}}{8 \text{ wires}} = 11.25 \text{ W}$$

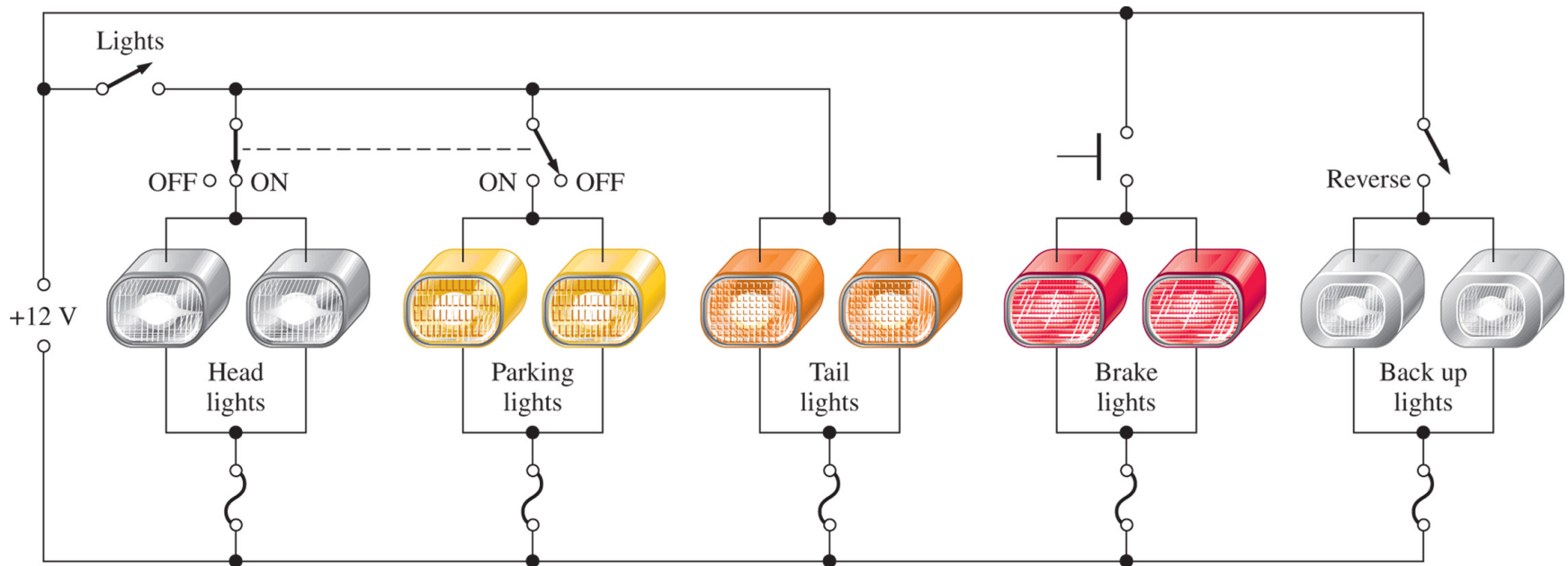
**(b) The total resistance is**

$$R = \frac{V^2}{P} = \frac{(12.6 \text{ V})^2}{90 \text{ W}} = 1.76 \Omega$$



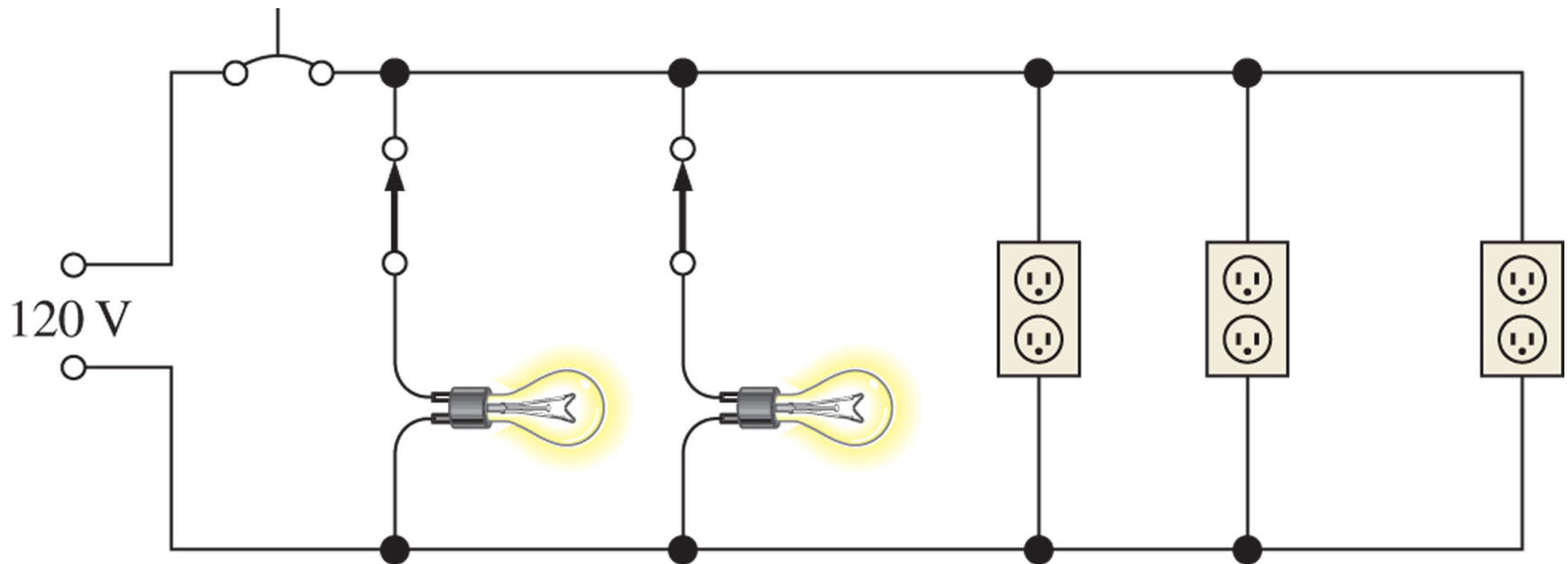
# A parallel circuit

## Simplified diagram of the exterior light system of a car



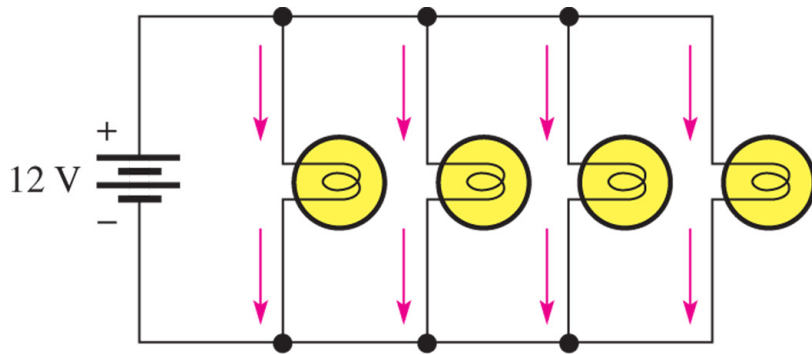
# Another parallel circuit

## Example of a parallel circuit in residential wiring

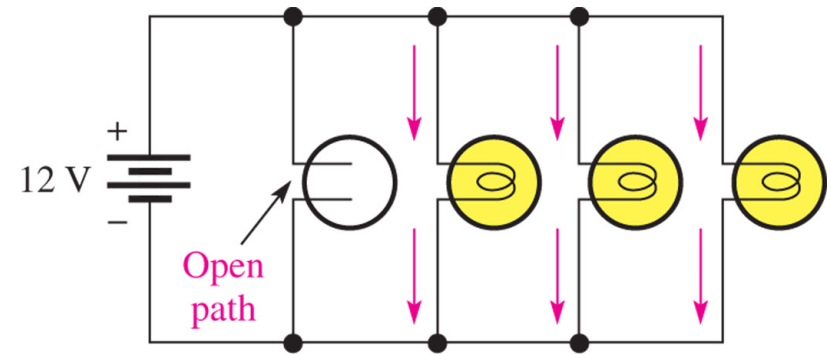


# What happens if one path opens?

- When one lamp opens, total current decreases and other branch currents remain unchanged



(a)



(b)

- Prove it!



# Ch.5 Summary

## Key Terms

### ***Parallel***

The relationship in electric circuits in which two or more current paths are connected between two separate points (nodes).

### ***Branch***

One current path in a parallel circuit.

### ***Kirchhoff's current law***

A law stating the total current into a node equals the total current out of the node.

### ***Node***

A point or junction in a circuit at which two or more components are connected.

### ***Current divider***

A parallel circuit in which the currents divide inversely proportional to the parallel branch resistances.



# Ch.5 Summary

## Quiz

1. The total resistance of parallel resistors is equal to
  - a. the sum of the resistances
  - b. the sum of the reciprocals of the resistances
  - c. the sum of the conductances
  - d. none of the above



# Ch.5 Summary

## Quiz

2. The number of nodes in a parallel circuit is
- a. one
  - b. two
  - c. three
  - d. any number

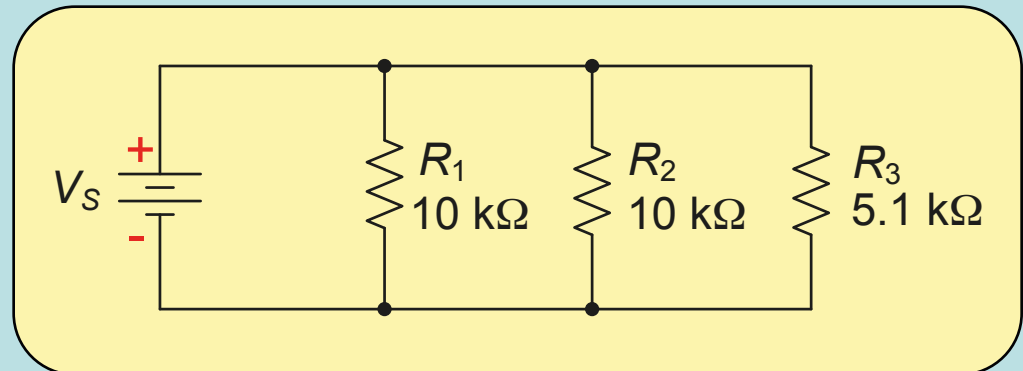


# Ch.5 Summary

## Quiz

3. The total resistance of the parallel resistors is

- a. 2.52 k $\Omega$
- b. 3.35 k $\Omega$
- c. 5.1 k $\Omega$
- d. 25.1 k $\Omega$



# Ch.5 Summary

## Quiz

4. If three equal resistors are in parallel, the total resistance is
- a. one third the value of one resistor.
  - b. the same as one resistor.
  - c. three times the value of one resistor.
  - d. the product of the three resistors



# Ch.5 Summary

## Quiz

5. In any circuit the total current entering a node is
- a. less than the total current leaving the node.
  - b. equal to the total current leaving the node.
  - c. greater than the total current leaving the node.
  - d. can be any of the above, depending on the circuit.



# Ch.5 Summary

## Quiz

6. The current divider formula to find  $I_1$  for the special case of two resistors is

a.  $I_1 = \left( \frac{R_1}{R_T} \right) \times I_T$

b.  $I_1 = \left( \frac{R_2}{R_T} \right) \times I_T$

c.  $I_1 = \left( \frac{R_2}{R_1 + R_2} \right) \times I_T$

d.  $I_1 = \left( \frac{R_1}{R_1 + R_2} \right) \times I_T$

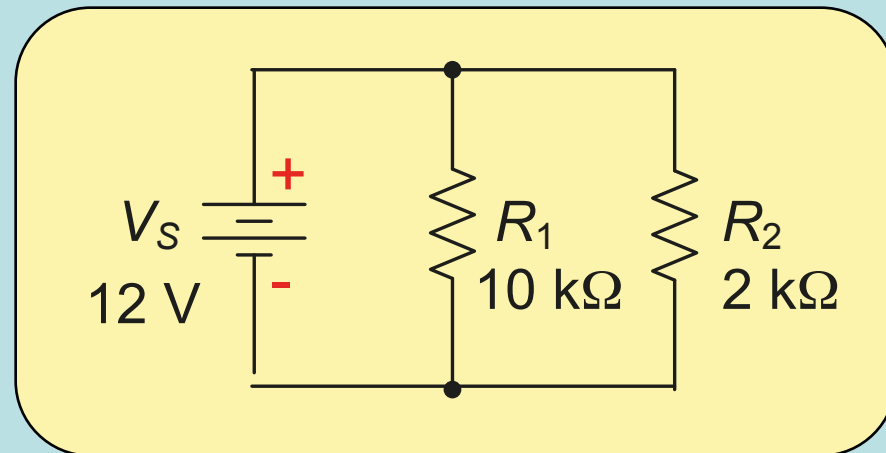


# Ch.5 Summary

## Quiz

7. The total current leaving the source is

- a. 1.0 mA
- b. 1.2 mA
- c. 6.0 mA
- d. 7.2 mA



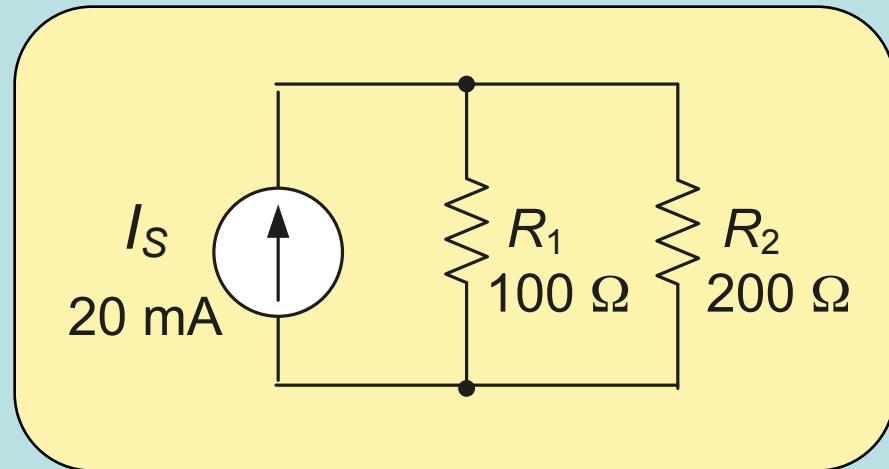


# Ch.5 Summary

## Quiz

8. The current in  $R_1$  is

- a. 6.7 mA
- b. 13.3 mA
- c. 20 mA
- d. 26.7 mA

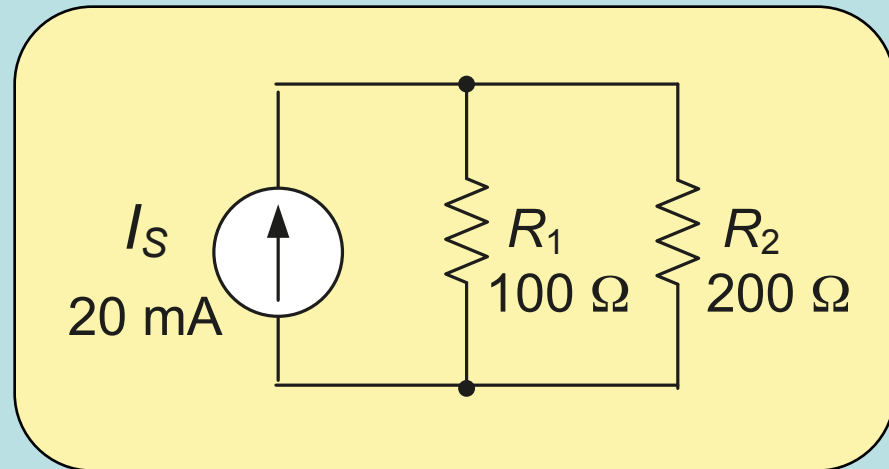


# Ch.5 Summary

## Quiz

9. The voltage across  $R_2$  is

- a. 0 V
- b. 0.67 V
- c. 1.33 V
- d. 4.0 V



# Ch.5 Summary

## Quiz

10. The total power dissipated in a parallel circuit is equal to the

- a. power in the largest resistor.
- b. power in the smallest resistor.
- c. average of the power in all resistors.
- d. sum of the power in all resistors.



# Ch.5 Summary

## Answers

- |      |       |
|------|-------|
| 1. d | 6. c  |
| 2. b | 7. d  |
| 3. a | 8. b  |
| 4. a | 9. c  |
| 5. b | 10. d |



# 6

## Series-Parallel Circuits

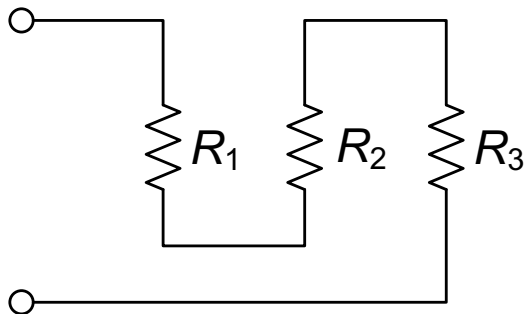


# Ch.6 Summary

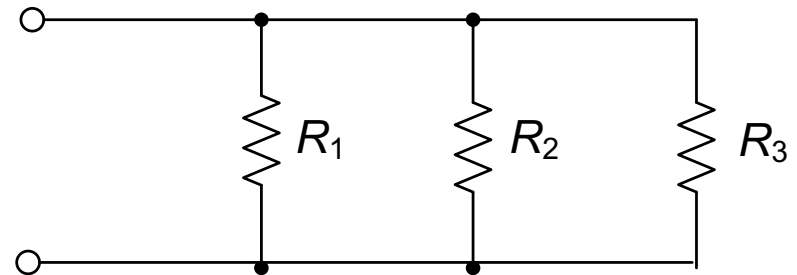
## Identifying Series-Parallel Relationships

**Most practical circuits have both series and parallel components.**

Components that are connected in series will share a common path.



Components that are connected in parallel will be connected across the same two nodes.



# Ch.6 Summary

## Combination Circuits

You can frequently simplify circuit analysis by combining series and parallel components.

An important analysis method is to form an **equivalent circuit.**

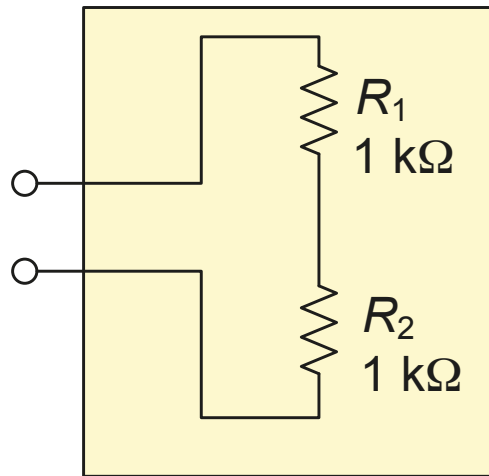
*An equivalent circuit is one with characteristics that are electrically the same as another circuit, but is generally simpler.*



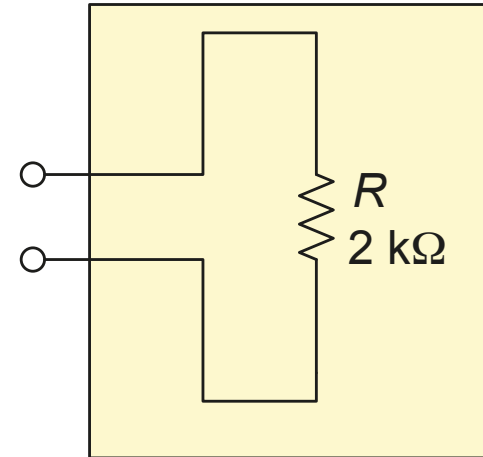
# Ch.6 Summary

## Equivalent Circuits

For example:



is equivalent to



There are no electrical measurements that can distinguish the boxes.

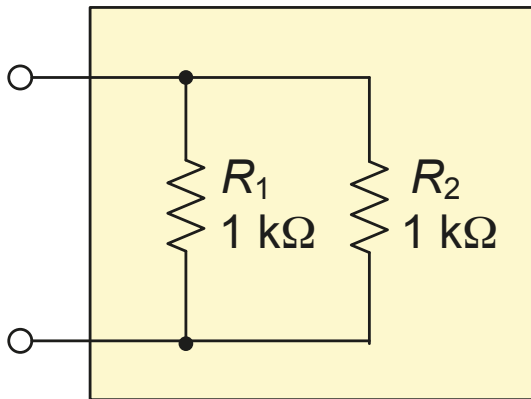




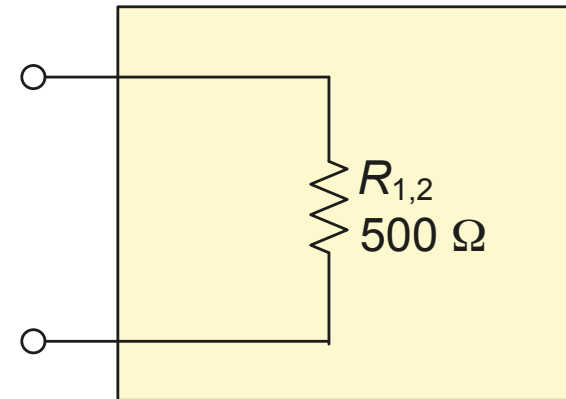
# Ch.6 Summary

## Equivalent Circuits

Another example:



is equivalent to

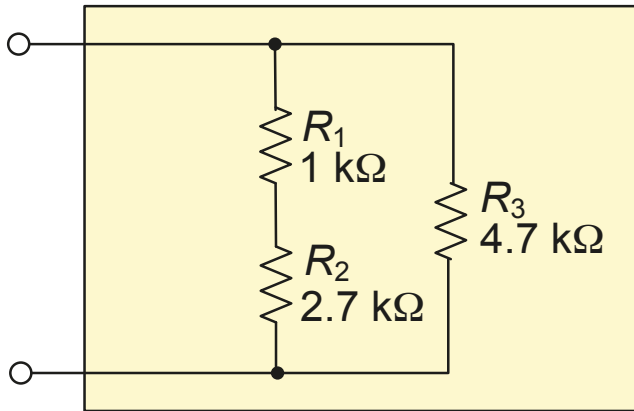


Again, there are no electrical measurements that can distinguish the boxes.

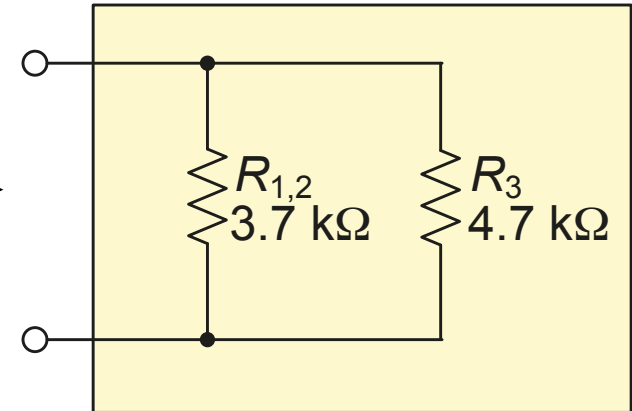


# Ch.6 Summary

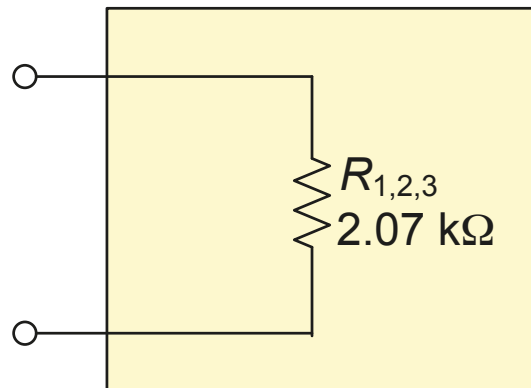
## Equivalent Circuits



is equivalent to



is equivalent to



There are no electrical measurements that can distinguish between the **three** boxes.

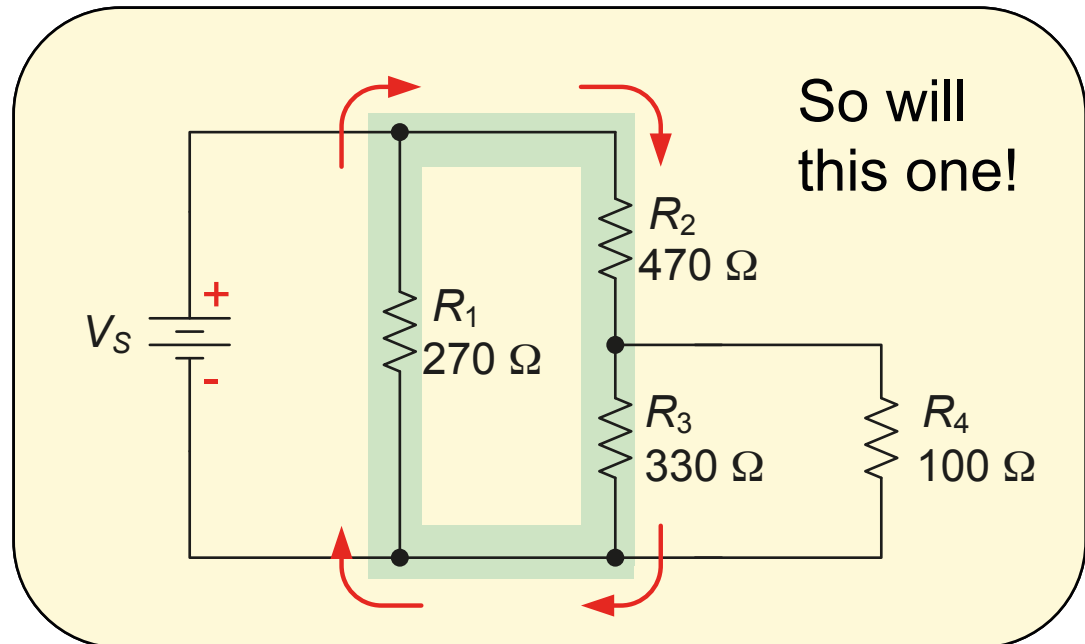


# Ch.6 Summary

## Kirchhoff's Law

**Kirchhoff's voltage law** and **Kirchhoff's current law** can be applied to any circuit, including combination circuits.

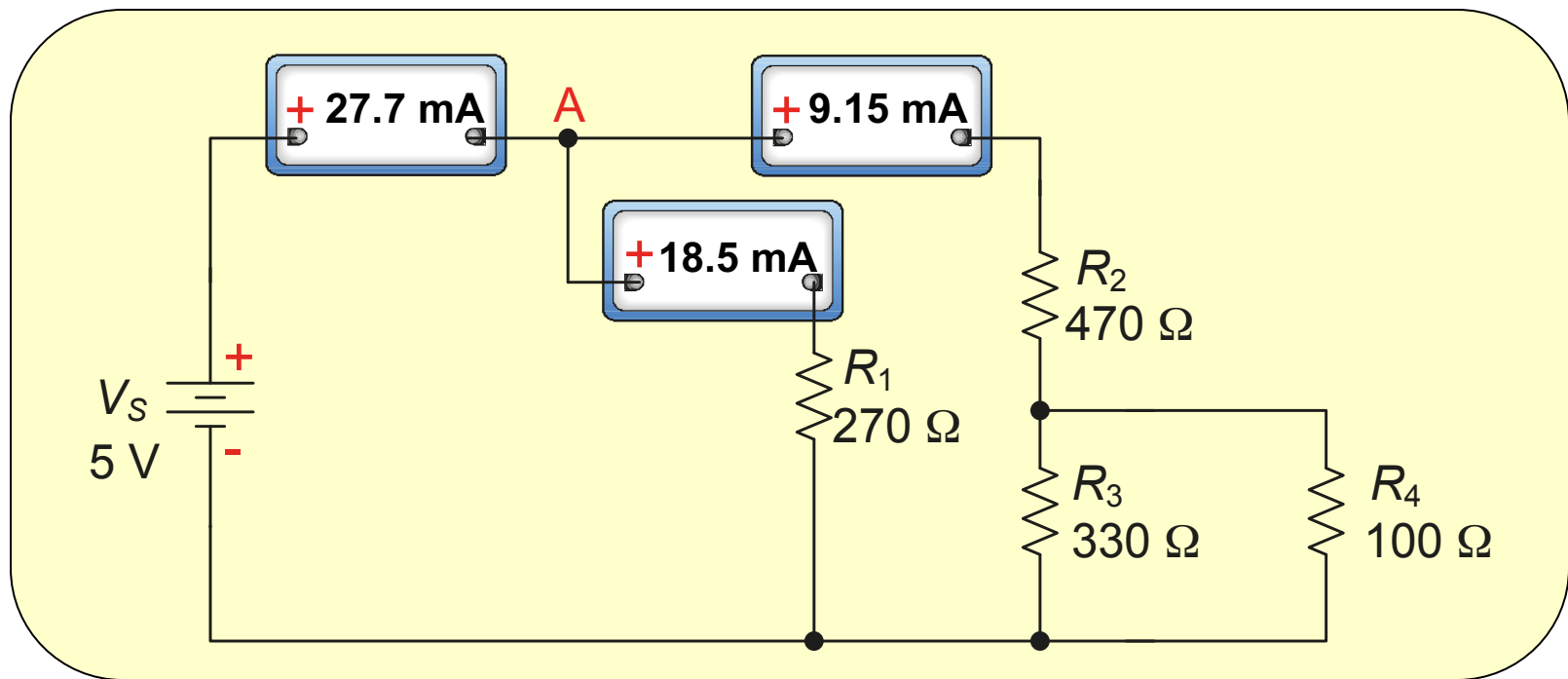
*For example, applying KVL, the path shown will have a sum of 0 V.*



# Ch.6 Summary

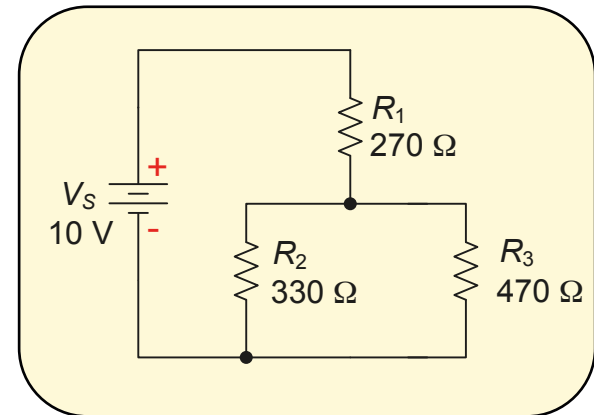
## Kirchhoff's Law

Kirchhoff's current law can also be applied to the same circuit. What are the readings for node A?



# Ch.6 Summary

## Combination Circuits



Tabulating current, resistance, voltage and power is a useful way to summarize parameters. Solve for the unknown quantities in the circuit shown.

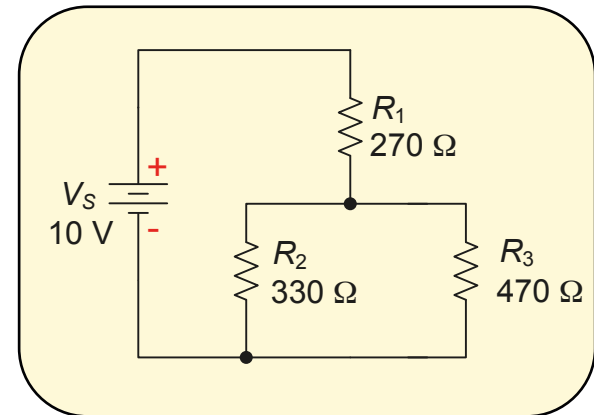
$I_1 = 21.6 \text{ mA}$	$R_1 = 270 \Omega$	$V_1 = 5.82 \text{ V}$	$P_1 = 126 \text{ mW}$
$I_2 = 12.7 \text{ mA}$	$R_2 = 330 \Omega$	$V_2 = 4.18 \text{ V}$	$P_2 = 53.1 \text{ mW}$
$I_3 = 8.9 \text{ mA}$	$R_3 = 470 \Omega$	$V_3 = 4.18 \text{ V}$	$P_3 = 37.2 \text{ mW}$
$I_T = 21.6 \text{ mA}$	$R_T = 464 \Omega$	$V_S = 10 \text{ V}$	$P_T = 216 \text{ mW}$



# Ch.6 Summary

## Application

Kirchhoff's laws can be applied as a check on the answer.



*Notice that the current in  $R_1$  is equal to the sum of the branch currents in  $R_2$  and  $R_3$ .*

The sum of the voltages around the outside loop is zero.

$I_1 = 21.6 \text{ mA}$	$R_1 = 270 \text{ W}$	$V_1 = 5.82 \text{ V}$	$P_1 = 126 \text{ mW}$
$I_2 = 12.7 \text{ mA}$	$R_2 = 330 \text{ W}$	$V_2 = 4.18 \text{ V}$	$P_2 = 53.1 \text{ mW}$
$I_3 = 8.9 \text{ mA}$	$R_3 = 470 \text{ W}$	$V_3 = 4.18 \text{ V}$	$P_3 = 37.2 \text{ mW}$
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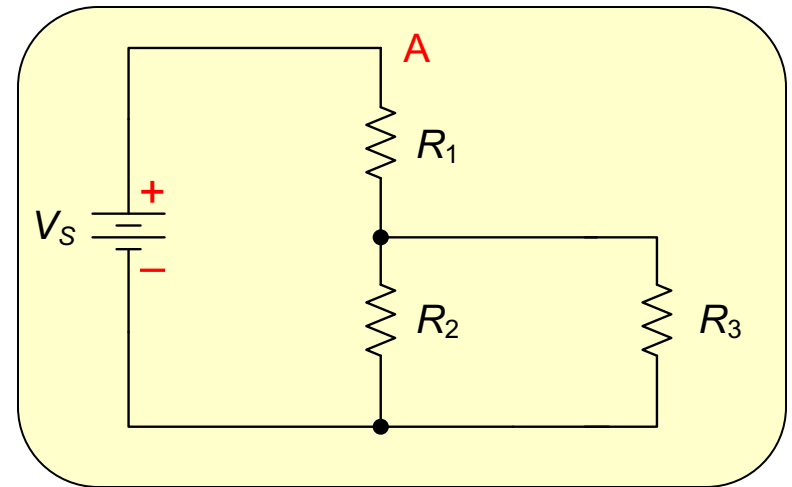


# Ch.6 Summary

## Loaded Voltage Divider

The voltage-divider equation was developed for a series circuit. Recall that the output voltage is given by

$$V_2 = \left( \frac{R_2}{R_T} \right) \times V_S$$



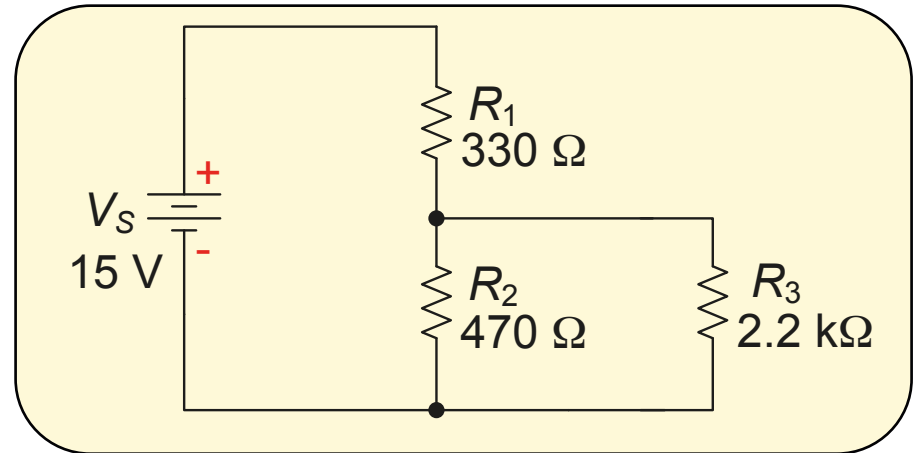
*A voltage-divider with a resistive load is a combinational circuit and the voltage divider is said to be loaded. The loading reduces the total resistance from node A to ground.*



# Ch.6 Summary

## Loaded Voltage Divider

*What is the voltage across  $R_3$ ?*



Form an equivalent series circuit by combining  $R_2$  and  $R_3$ ; then apply the voltage-divider formula to the equivalent circuit:

$$R_{2,3} = R_2 \parallel R_3 = 470\ \Omega \parallel 2.2\ \text{k}\Omega = 387\ \Omega$$

$$V_3 = V_{2,3} = \left( \frac{R_{2,3}}{R_1 + R_{2,3}} \right) V_S = \left( \frac{387\ \Omega}{330\ \Omega + 387\ \Omega} \right) (15\ \text{V}) = \mathbf{8.10\ \text{V}}$$

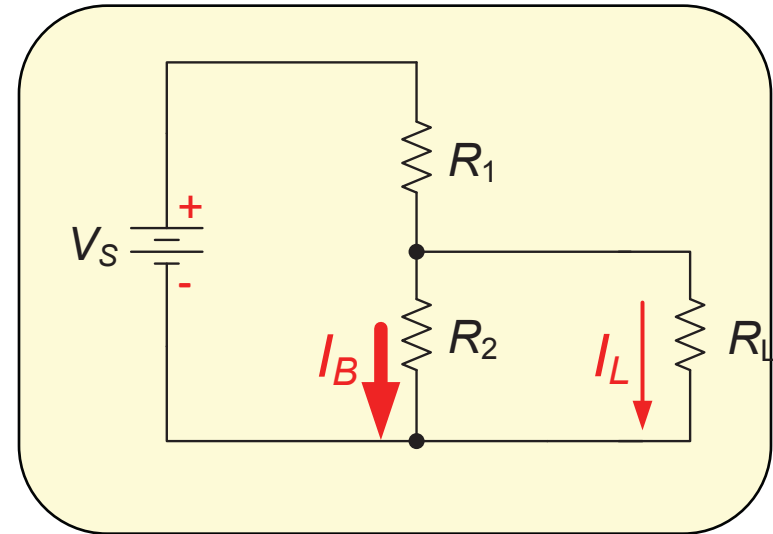




# Ch.6 Summary

## Stiff Voltage Divider

A **stiff voltage-divider** provides a load voltage that is nearly equal to its no-load output voltage. To accomplish this, the load current must be much less than the bleeder current (or  $R_L > 10R_2$ ).



*If  $R_1 = R_2 = 1.0 \text{ k}\Omega$ , what value of  $R_L$  will produce a stiff voltage divider?  
What fraction of the no-load voltage is the load voltage?*

$R_L > 10 R_2$ ;  $R_L$  should be  $10 \text{ k}\Omega$  or greater. For a  $10 \text{ k}\Omega$  load,

$$V_L = \left( \frac{R_2 \parallel R_L}{R_1 + (R_2 \parallel R_L)} \right) V_s = \left( \frac{0.91 \text{ k}\Omega}{1 \text{ k}\Omega + 0.91 \text{ k}\Omega} \right) V_s = (0.476) V_s$$

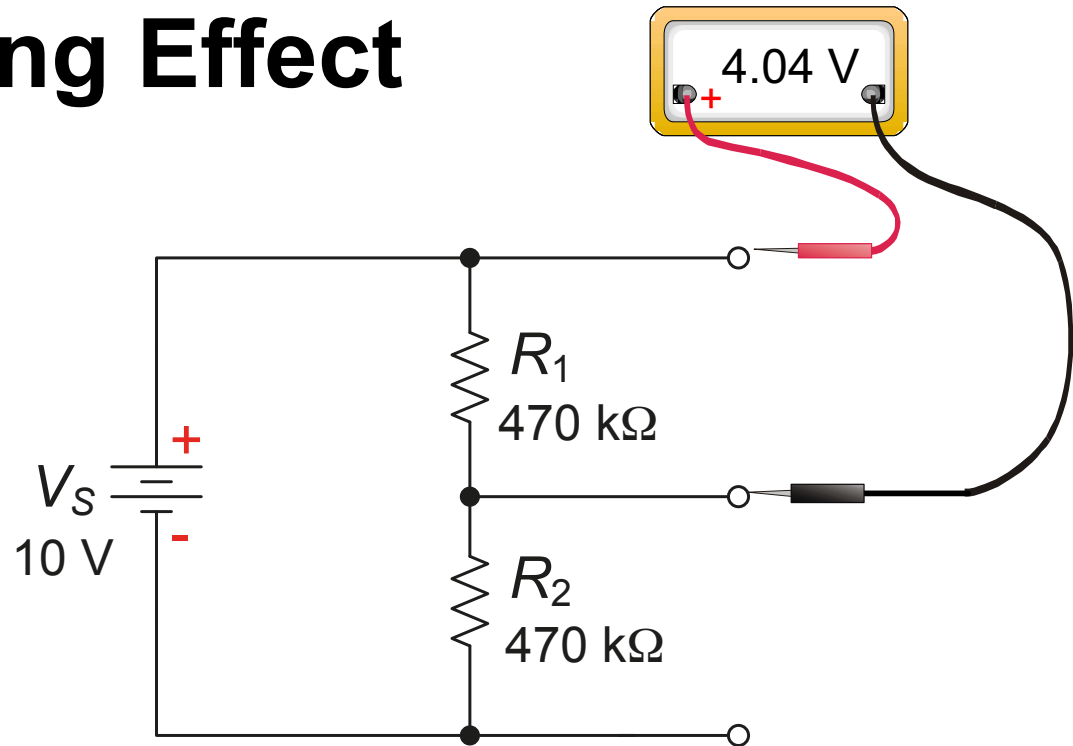
*This is 95% of  
the no-load  
output voltage.*



# Ch.6 Summary

## Voltmeter Loading Effect

Assume  $V_S = 10\text{ V}$ , but the meter reads only  $4.04\text{ V}$  when it is across either  $R_1$  or  $R_2$ . Can you explain what is happening?



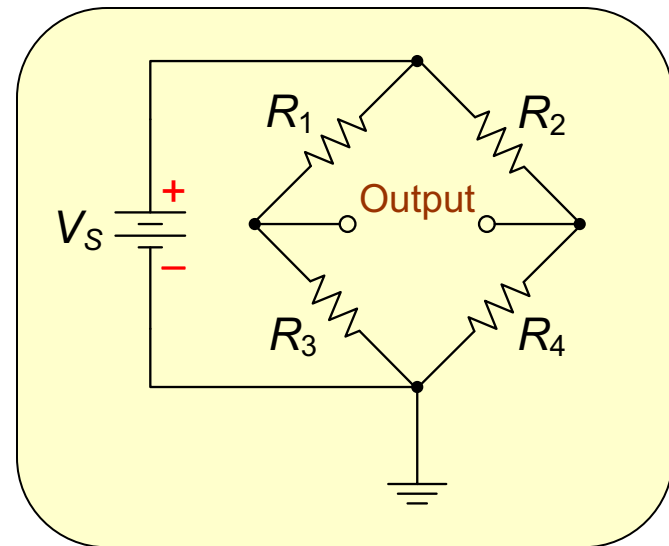
All measurements affect the quantity being measured. A voltmeter has internal resistance, which can change the resistance of the circuit under test. In this case, a  $1\text{ M}\Omega$  internal resistance of the meter accounts for the readings.



# Ch.6 Summary

## Wheatstone Bridge

The Wheatstone bridge contains four resistive arms forming two voltage dividers. The output is taken between the dividers. Typically, one of the bridge resistors is adjustable.



When the output voltage equals 0 V, the bridge is said to be **balanced**. This occurs when  $R_1 \times R_4 = R_2 \times R_3$ .

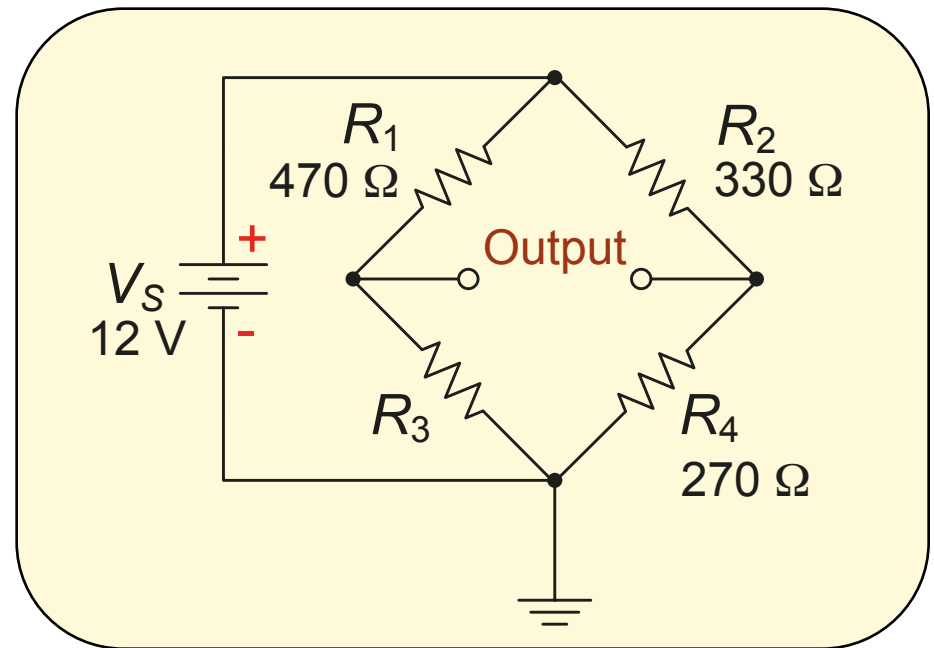


# Ch.6 Summary

## Wheatstone Bridge

What value of  $R_3$  will balance the bridge?

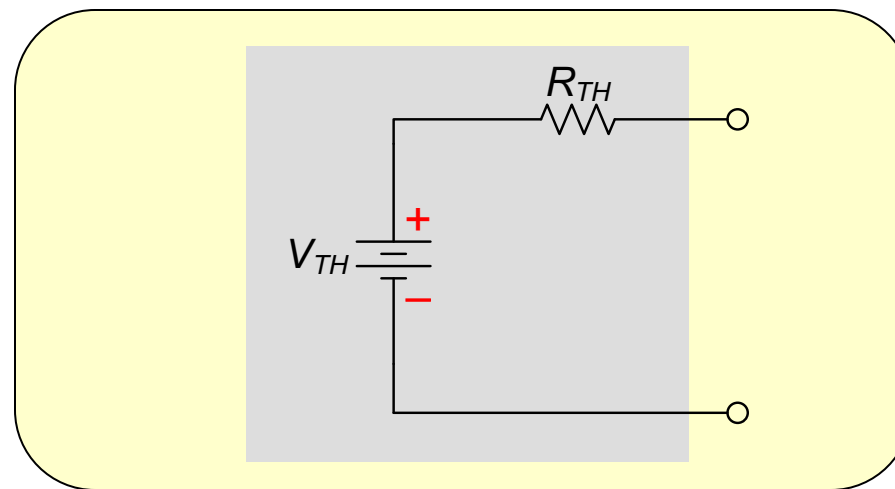
**384  $\Omega$**



# Ch.6 Summary

## Thevenin's Theorem

**Thevenin's theorem** states that any two-terminal, resistive circuit can be replaced with a simple equivalent circuit when viewed from two output terminals. This **Thevenin equivalent circuit** looks like:

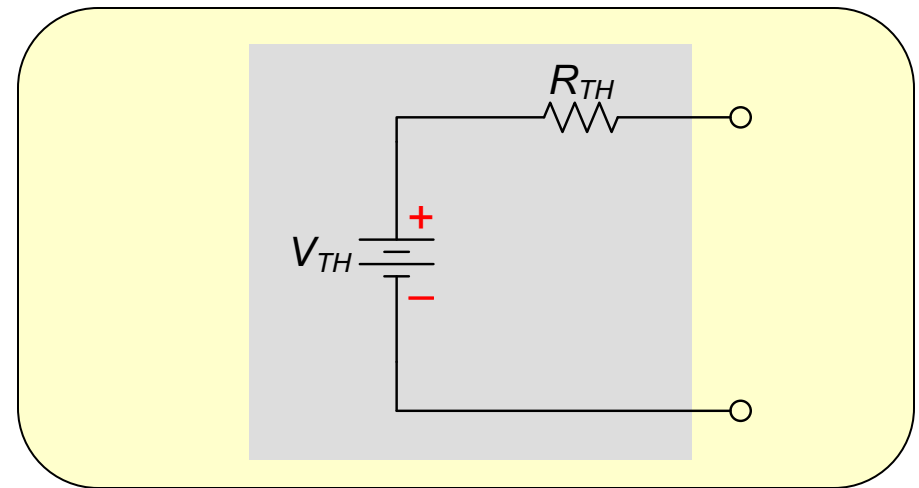


# Ch.6 Summary

## Thevenin's Theorem

$V_{TH}$  is defined as the open circuit voltage between the two output terminals of a circuit.

$R_{TH}$  is defined as the total resistance appearing between the two output terminals when all sources have been replaced by their internal resistances.

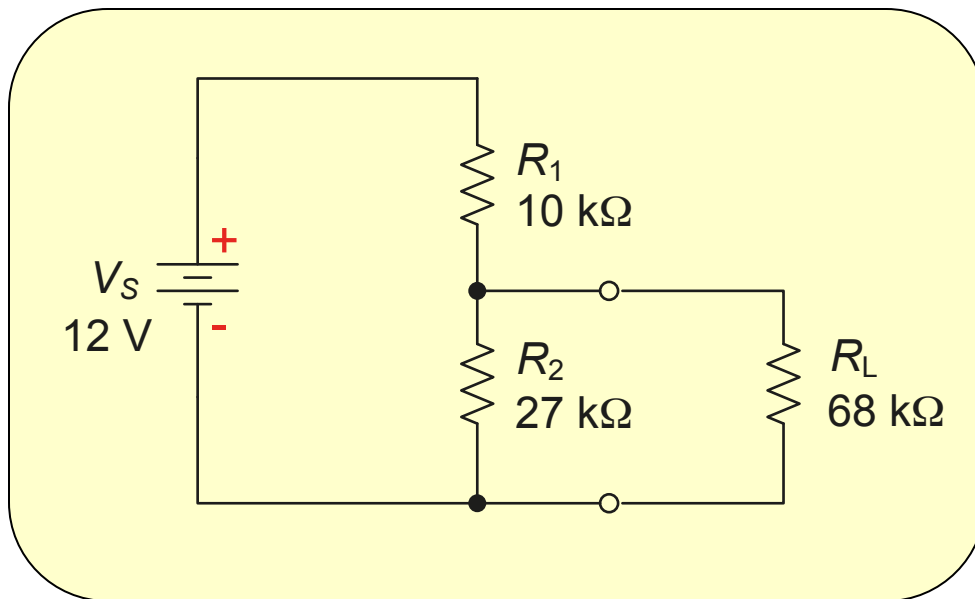


# Ch.6 Summary

## Thevenin's Theorem

What is the Thevenin voltage for the circuit? **8.76 V**

What is the Thevenin resistance for the circuit? **7.30 k $\Omega$**



*Remember, the load resistor has no effect on the Thevenin parameters.*

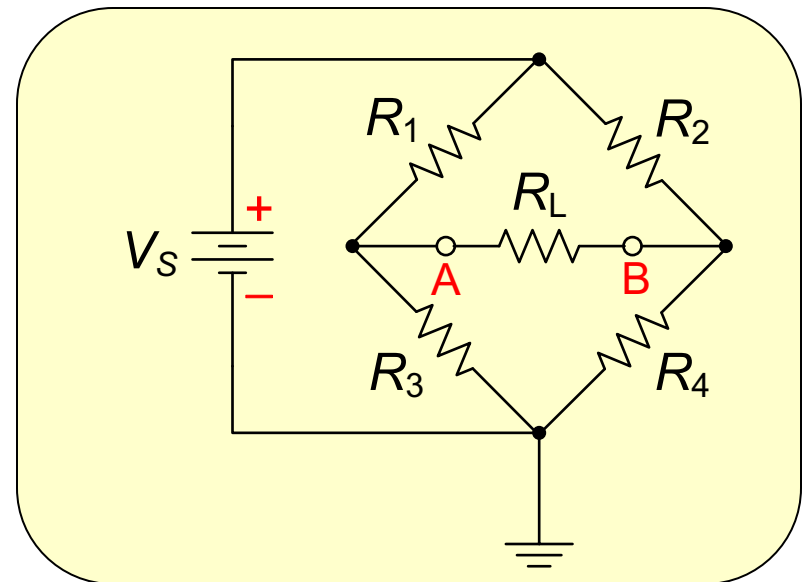


# Ch.6 Summary

## Thevenin's Theorem

*Thevenin's theorem is useful for solving the Wheatstone bridge. One way to "Thevenize" the bridge is to create two Thevenin circuits - from A to ground and from B to ground.*

The resistance between point A and ground is  $R_1 || R_3$  and the resistance from B to ground is  $R_2 || R_4$ . The voltage on each side of the bridge is found using the voltage divider rule.



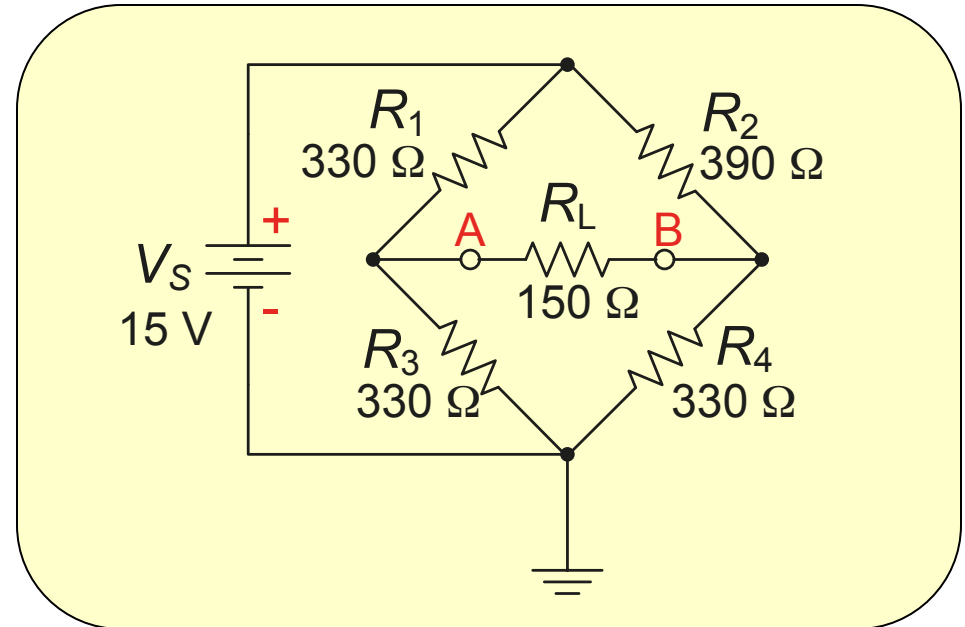


# Ch.6 Summary

## Thevenin's Theorem

For the bridge shown,  
 $R_1 || R_3 = 165 \Omega$  and  
 $R_2 || R_4 = 179 \Omega$ .

The voltage from A to ground (with no load) is 7.5 V and from B to ground (with no load) is 6.87 V.

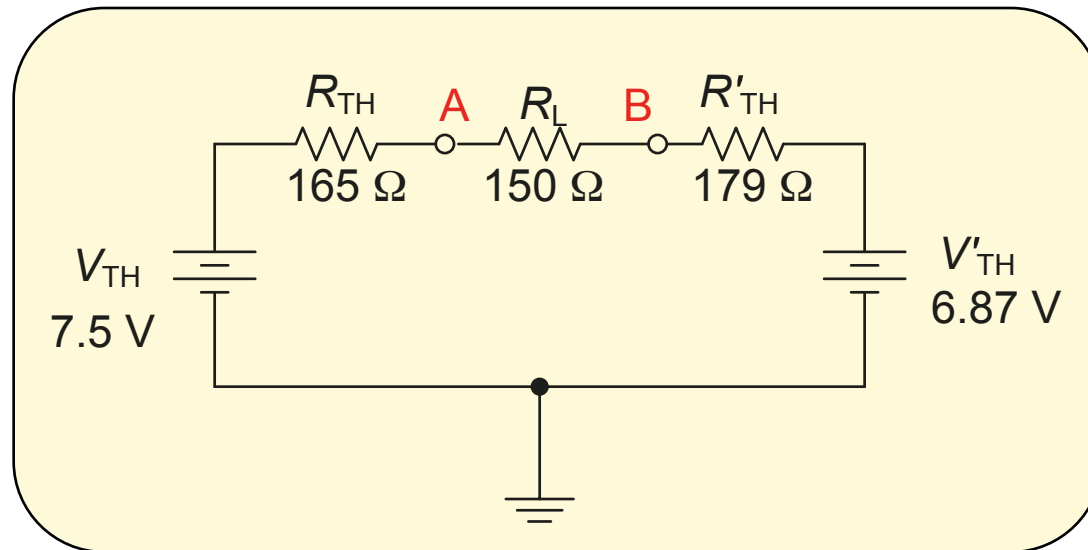


The Thevenin circuits for each of the bridge are shown on the following slide.



# Ch.6 Summary

## Thevenin's Theorem



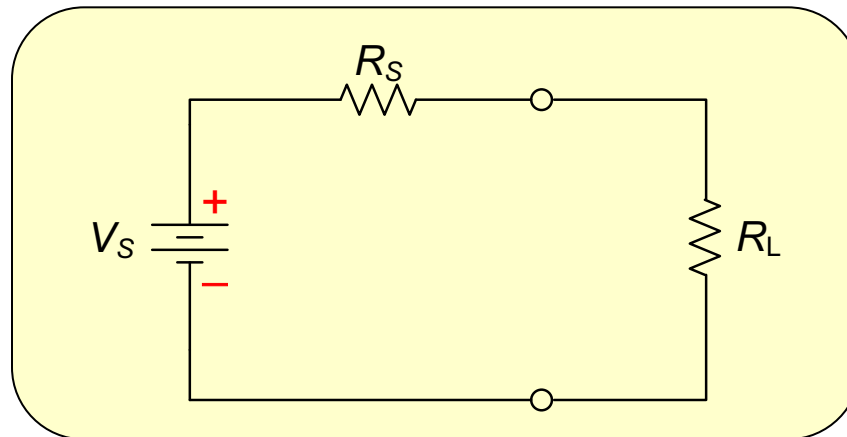
Putting the load on the Thevenin circuits and applying the superposition theorem allows you to calculate the load current. The load current is: **1.27 mA**



# Ch.6 Summary

## Maximum Power Transfer

The maximum power is transferred from a source to a load when the load resistance is equal to the internal source resistance.



*The maximum power transfer theorem assumes the source voltage and resistance are fixed.*



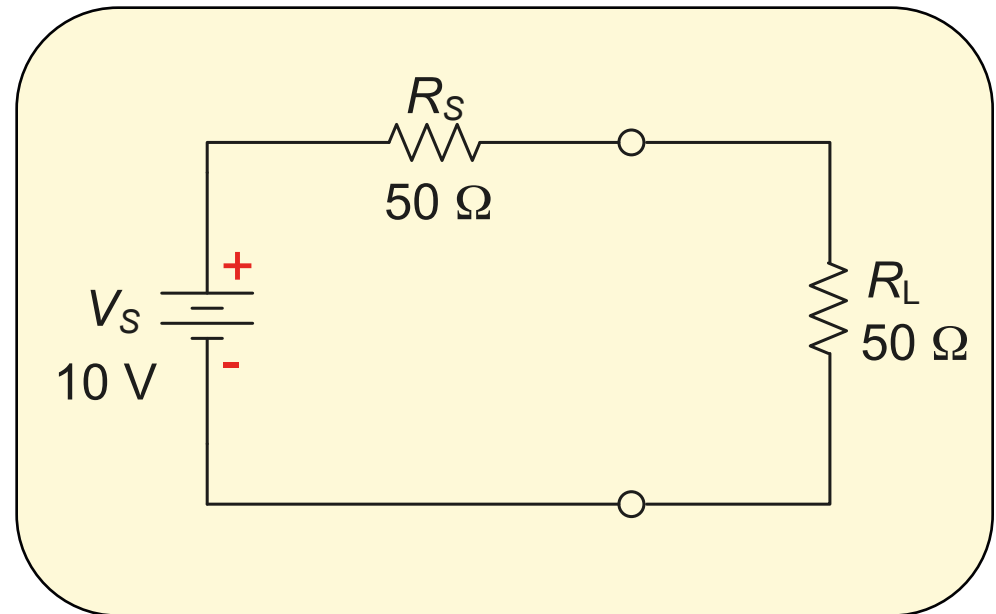
# Ch.6 Summary

## Maximum Power Transfer

*What is the power delivered to the matching load?*

The voltage to the load is 5.0 V.  
The power delivered is:

$$P_L = \frac{V_L^2}{R_L} = \frac{(5.0 \text{ V})^2}{50 \Omega} = 0.5 \text{ W}$$

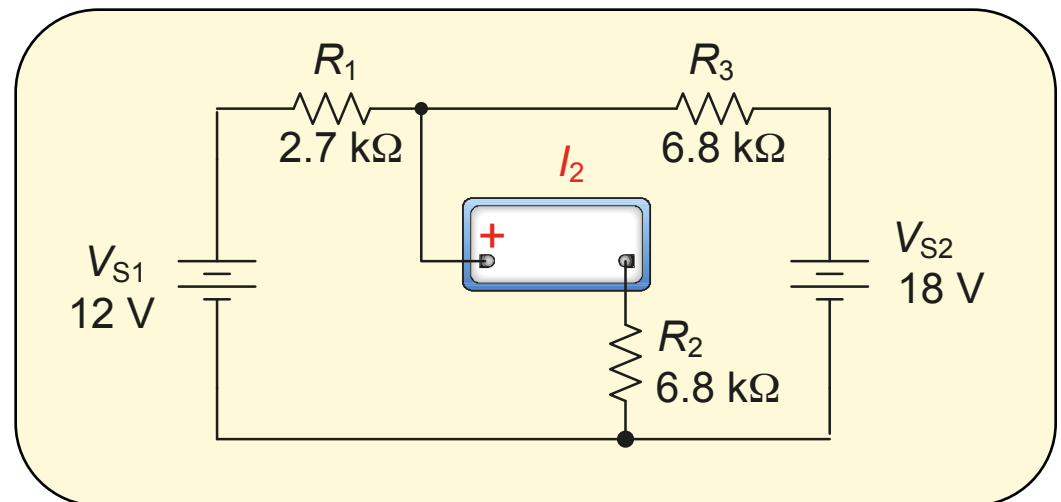


# Ch.6 Summary

## Superposition Theorem

The **superposition theorem** is a way to determine currents and voltages in a linear circuit that has multiple sources by taking one source at a time and algebraically summing the results.

*What does the ammeter read for  $I_2$ ? (See next slide for the method and the answer).*

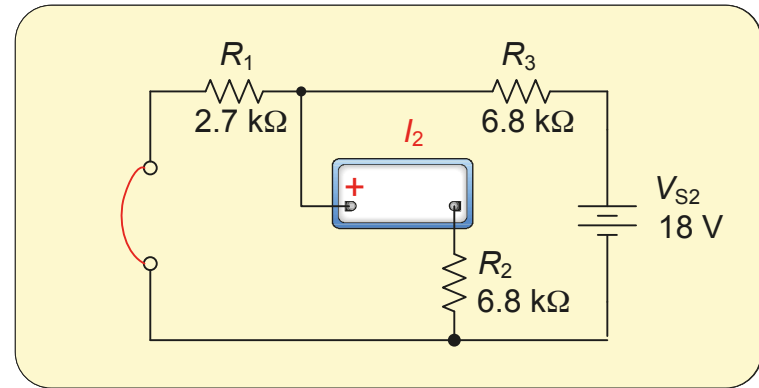


# Ch.6 Summary

## Solution:

What does the ammeter read for  $I_2$ ?

Set up a table of pertinent information and solve for each quantity listed:



Source 1:	$R_{T(S1)} = 6.10 \text{ k}\Omega$	$I_1 = 1.97 \text{ mA}$	$I_2 = 0.98 \text{ mA}$
Source 2:	$R_{T(S2)} = 8.73 \text{ k}\Omega$	$I_3 = 2.06 \text{ mA}$	$I_2 = 0.58 \text{ mA}$
Both sources			$I_2 = 1.56 \text{ mA}$

**The total current is the algebraic sum.**



# Ch.6 Summary

## Troubleshooting

The effective troubleshooter must think logically about circuit operation.

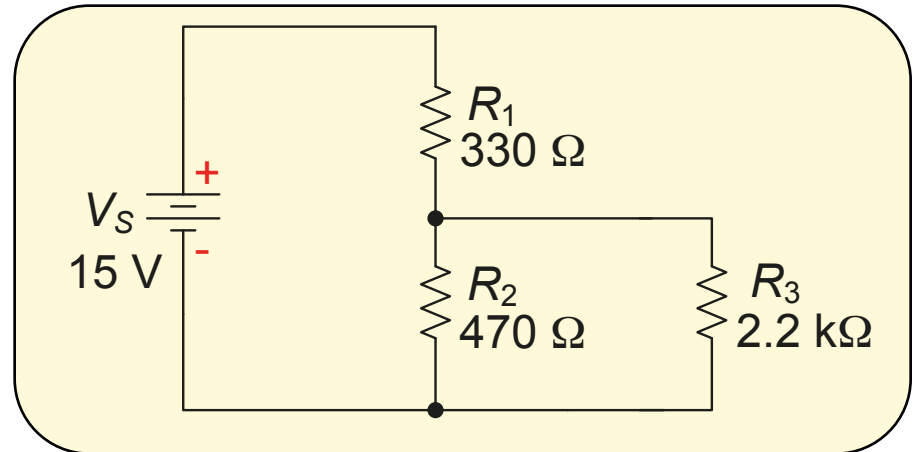
- 1.** Understand normal circuit operation and find out the symptoms of the failure.
- 2.** Decide on a logical set of steps to find the fault.
- 3.** Following the steps in the plan, make measurements to isolate the problem. Modify the plan if necessary.



# Ch.6 Summary

## Troubleshooting

The output of the voltage-divider is 6.0 V. Describe how you would use analysis and planning in finding the fault.



- 1.** From an earlier calculation,  $V_3$  should equal **8.10 V**. A low voltage is most likely caused by a low source voltage or incorrect resistors (possibly  $R_1$  and  $R_2$  reversed). If the circuit is new, incorrect components are possible.
- 2.** Decide on a logical set of steps to locate the fault. You could decide to 1) check the source voltage, 2) disconnect the load and check the output voltage, and if it is correct, 3) check the load resistance. If  $R_3$  is correct, check other resistors.





# Ch.6 Summary

## Selected Key Terms

***Loading*** The effect on a circuit when an element that draws current from the circuit is connected across the output terminals.

***Load current*** The output current supplied to a load.

***Bleeder current*** The current left after the load current is subtracted from the total current into the circuit.

***Wheatstone bridge*** A 4-legged type of bridge circuit with which an unknown resistance can be accurately measured using the balanced state. Deviations in resistance can be measured using the unbalanced state.



# Ch.6 Summary

## Selected Key Terms

### *Thevenin's theorem*

A circuit theorem that provides for reducing any two-terminal resistive circuit to a single equivalent voltage source in series with an equivalent resistance.

### *Maximum power transfer*

The condition, when the load resistance equals the source resistance, under which maximum power is transferred to the load.

### *Superposition*

A method for analyzing circuits with two or more sources by examining the effects of each source by itself and then combining the effects.



# Ch.6 Summary

## Quiz

1. Two circuits that are equivalent have the same
  - a. number of components
  - b. response to an electrical stimulus
  - c. internal power dissipation
  - d. all of the above



# Ch.6 Summary

## Quiz

2. If a series equivalent circuit is drawn for a complex circuit, the equivalent circuit can be analyzed with

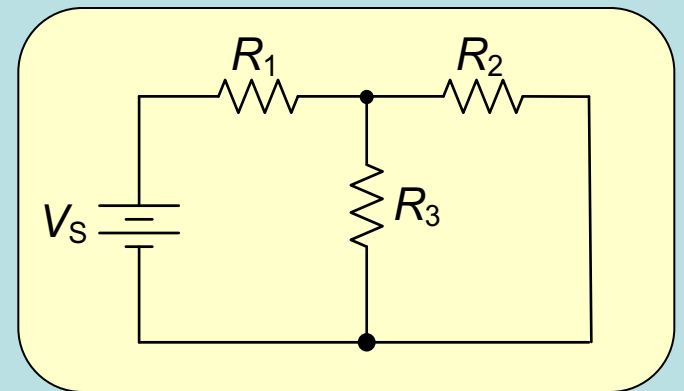
- a. the voltage divider theorem
- b. Kirchhoff's voltage law
- c. both of the above
- d. none of the above



# Ch.6 Summary

## Quiz

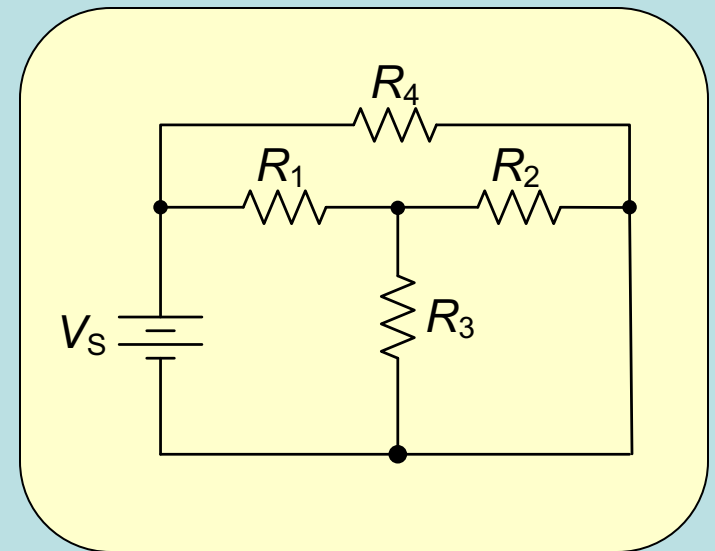
3. For the circuit shown,
- a.  $R_1$  is in series with  $R_2$
  - b.  $R_1$  is in parallel with  $R_2$
  - c.  $R_2$  is in series with  $R_3$
  - d.  $R_2$  is in parallel with  $R_3$



# Ch.6 Summary

## Quiz

4. For the circuit shown,
- a.  $R_1$  is in series with  $R_2$
  - b.  $R_4$  is in parallel with  $R_1$
  - c.  $R_2$  is in parallel with  $R_3$
  - d. none of the above



# Ch.6 Summary

## Quiz

5. A signal generator has an output voltage of 2.0 V with no load. When a  $600\ \Omega$  load is connected to it, the output drops to 1.0 V. The Thevenin resistance of the generator is

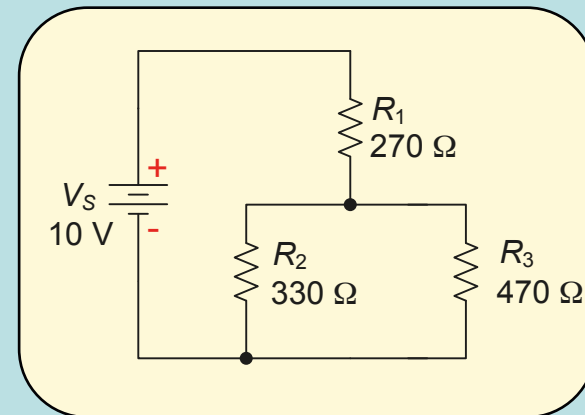
- a.  $300\ \Omega$
- b.  $600\ \Omega$
- c.  $900\ \Omega$
- d.  $1200\ \Omega$



# Ch.6 Summary

## Quiz

6. For the circuit shown, Kirchhoff's voltage law
- applies only to the outside loop
  - applies only to the A junction.
  - can be applied to any closed path.
  - does not apply.





# Ch.6 Summary

## Quiz

7. The effect of changing a measured quantity due to connecting an instrument to a circuit is called

- a. loading
- b. clipping
- c. distortion
- d. loss of precision

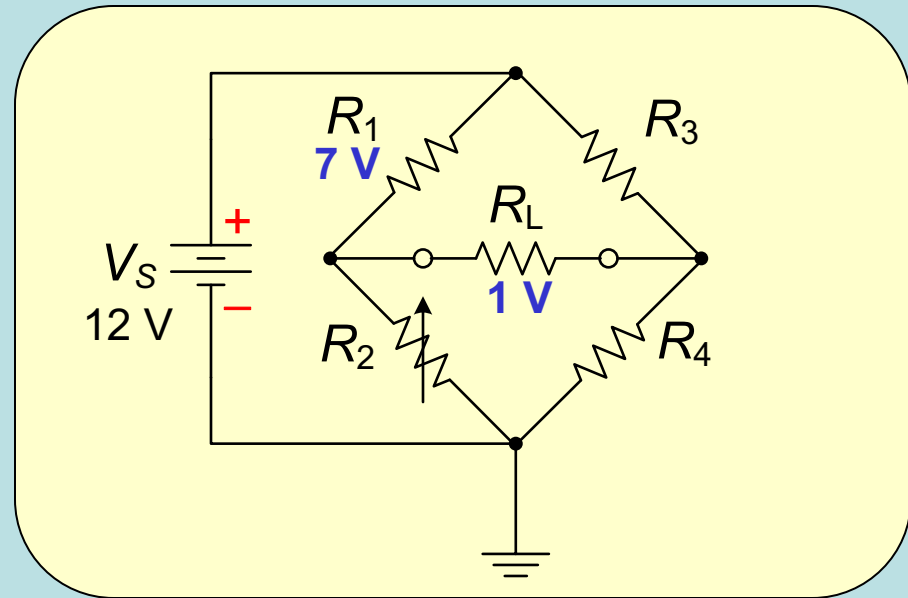


# Ch.6 Summary

## Quiz

8. An unbalanced Wheatstone bridge has the voltages shown. The voltage across  $R_4$  is

- a. 4.0 V
- b. 5.0 V
- c. 6.0 V
- d. 7.0 V

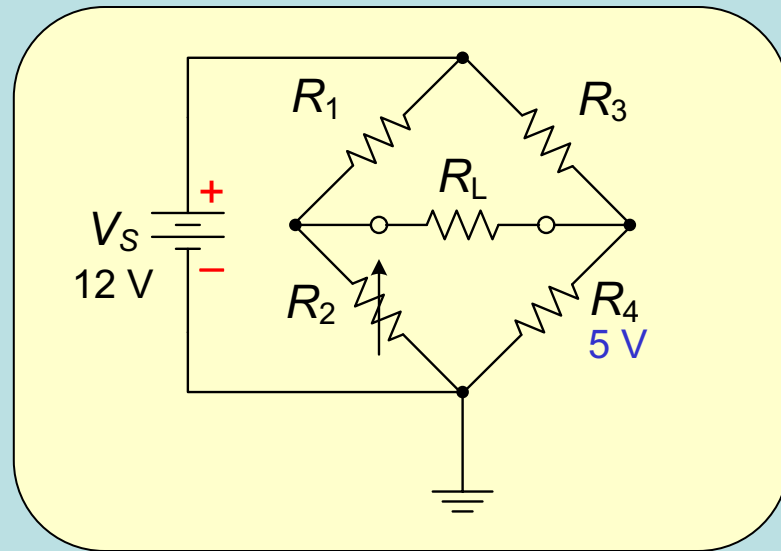


# Ch.6 Summary

## Quiz

9. Assume  $R_2$  is adjusted until the Wheatstone bridge is balanced. At this point, the voltage across  $R_4$  is measured and found to be 5.0 V. The voltage across  $R_1$  will be

- a. 4.0 V
- b. 5.0 V
- c. 6.0 V
- d. 7.0 V



# Ch.6 Summary

## Quiz

10. Maximum power is transferred from a fixed source when

- a. the load resistor is  $\frac{1}{2}$  the source resistance
- b. the load resistor is equal to the source resistance
- c. the load resistor is twice the source resistance
- d. none of the above



# Ch.6 Summary

## Answers

- |      |       |
|------|-------|
| 1. b | 6. c  |
| 2. c | 7. a  |
| 3. d | 8. a  |
| 4. d | 9. d  |
| 5. b | 10. b |



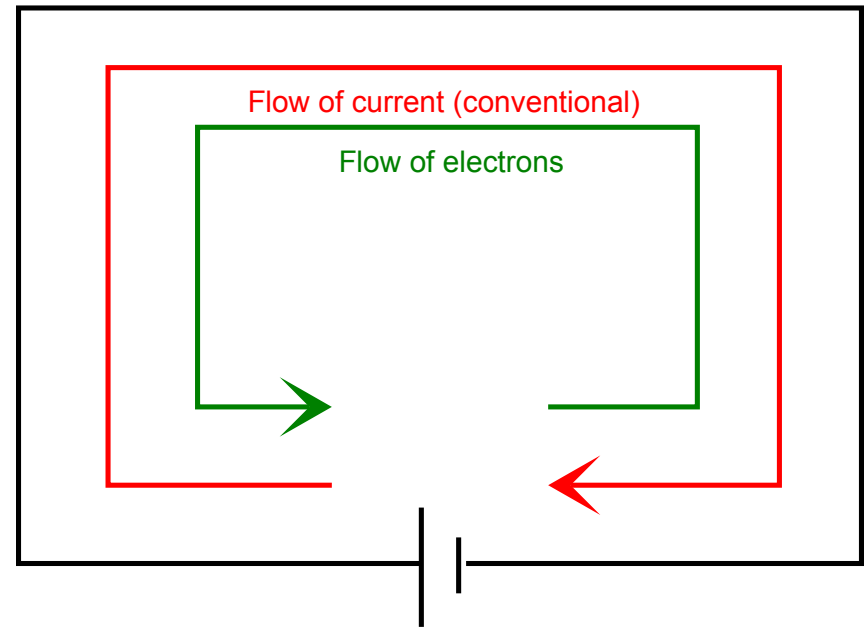
# 16

## Diodes and Applications



# Aside: Conventional Current

- We assume current flows out of the positive side of a voltage source and back to the negative side (the electrons flow in the opposite direction)



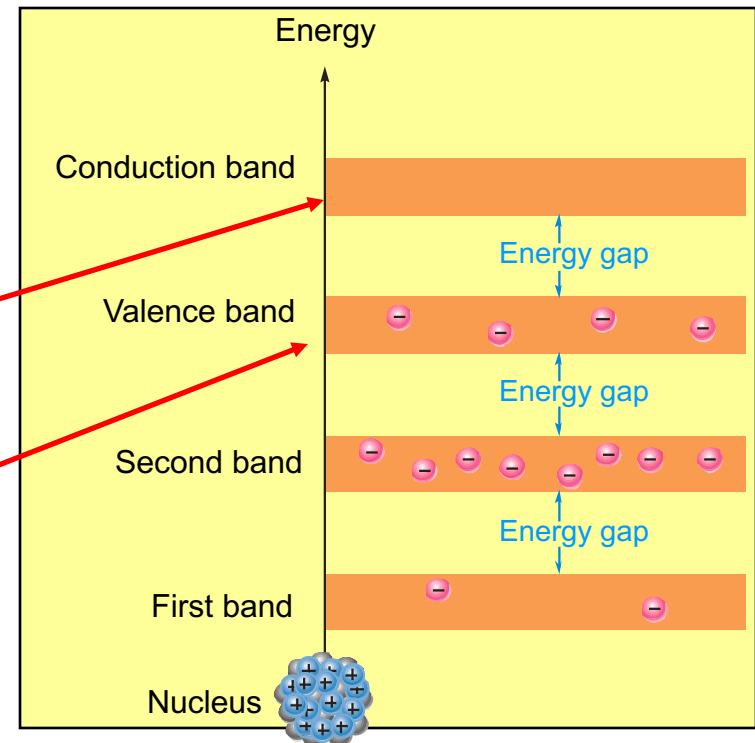
# Semiconductors

Semiconductors (e.g. Si, Ge) are crystalline materials that are characterized by specific energy bands for electrons.

Between the bands are gaps; these gaps represent energies that electrons cannot possess.

The last energy band is the **conduction band**, where electrons are mobile.

The next to the last band is the **valence band**, which is the energy level associated with electrons involved in bonding.





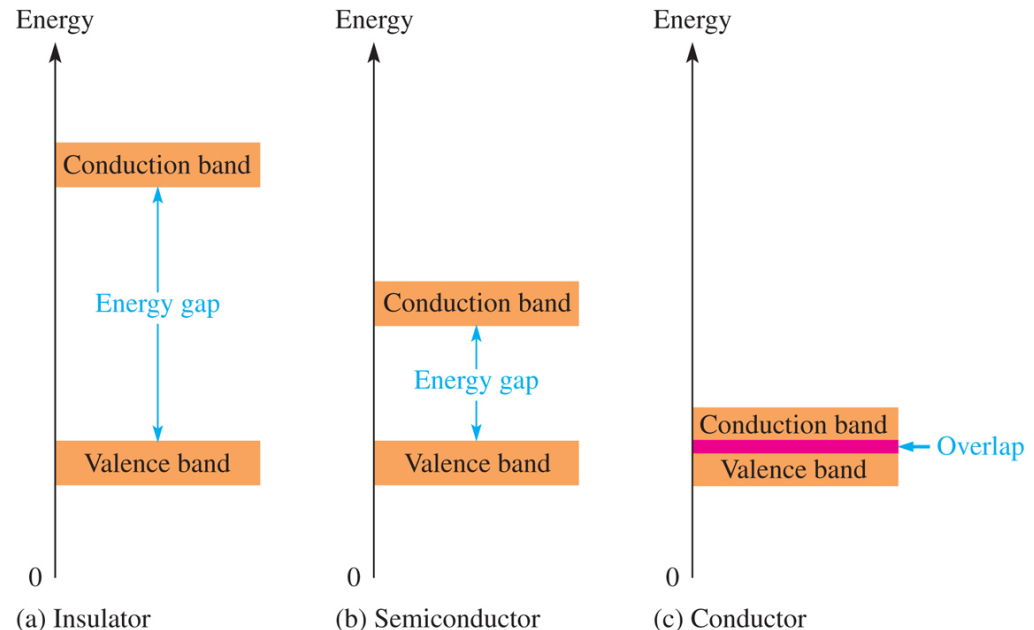
# Ch.16 Summary

## Energy Gaps

**Valence band:** The band of energy levels for valence electrons.

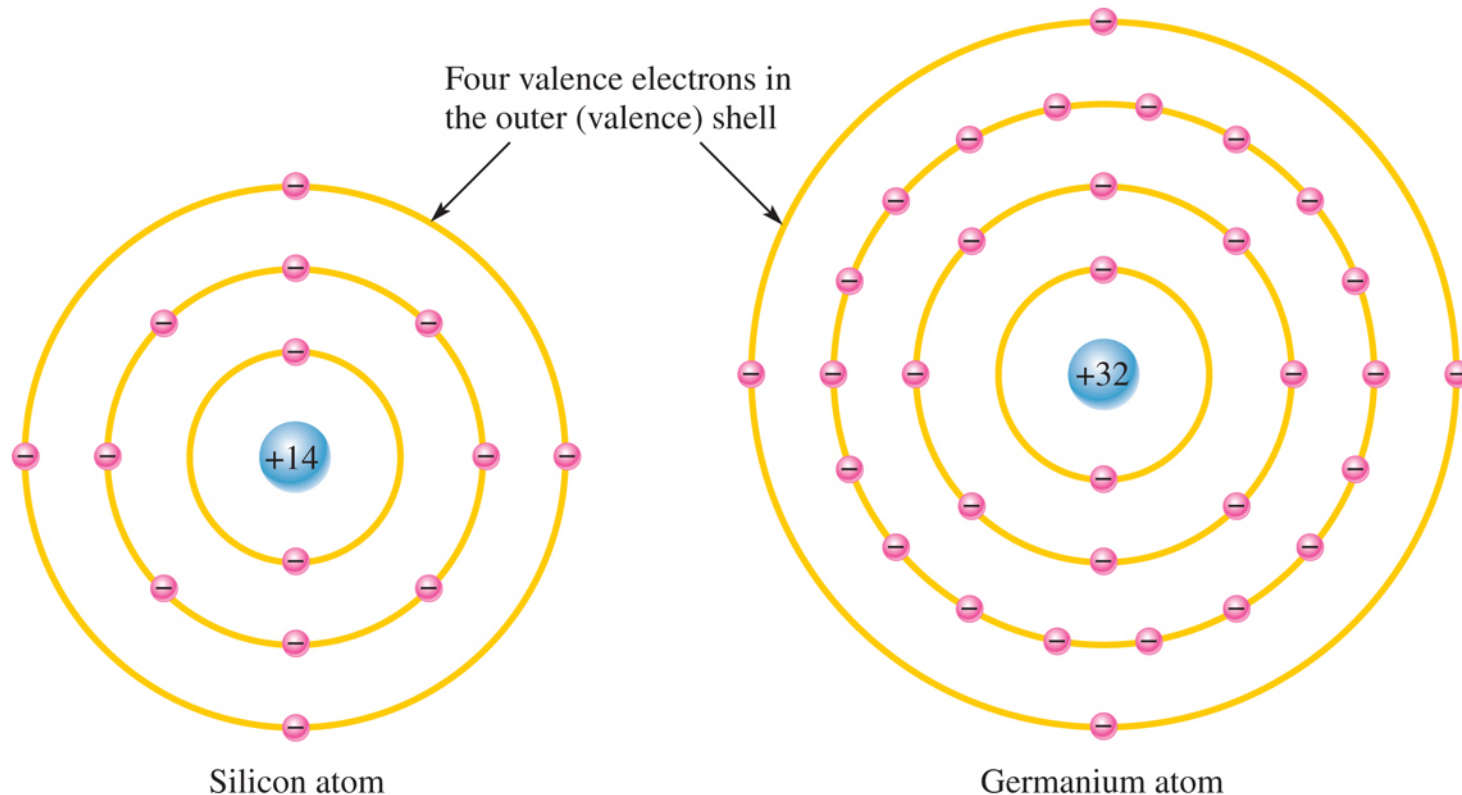
**Conduction band:** The band of energy levels just beyond the valence band. Free electrons travel in the conduction band.

**Energy gap:** The difference between the energy levels of the valence band and the conduction band. The narrower the energy gap, the easier it is for electrons to travel back and forth between the bands.



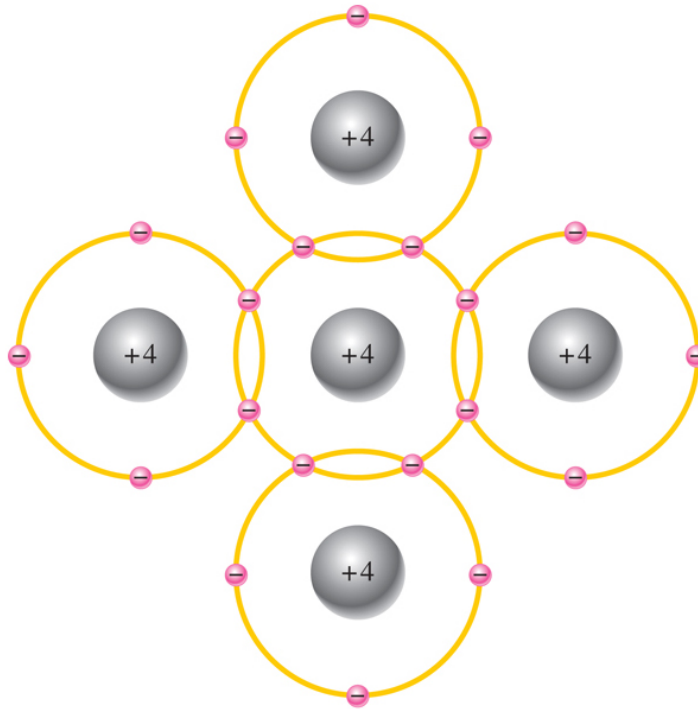
# Ch.16 Summary

## Silicon (Si) and Germanium (Ge)

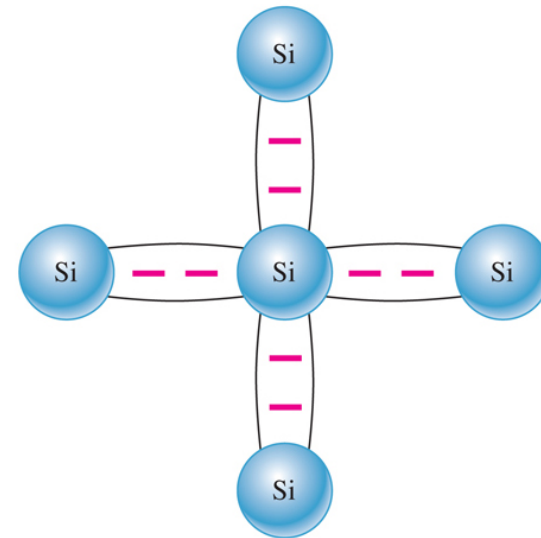


# Ch.16 Summary

## Atomic Bonding



(a) The center silicon atom shares an electron with each of the four surrounding silicon atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.



(b) Bonding diagram. The red negative signs represent the shared valence electrons.



# Ch.16 Summary

## Electrons and Holes

At room temperature, some electrons have enough energy to jump into the conduction band.

When an electron jumps to the conduction band, a vacancy is left in the valence band. This vacancy is called a **hole**.

After jumping the gap, these electrons are free to drift throughout the material and form electron current when a voltage is applied.

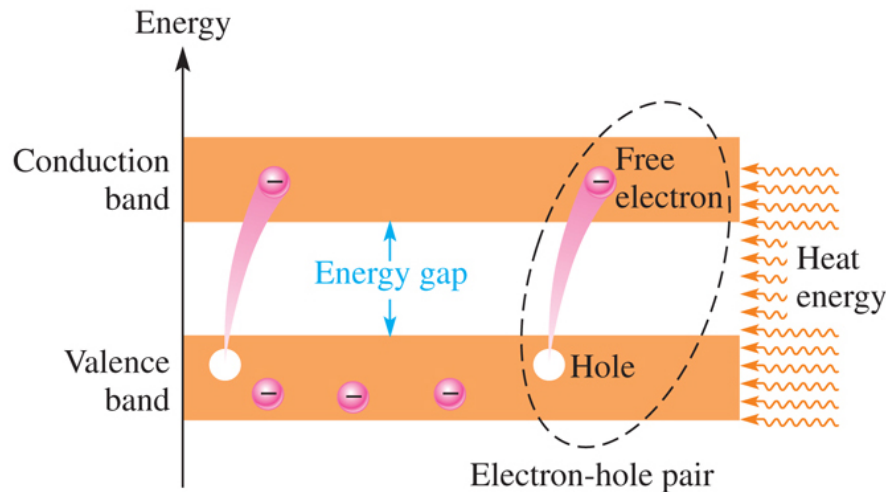
For every electron raised to the conduction band by thermal or light energy, there is one hole left in the valence band, creating what is called an **electron-hole pair**.

**Recombination** occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

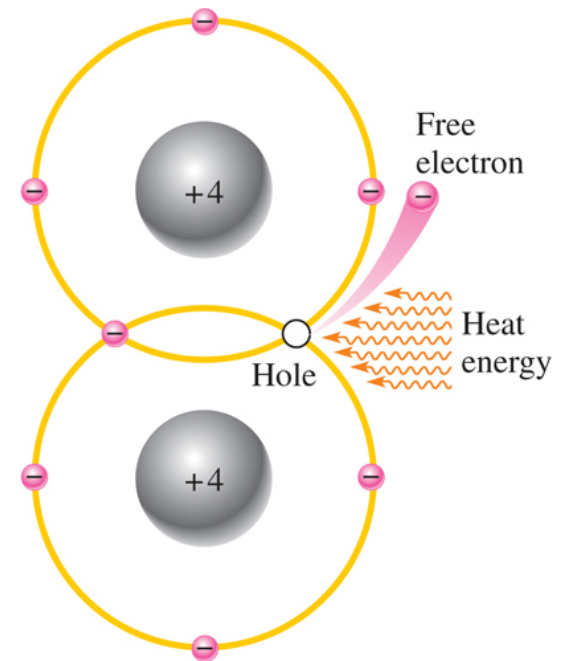


# Ch.16 Summary

## Generating Electron-Hole Pairs



(a) Energy diagram

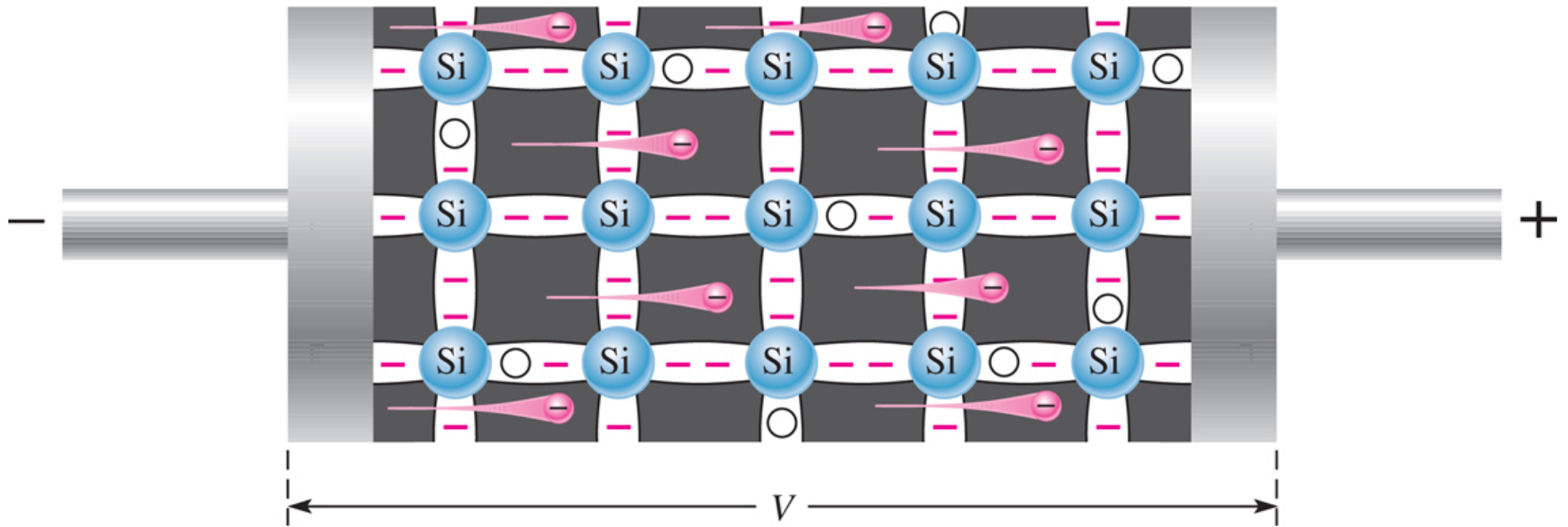


(b) Bonding diagram



# Ch.16 Summary

## Free Electron Current



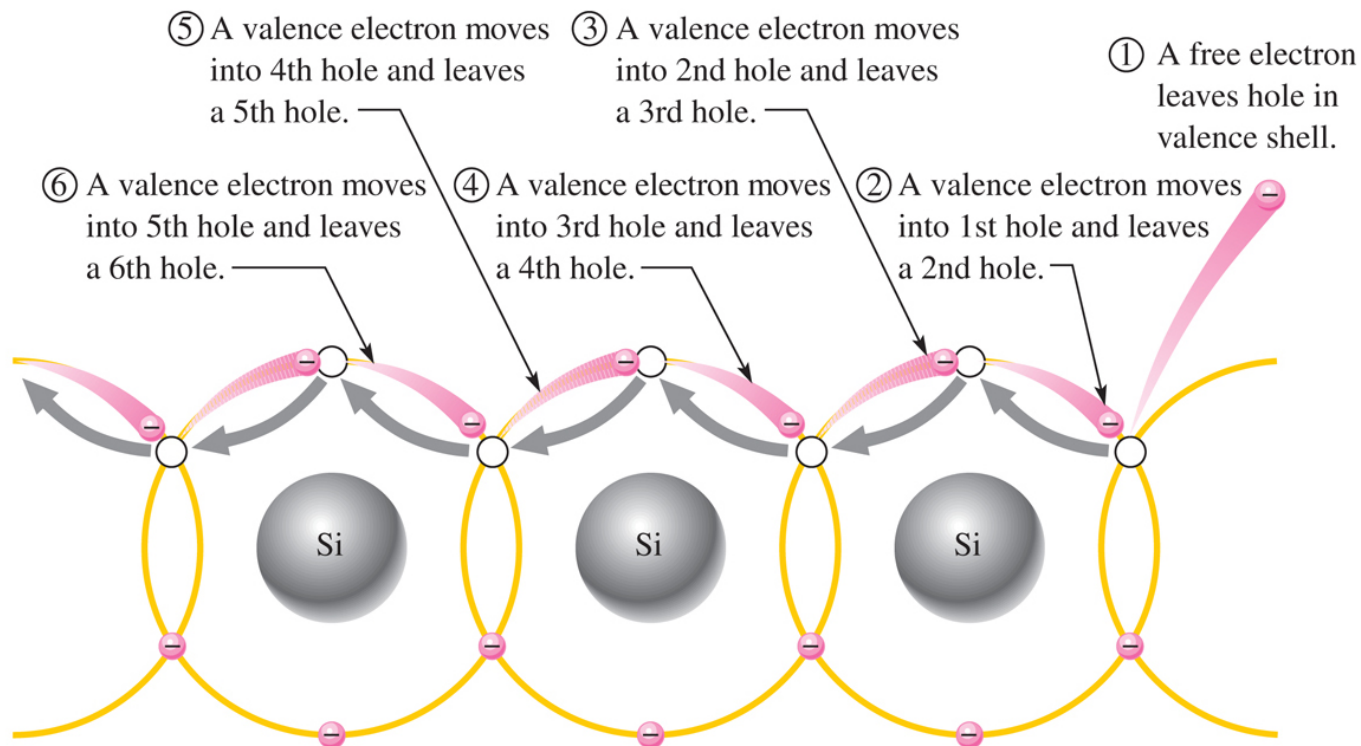
# Electron and Hole Current

- The electrons in the conduction band and the holes in the valence band are the charge carriers
- In other words, current in the conduction band is by electrons
- Current in the valence band is by holes
- When an electron jumps to the conduction band, valence electrons move from hole-to-hole in the valence band, effectively creating “hole current” shown by gray arrows (next slide)



# Ch.16 Summary

## Current in Intrinsic Silicon



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.





# Impurities

By adding certain impurities to pure (intrinsic) silicon, more holes or more electrons can be produced within the crystal.

To increase the number of conduction band electrons, pentavalent impurities are added, forming an  $n$ -type semiconductor. These are elements to the right of Si on the Periodic Table.

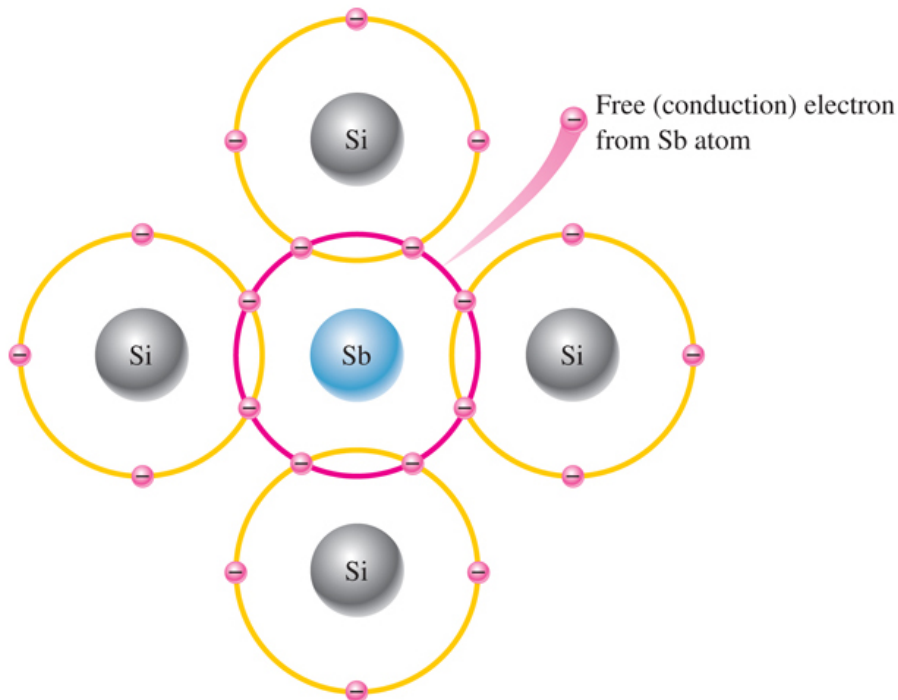
To increase the number of holes, trivalent impurities are added, forming a  $p$ -type semiconductor. These are elements to the left of Si on the Periodic Table.

III	IV	V
B	C	N
Al	Si	P
Ga	Ge	As
In	Sn	Sb

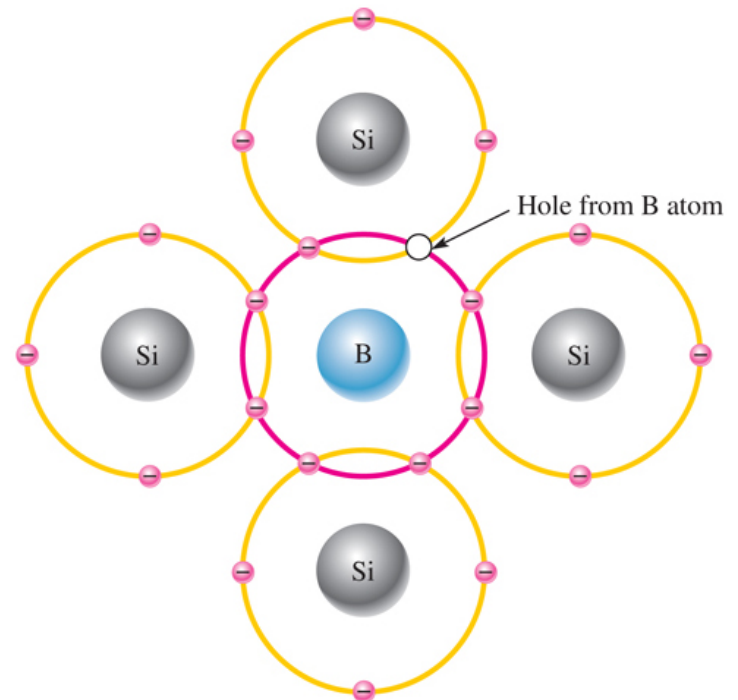


# Ch.16 Summary

## Pentavalent and Trivalent Impurities



(a) Pentavalent impurity atom in a silicon crystal. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.



(b) Trivalent impurity atom in a silicon crystal. A boron (B) impurity atom is shown in the center.



# Ch.16 Summary

## PN Junctions

When a piece of intrinsic silicon is doped so that half is  $n$ -type and the other half is  $p$ -type, a  **$pn$  junction** is formed between the two regions.

- The  $n$  region has many free electrons (majority carriers) and only a few thermally generated holes (minority carriers).
- The  $p$  region has many holes (majority carriers) and only a few thermally generated free electrons (minority carriers).

The  $pn$  junction forms a basic diode and is fundamental to the operation of all solid-state devices. A **diode** is a device that allows current in only one direction.



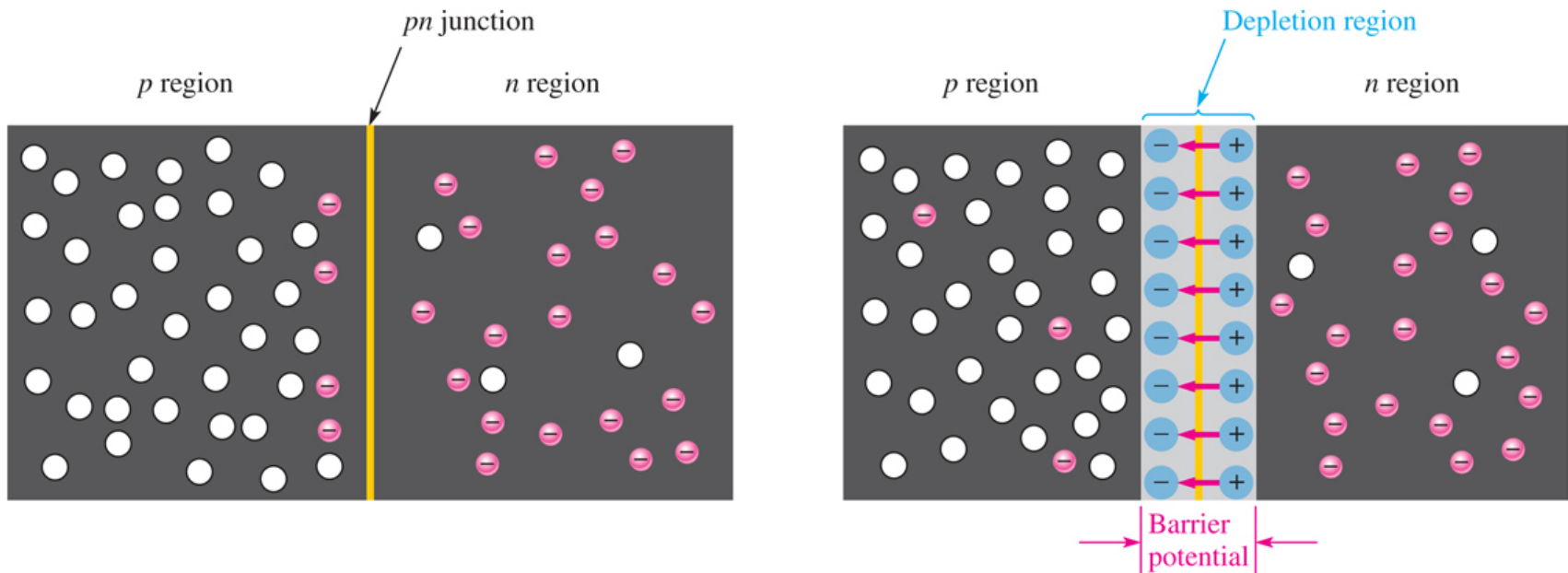
# Depletion Region / Barrier

- When a  $pn$  junction is formed, electrons in the  $n$ -material diffuse across the junction and recombine with holes in the  $p$ -material
- This action continues until the voltage of the barrier repels further diffusion
- Further diffusion across the barrier requires the application of a voltage



# Ch.16 Summary

## The Depletion Region



(a) At the instant of junction formation, free electrons in the  $n$  region near the  $pn$  junction begin to diffuse across the junction and fall into holes near the junction in the  $p$  region.

(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the  $n$  region and a negative charge is created in the  $p$  region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion.



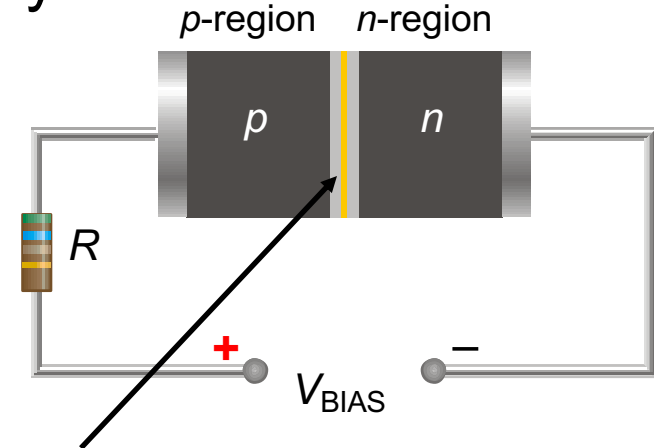
# Ch.16 Summary

## Forward Bias Connection

When a  $pn$  junction is forward-biased, current is permitted. The bias voltage pushes conduction-band electrons in the  $n$ -region and holes in the  $p$ -region toward the junction where they combine.

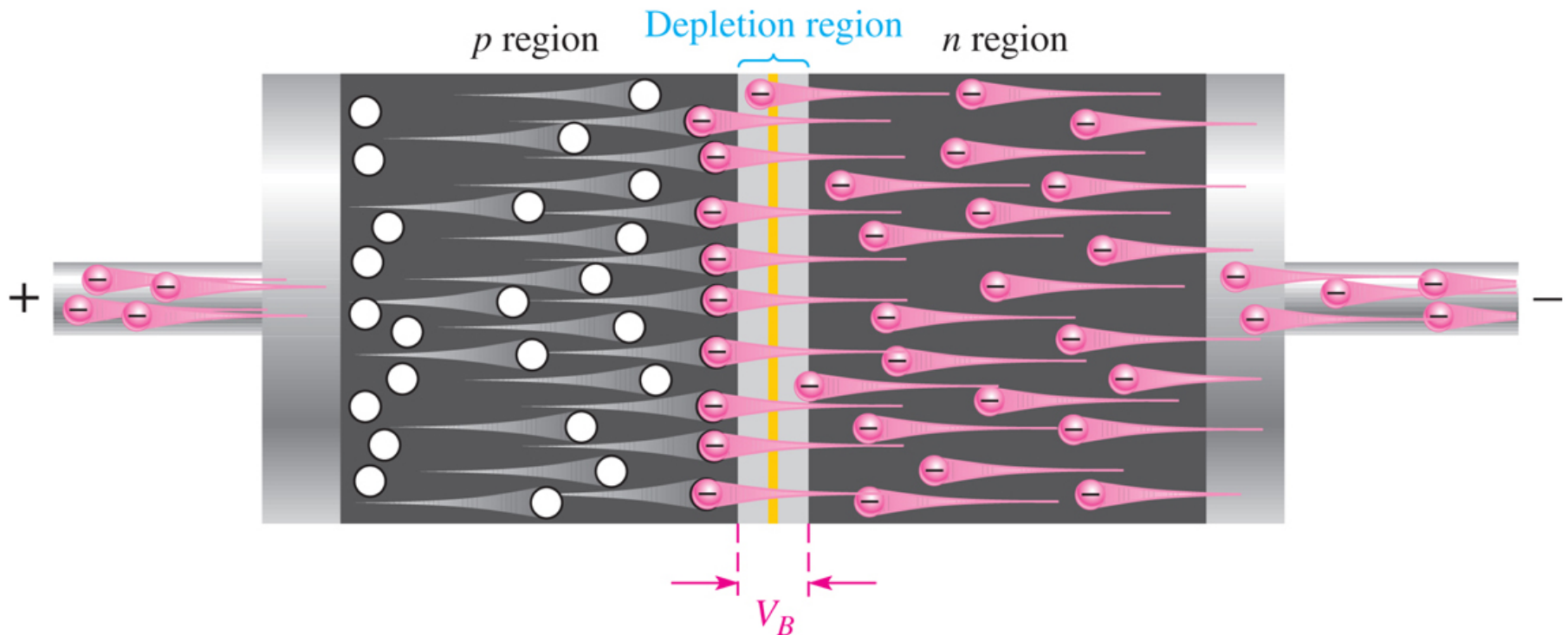
The barrier potential in the depletion region must be overcome in order for the external source to cause current. For a silicon diode, this is about 0.7 V.

The forward-bias causes the depletion region to be narrow.



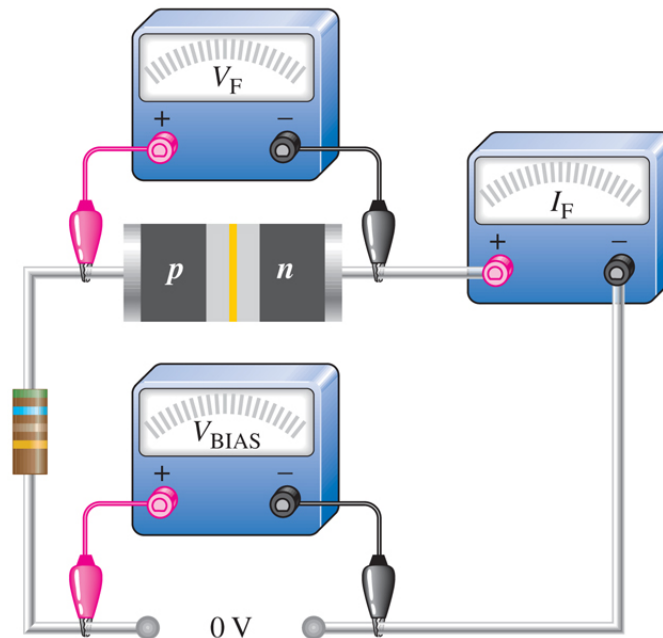
# Ch.16 Summary

## Current in a Forward-biased Diode



# Ch.16 Summary

## Zero-Bias (No Voltage) Diode Operation



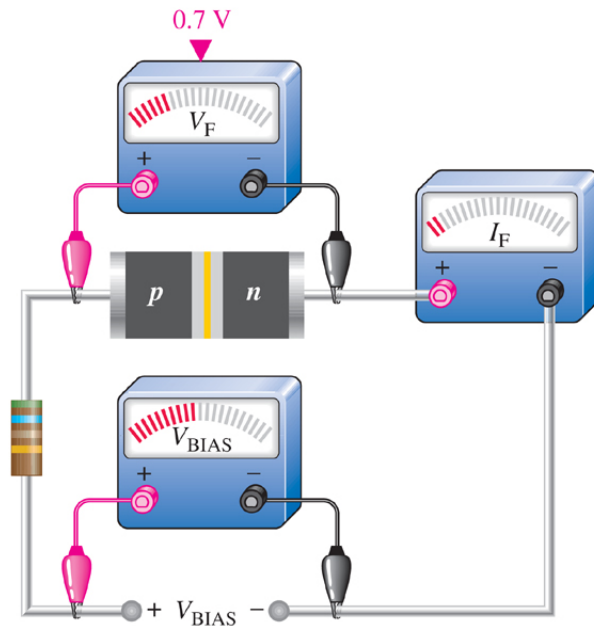
(a) No bias voltage. The  $pn$  junction of the diode is at equilibrium.



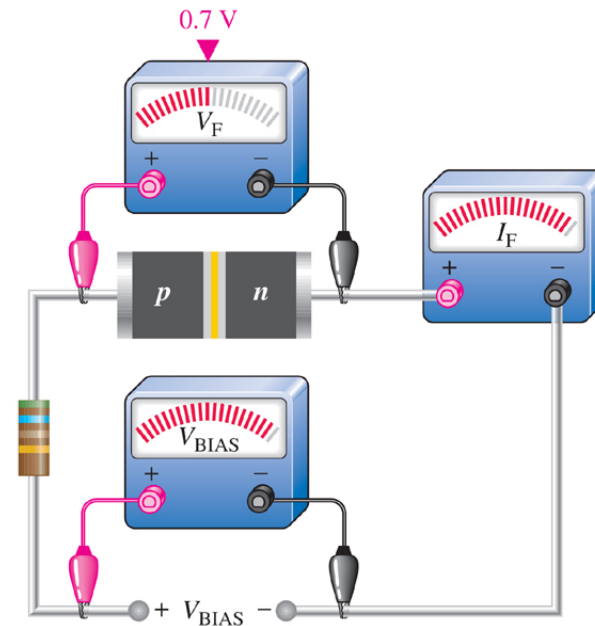


# Ch.16 Summary

## Forward Bias Diode Operation



(b) Small forward-bias voltage ( $V_F < 0.7$  V), very small forward current.



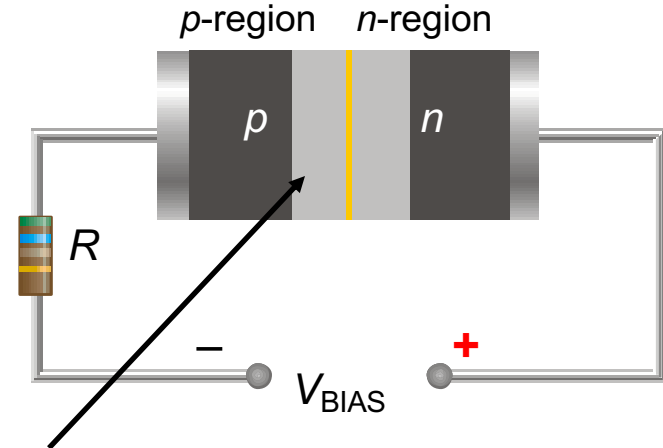
(c) Forward voltage reaches and remains at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.



# Reverse Bias

When a  $pn$  junction is reverse-biased, the bias voltage moves conduction-band electrons and holes away from the junction, so current is prevented.

The diode effectively acts as an insulator. A relatively few electrons manage to diffuse across the junction, creating only a tiny reverse current.

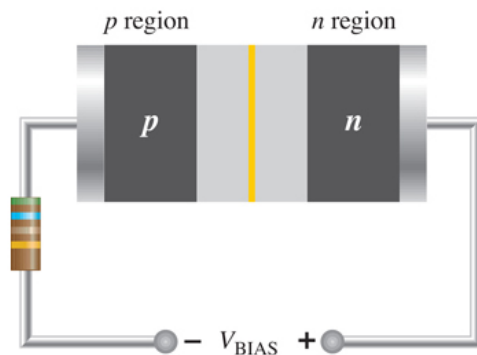


The reverse-bias causes the depletion region to widen.

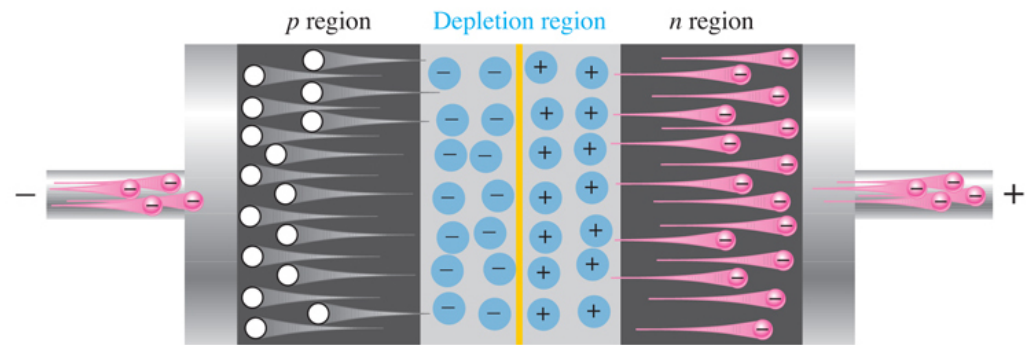


# Ch.16 Summary

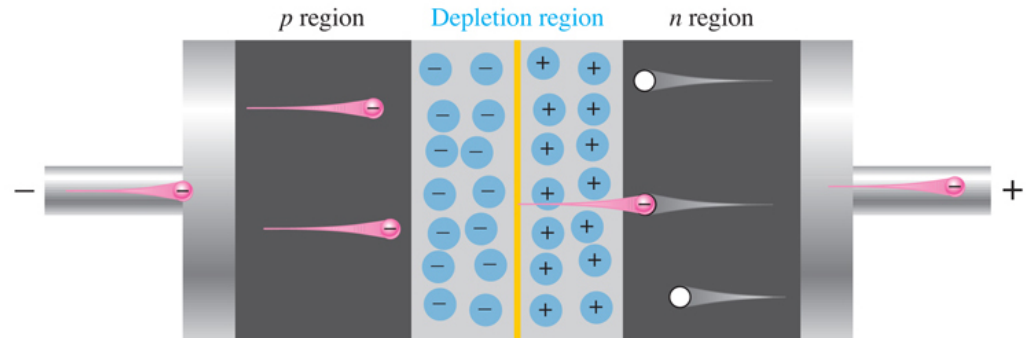
## Reverse Bias



(a) Reverse-bias connection.



(b) There is transient current as depletion region widens.



(c) Majority current ceases when barrier potential equals bias voltage. There is an extremely small reverse current due to minority carriers.



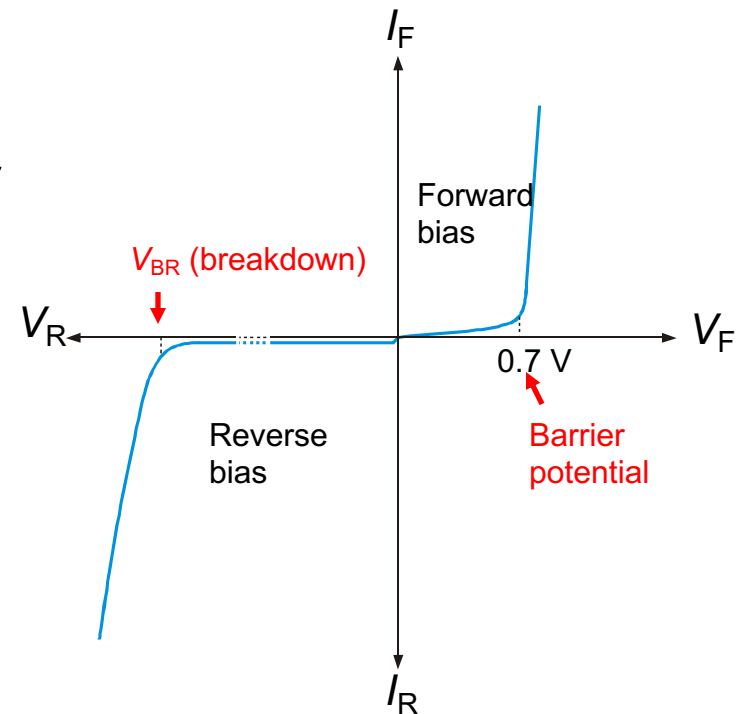
# Ch.16 Summary

## Diode $V$ - $I$ Characteristic Curve

The forward and reverse characteristics are shown on a  $V$ - $I$  characteristic curve.

In the forward bias region, current increases dramatically after the barrier potential (0.7 V for Si) is reached. The voltage across the diode remains approximately equal to the barrier potential.

The reverse-biased diode effectively acts as an insulator until breakdown is reached.



# Ch.16 Summary

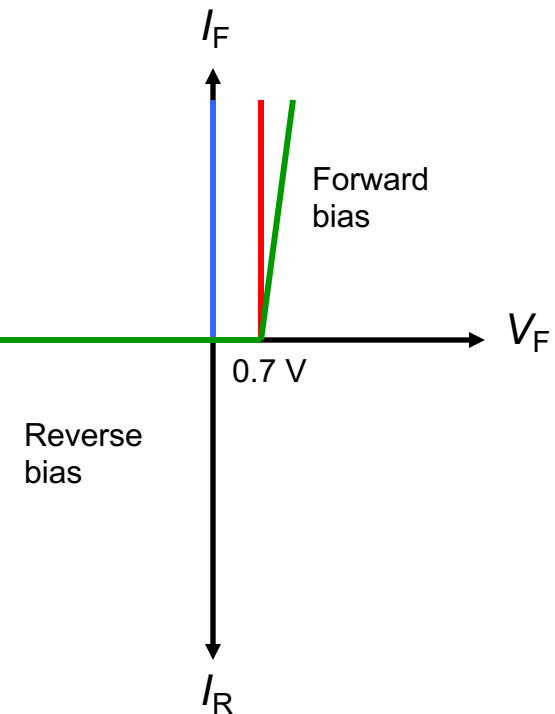
## Diode Models

The characteristic curve for a diode can be approximated by various models of diode behavior. The model you will use depends on your requirements.

The ideal model assumes the diode is either an open or closed switch.

The practical model includes the barrier voltage in the approximation.

The complete model includes the forward resistance of the diode.

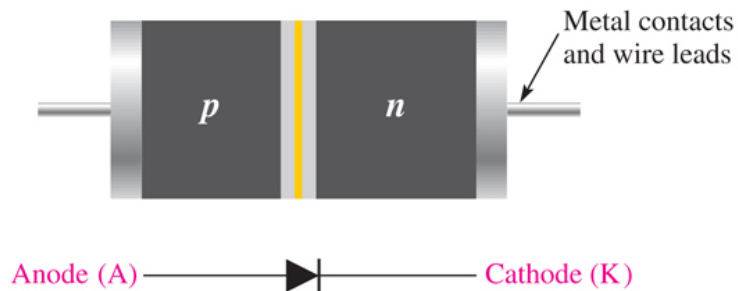


# Ch.16 Summary

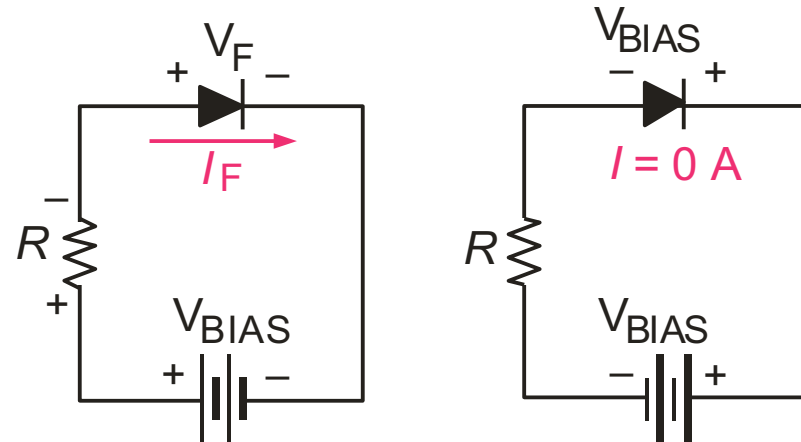
## Diode Symbol and Biasing

The two diode terminals are the **cathode (K)** and the **anode (A)**.

- A diode is forward biased when the anode is *positive* with respect to the cathode.
- A diode is reverse biased when the anode is *negative* with respect to the cathode.

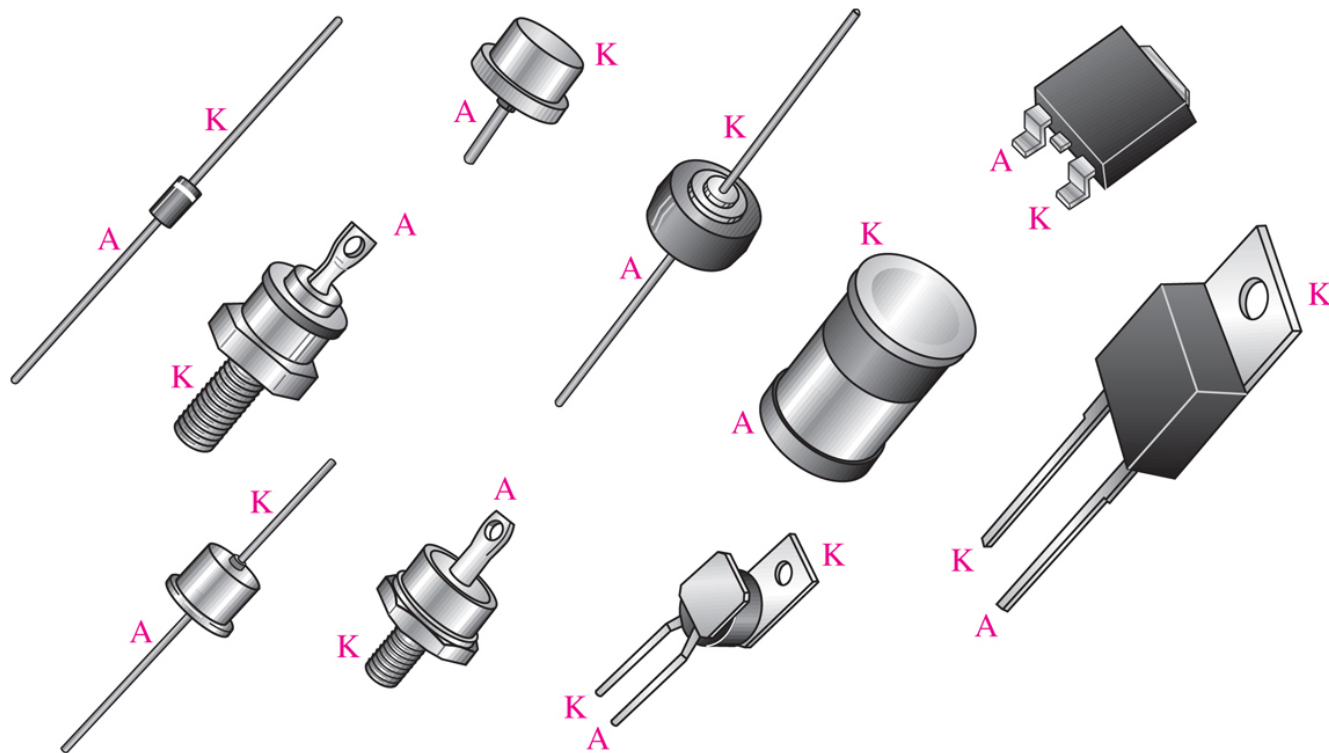


(a) Basic diode structure and symbol



# Ch.16 Summary

## Typical Diode Packages



# Ch.16 Summary

## Half-Wave Rectifier

**Rectifier:** A circuit that converts ac to pulsating dc.

**Half-wave rectifier:** A circuit that eliminates either the positive or negative alternations of its input signal.

The basic half-wave rectifier shown is a diode that is connected in series between an ac source and a load resistance.



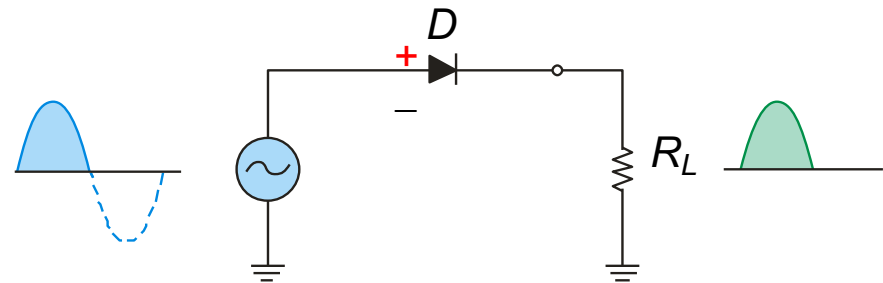


# Ch.16 Summary

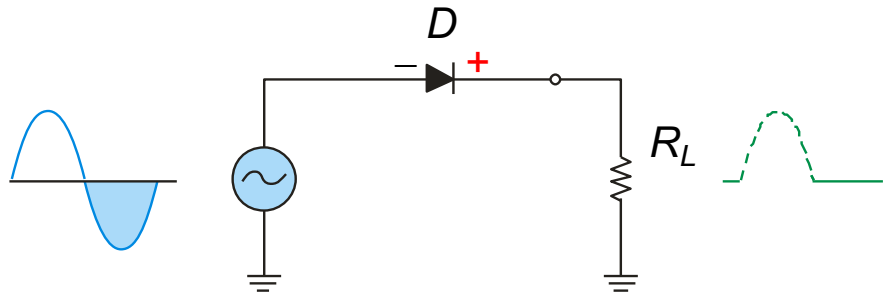
## Half-Wave Rectifier Operation

Rectifiers are circuits that convert ac to dc. Special diodes, called rectifier diodes, are designed to handle the higher current requirements in these circuits.

The half-wave rectifier converts ac to pulsating dc by acting as a closed switch during the positive alteration.



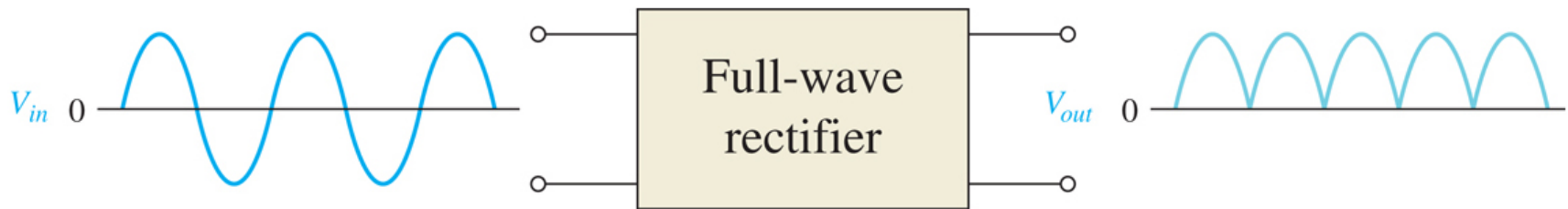
The diode acts as an open switch during the negative alteration.



# Ch.16 Summary

## Full-Wave Rectification

**Full-wave rectifier:** A circuit that converts ac to pulsating dc by controlling the direction of the load current so that only positive (or negative) output alternations are produced.



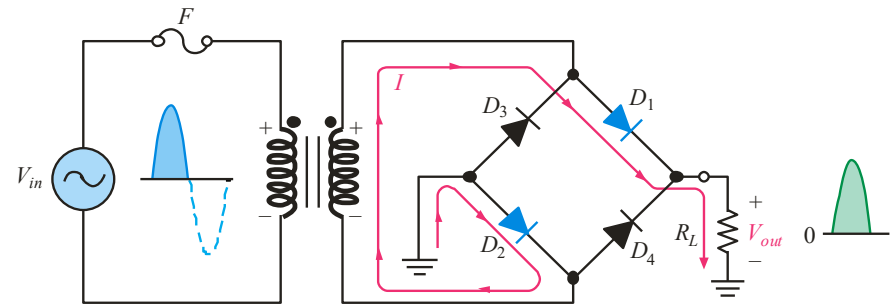
# Ch.16 Summary

## Full-Wave Bridge Rectifier

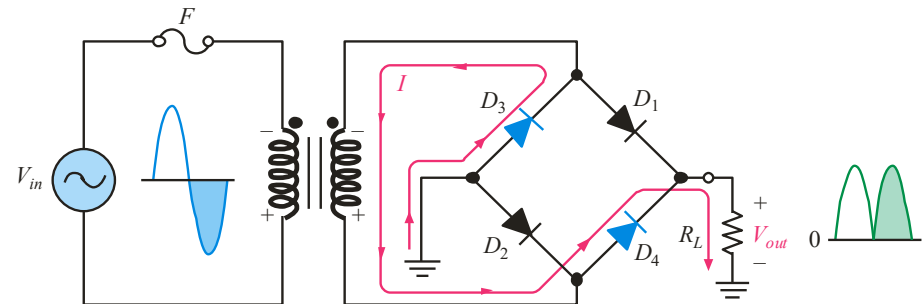
Bridge rectifier operation is based on the principle of switching current paths.

During the positive alternation of the input,  $D_1$  and  $D_2$  conduct and  $V_{out}$  is positive.

During the negative alternation of the input,  $D_3$  and  $D_4$  conduct and  $V_{out}$  is positive.



Conduction path for the positive half-cycle.



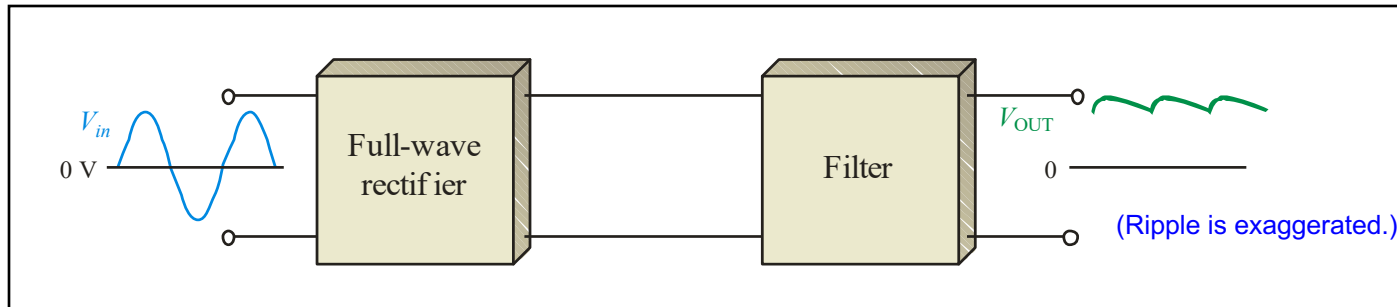
Conduction path for the negative half-cycle.



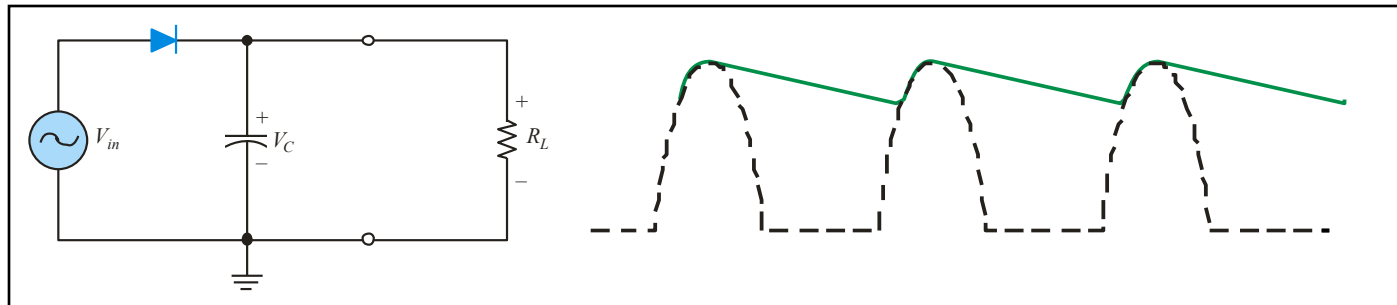
# Ch.16 Summary

## Power Supply Filters

Filtering is the process of smoothing the ripple from the rectifier.



The capacitor input filter is widely used. A half-wave rectifier and capacitor-input filter are shown:

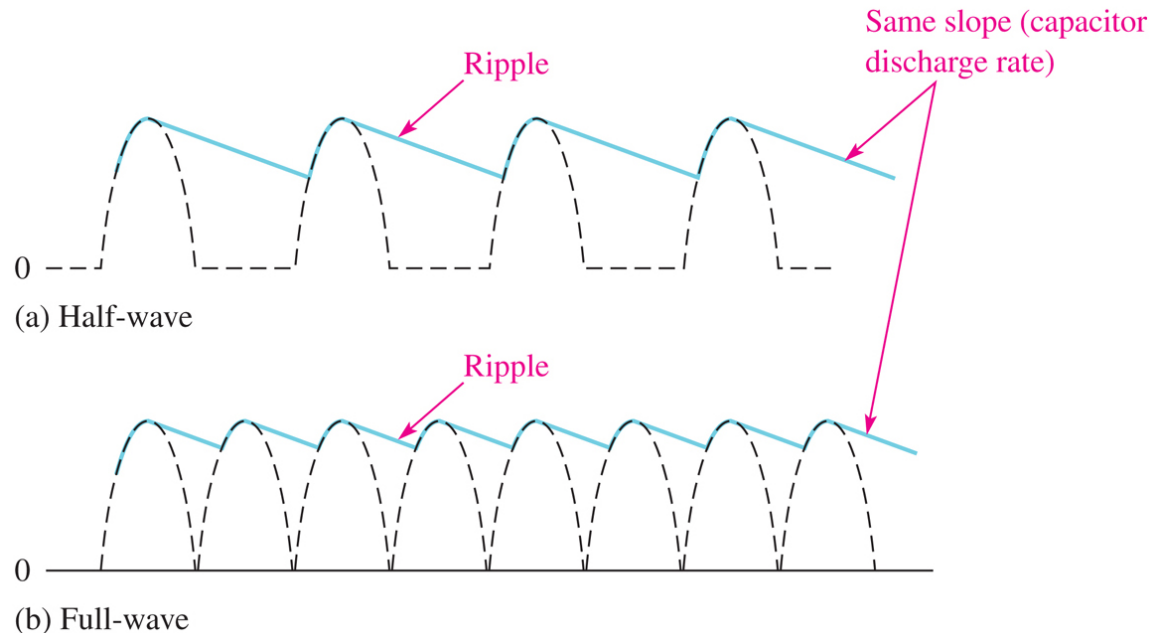


# Ch.16 Summary

## Ripple Voltage

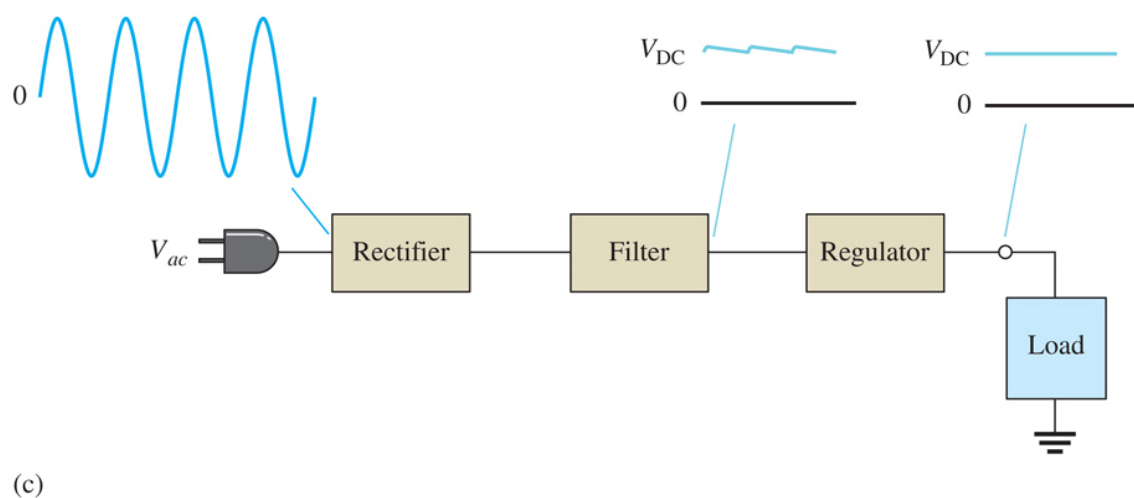
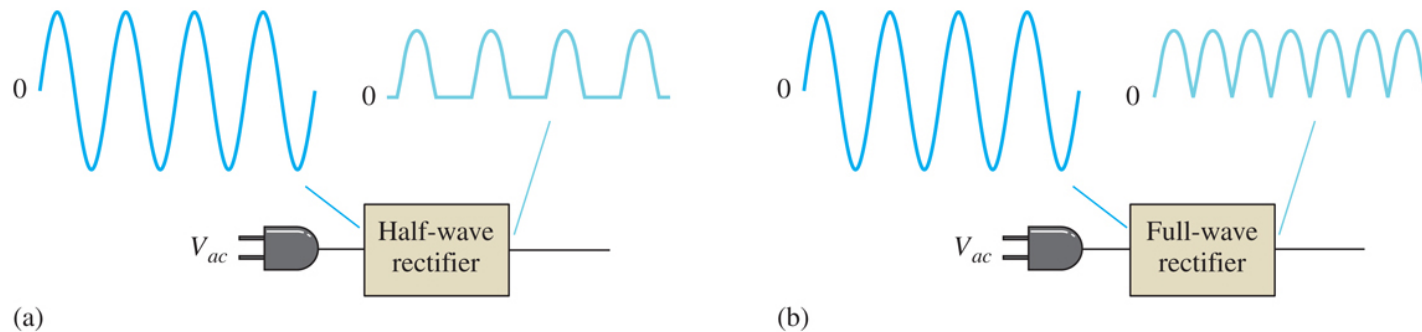
The variation in output voltage that occurs when the capacitor is discharging is called **ripple voltage**.

The longer the time period between capacitor charge cycles, the greater the ripple voltage. This is why the full-wave rectifier has less ripple than a comparable half-wave rectifier.



# Ch.16 Summary

## DC Power Supply Block Diagram



# Ch.16 Summary

## IC Regulators

An IC (**integrated circuit**) is a complete functional circuit constructed on a single, tiny chip of silicon. An integrated circuit **regulator** is an IC that is connected to the output of a rectifier and maintains a constant output voltage (or current) despite changes in the input, the load current, or the temperature.

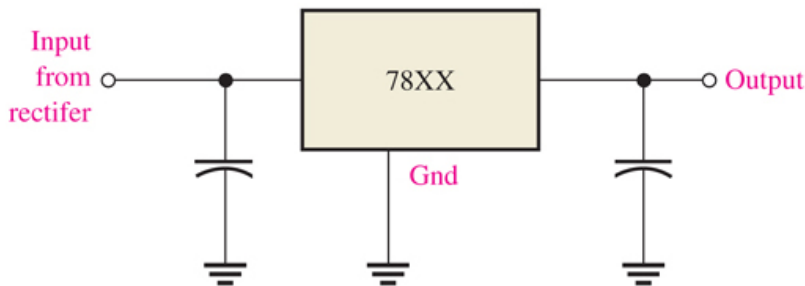
- The most popular IC regulators have three terminals—an input terminal, an output terminal, and a reference (or adjust) terminal.
- Three-terminal regulators designed for a fixed output voltage require only external capacitors to complete the regulation portion of the power supply.



# Ch.16 Summary

## 78XX Series Regulators

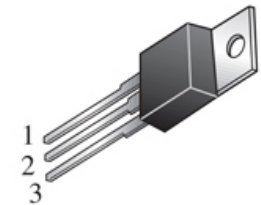
The 78XX series regulators provide fixed-positive output voltages when supplied with an input voltage that is within the component parameters.



(a) Standard configuration

Type number	Output voltage
7805	+5.0 V
7806	+6.0 V
7808	+8.0 V
7809	+9.0 V
7812	+12.0 V
7815	+15.0 V
7818	+18.0 V
7824	+24.0 V

(b) The 7800 series



(Heatsink surface connected to Pin 2)

(c) Typical package

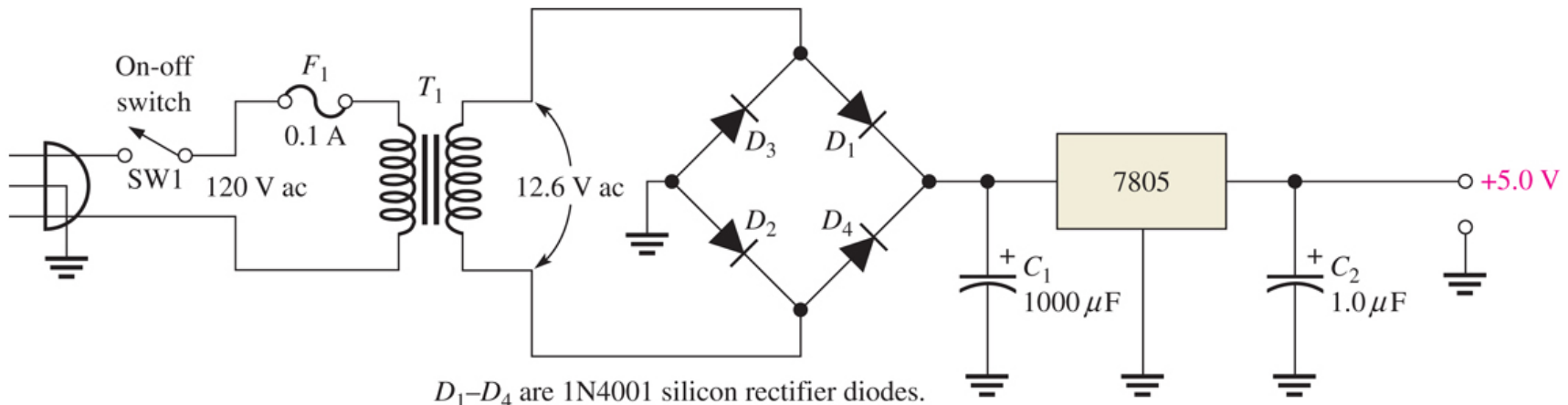




# Ch.16 Summary

## A +5V Power Supply

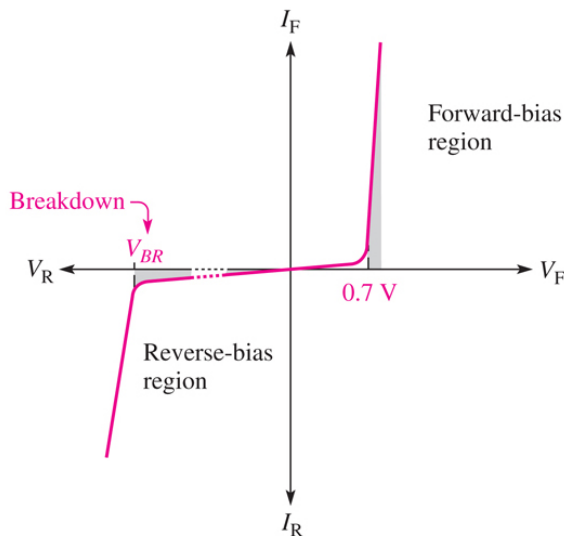
- The power supply below contains a bridge rectifier, a capacitive filter, and a 7805 (+5 V) voltage regulator.
- Typically, a large electrolytic capacitor is used as a filter before the regulator, with a smaller one following the regulator to complete filtering action.



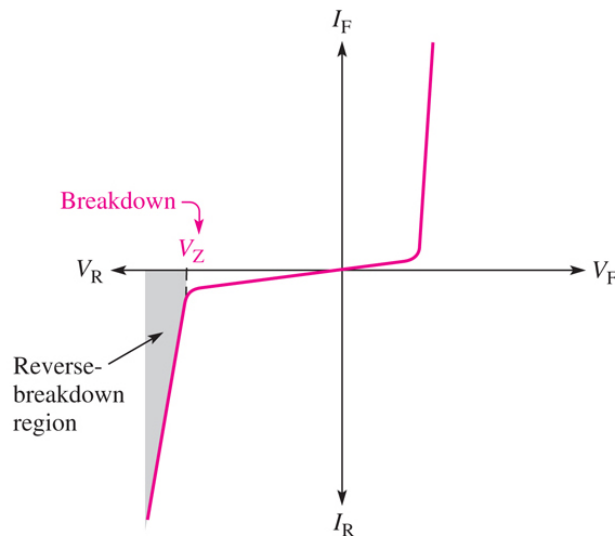
# Ch.16 Summary

## Zener Diodes

**Zener diode:** A silicon *pn* junction device that differs from the rectifier diode in that it is designed to operate in its reverse-breakdown region.



(a) The normal operating regions for a rectifier diode are shown as shaded areas.



(b) The normal operating region for a zener diode is shaded.

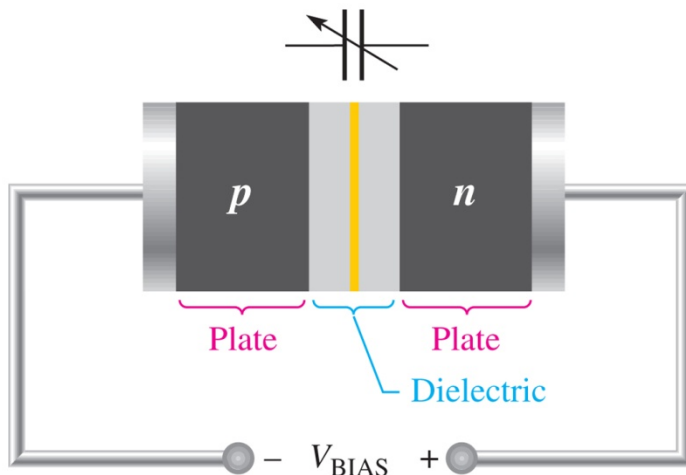


# Ch.16 Summary

## Varactor Diodes

**Varactor:** A reverse-biased  $pn$  junction that utilizes the inherent capacitance of the depletion region.

The depletion region, created by the reverse bias, acts as a capacitor dielectric because of its nonconductive characteristic. The  $p$  and  $n$  regions are conductive and act as the capacitor plates.



(a) Symbol



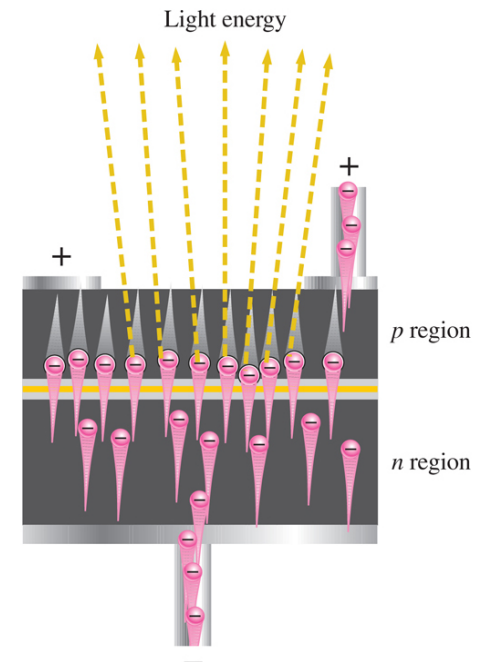
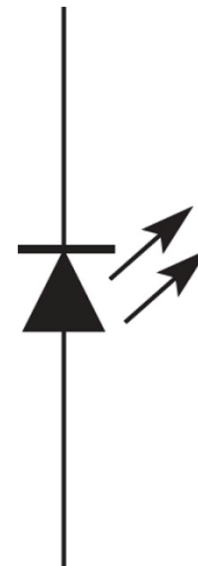
(b) Equivalent circuit



# Ch.16 Summary

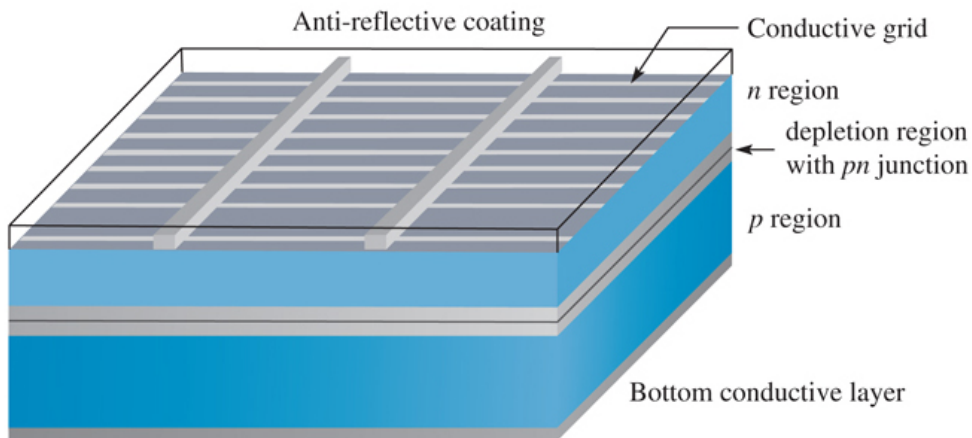
## Light-Emitting Diodes (LEDs)

**Light-emitting diode:** A light emitter; LEDs are used as indicators (such as power indicator lights), in displays such as the familiar seven-segment displays used in many digital clocks, and as sources for optical fiber communication systems.

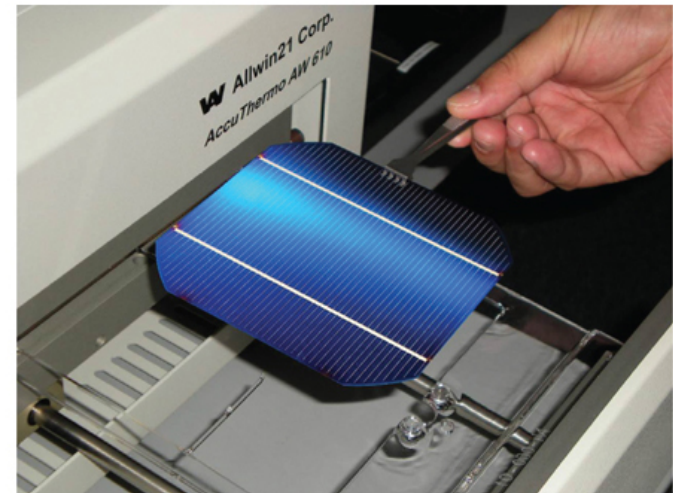


# Ch.16 Summary

## PV Solar Cell



(a) Construction



(b) Completed cell, showing the top surface and the grid

Courtesy of Allwin21

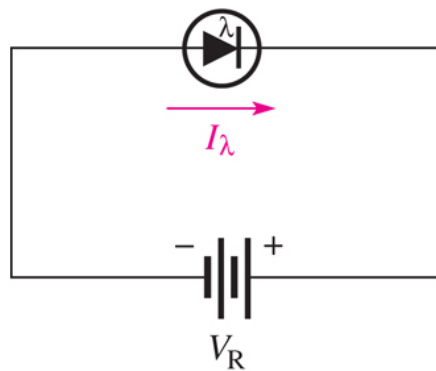


# Ch.16 Summary

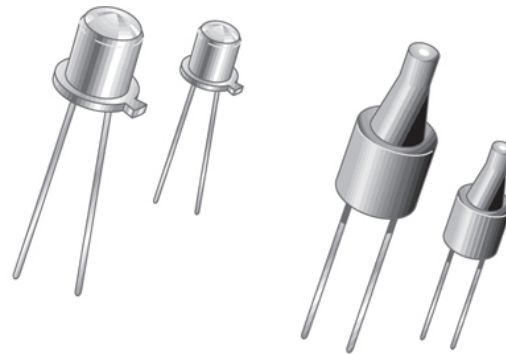
## Photodiodes

A **photodiode** is one whose reverse current is controlled by light intensity at the exposed pn junction.

- An increase in light intensity results in an increase in diode reverse current.
- A decrease in light intensity results in a decrease in diode reverse current.



(a) Reverse-bias operation



(b) Typical devices



(c) Alternate symbol



# Ch.16 Summary

## Key Terms

**Energy** The ability to do work.

**Electron** The basic particle of negative electrical charge in matter.

**Semiconductor** A material that has a conductance value between that of a conductor and that of an insulator.

**PN junction** The boundary between *n*-type and *p*-type materials.

**Diode** An electronic device that permits current in only one direction.



# Ch.16 Summary

## Key Terms

**Bias** The application of dc voltage to a diode or other electronic device to produce a desired mode of operation.

**Forward bias** A potential that causes a *pn* junction to conduct current.

**Reverse bias** A potential that causes a *pn* junction to block current.

**Rectifier** An electronic circuit that converts ac into pulsating dc.

**Filter** A power supply circuit that reduces the variations in the output from a rectifier.





# Ch.16 Summary

## Key Terms

### **Integrated circuit**

A type of circuit in which all the components are constructed on a single tiny chip of silicon.



# Ch.16 Summary

## Quiz

1. When an electron jumps from the valence band of its parent atom to the conduction band, it creates a/an
  - a. Free electron
  - b. Valence-band hole
  - c. Electron-hole pair
  - d. All of the above



# Ch.16 Summary

## Quiz

2.  $n$ -type and  $p$ -type materials are produced using a process called

- a. Amplification
- b. Doping
- c. Biasing
- d. None of the above



# Ch.16 Summary

## Quiz

3. Which of the following is considered to be the basic element of nearly every solid-state component?

- a. n-type material
- b. p-type material
- c. Electrons and holes
- d. The *pn* junction



# Ch.16 Summary

## Quiz

4. A diode is reverse biased when
- a. Its anode is more positive than its cathode
  - b. Its anode is more negative than its cathode
  - c. Its anode and cathode are both grounded
  - d. Either the anode or the cathode is grounded (but not both).



# Ch.16 Summary

## Quiz

5. A diode is forward biased when
- a. Its anode is more positive than its cathode
  - b. Its anode is more negative than its cathode
  - c. Its anode and cathode are both grounded
  - d. Either the anode or the cathode is grounded (but not both).



# Ch.16 Summary

## Quiz

6. Which of the circuits listed converts ac to pulsating dc?

- a. A rectifier
- b. A filter
- c. A voltage regulator
- d. A dc restorer



# Ch.16 Summary

## Quiz

7. Which of the circuits listed maintains a constant output voltage despite anticipated variations in its input voltage and/or load resistance?

- a. A rectifier
- b. A filter
- c. A voltage regulator
- d. A dc restorer





# Ch.16 Summary

## Quiz

8. Which of the following circuits reduces the variations in the output from a rectifier?

- a. A filter
- b. A dc power supply
- c. A clamper
- d. None of the above



# Ch.16 Summary

## Answers

- |      |      |
|------|------|
| 1. a | 6. a |
| 2. b | 7. c |
| 3. d | 8. a |
| 4. b |      |
| 5. a |      |



# 17

## Transistors and Applications (*excerpts as bridge from analogue to digital halves*)



# Ch.17 Summary

## Field-Effect Transistors (FETs)

In a FET, a narrow conducting channel physically exists or is induced between two leads called the **source** and the **drain**. This channel is either *n*-type or *p*-type.

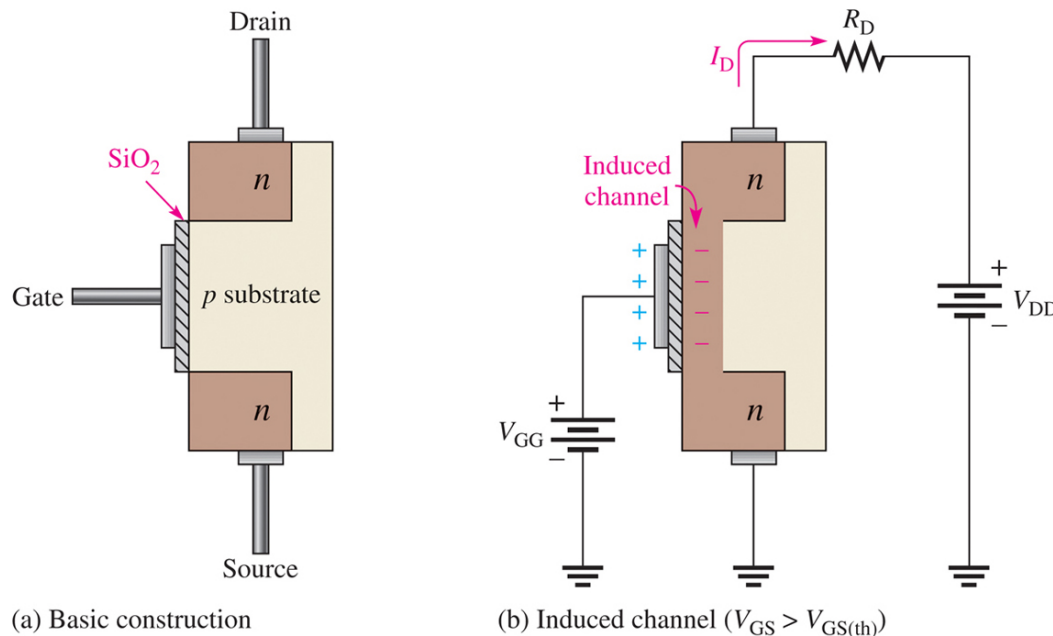
- As the term *field-effect* implies, conduction in the channel is controlled by an electric field.
- JFETs (junction-gate FETs); **MOSFETs** (metal-oxide-semiconductor FETs, AKA insulated-gate FETs or IGFETs)
- Two types of MOSFET: Depletion MOSFET (D-MOSFET), Enhancement MOSFET (**E-MOSFET**) [more common].



# Ch.17 Summary

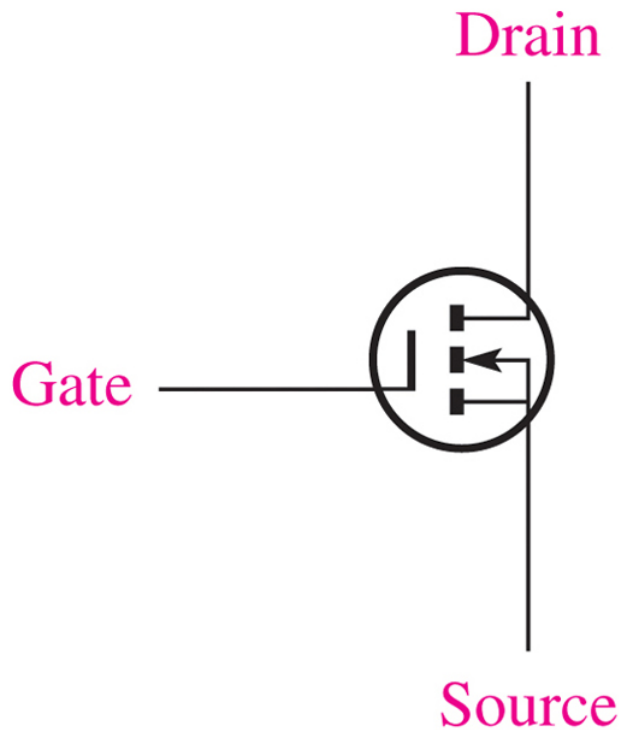
## Enhancement MOSFETs (E-MOSFETs)

**E- MOSFET:** A MOSFET that operates only in the enhancement mode; it has no physical channel between the drain and source.

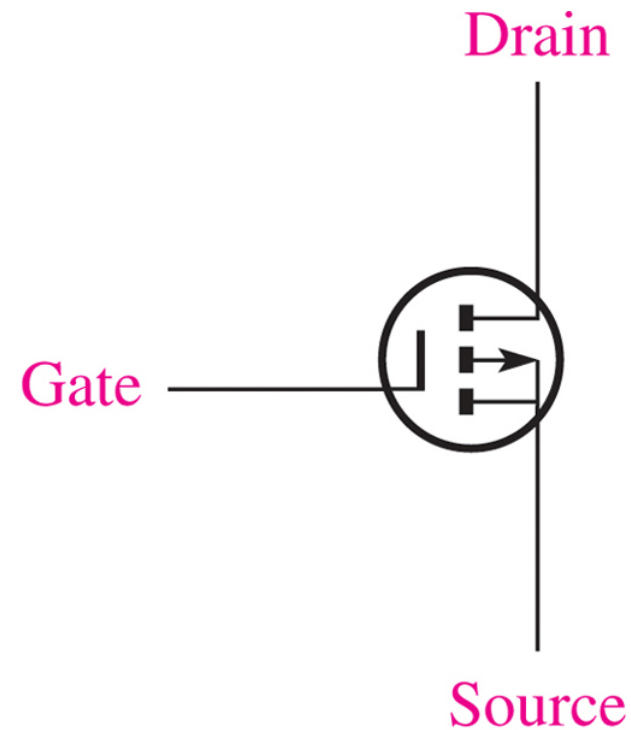


# Ch.17 Summary

## E-MOSFET Schematic Symbols



(a)  $n$  channel



(b)  $p$  channel



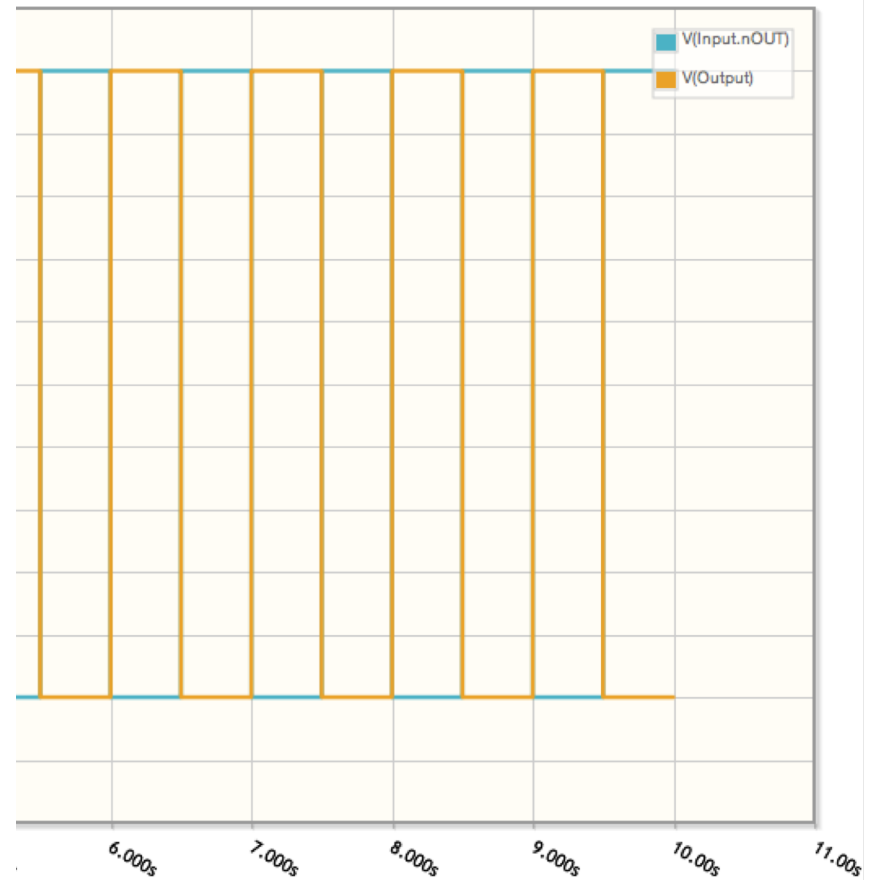
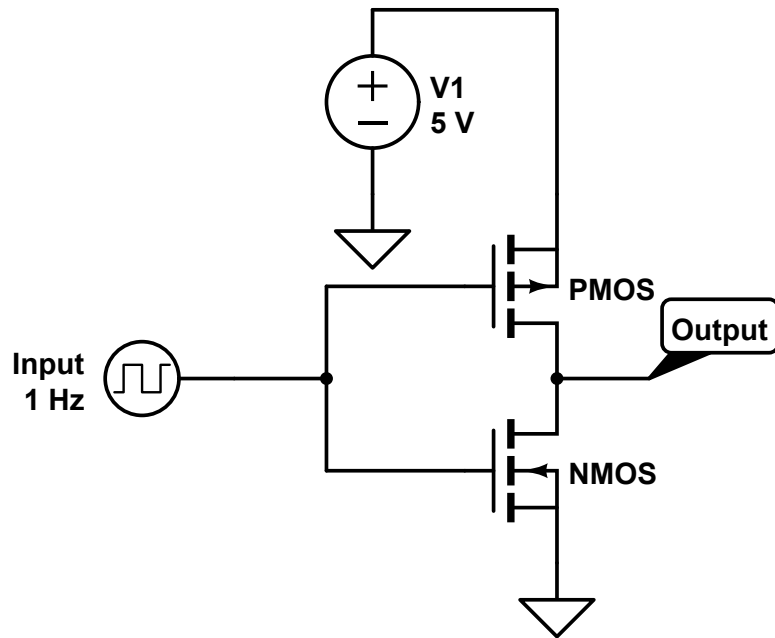
# MOSFETs and digital circuits

- MOSFETs are commonly used in *digital* (computer) logic circuits
- These circuits are designed to work with signals that are made up of alternating dc voltage levels, called *logic levels*
  - e.g. logic '1' = 5 V, and logic '0' = 0 V
- Complementary metal–oxide–semiconductor (CMOS) is a technology for constructing integrated circuits
- Used in micro-processors, micro-controllers, static RAM, and other digital logic circuits



# A CMOS inverter (1 -> 0, 0 -> 1)

<https://www.circuitlab.com/circuit/4vx778/cmos-inverter/>





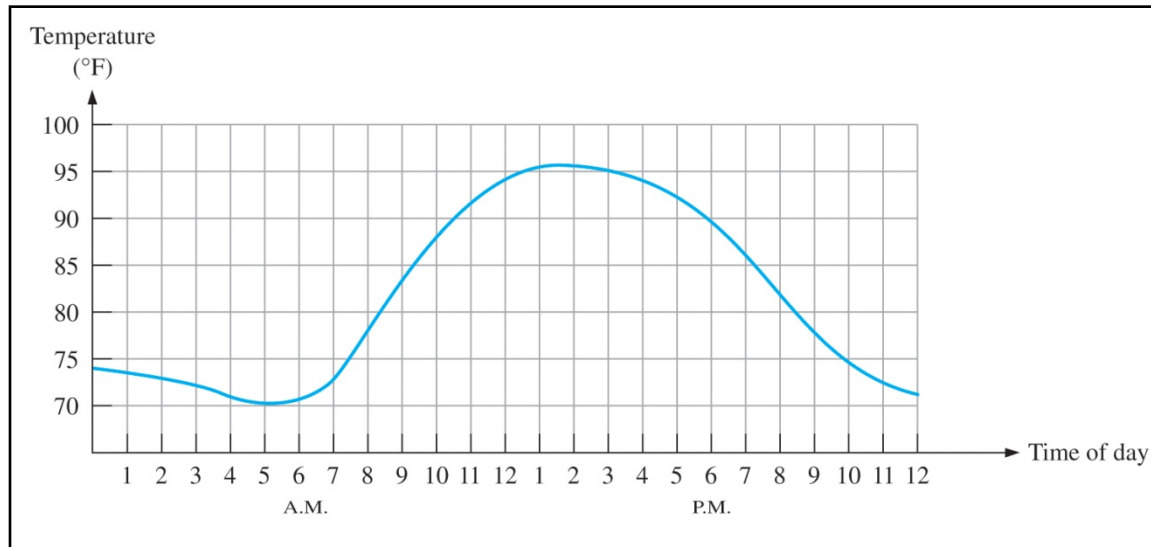
## Chapter 1

# Introduction to Digital Systems



## Analog Quantities

Most natural quantities that we see are **analog** and vary continuously. Analog systems can generally handle higher power than digital systems.



Digital systems can process, store, and transmit data more efficiently but can only assign discrete values to each point.



# Analog Signals

A waveform that continually varies in a certain manner is classified as an **analog signal**.

Examples:

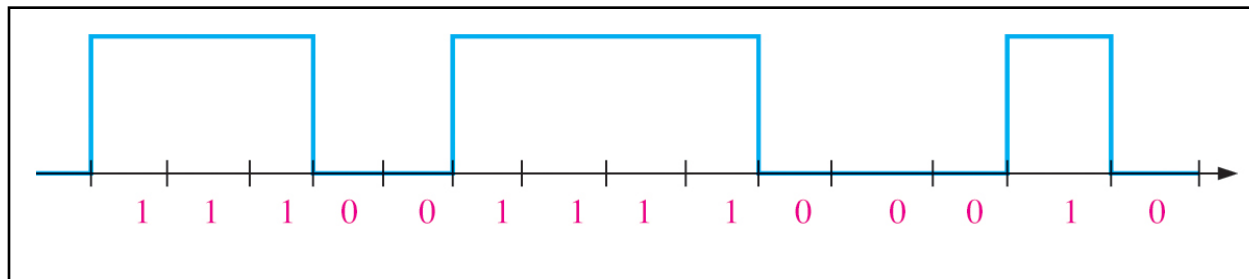
- Sine waves
- Audio waves
- Amplitude modulated (AM) signals
- Frequency modulated (FM) signals



## Digital Signals

A waveform that represents a sequence of discrete values (1's and 0's) is called a **digital signal**.

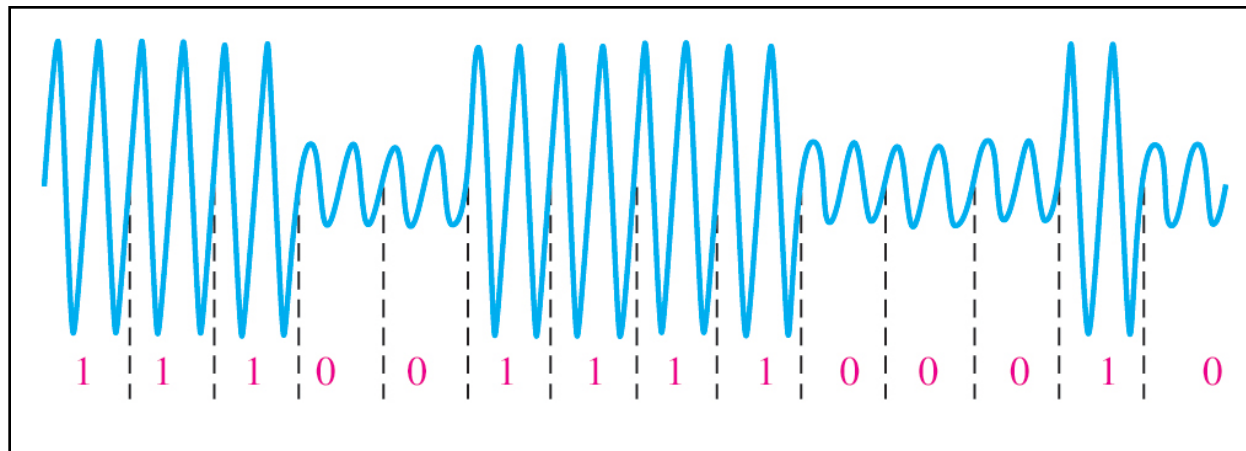
Bit streams are found in telecommunications, computers, and other data system applications.



## Digital Modulation

**Digital modulation** provides a means of transmitting data from one system to another.

**One** approach is to use digital data to modulate the amplitude of a sine wave, called a **carrier**, as shown.

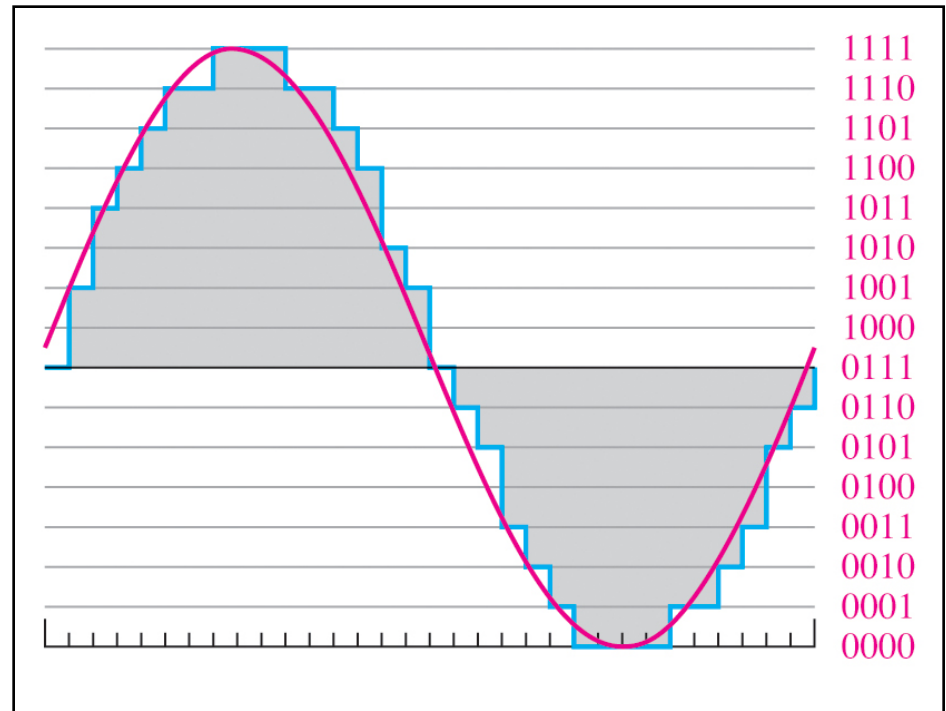


## Pulse-code Modulation (PCM)

PCM uses a sequence of digital codes to represent a sampled analog signal.

Sampling produces the “stair-step” voltage shown.

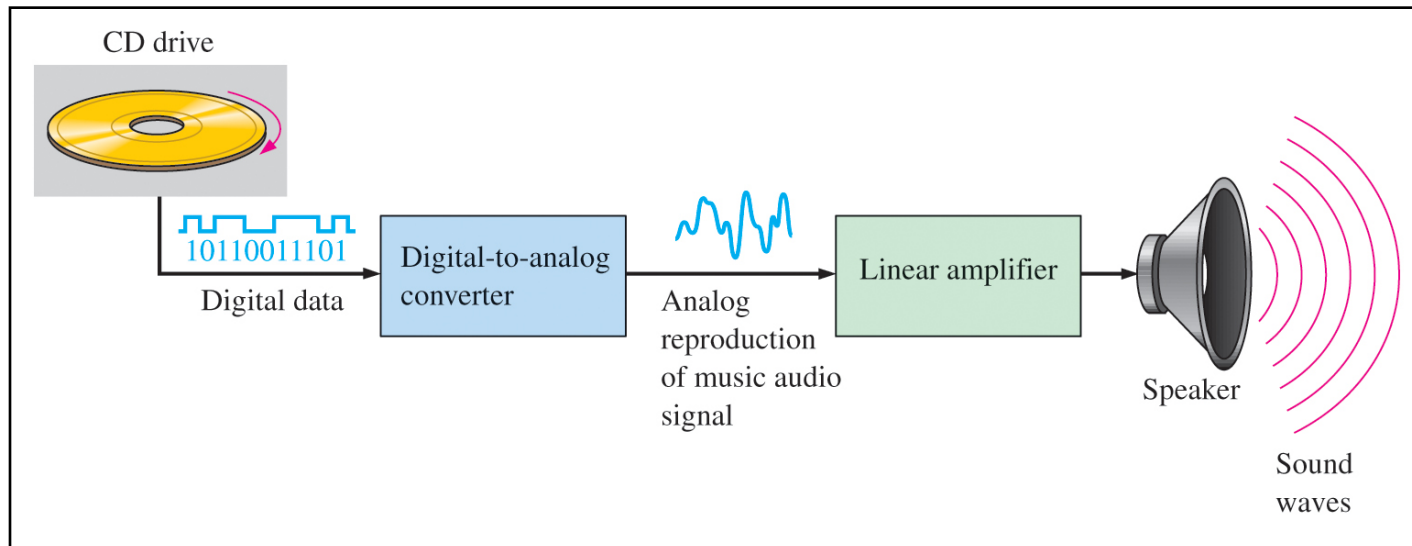
The higher the sampling rate, the more accurate the digitized waveform.



## Ch.1 Summary

# Analog and Digital Systems

Many systems use a mix of analog and digital circuits to utilize the advantages of each. A typical CD player accepts digital data from the CD drive and converts it to an analog signal for amplification.

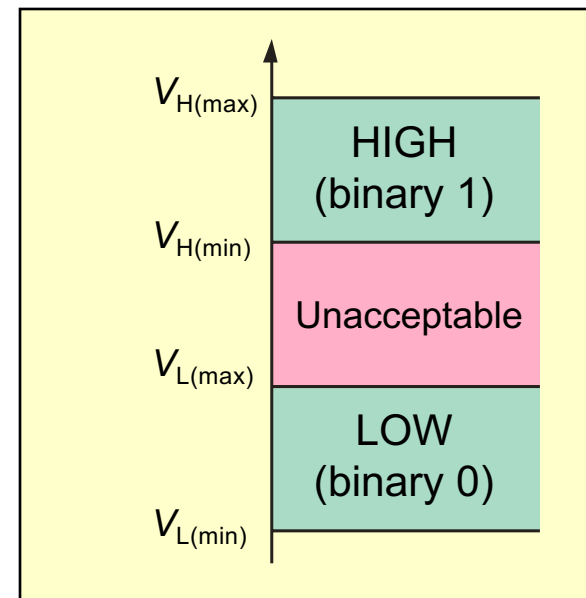


# Ch.1 Summary

## Binary Digits and Logic Levels

Digital electronics uses circuits that have two states, which are represented by two different voltage levels called HIGH and LOW. The voltages represent numbers in the binary system.

*In binary, a single number is called a **bit** (for **binary digit**). A bit can have the value of either a 0 or a 1, depending on if the voltage is HIGH or LOW.*





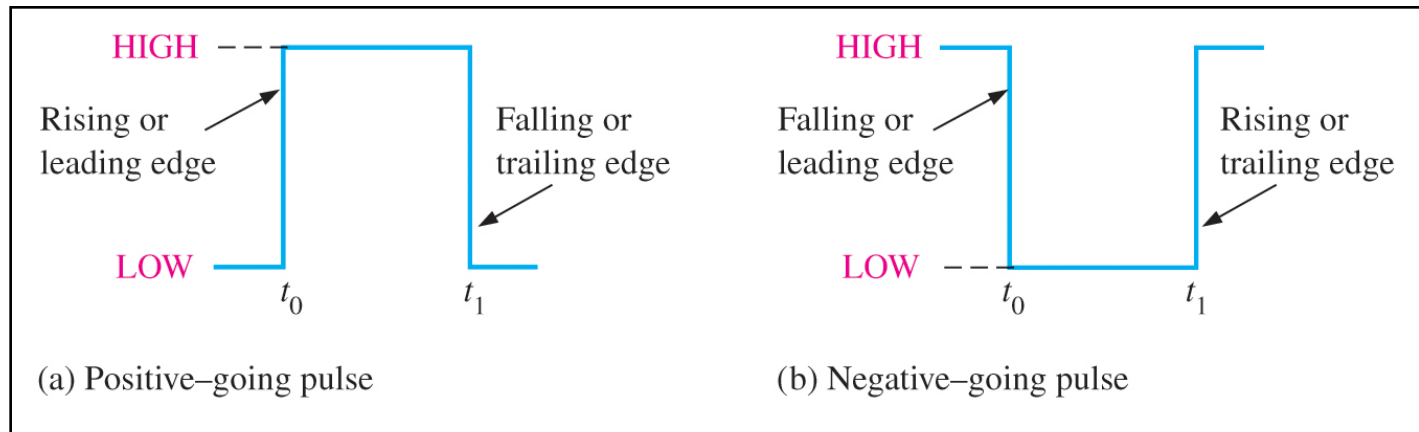
# Ch.1 Summary

## Digital Waveforms

Digital waveforms change between the LOW and HIGH levels.

A **positive-going pulse** is one that goes from a normally LOW level to a HIGH level and then back again.

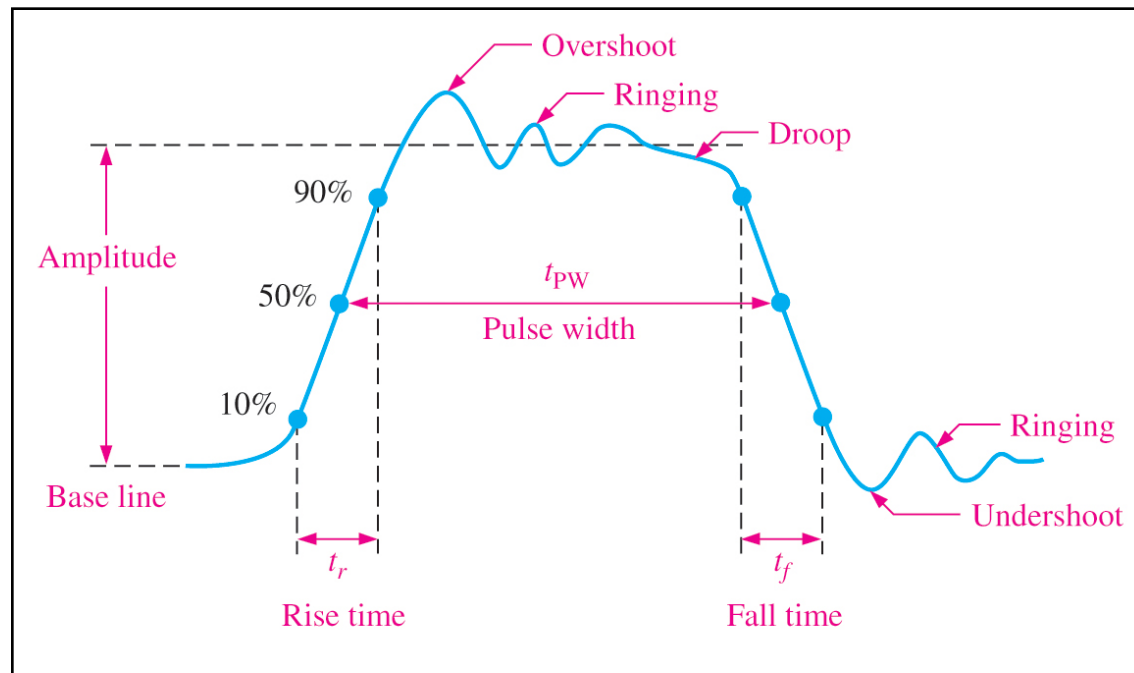
A **negative-going pulse** is one that goes from a normally HIGH level to LOW level and then back again.



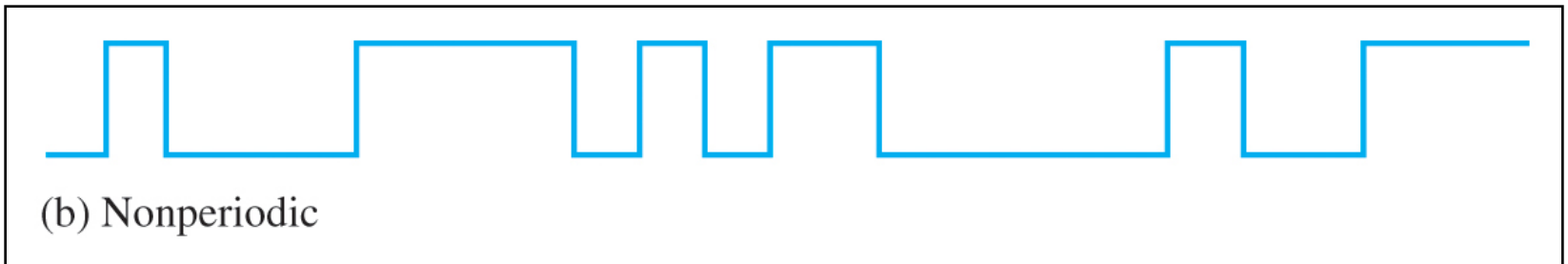
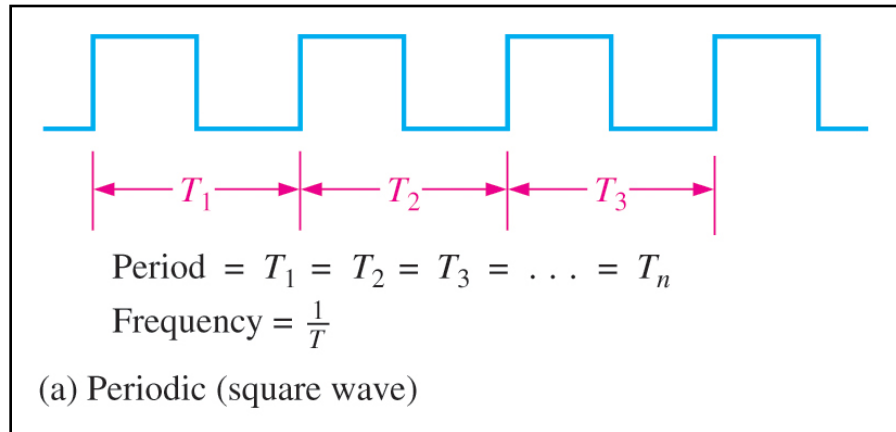
# Ch.1 Summary

## Pulse Definitions

Actual pulses are not ideal but are described by the rise time, fall time, amplitude, and other characteristics.



## Periodic and Nonperiodic Pulse Waveforms



## Periodic Pulse Waveforms

Periodic pulse waveforms are composed of pulses that repeats in a fixed interval called the **period**. The **frequency** is the rate it repeats and is measured in hertz.

$$f = \frac{1}{T} \quad T = \frac{1}{f}$$

The **clock** is a basic timing signal that is an example of a periodic wave.

*What is the period of a repetitive wave if  $f = 3.2 \text{ GHz}$ ?*

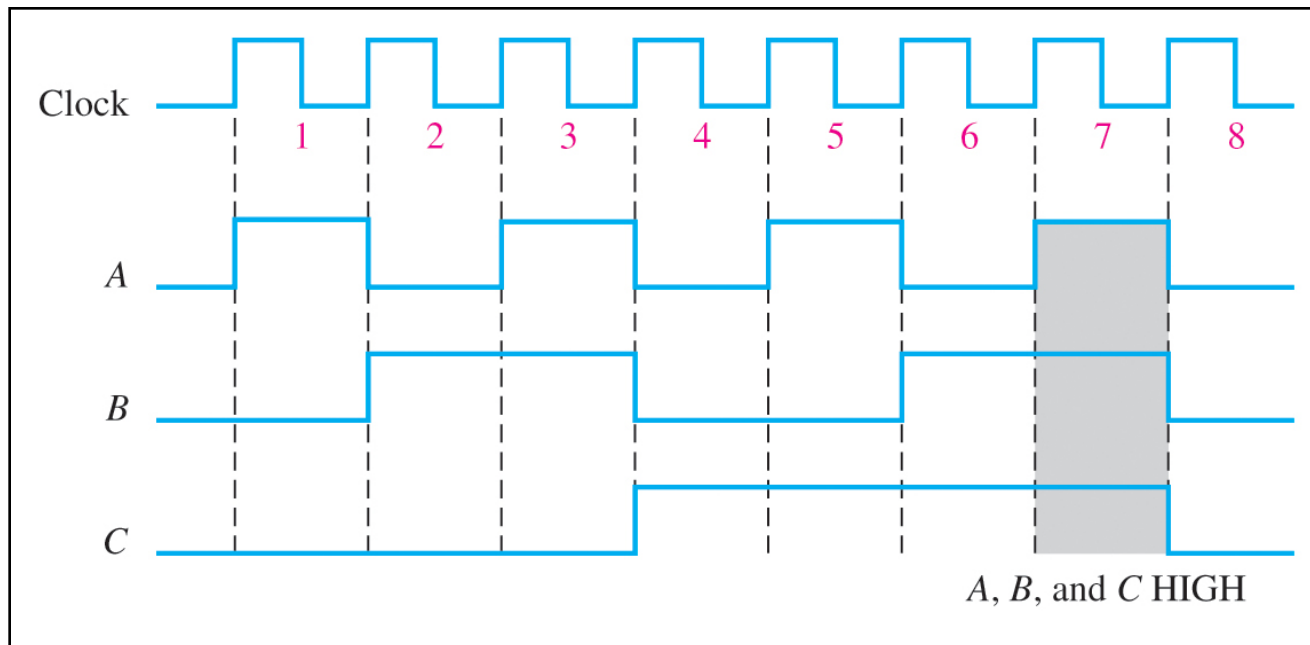
$$T = \frac{1}{f} = \frac{1}{3.2 \text{ GHz}} = \mathbf{313 \text{ ps}}$$



# Ch.1 Summary

## Timing Diagrams

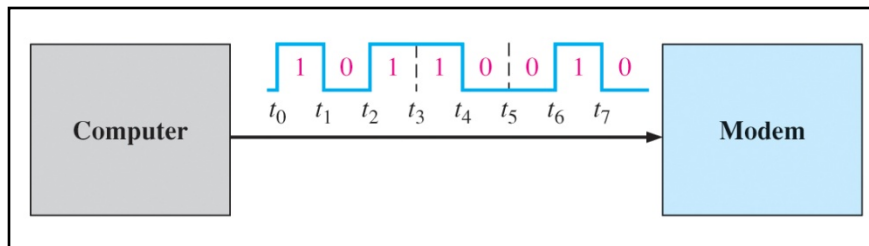
A timing diagram is used to show the relationship between two or more digital waveforms,



# Ch.1 Summary

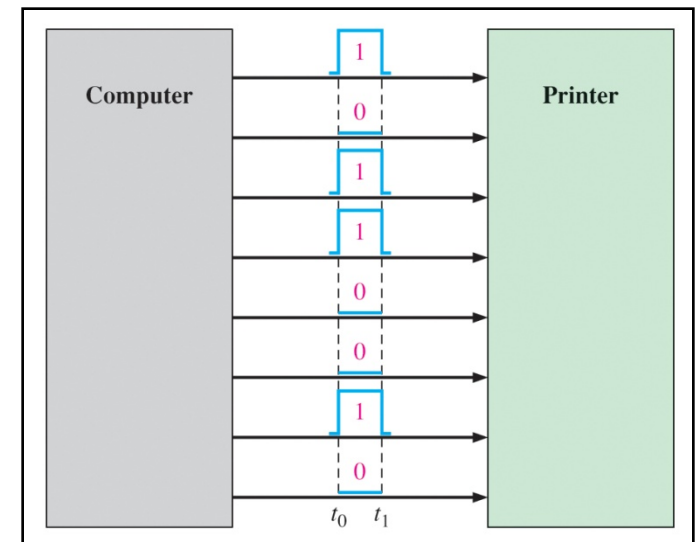
## Series and Parallel Data

Data can be transmitted by either serial transfer or parallel transfer.



**Serial data transfer**

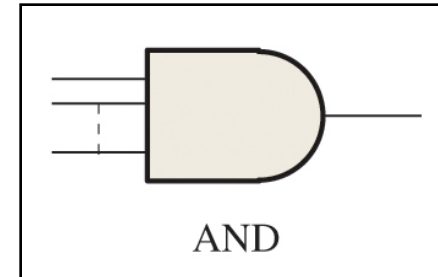
### Parallel data transfer



## Basic Logic Functions

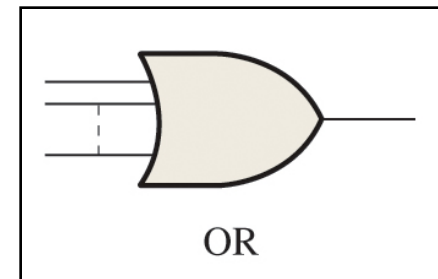
### AND

Produces a high output only if all inputs are high.



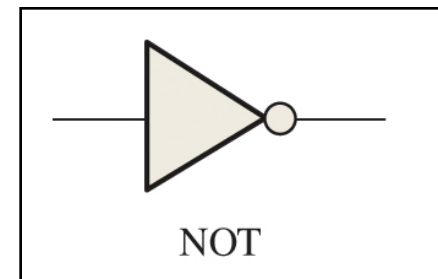
### OR

Produces a high output if one or more inputs are high.



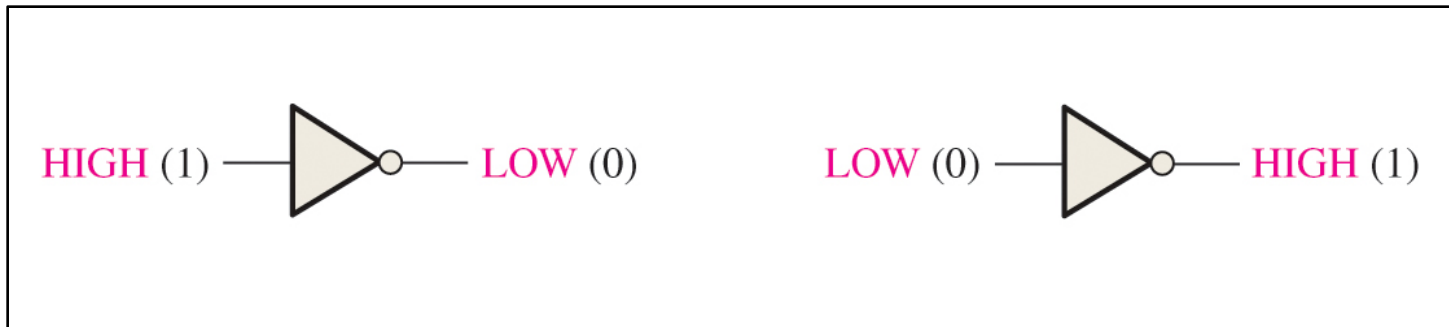
### NOT

Changes one logic level to the other logic level.



## The NOT Operation

Changes one logic level to the other logic level.



The NOT operation is performed by a circuit called an **inverter**.



## The AND Operation

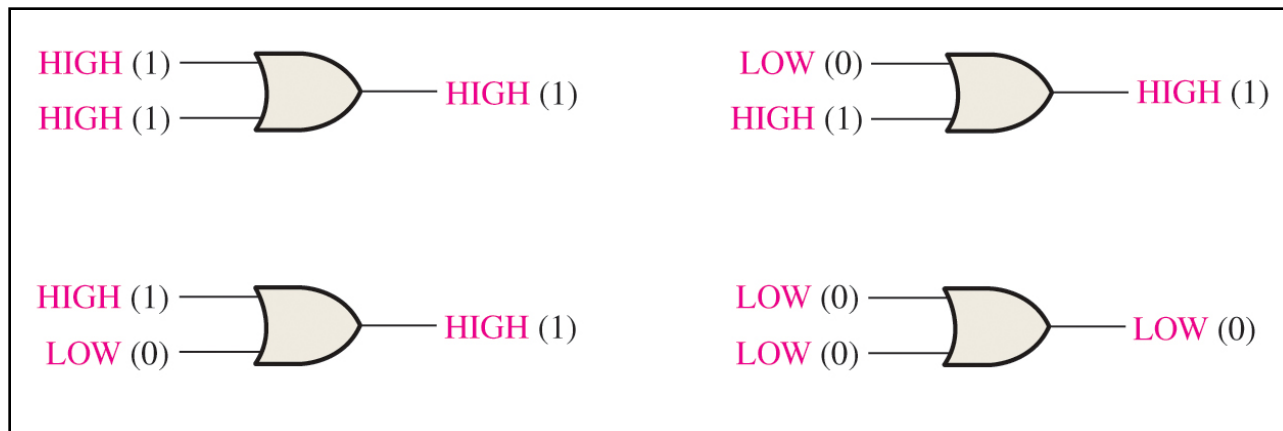
Produces a high output only when ALL inputs are high.



The AND operation is performed by a circuit called an **AND gate**.

## The OR Operation

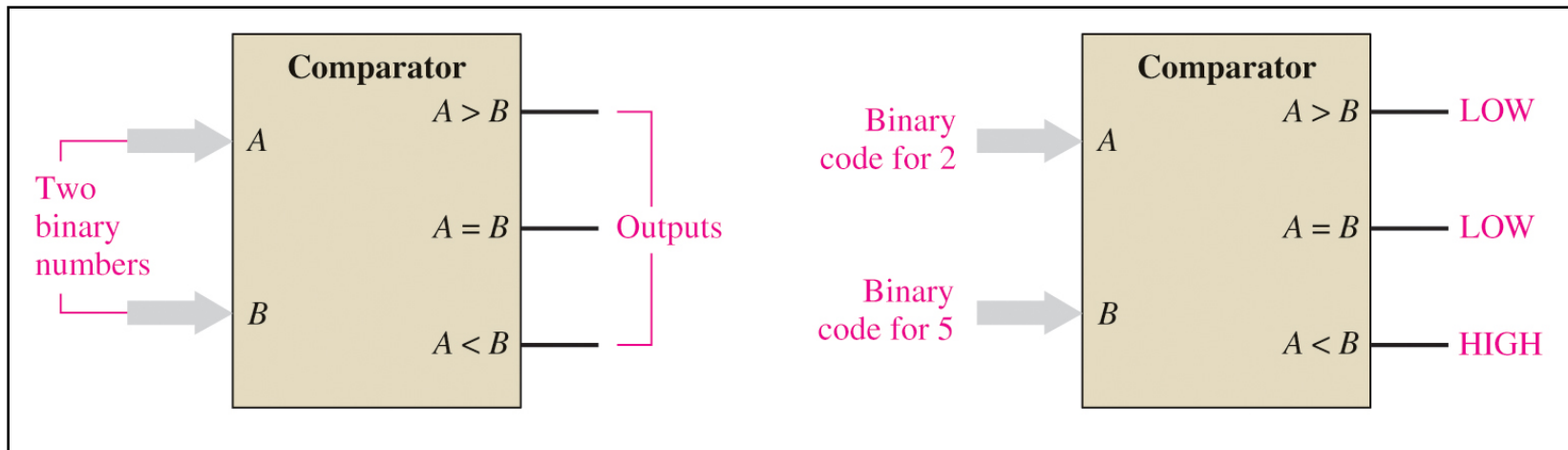
Produces a high output when one or more inputs are high.



The OR operation is performed by a circuit called an **OR gate**.

## The Comparison Function

**And**, **or**, and **not** elements can be combined to form various logic functions. The **comparison function** indicates whether a binary value is greater than, equal to, or less than, another.



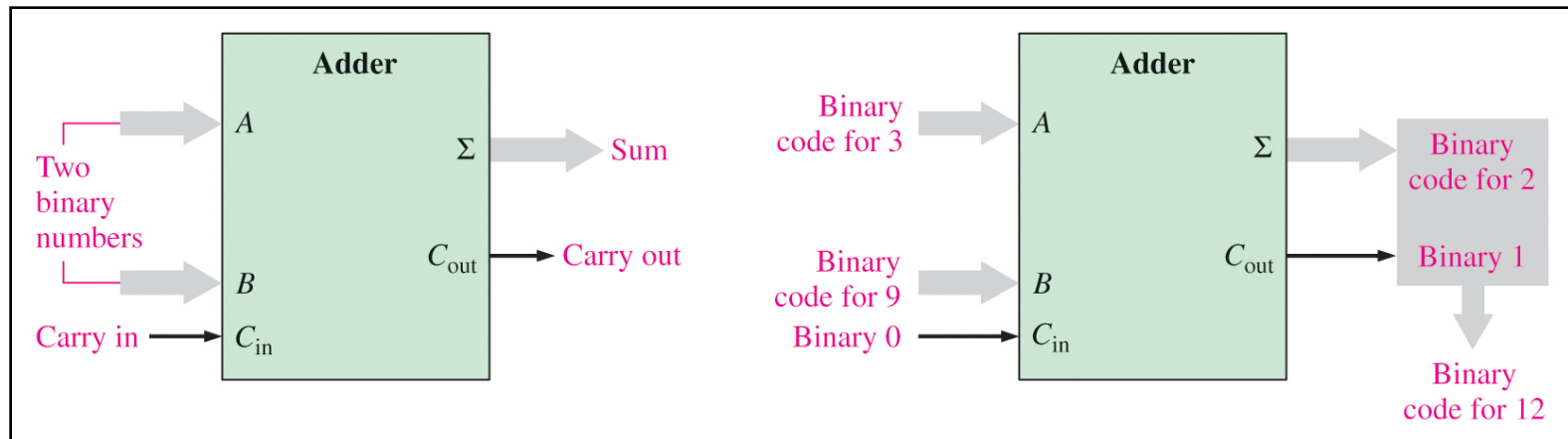
The comparison function is performed by a circuit called a **comparator**.



# Ch.1 Summary

## The Arithmetic Functions

The **arithmetic functions** include addition, subtraction, multiplication, and division.



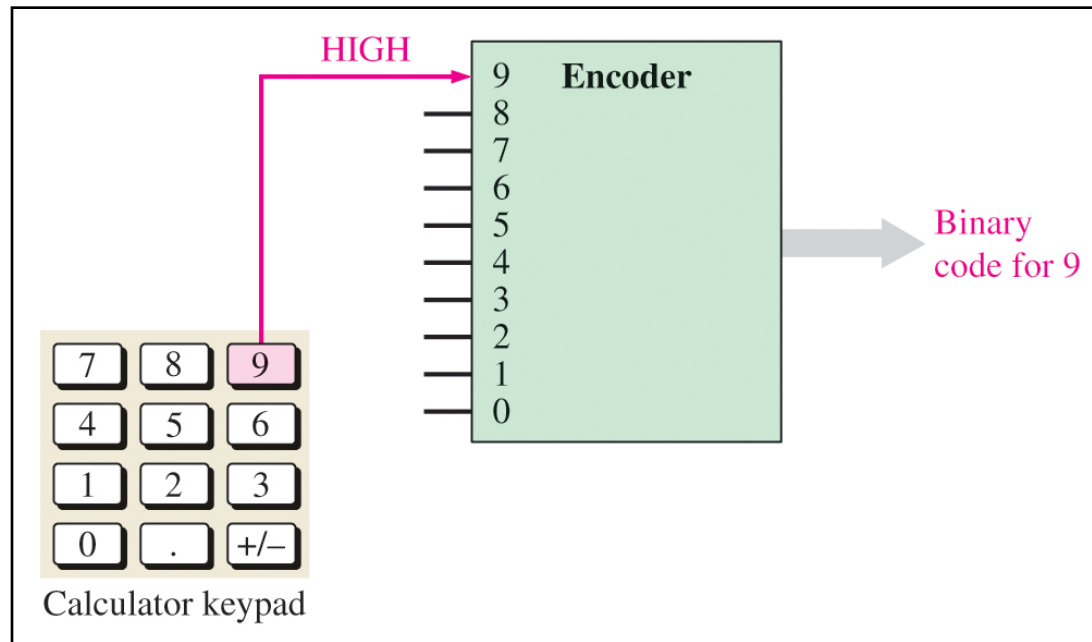
Addition is performed by an **adder** and subtraction by a **subtractor**. Multiplication and division are performed using circuits that are similar to adders and subtractors.



# Ch.1 Summary

## The Encoder Function

**Code:** A set of bits arranged in a unique pattern that represents specific information.



**Encoder:** A circuit that converts information into a coded form.

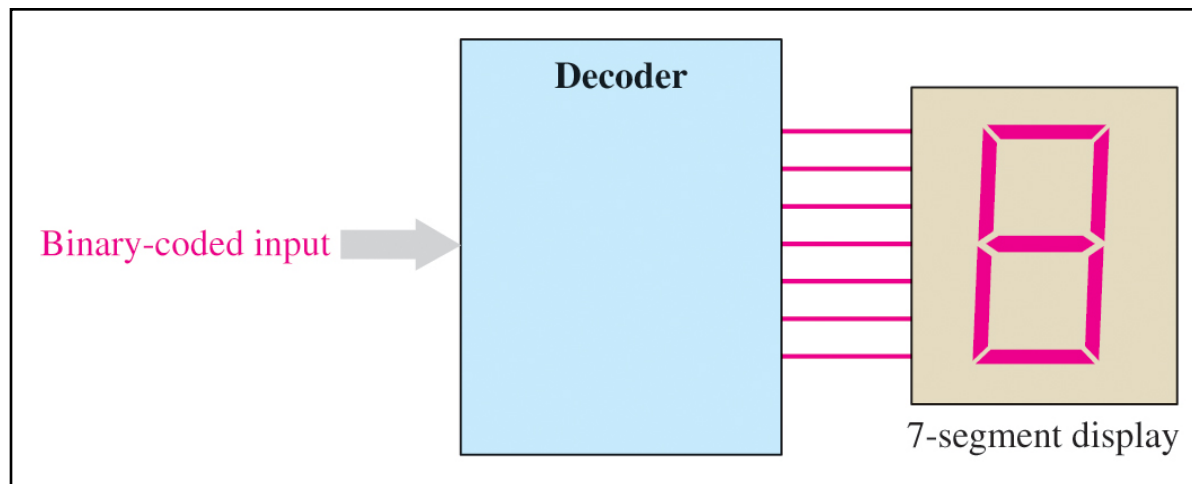


# Ch.1 Summary

## The Decoder Function

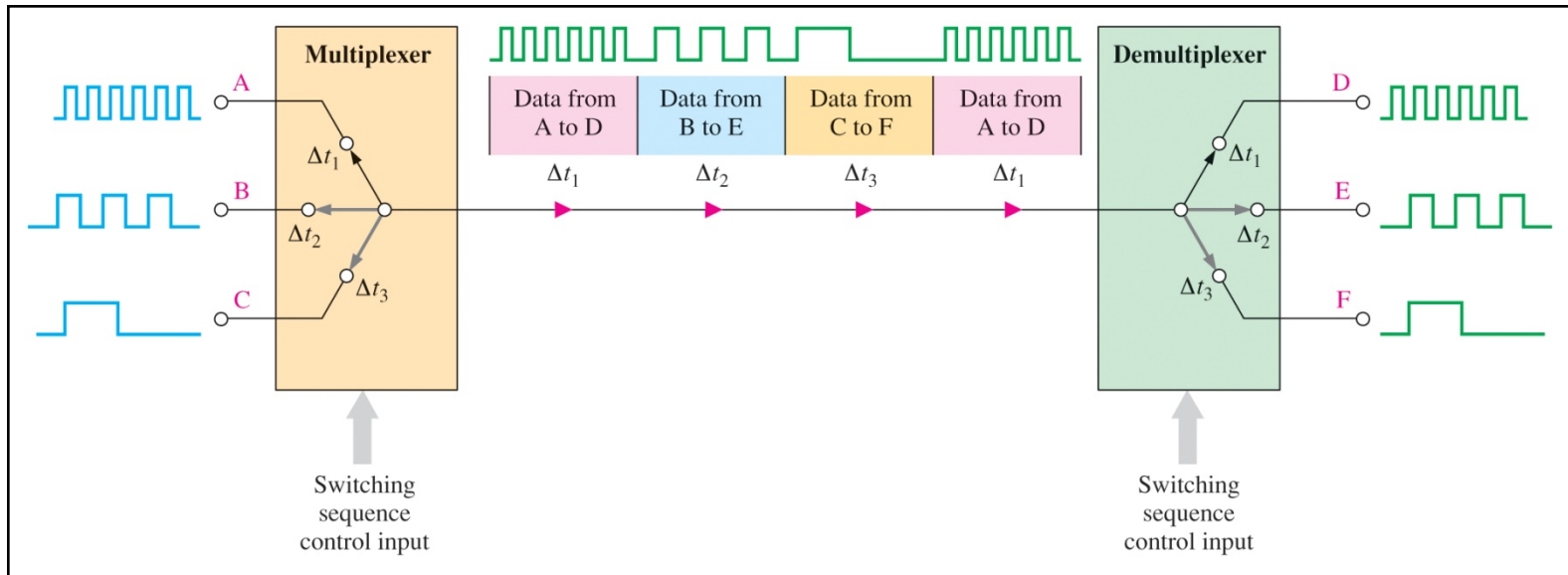
**Decoder:** A circuit that converts a binary code into a non-binary code of some kind.

**Example:** The decoder below converts a binary coded input to a form that will light the segments in the 7-segment display required to display a specific character.



## The Data Selection Function

**Multiplexer:** A circuit that connects one of several data inputs to a single data output line; also called a **mux**

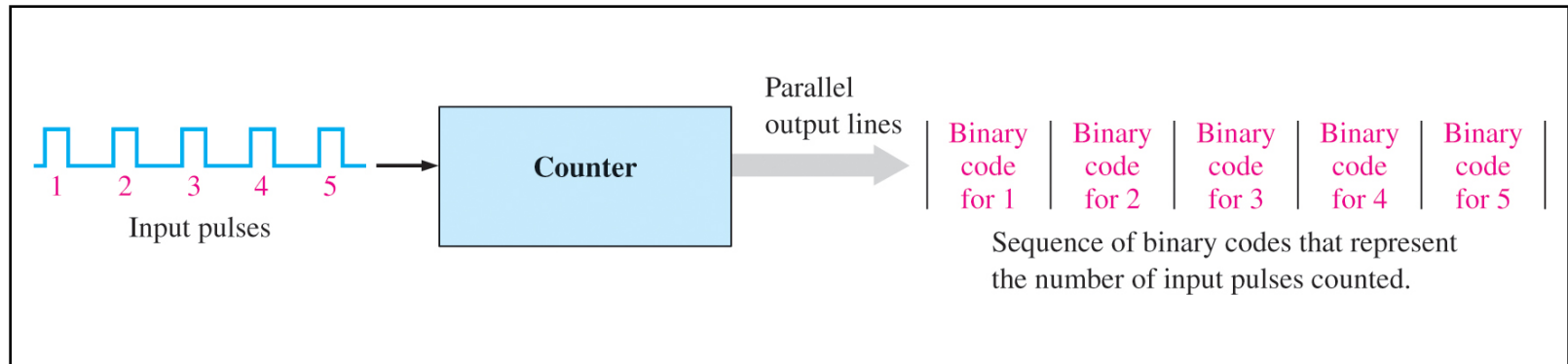


**Demultiplexer:** A circuit that connects one data input line to one of several data output lines; also called a **demux**

# Ch.1 Summary

## The Counting Function

**Counter:** A sequential device; a **state machine** that has a unique internal sequence of states. Counters are used to count events or to generate output sequences represented by changing levels or pulses.

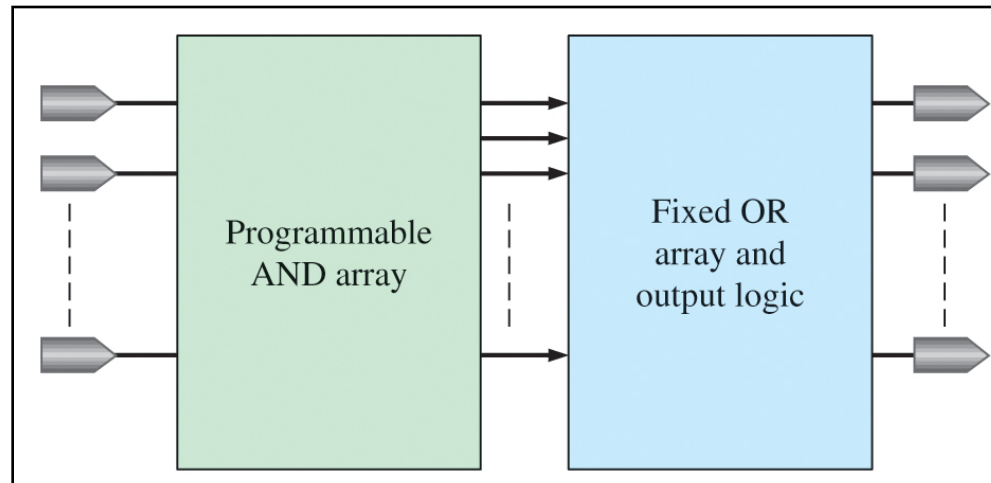




# Ch.1 Summary

## Programmable Logic

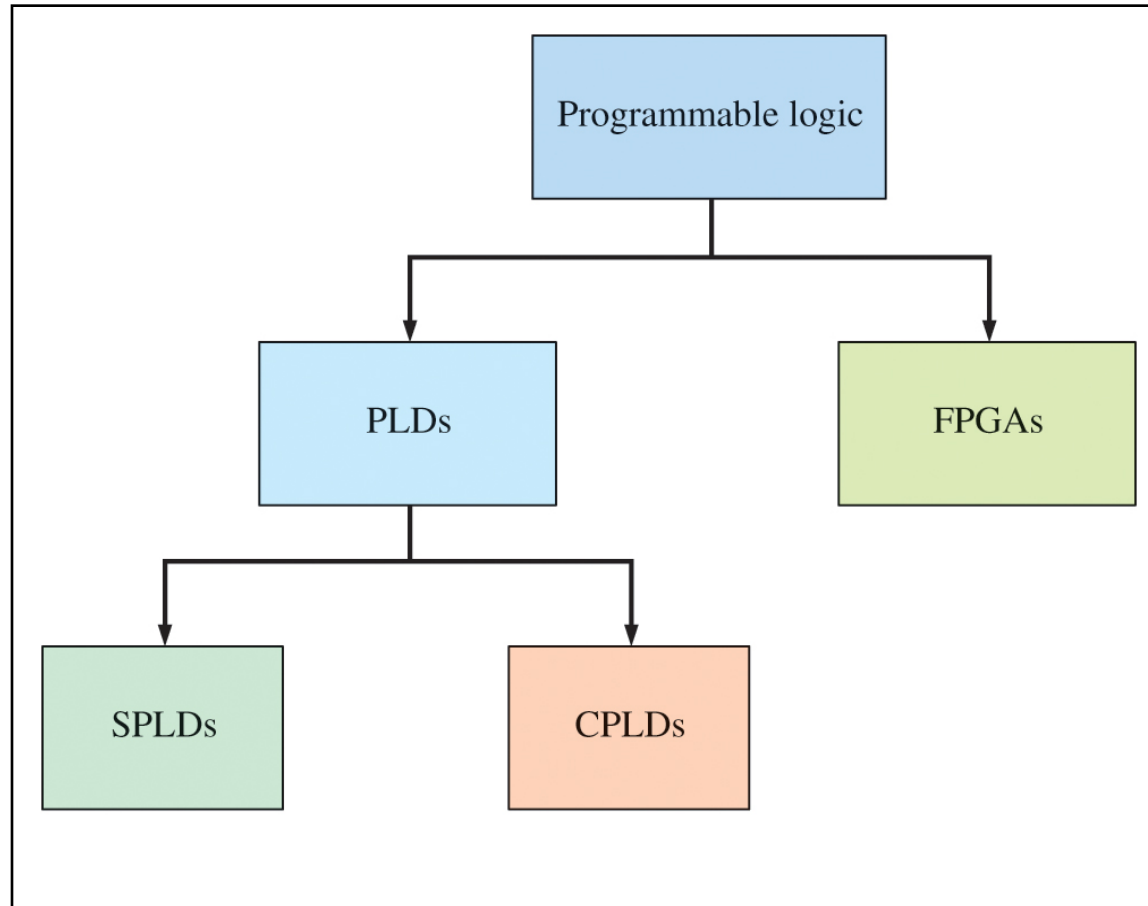
Programmable logic devices (PLDs) are an alternative to fixed function devices. The logic can be programmed for a specific purpose. In general, they cost less and use less board space than fixed function devices.



A PAL device is a form of PLD that uses a combination of a programmable AND array and a fixed OR array.



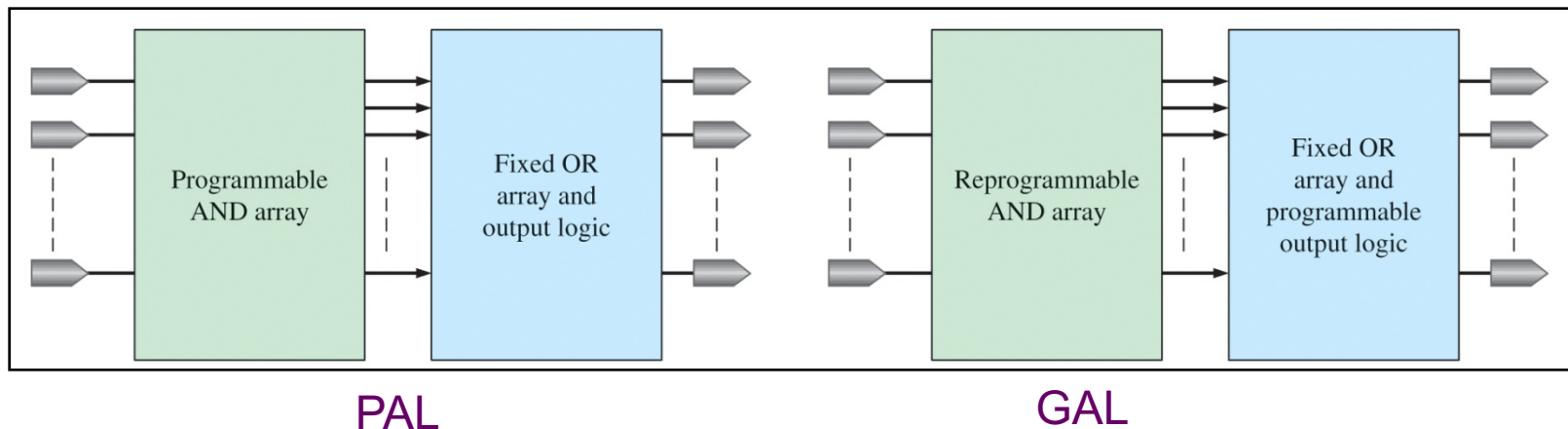
## Programmable Logic Hierarchy



## Simple Programmable Logic Devices (SPLD)

**Programmable Array Logic (PAL)** can be programmed once; has a programmable array of AND gates and a fixed array of OR gates.

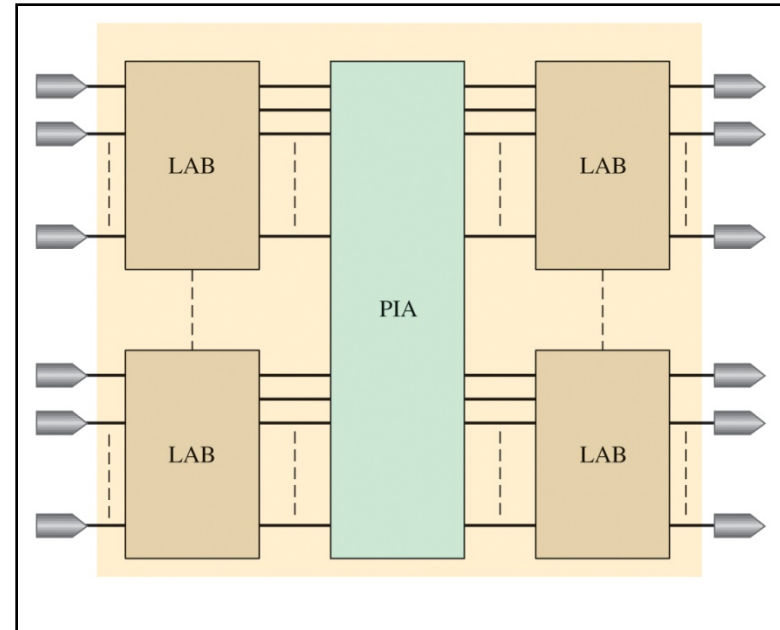
**Generic Array Logic (GAL)** is very similar to PAL, but can be reprogrammed.



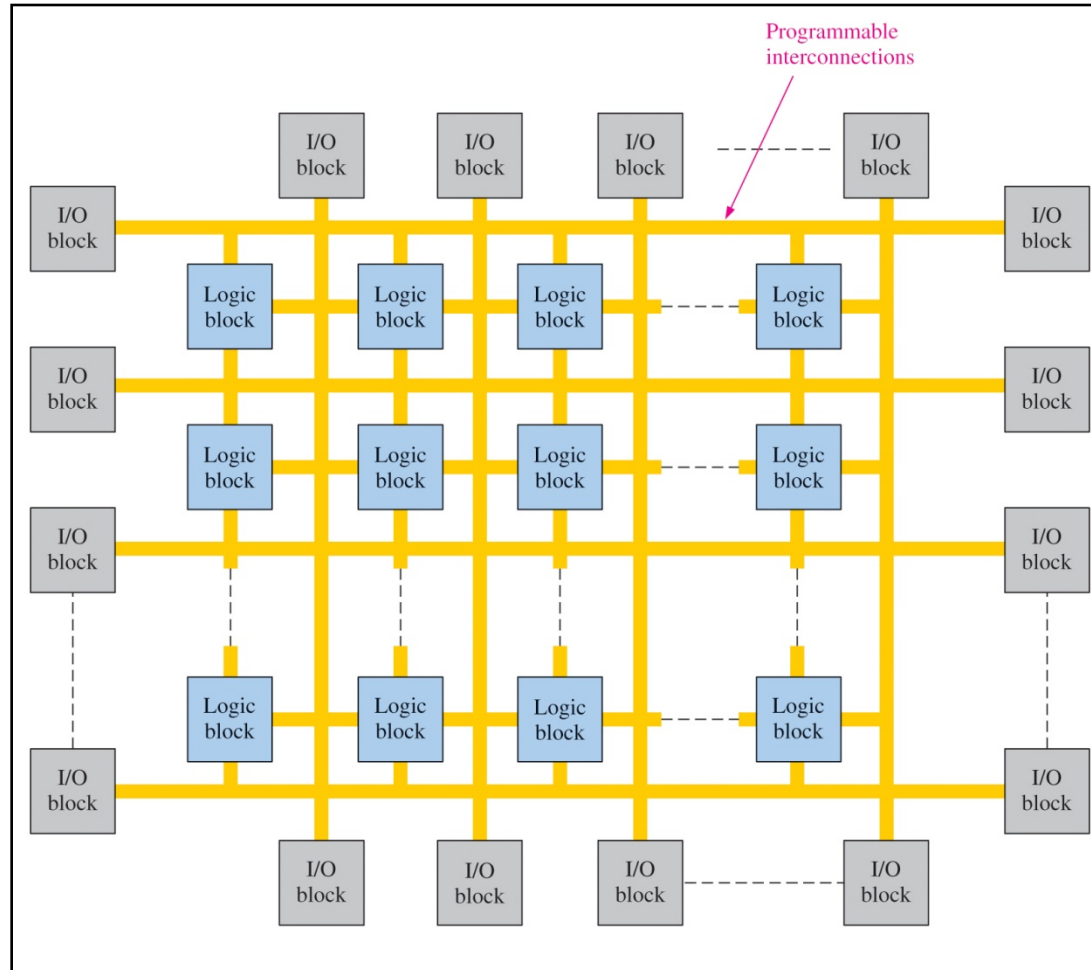
## Complex Programmable Logic Devices (CPLD)

**Complex Programmable Logic Devices (CPLDs)** are devices that contain multiple SPLDs.

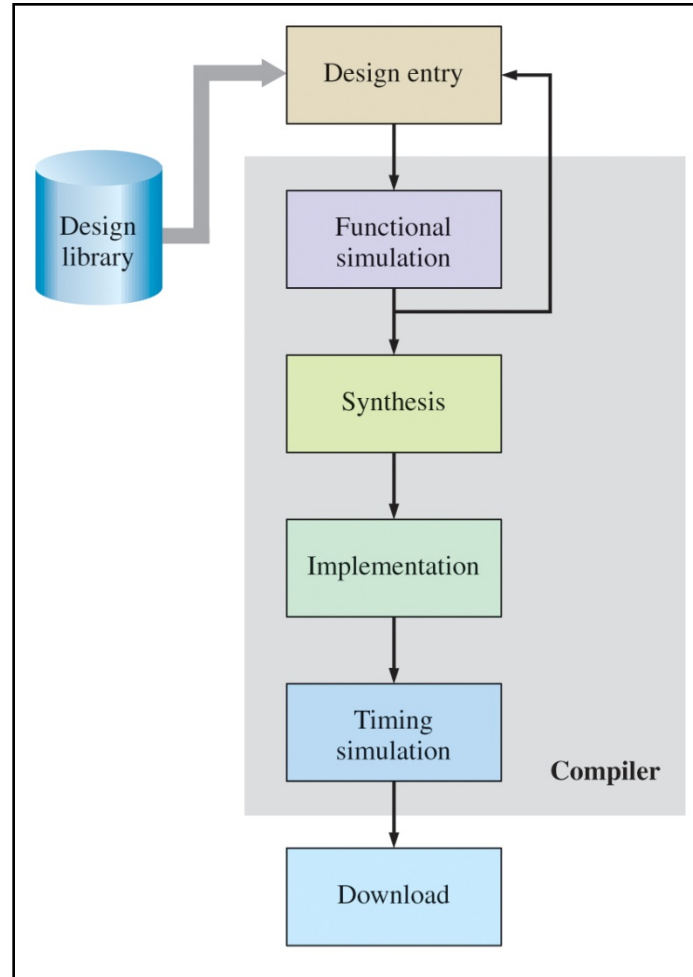
One CPLD can contain from two to 64 Logic Array Blocks (LABs); each LAB being roughly equal to one SPLD.



## Field Programmable Gate Array



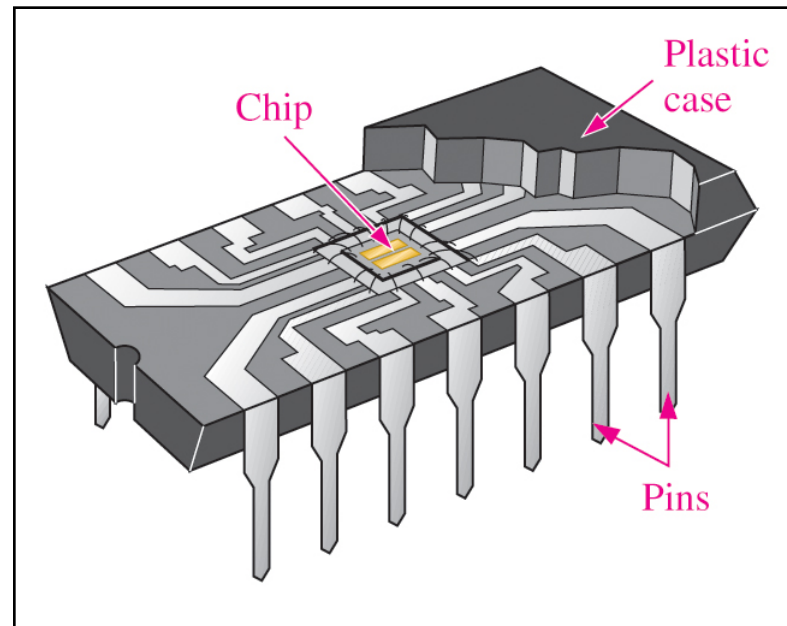
## Programming Flow Block Diagram



## Ch.1 Summary

# Integrated Circuits

Cutaway view of a DIP (**D**ual-**I**n-line **P**ackage) chip:



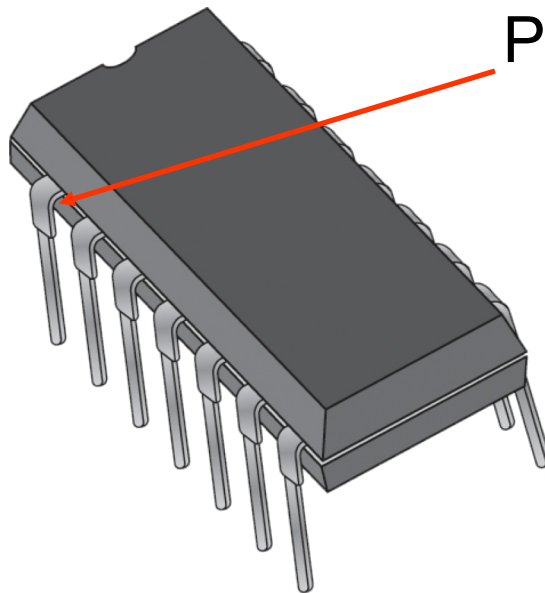
The TTL series, available as DIPs are popular for laboratory experiments with logic.



# Ch.1 Summary

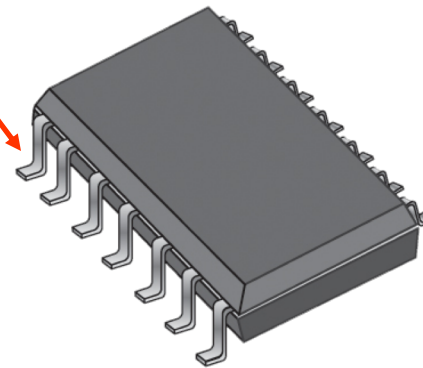
## Integrated Circuit (IC) Packages

DIP and surface mount chips



Dual in-line package

Pin 1



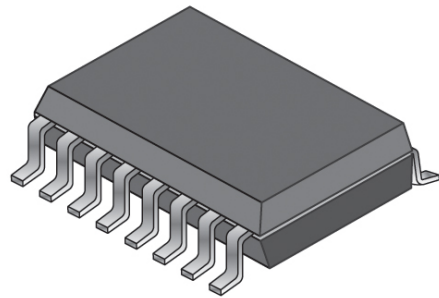
Small outline IC (SOIC)



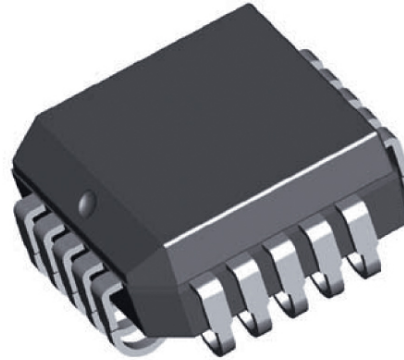


# Ch.1 Summary

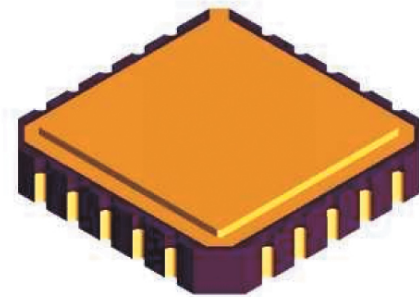
## More IC Packages



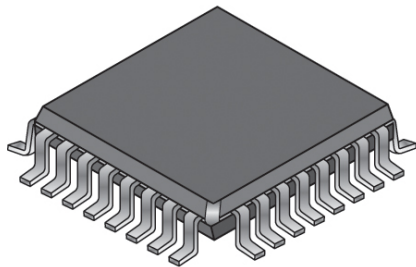
(a) SSOP ( $153 \times 193$  mils)



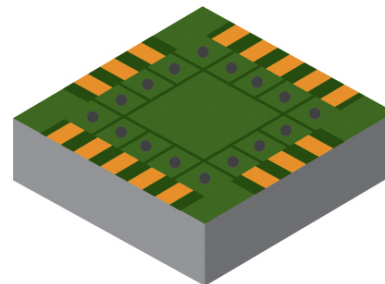
(b) PLCC ( $350 \times 350$  mils)



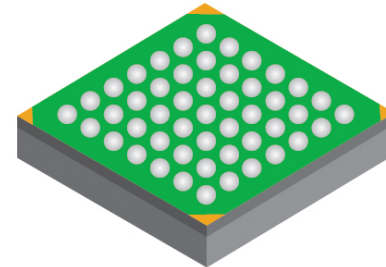
(c) LCC ( $350 \times 350$  mils)



(d) LQFP ( $7 \times 7$  mm)



(e) Laminate CSP ( $3.5 \times 3.5$  mm)

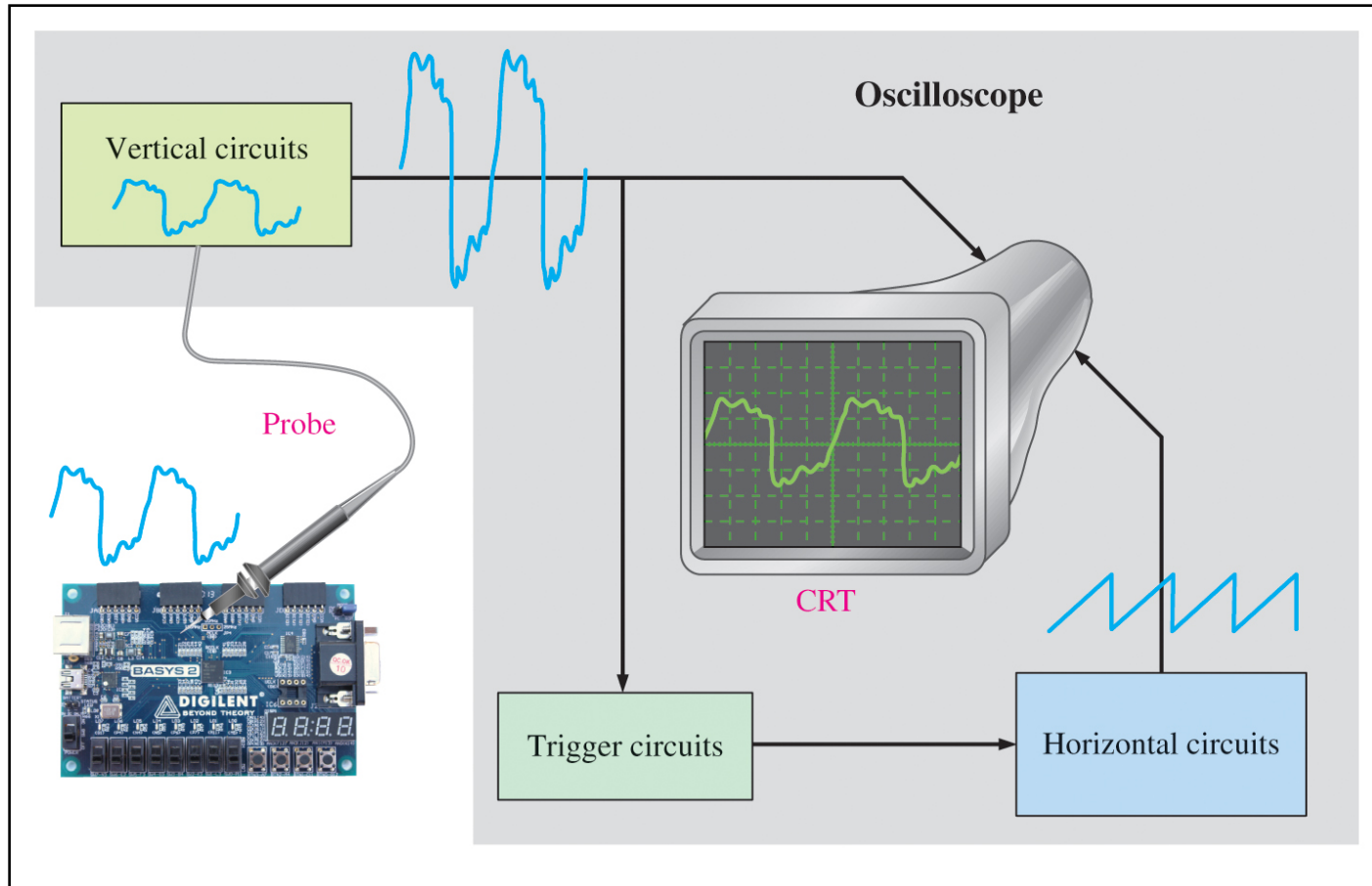


(f) FBGA ( $4 \times 4$  mm)



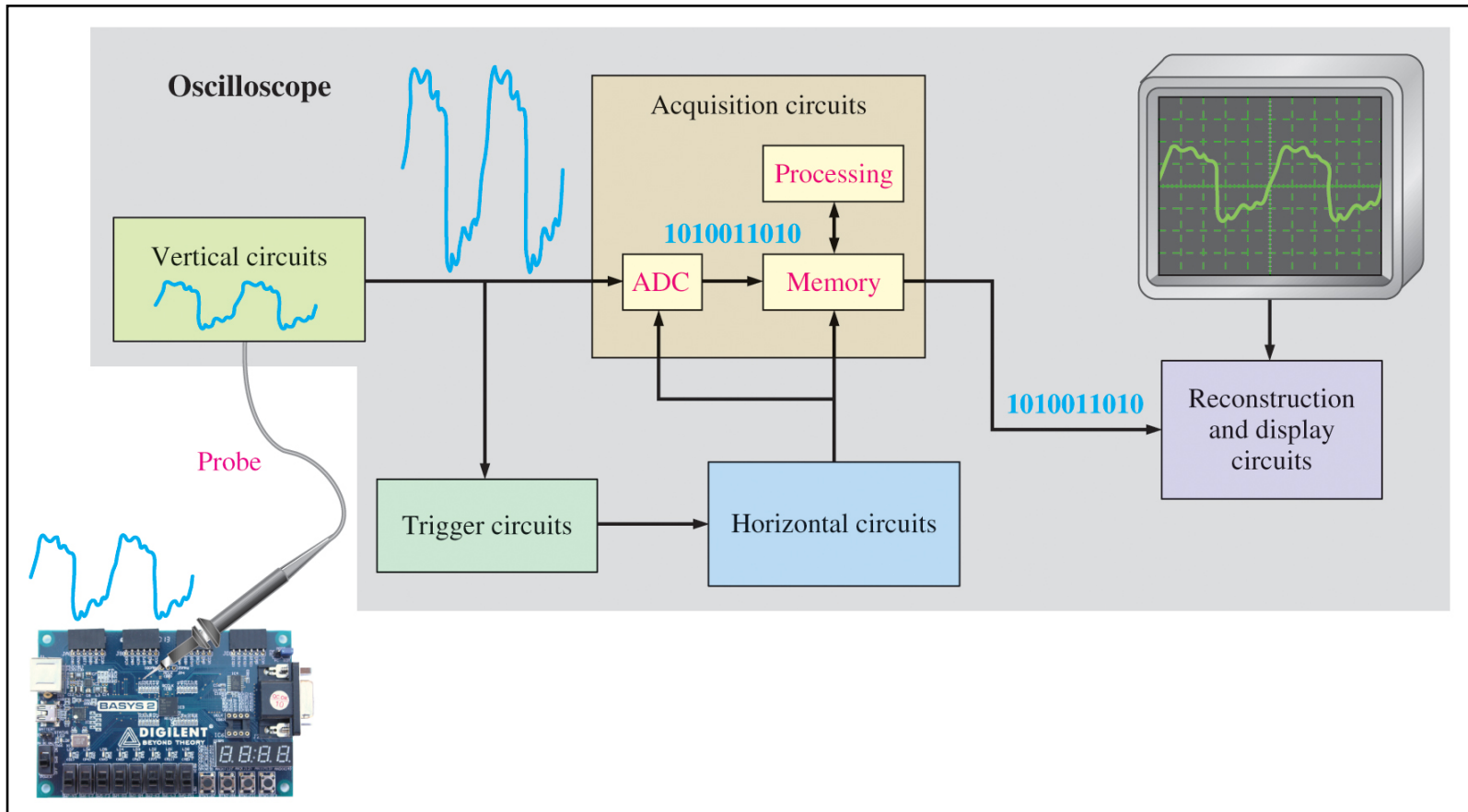
# Ch.1 Summary

## Analog Oscilloscope Block Diagram



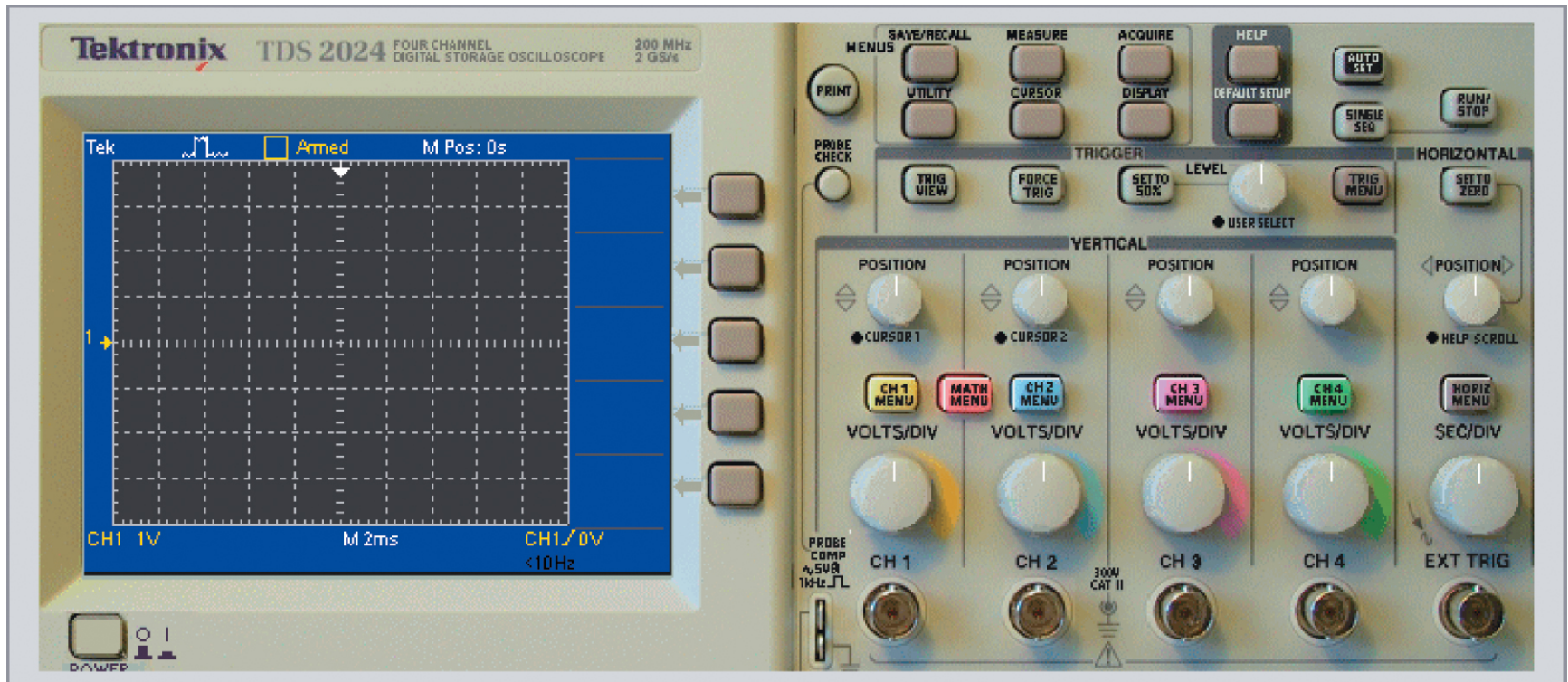
# Ch.1 Summary

## Digital Oscilloscope Block Diagram



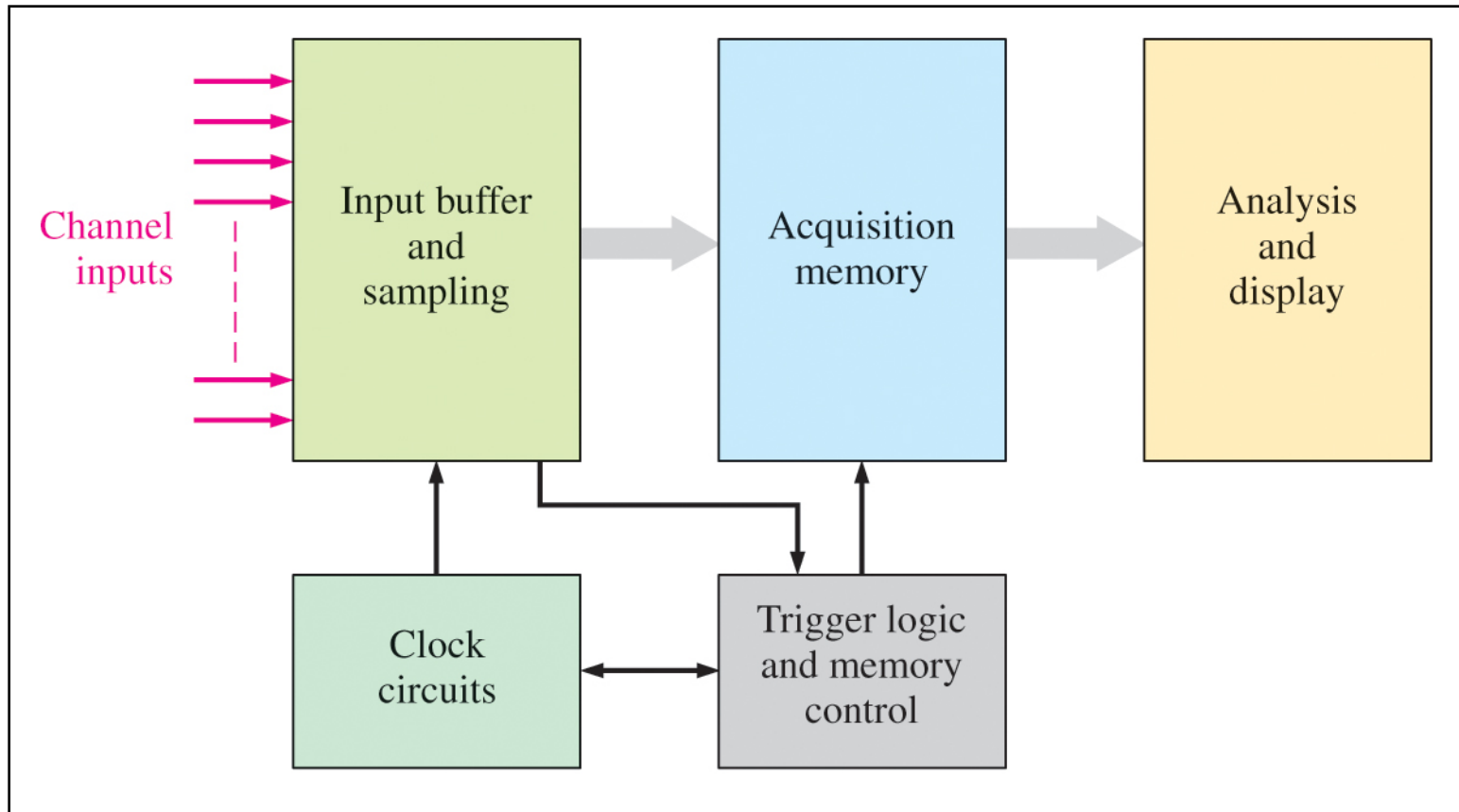
# Ch.1 Summary

## Digital Oscilloscope Front Panel



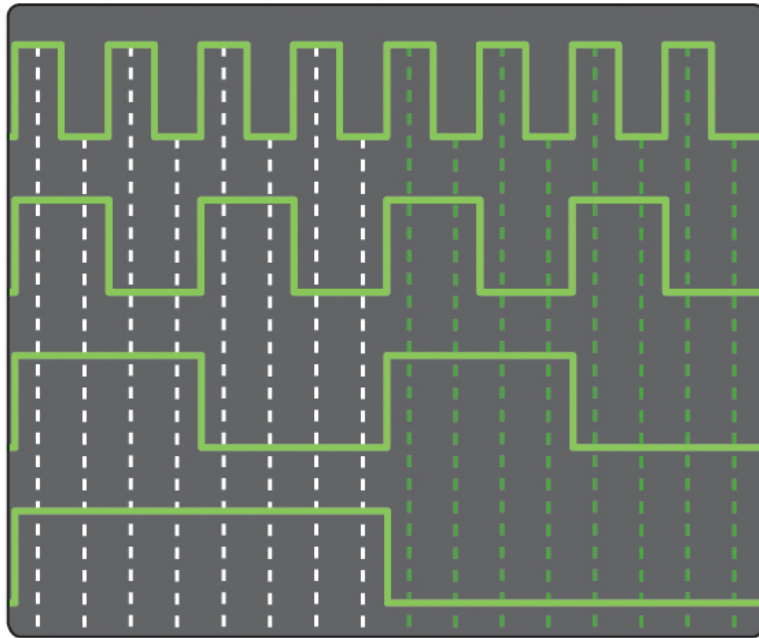
# Ch.1 Summary

## Logic Analyzer Block Diagram



# Ch.1 Summary

## Logic Analyzer Display Modes



1 2 3 4 5 6 7 8

(a) Waveform display

Sample	Binary	Hex	Time
1	1111	F	1 ns
2	1110	E	10 ns
3	1101	D	20 ns
4	1100	C	30 ns
5	1011	B	40 ns
6	1010	A	50 ns
7	1001	9	60 ns
8	1000	8	70 ns

(b) Listing display



## Key Terms

- Analog** Being continuous or having continuous values.
- Digital** Related to digits or discrete quantities; having a set of discrete values.
- Binary** Having two values or states; describes a number system that has a base of two and utilizes 1 and 0 as its digits.
- Bit** A binary digit, which can be a 1 or a 0.
- Pulse** A sudden change from one level to another, followed after a time, called the pulse width, by a sudden change back to the original level.



## Key Terms

- Clock** A basic timing signal in a digital system; a periodic waveform used to synchronize actions.
- Gate** A logic circuit that performs a basic logic operations such as AND or OR.
- NOT** A basic logic function that performs inversion.
- AND** A basic logic operation in which a true (HIGH) output occurs only when all input conditions are true (HIGH).
- OR** A basic logic operation in which a true (HIGH) output occurs when when one or more of the input conditions are true (HIGH).





## Key Terms

***Fixed-function logic*** A category of digital integrated circuits having functions that cannot be altered.

***Programmable logic*** A category of digital integrated circuits capable of being programmed to perform specified functions.



# Ch.1 Summary

## Quiz

1. Compared to analog systems, digital systems
  - a. are less prone to noise
  - b. can represent an infinite number of values
  - c. can handle much higher power
  - d. all of the above



# Ch.1 Summary

## Quiz

2. The number of values that can be assigned to a bit are
- a. one
  - b. two
  - c. three
  - d. ten



# Ch.1 Summary

## Quiz

3. The time measurement between the 50% point on the leading edge of a pulse to the 50% point on the trailing edge of the pulse is called the
- a. rise time
  - b. fall time
  - c. period
  - d. pulse width



# Ch.1 Summary

## Quiz

4. The time measurement between the 90% point on the trailing edge of a pulse to the 10% point on the trailing edge of the pulse is called the
- a. rise time
  - b. fall time
  - c. period
  - d. pulse width



# Ch.1 Summary

## Quiz

5. The reciprocal of the frequency of a clock signal is the
- a. rise time
  - b. fall time
  - c. period
  - d. pulse width



# Ch.1 Summary

## Quiz

6. If the period of a clock signal is 500 ps, the frequency is
- a. 20 MHz
  - b. 200 MHz
  - c. 2 GHz
  - d. 20 GHz



# Ch.1 Summary

## Quiz

7. AND, OR, and NOT gates can be used to form
- a. storage devices
  - b. comparators
  - c. data selectors
  - d. all of the above





# Ch.1 Summary

## Quiz

8. A shift register is an example of a
- a. storage device
  - b. comparator
  - c. data selector
  - d. counter



# Ch.1 Summary

## Quiz

9. A device that is used to switch one of several input lines to a single output line is called a
- a. comparator
  - b. decoder
  - c. counter
  - d. multiplexer



# Ch.1 Summary

## Quiz

10. For most digital work, an oscilloscope should be coupled to the signal using

- a. ac coupling
- b. dc coupling
- c. GND coupling
- d. none of the above



# Ch.1 Summary

## Answers

- |      |       |
|------|-------|
| 1. a | 6. c  |
| 2. b | 7. d  |
| 3. d | 8. a  |
| 4. b | 9. d  |
| 5. c | 10. b |



## Chapter 3

# Logic Gates and Gate Combinations



# Boolean Variables

A **variable** is a symbol used to represent an action, a condition, or data. Each variable has a value of 1 or 0.

The **complement** represents the inverse of a variable;  $\bar{\quad}$  indicated by an over-bar. Thus, the complement of  $A$  is  $\bar{A}$ .

A **literal** is a variable or its complement.



# Boolean Addition

Addition is equivalent to the OR operation. The sum term is 1 if one or more of the literals are 1. The sum term is zero only if each literal is 0.

Determine the values of  $\bar{A}$ ,  $\bar{B}$ , and  $\bar{C}$  that make the sum term of the expression  $\bar{A} + \bar{B} + \bar{C} = 0$

Each literal must equal 0; therefore  $A = 1$ ,  $B = 0$  and  $C = 1$ .



# Boolean Multiplication

In Boolean algebra, multiplication is equivalent to the AND operation. The product of literals forms a product term. The product term (AND gate output) equals 1 only when each literal equals 1.

What are the values of the  $A$ ,  $B$  and  $C$  if the product term of  $\overline{A} \cdot \overline{B} \cdot C = 1$ ?

Each literal must = 1; therefore  $A = 0$ ,  $B = 0$  and  $C = 1$ .





# Commutative Laws

The **commutative laws** apply to both addition and multiplication. For addition, the commutative law states:

In terms of the result, the order in which variables are ORed makes no difference.

$$A + B = B + A$$

For multiplication, the commutative law states:

In terms of the result, the order in which variables are ANDed makes no difference.

$$AB = BA$$



# Associative Laws

The **associative laws** also apply to both addition and multiplication. For addition, the associative law states:

When ORing more than two variables, the result is the same regardless of the grouping of the variables.

$$A + (B + C) = (A + B) + C$$

For multiplication, the associative law states:

When ANDing more than two variables, the result is the same regardless of the grouping of the variables.

$$A(BC) = (AB)C$$

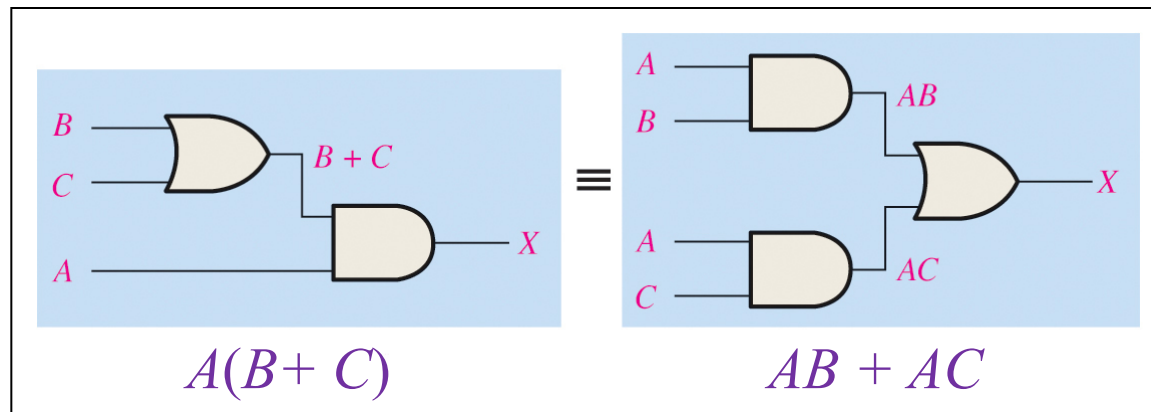


## Distributive Law

The **distributive law** is the *factoring law*. A common variable can be factored from an expression just as in ordinary algebra. That is:

$$AB + AC = A(B + C)$$

The distributive law can be illustrated with equivalent circuits:



## Ch.3 Summary

# Rules of Boolean Algebra

1.  $A + 0 = A$

2.  $A + 1 = 1$

3.  $A \cdot 0 = 0$

4.  $A \cdot 1 = A$

5.  $A + A = A$

6.  $A + \bar{A} = 1$

7.  $A \cdot A = A$

8.  $A \cdot \bar{A} = 0$

9.  $\bar{\bar{A}} = A$

10.  $A + AB = A$

11.  $A + \bar{A}B = A + B$

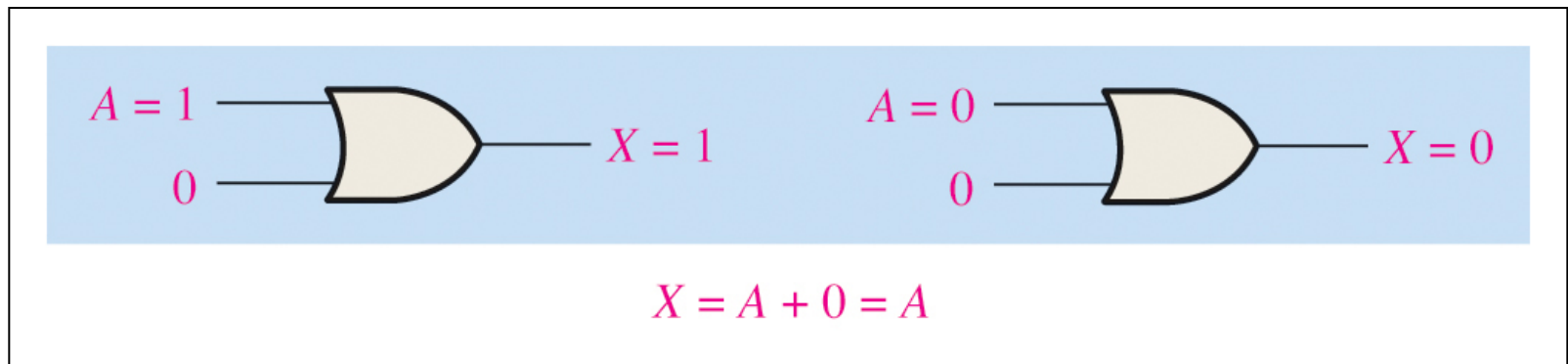
12.  $(A + B)(A + C) = A + BC$



## Rules of Boolean Algebra

### Rule 1: $A + 0 = A$

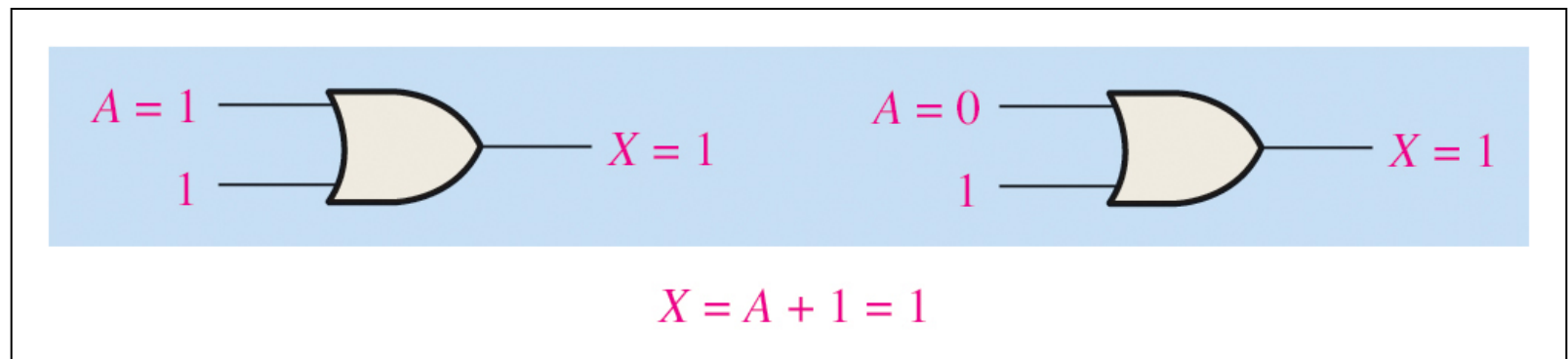
When  $A = 1$ , the input causes the output to go to  $X = 1$ .  
When  $A = 0$ , the 0 inputs cause the output to go to  $X = 0$ .  
In either case, the value of  $X$  equals the value of  $A$ .



## Rules of Boolean Algebra

### Rule 2: $A + 1 = 1$

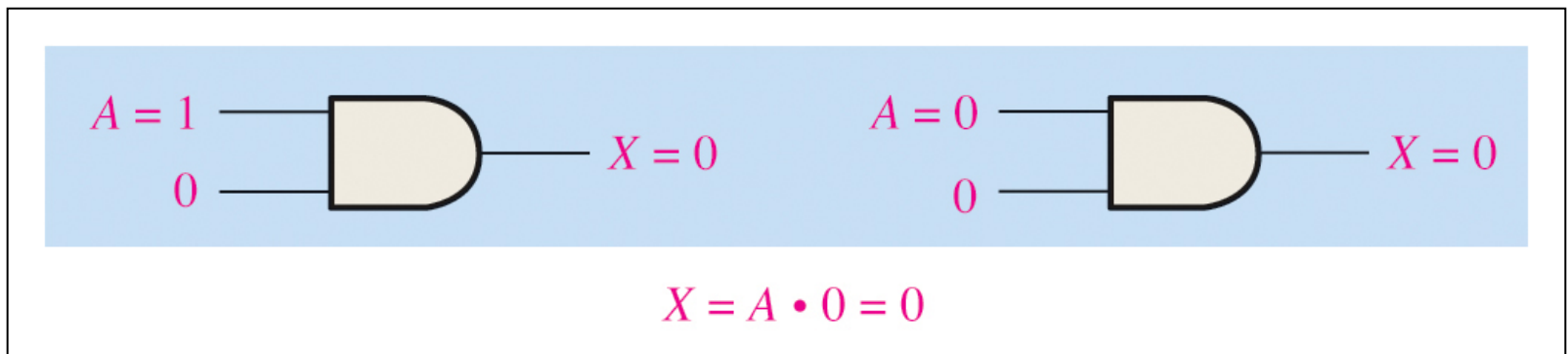
When  $A = 1$ , the inputs cause the output to go to  $X = 1$ .  
When  $A = 0$ , the 1 input caused the output to go to  $X = 1$ .  
In either case, the value of  $X$  equals one (1).



## Rules of Boolean Algebra

### Rule 3: $A \cdot 0 = 0$

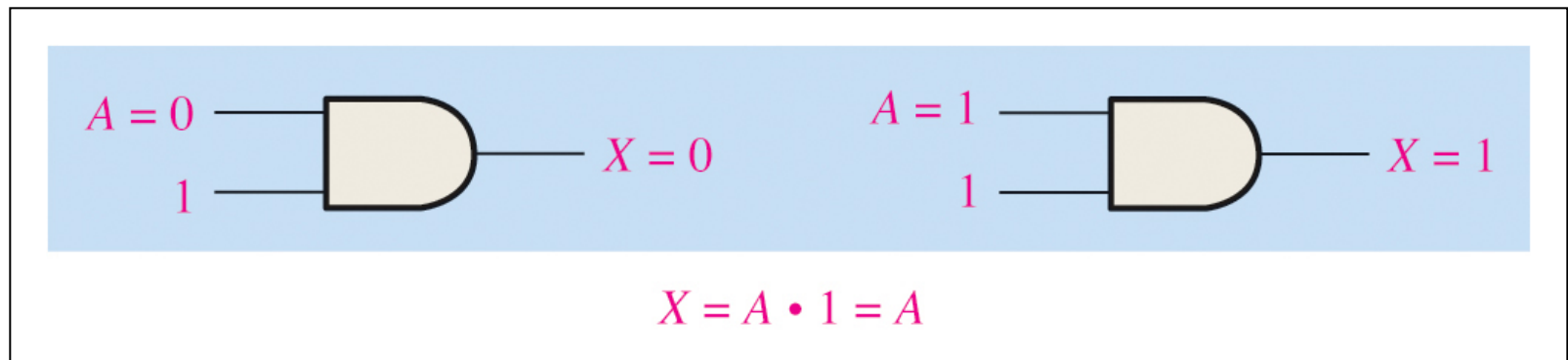
When either input to an AND gate equals 0, the output from the gate has a value of  $X = 0$ , regardless of the value at the other input.



## Rules of Boolean Algebra

### Rule 4: $A \cdot 1 = A$

When one input to an AND gate equals 1, the output from the gate has a value of  $X = A$ . As shown,  $X = 1$  when  $A = 1$  and  $X = 0$  when  $A = 0$ .

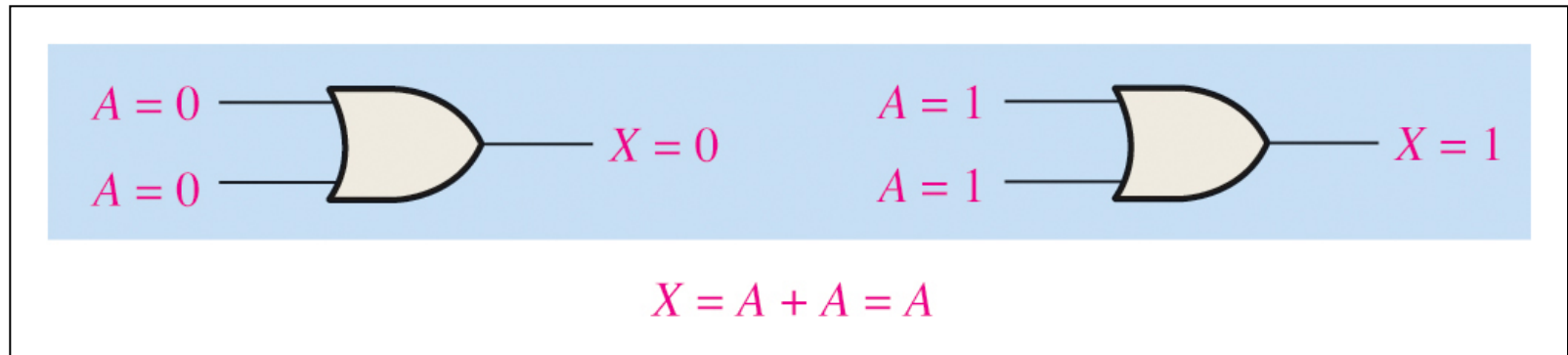




## Rules of Boolean Algebra

### Rule 5: $A + A = A$

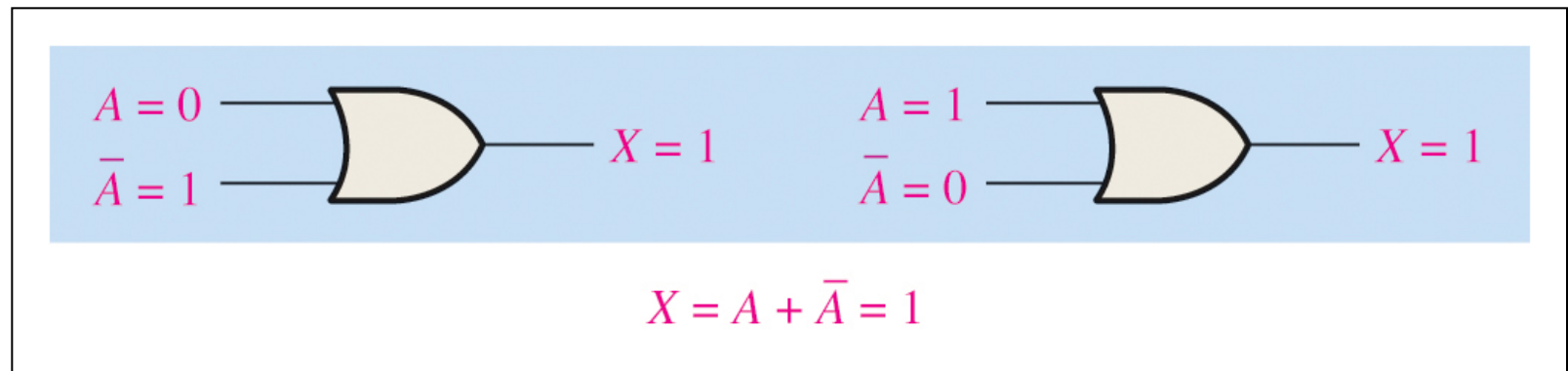
When the inputs to an OR gate are equal, the output equals the value at the inputs. When both inputs equal 1, the gate output is  $X = 1$ . When both inputs equal 0, the gate output is  $X = 0$ .



## Rules of Boolean Algebra

### Rule 6: $A + \bar{A} = 1$

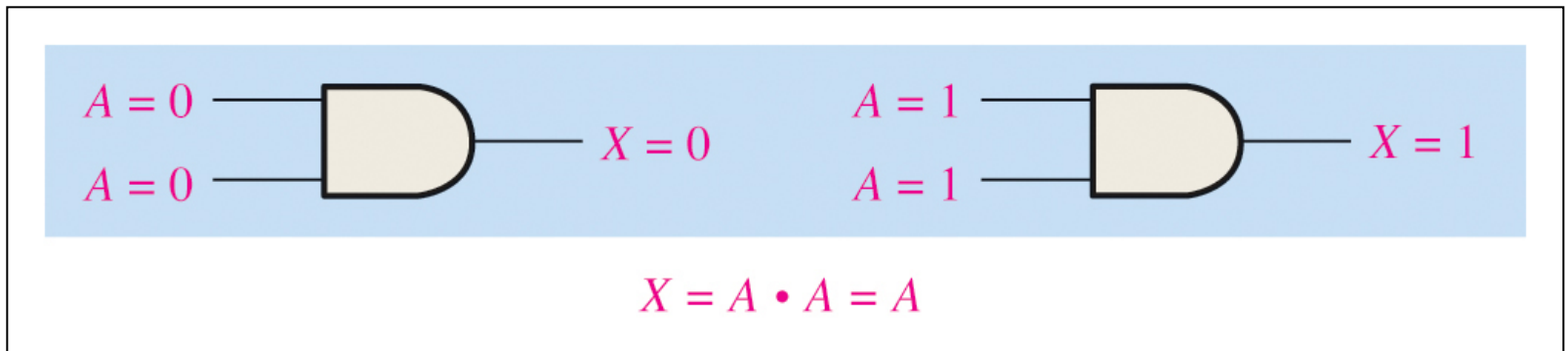
When the inputs to an OR gate are unequal (complements), one of the two always equals 1. When either input equals 1, the gate output is  $X = 1$ . Therefore, the output from the OR gate equals 1 whenever the inputs are unequal (complementary).



## Rules of Boolean Algebra

### Rule 7: $A \cdot A = A$

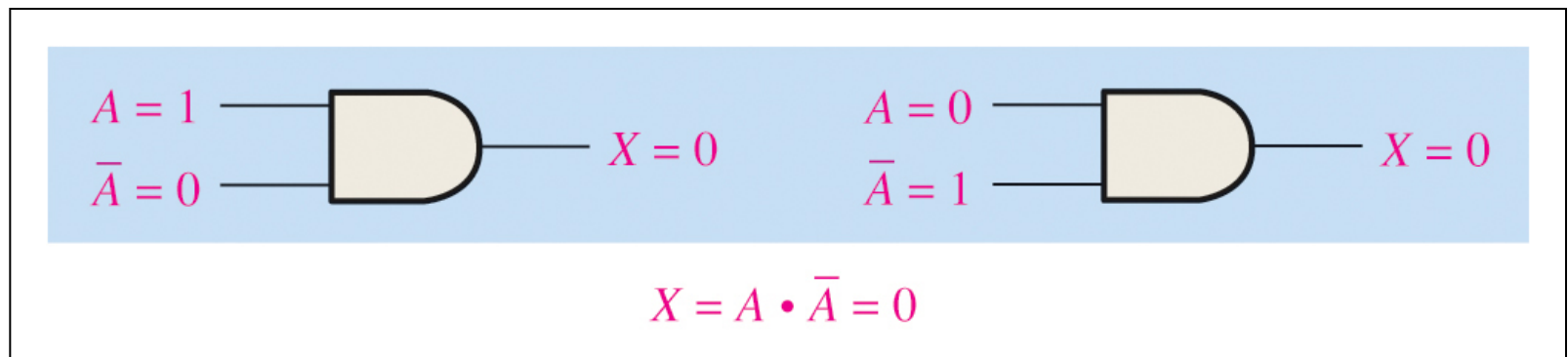
When the inputs to an AND gate are equal, the gate output also equals that value. Thus,  $X = 1$  when both inputs equal 1 and  $X = 0$  when both inputs equal 0.



## Rules of Boolean Algebra

### Rule 8: $A \cdot \bar{A} = 0$

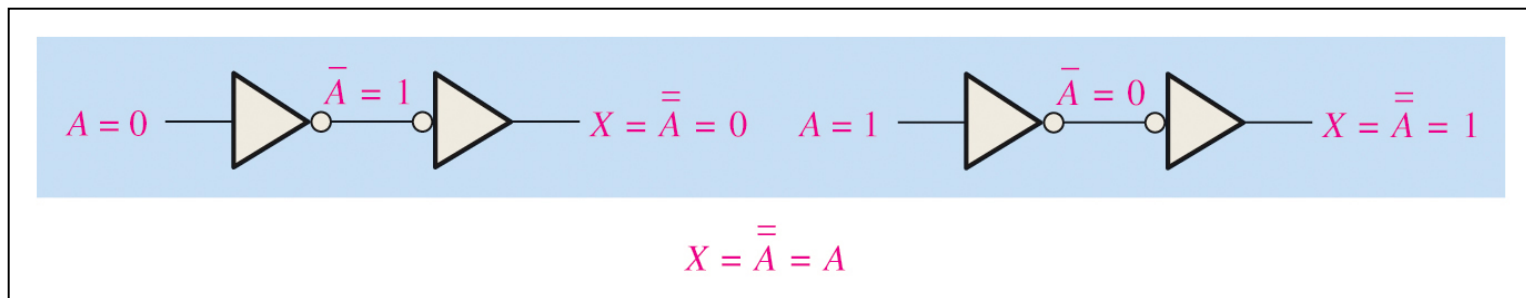
When the inputs to an AND gate are unequal (complements), one of the two always equals 0. When either input equals 0, the gate output is  $X = 0$ . Therefore, the output from the AND gate equals 0 whenever the inputs are unequal (complementary).



## Rules of Boolean Algebra

### Rule 9: $\overline{\overline{A}} = A$

When a value is inverted, it is the complement of the original value. When inverted a second time, it returns to its original value. Thus,  $A = 0$  inverted twice equals 0 and  $A = 1$  inverted twice equals 1.



## Rules of Boolean Algebra

### Rule 10: $A + AB = A$

The circuit and truth table (below) can be used to demonstrate this rule. The truth table shows the outputs from the circuit for every possible combination of A and B. In each case, the output from the OR gate equals the value of A. Thus,  $A + AB$  always equals the value of A.

<i>A</i>	<i>B</i>	<i>AB</i>	<i>A + AB</i>
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	1

↑ equal ↑

The diagram shows a logic circuit with two inputs, A and B. Input A is connected to both an AND gate and an OR gate. Input B is connected to the AND gate. The output of the AND gate is connected to the OR gate. A red arrow points from the output of the AND gate to the OR gate. A straight connection from input A to the output is labeled 'straight connection'.

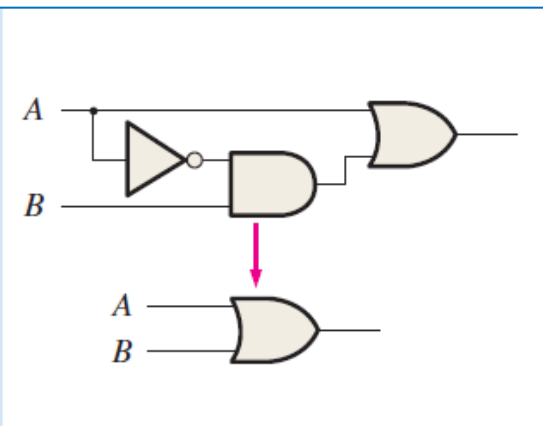
## Rules of Boolean Algebra

### Rule 11: $A + \overline{A}B = A + B$

The circuits and truth table (below) demonstrate this rule. The truth table shows the outputs from the two circuits are equal for every possible combination of  $A$  and  $B$ . As such, the two functions ( $A + \overline{A}B$ ) and ( $A + B$ ) are equal.

$A$	$B$	$\overline{A}B$	$A + \overline{A}B$	$A + B$
0	0	0	0	0
0	1	1	1	1
1	0	0	1	1
1	1	0	1	1

↑ equal ↑



## Rules of Boolean Algebra

### Rule 12: $(A + B)(A + C) = A + BC$

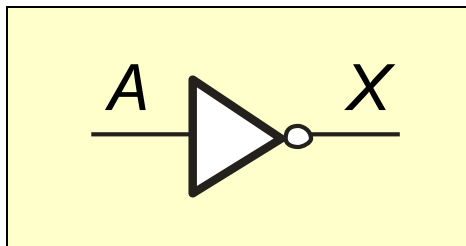
The circuits and truth table (below) demonstrate this rule. The truth table shows the outputs from the two circuits are equal for every possible combination of  $A$  and  $B$ . As such, the two functions  $(A + B)(A + C)$  and  $(A + BC)$  are equal.

$A$	$B$	$C$	$A + B$	$A + C$	$(A + B)(A + C)$	$BC$	$A + BC$
0	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0
0	1	0	1	0	0	0	0
0	1	1	1	1	1	1	1
1	0	0	1	1	1	0	1
1	0	1	1	1	1	0	1
1	1	0	1	1	1	0	1
1	1	1	1	1	1	1	1



## The Inverter

The inverter performs the Boolean **NOT** operation. When the input is LOW, the output is HIGH; when the input is HIGH, the output is LOW.



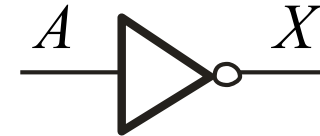
Input	Output
$A$	$X$
LOW (0)	HIGH (1)
HIGH (1)	LOW (0)

The **NOT** operation (complement) is shown with an overbar. Thus, the Boolean expression for an inverter is  $X = \overline{A}$ .

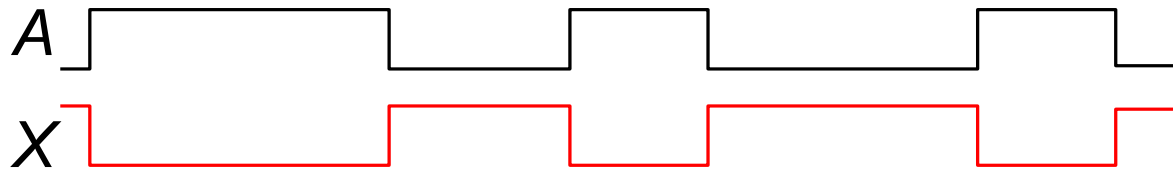


# Ch.3 Summary

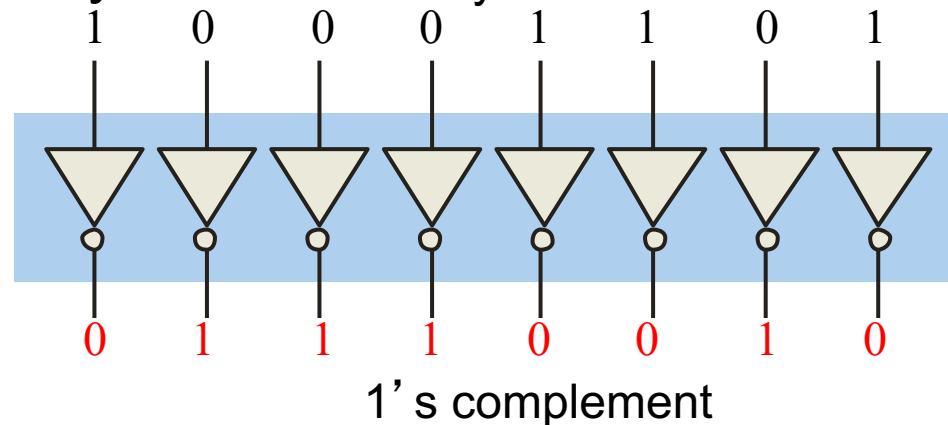
## An Inverter Application



Example waveforms:

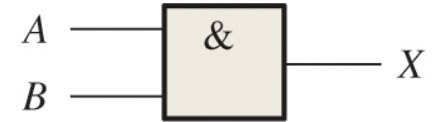
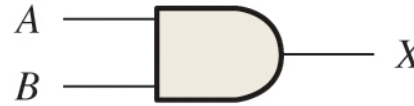


A group of inverters can be used to form the 1's complement of a binary number



## Ch.3 Summary

# The AND Gate



The **AND** gate produces a HIGH output when all inputs are HIGH; otherwise, the output is LOW. For a 2-input gate, the truth table is

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	0
1	0	0
1	1	1

The **AND** operation is usually shown with a dot between the variables but it may be implied (no dot). Thus, the AND operation is written as  $X = A \cdot B$  or  $X = AB$ .

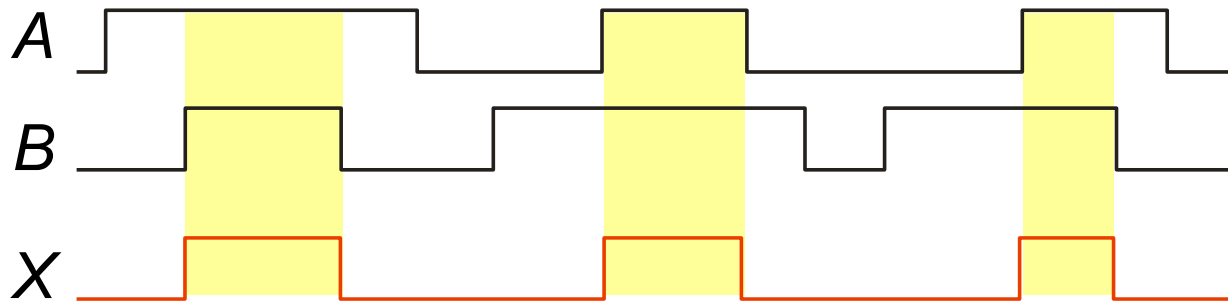


# Ch.3 Summary

## The AND Gate



Example waveforms:



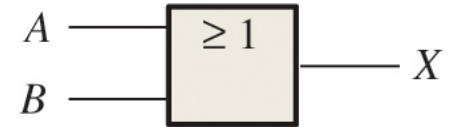
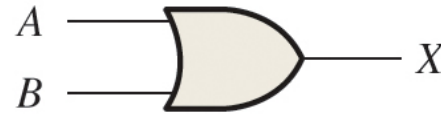
The AND operation is used in computer programming as a selective mask. If you want to retain certain bits of a binary number but reset the other bits to 0, you could set a mask with 1's in the position of the retained bits.

If the binary number 10100011 is ANDed with the mask 00001111, what is the result? **00000011**



## Ch.3 Summary

# The OR Gate



The **OR gate** produces a HIGH output if any input is HIGH; if all inputs are LOW, the output is LOW. For a 2-input gate, the truth table is

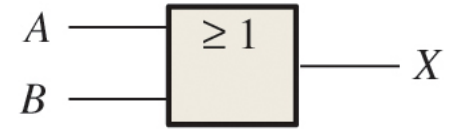
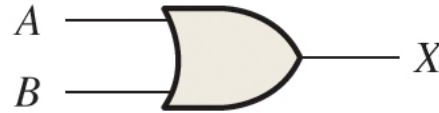
Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	1

The **OR** operation is shown with a plus sign (+) between the variables. Thus, the OR operation is written as  $X = A + B$ .

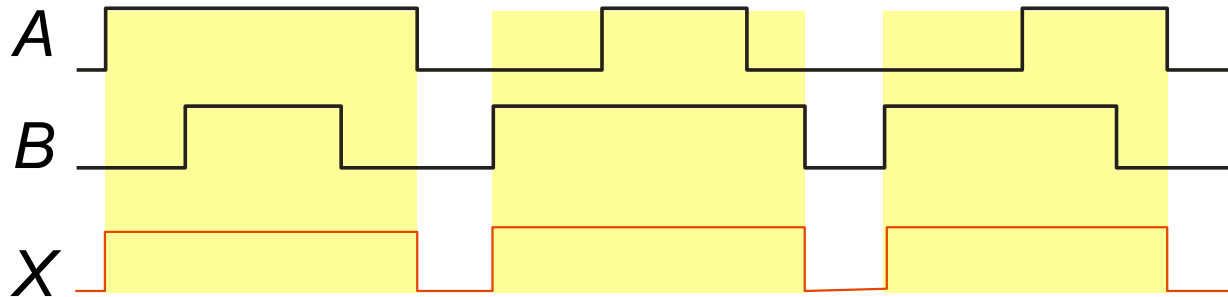


## Ch.3 Summary

# The OR Gate



Example waveforms:



The OR operation can be used in computer programming to set certain bits of a binary number to 1.

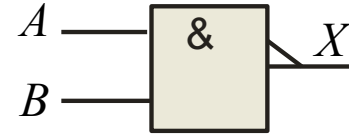
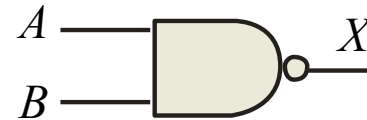
ASCII letters have a 1 in the bit 5 position for lower case letters and a 0 in this position for capitals. (Bit positions are numbered from right to left starting with 0.) What will be the result if you OR an ASCII letter with the 8-bit mask 00100000?

**The resulting letter will be lower case.**



## Ch.3 Summary

# The NAND Gate



The **NAND gate** produces a LOW output when all inputs are HIGH; otherwise, the output is HIGH. For a 2-input gate, the truth table is

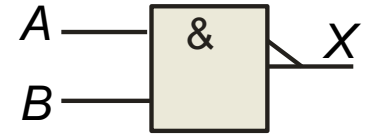
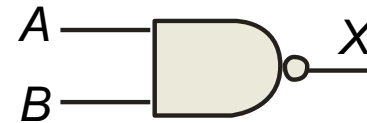
Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	1
0	1	1
1	0	1
1	1	0

The **NAND** operation is shown with a dot between the variables and an over-bar covering them. Thus, the NAND operation is written as  $X = \overline{A \cdot B}$  (Or,  $X = \overline{AB}$ .)

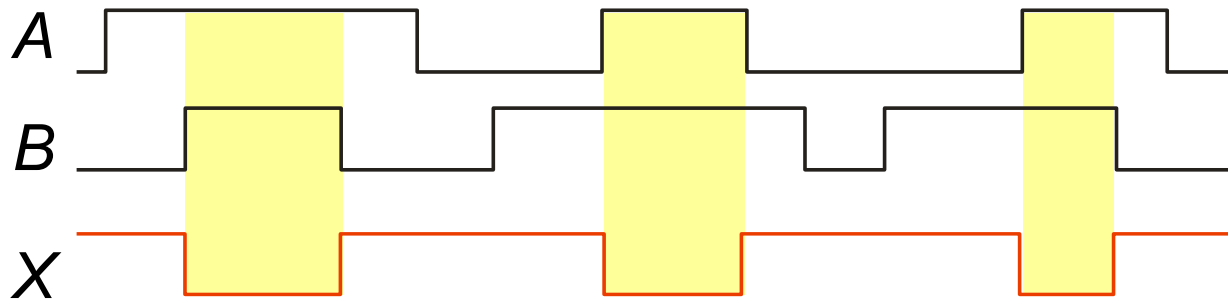


# Ch.3 Summary

## The NAND Gate

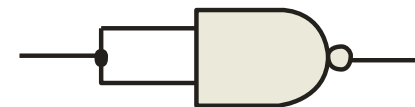


Example waveforms:



The NAND gate is referred to as a “universal” gate because all other basic gates can be constructed from NAND gates.

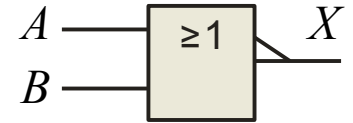
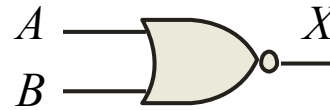
How would you connect a 2-input NAND gate to form a basic inverter?





## Ch.3 Summary

# The NOR Gate



The **NOR gate** produces a LOW output if any input is HIGH; if all inputs are LOW, the output is HIGH. For a 2-input gate, the truth table is

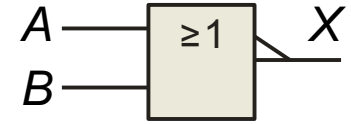
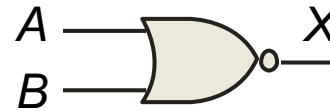
Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	1
0	1	0
1	0	0
1	1	0

The **NOR** operation is shown with a plus sign (+) between the variables and an overbar covering them. Thus, the NOR operation is written as  $X = A + B$ .

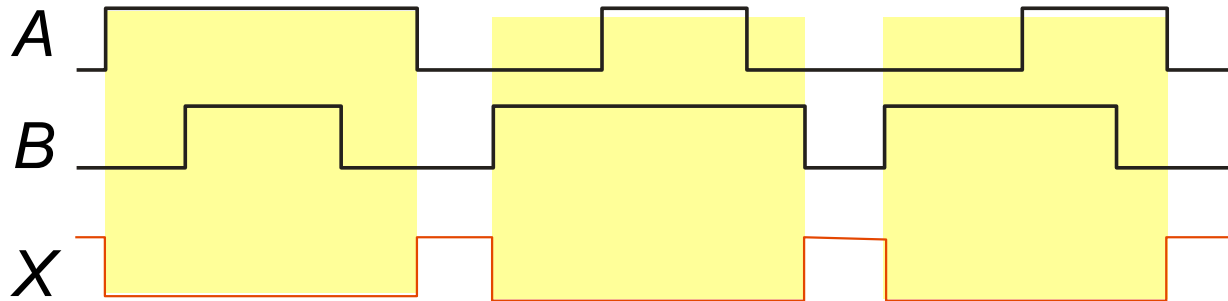


# Ch.3 Summary

## The NOR Gate



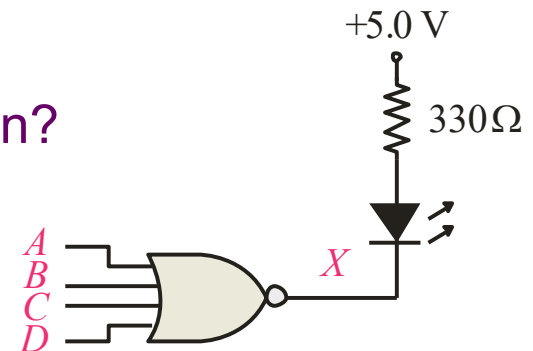
Example waveforms:



The NOR operation will produce a LOW if any input is HIGH.

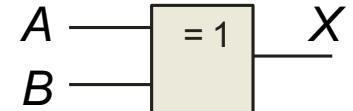
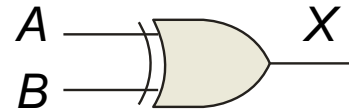
When is the LED is ON for the circuit shown?

The LED will be on when any of the four inputs are HIGH.



## Ch.3 Summary

# The XOR Gate



The **XOR** gate produces a HIGH output only when both inputs are at opposite logic levels. The truth table is

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	0

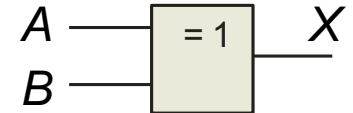
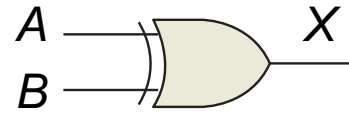
The **XOR** operation is written as  $X = A\bar{B} + \bar{A}B$ . Alternatively, it can be written with a circled plus sign between the variables as

$$X = A \oplus B.$$

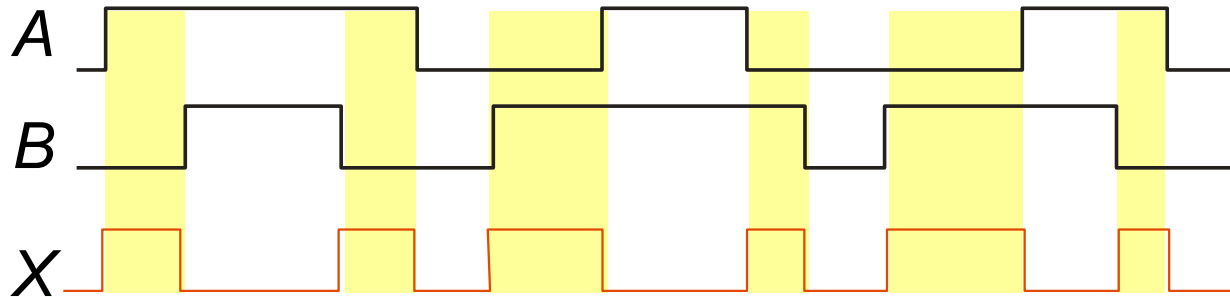


## Ch.3 Summary

# The XOR Gate



Example waveforms:



Notice that the XOR gate will produce a HIGH only when exactly one input is HIGH.

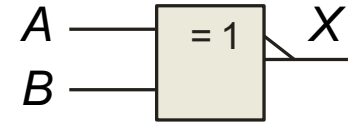
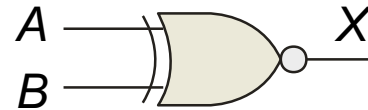
If the *A* and *B* waveforms are both inverted for the above waveforms, how is the output affected?

**There is no change in the output.**



## Ch.3 Summary

# The XNOR Gate



The **XNOR gate** produces a HIGH output only when both inputs are at the same logic level. The truth table is

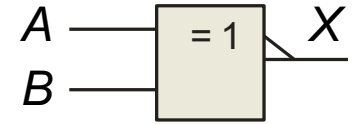
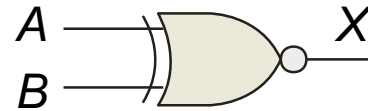
Inputs		Output
A	B	X
0	0	1
0	1	0
1	0	0
1	1	1

The **XNOR** operation shown as  $X = \overline{A}B + A\overline{B}$ . Alternatively, the XNOR operation can be shown with a circled dot between the variables. Thus, it can be shown as  $X = \overline{A \oplus B}$ .

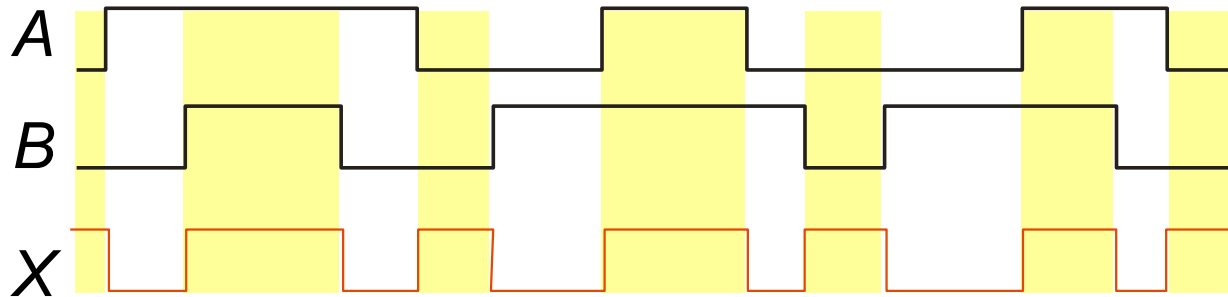


## Ch.3 Summary

# The XNOR Gate



Example waveforms:



Notice that the XNOR gate will produce a HIGH when both inputs are the same. This makes it useful for comparison functions.

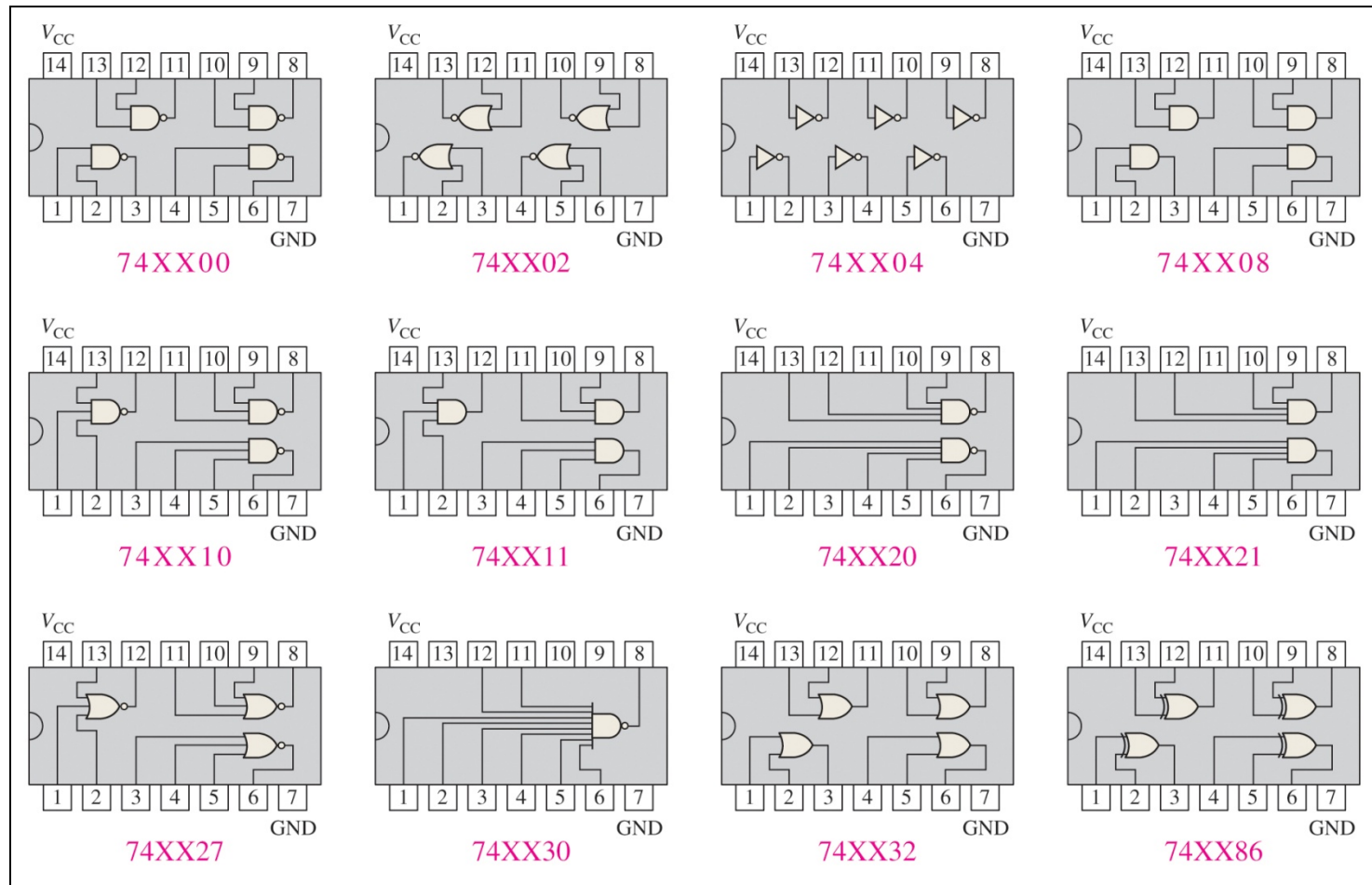
If the  $A$  waveform is inverted but  $B$  remains the same, how is the output affected?

**The output will be inverted.**



# Ch.3 Summary

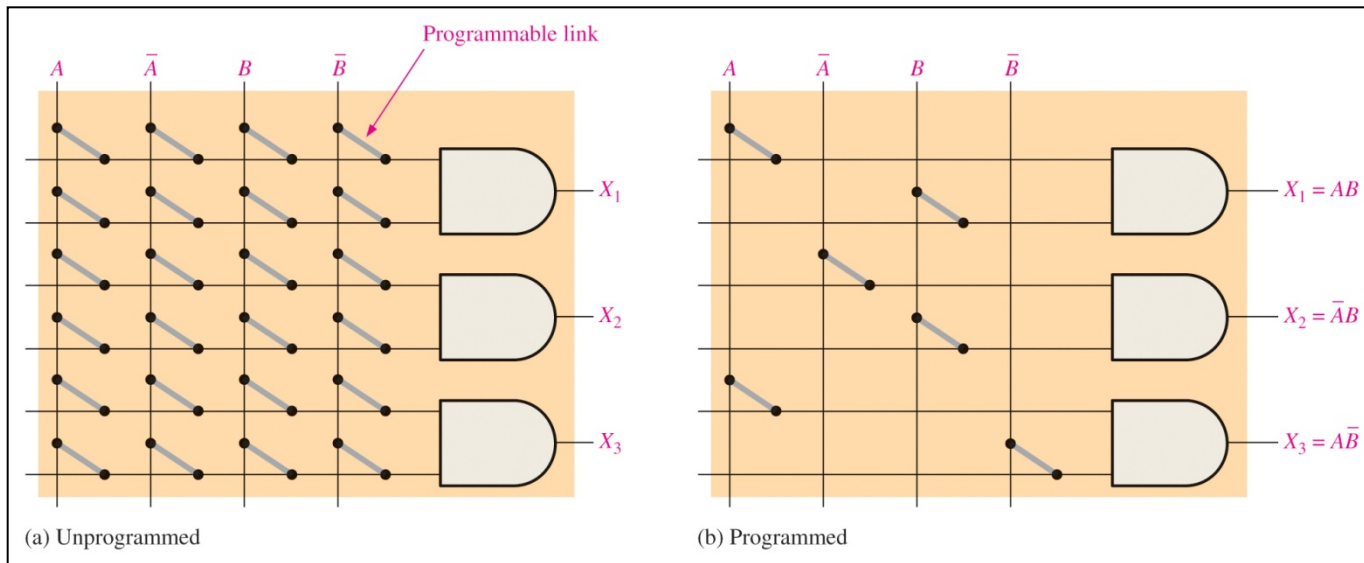
## Fixed Function Logic



## Ch.3 Summary

# Programmable Logic: AND Array

An **AND Array** contains a number of AND gates that are connected to the component inputs via “programmable” links.



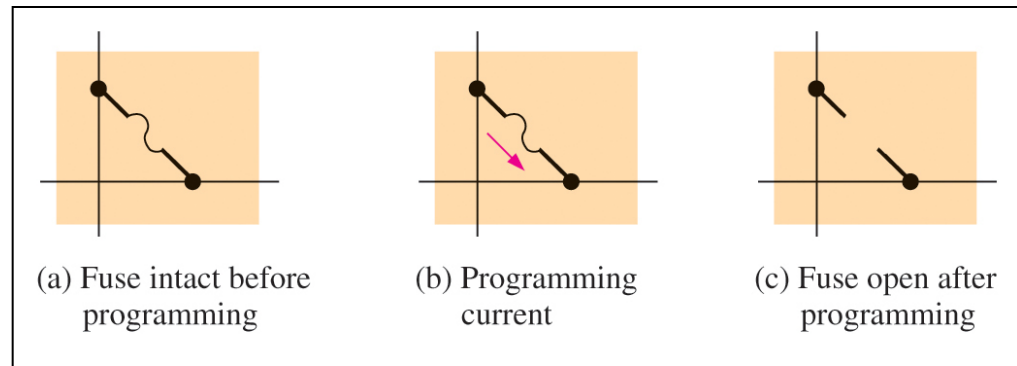
The device is programmed by identifying the desired input connections to each AND gate and removing the others (electronically).



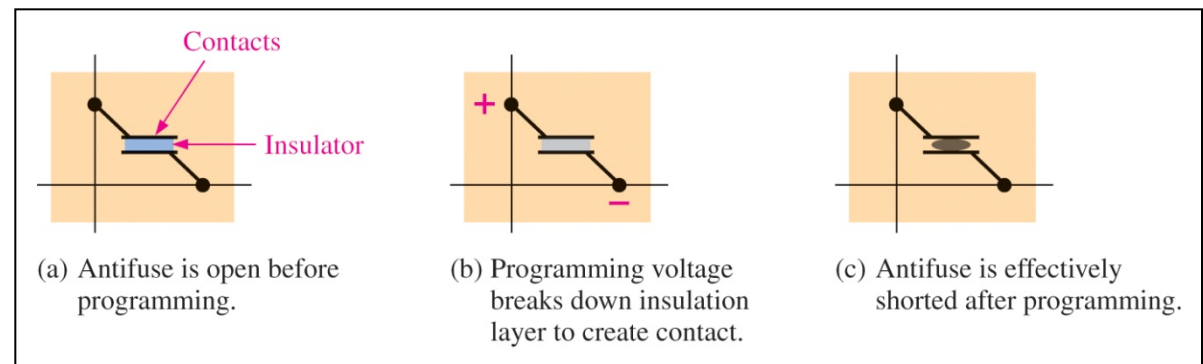


## Programmable Link Technologies

### Fuse Technology



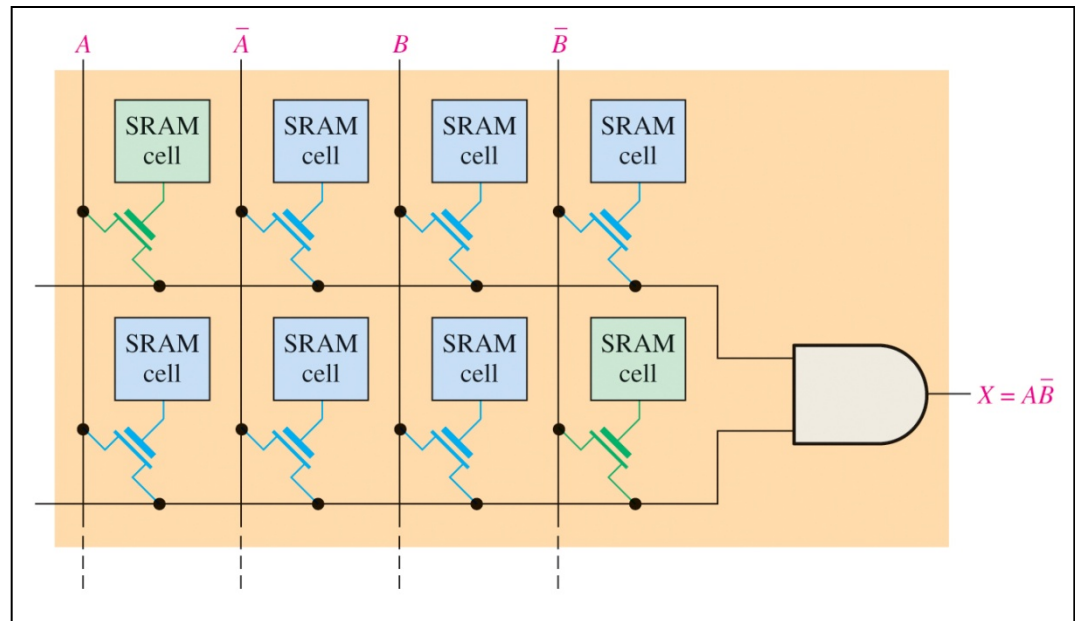
### Antifuse Technology



## SRAM Technology

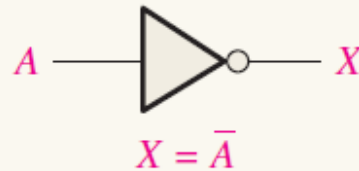
**Static-Random-Access-Memory (SRAM)** uses cell outputs to turn the links (transistors) on or off. A (1) in a cell turns its output transistor ON, while a (0) turns its output transistor OFF.

SRAM is volatile, meaning that it loses its data when power is disconnected.



## Ch.3 Summary

# VHDL and Verilog: Inverter



### VHDL

```
entity Inverter is
  port (A: in bit; X: out bit);
end entity Inverter;
architecture NOTfunction of Inverter is
begin
  X <= not A;
end architecture NOTfunction;
```

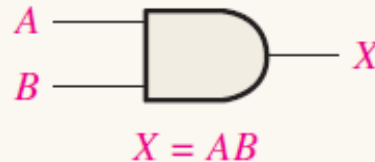
### Verilog

```
module Inverter (A, X);
  input A;
  output X;
  assign X = !A;
endmodule
```



## Ch.3 Summary

# VHDL and Verilog: AND Gate



### VHDL

```
entity ANDgate is
  port (A, B: in bit; X: out bit);
end entity ANDgate;
architecture ANDfunction of ANDgate is
begin
  X <= A and B;
end architecture ANDfunction;
```

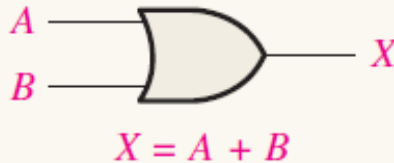
### Verilog

```
module ANDgate (A, B, X);
  input A, B;
  output X;
  assign X = A && B;
endmodule
```



## Ch.3 Summary

# VHDL and Verilog: OR Gate



### VHDL

```
entity ORgate is
  port (A, B: in bit; X: out bit);
end entity ORgate;
architecture ORfunction of ORgate is
begin
  X <= A or B;
end architecture ORfunction;
```

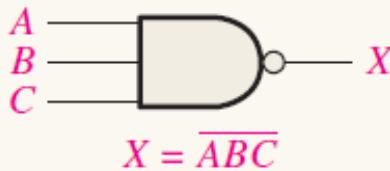
### Verilog

```
module ORgate (A, B, X);
  input A, B;
  output X;
  assign X = A || B;
endmodule
```



## Ch.3 Summary

# VHDL and Verilog: NAND Gate



### VHDL

```
entity NANDgate is
  port (A, B, C: in bit; X: out bit);
end entity NANDgate;
architecture NANDfunction of NANDgate is
begin
  X <= A nand B nand C;
end architecture NANDfunction;
```

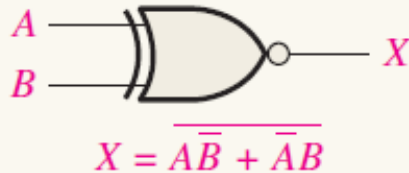
### Verilog

```
module NANDgate (A, B, C, X);
  input A, B, C;
  output X;
  assign X = !(A && B && C);
endmodule
```



## Ch.3 Summary

# VHDL and Verilog: XNOR Gate



### VHDL

```
entity XNORgate is
  port (A, B: in bit; X: out bit);
end entity XNORgate;
architecture XNORfunction of XNORgate is
begin
  X <= A xnor B;
end architecture XNORfunction;
```

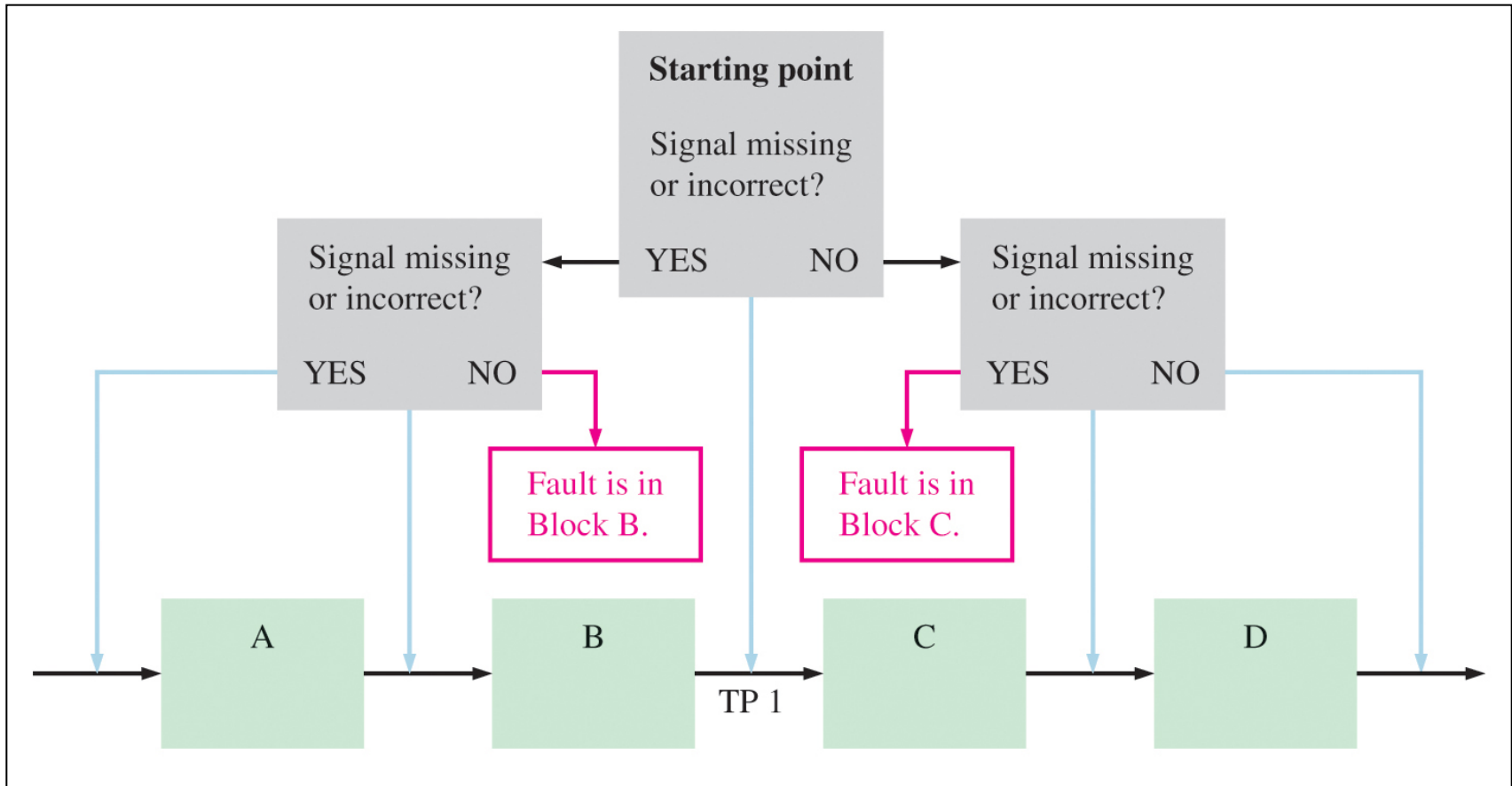
### Verilog

```
module XNORgate (A, B, X);
  input A, B;
  output X;
  assign X = !((A && !B) || (!A && B));
endmodule
```



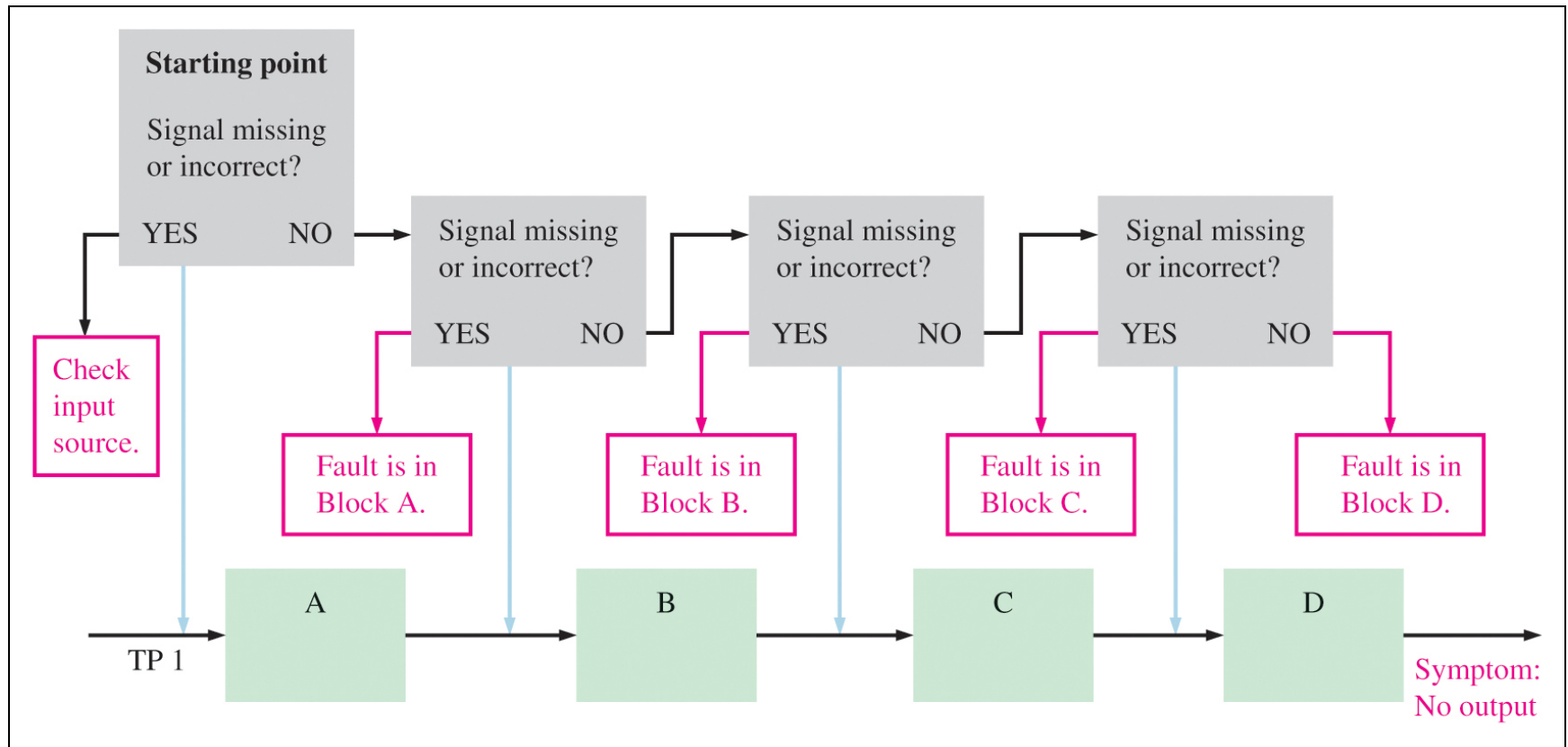
## Ch.3 Summary

# Troubleshooting: Half-splitting Method





## Troubleshooting: Signal Tracing Method



# Ch.3 Summary

## Key Terms

***Inverter*** A logic circuit that inverts or complements its inputs.

***Truth table*** A table showing the inputs and corresponding output(s) of a logic circuit.

***Timing diagram*** A diagram of waveforms showing the proper time relationship of all of the waveforms.

***Boolean algebra*** The mathematics of logic circuits.

***AND gate*** A logic gate that produces a HIGH output only when all of its inputs are HIGH.



# Ch.3 Summary

## Key Terms

**OR gate** A logic gate that produces a HIGH output when one or more inputs are HIGH.

**NAND gate** A logic gate that produces a LOW output only when all of its inputs are HIGH.

**NOR gate** A logic gate that produces a LOW output when one or more inputs are HIGH.

**Exclusive-OR gate** A logic gate that produces a HIGH output only when its two inputs are at opposite levels.

**Exclusive-NOR gate** A logic gate that produces a LOW output only when its two inputs are at opposite levels.



## Quiz

1. The truth table for a 2-input AND gate is

a.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	0

b.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	1
0	1	0
1	0	0
1	1	0

c.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	0
1	0	0
1	1	1

d.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	1



## Quiz

2. The truth table for a 2-input NOR gate is

a.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	0

b.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	1
0	1	0
1	0	0
1	1	0

c.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	0
1	0	0
1	1	1

d.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	1



# Ch.3 Summary

## Quiz

3. The truth table for a 2-input XOR gate is

a.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	0

b.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	1
0	1	0
1	0	0
1	1	0

c.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	0
1	0	0
1	1	1

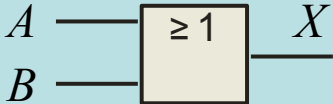
d.

Inputs		Output
<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	1



# Ch.3 Summary

## Quiz

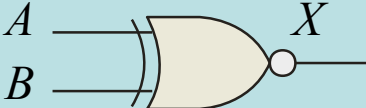
4. The symbol  is for a(n)

- a. OR gate
- b. AND gate
- c. NOR gate
- d. XOR gate



# Ch.3 Summary

## Quiz

5. The symbol  is for a(n)

- a. OR gate
- b. AND gate
- c. NOR gate
- d. XOR gate





## Quiz

6. A logic gate that produces a HIGH output only when all of its inputs are HIGH is a(n)

- a. OR gate
- b. AND gate
- c. NOR gate
- d. NAND gate



## Quiz

7. The expression  $X = A \oplus B$  means

- a.  $A$  OR  $B$
- b.  $A$  AND  $B$
- c.  $A$  XOR  $B$
- d.  $A$  XNOR  $B$

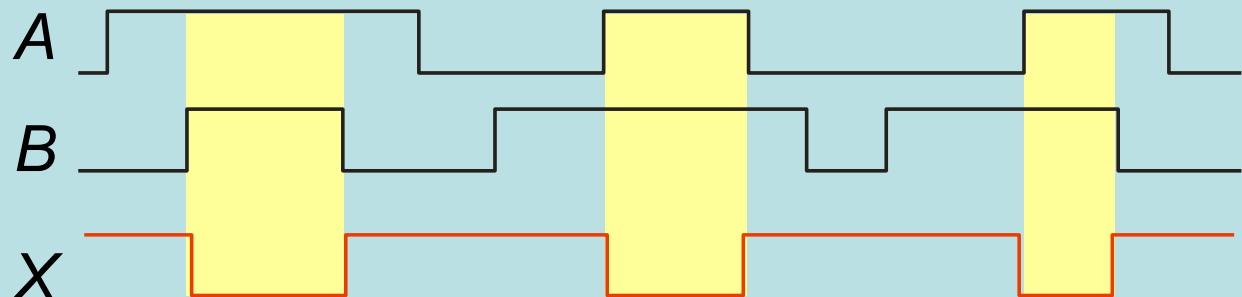


# Ch.3 Summary

## Quiz

8. A 2-input gate produces the output shown. (X represents the output.) This is a(n)

- a. OR gate
- b. AND gate
- c. NOR gate
- d. NAND gate



# Quiz

9. A 2-input gate produces a HIGH output only when the inputs agree. This type of gate is a(n)

- a. OR gate
- b. AND gate
- c. NOR gate
- d. XNOR gate



# Ch.3 Summary

## Quiz

10. The required logic for a PLD can be specified in an Hardware Description Language by
- a. text entry
  - b. schematic entry
  - c. state diagrams
  - d. all of the above



## Ch.3 Summary

# Answers

- |      |       |
|------|-------|
| 1. c | 6. b  |
| 2. b | 7. c  |
| 3. a | 8. d  |
| 4. a | 9. d  |
| 5. d | 10. d |



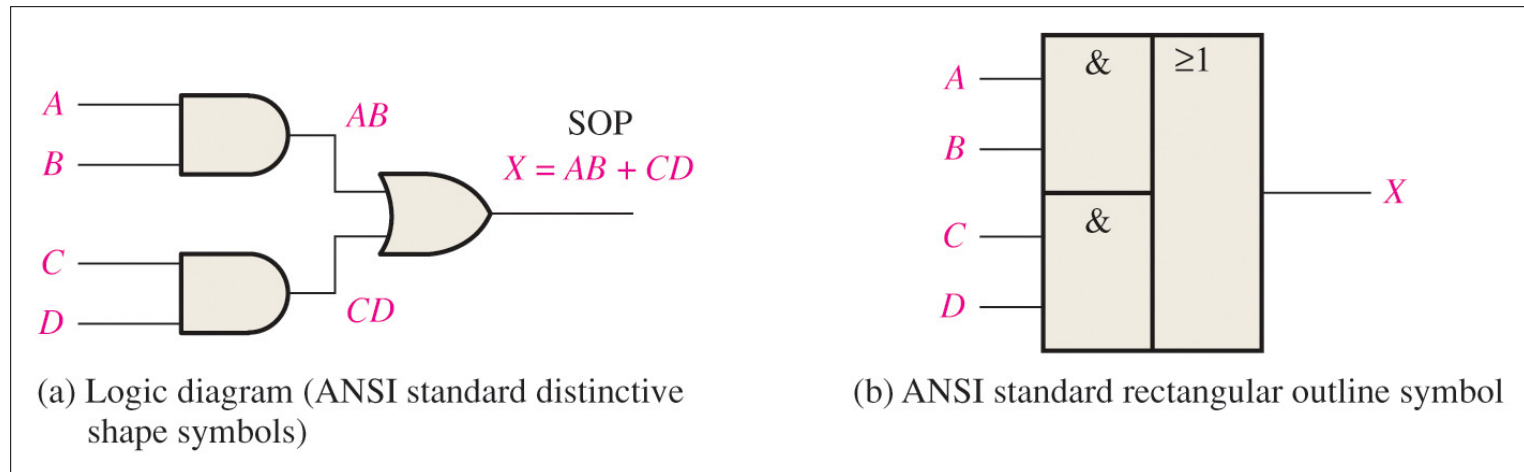
## Chapter 4

# Combinational Logic



## Combinational Logic Circuits

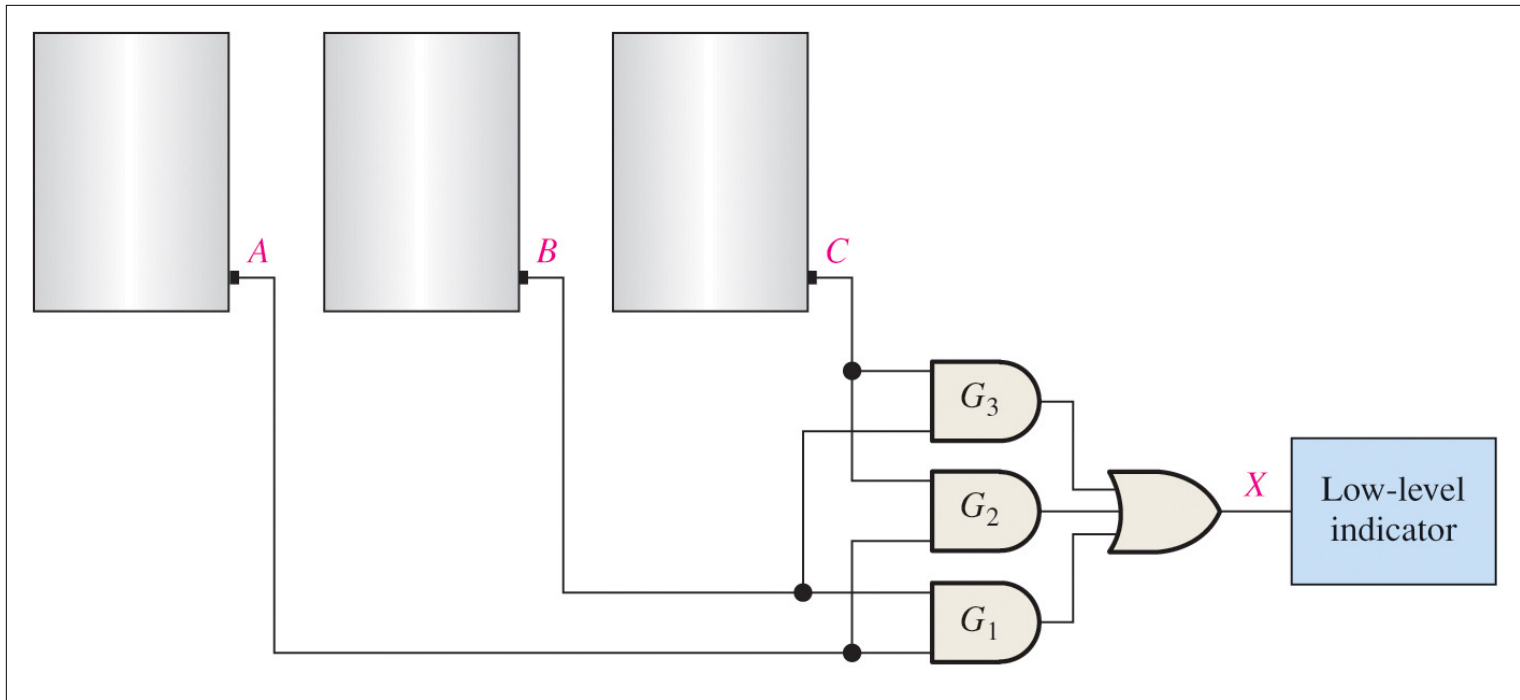
In Sum-of-Products (SOP) form, basic combinational circuits can be directly implemented with AND-OR combinations if the necessary complement terms are available.





## Combinational Logic Circuit Application

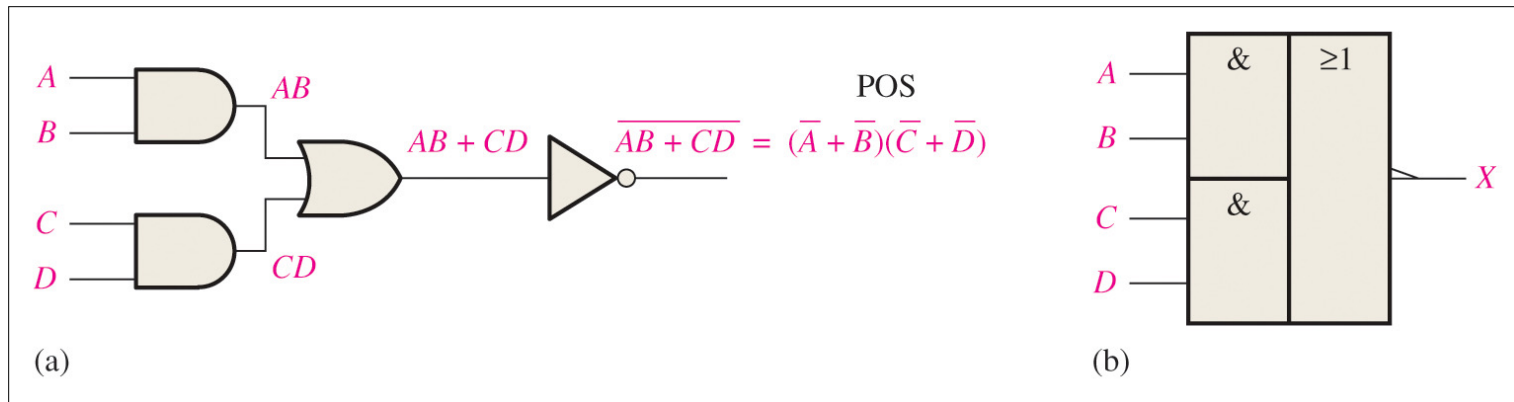
### A storage tank monitor



## Ch.4 Summary

# AND-OR-Invert Logic

When the output of a SOP form is inverted, the circuit is called an AND-OR-Invert circuit. The AOI configuration lends itself to product-of-sums (POS) implementation.



The output from an AND-OR-Invert logic circuit is LOW whenever A and B are HIGH, or C and D are HIGH.



# Ch.4 Summary

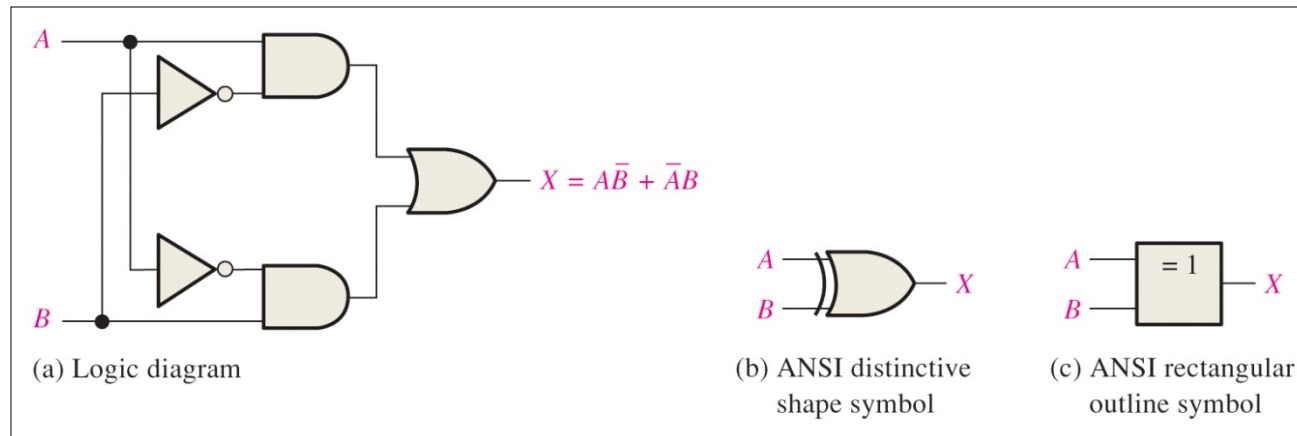
## Exclusive-OR Logic

The truth table for an exclusive-OR gate is shown (right). Note that the output is HIGH whenever A and B are unequal.

TABLE 4-2 • Truth table for an exclusive-OR.

A	B	X
0	0	0
0	1	1
1	0	1
1	1	0

The Boolean expression is  $X = \bar{A}B + A\bar{B}$



# Ch.4 Summary

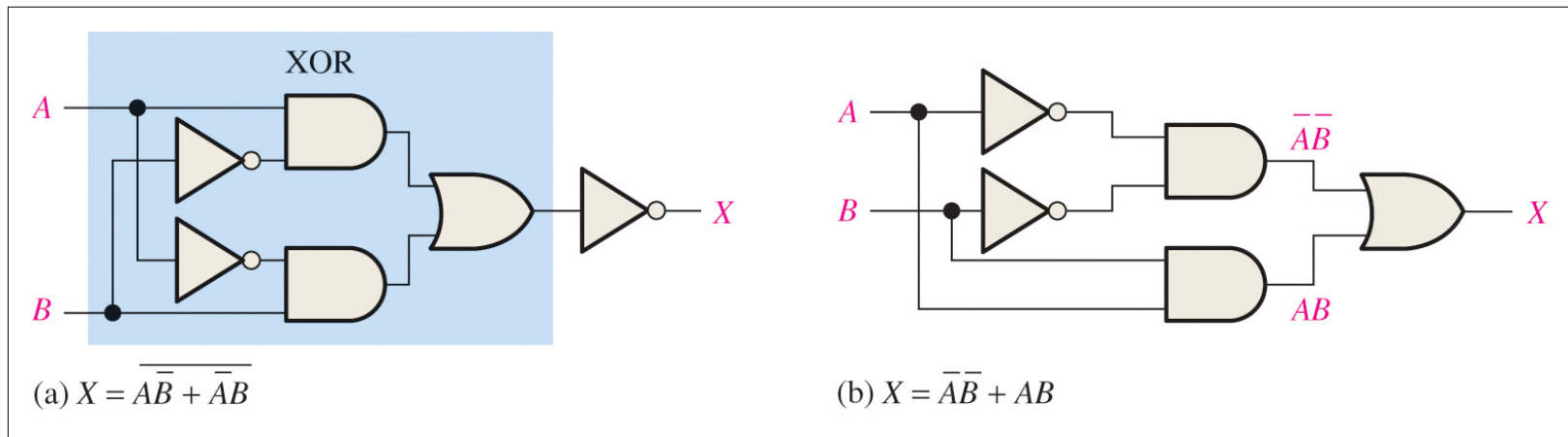
## Exclusive-NOR Logic

The truth table for an exclusive-NOR gate is shown (right). Note that the output is HIGH whenever A and B are equal.

TABLE 3-16 • Truth table for an exclusive-NOR gate.

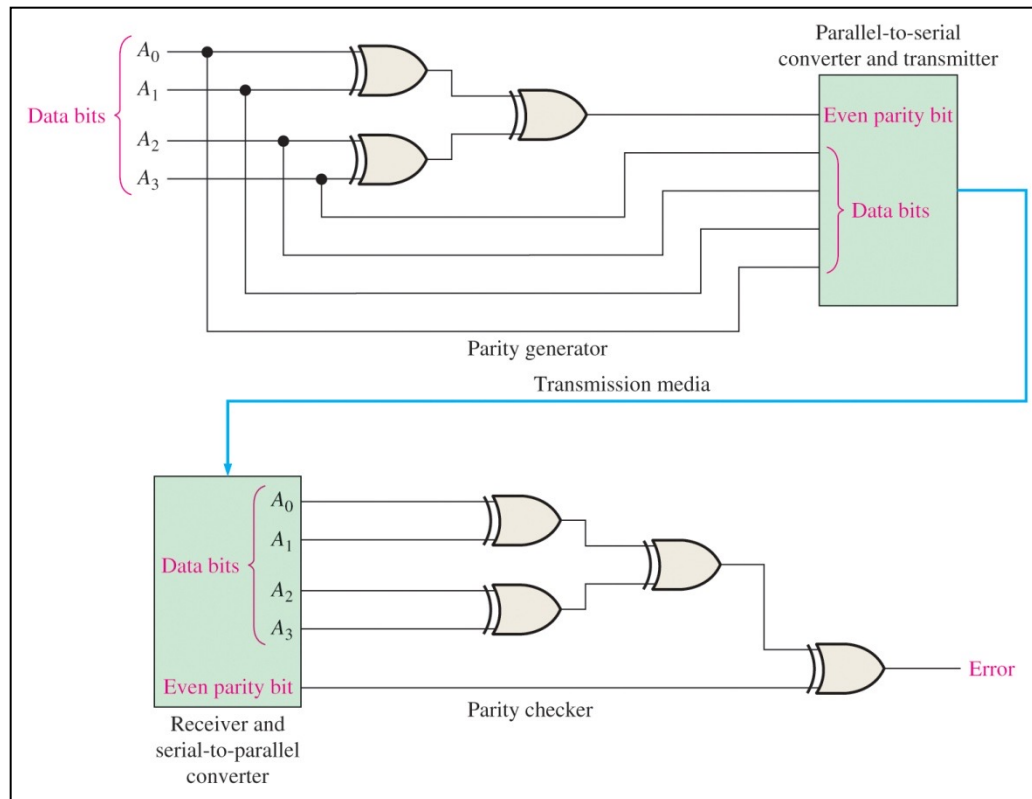
INPUTS		OUTPUT
A	B	X
0	0	1
0	1	0
1	0	0
1	1	1

The Boolean expression is  $X = \overline{A}B + A\overline{B}$



## An Exclusive-NOR Logic Application

### Data transmission with error detection



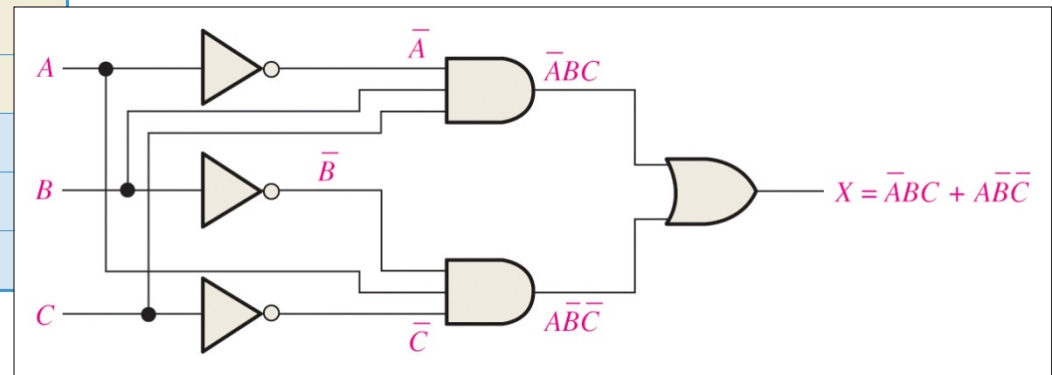
# Ch.4 Summary

## Implementing Combinational Logic

Implementing a SOP expression is done by first forming the AND terms; then the terms are ORed together.

TABLE 4-3

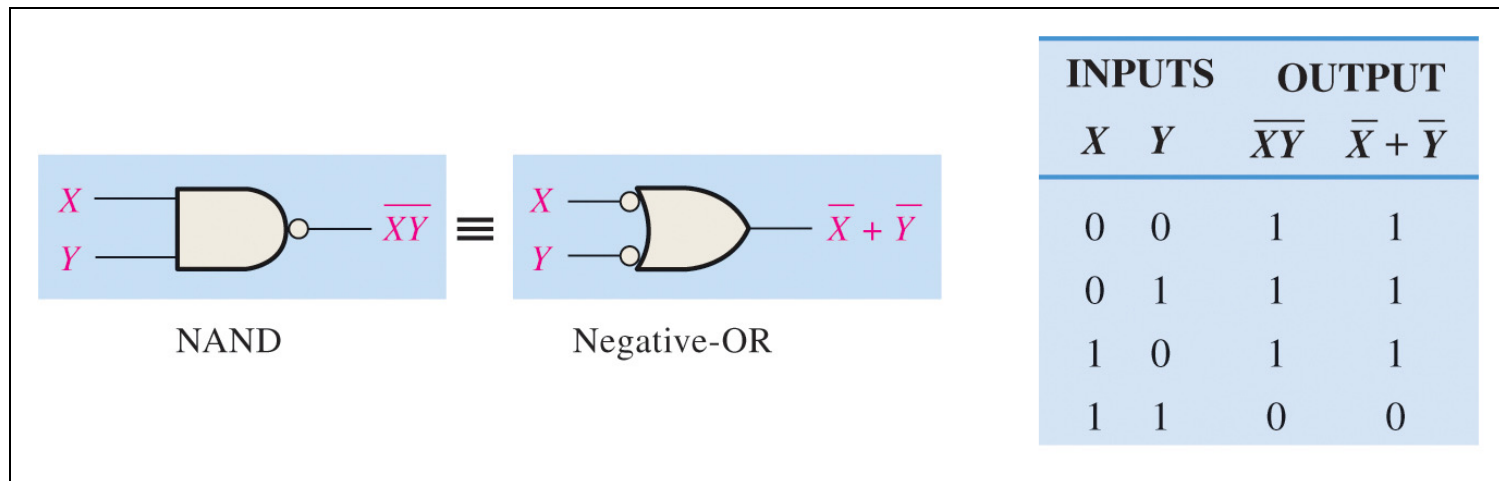
INPUTS			OUTPUT	PRODUCT TERM
A	B	C	X	
0	0	0	0	
0	0	1	0	
0	1	0	0	
0	1	1	1	$\bar{A}BC$
1	0	0	1	$A\bar{B}\bar{C}$
1	0	1	0	
1	1	0	0	
1	1	1	0	



## DeMorgan's Theorem

The complement of two or more ANDed variables equals the OR of the individual variable complements.

$$\overline{XY} = \overline{X} + \overline{Y}$$

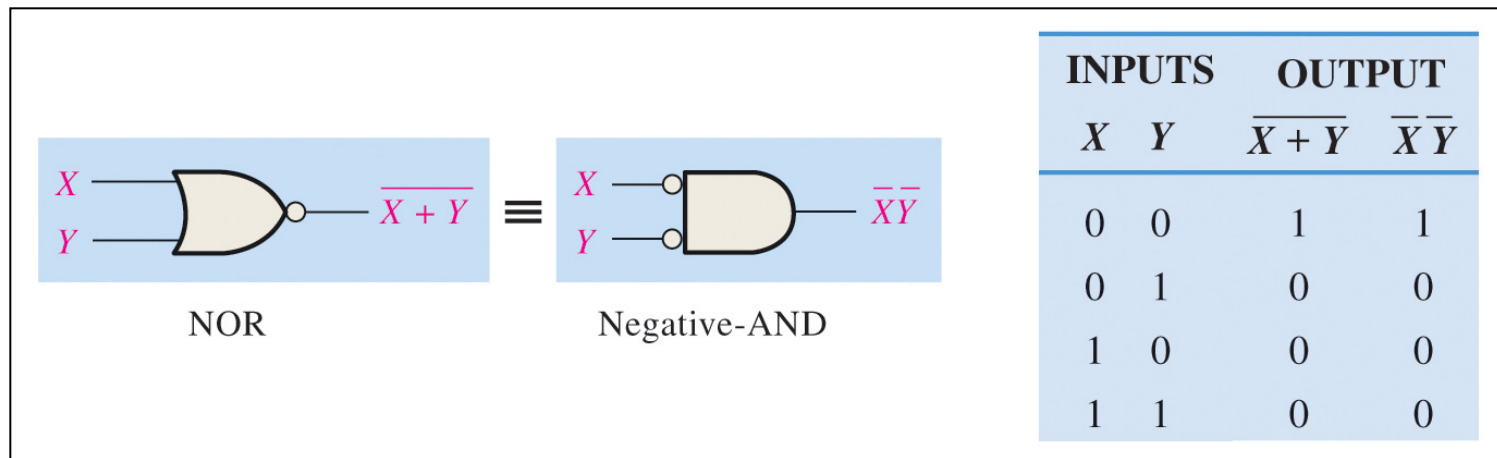


## Ch.4 Summary

# DeMorgan's Theorem

The complement of two or more ORed variables equals the AND of the individual variable complements.

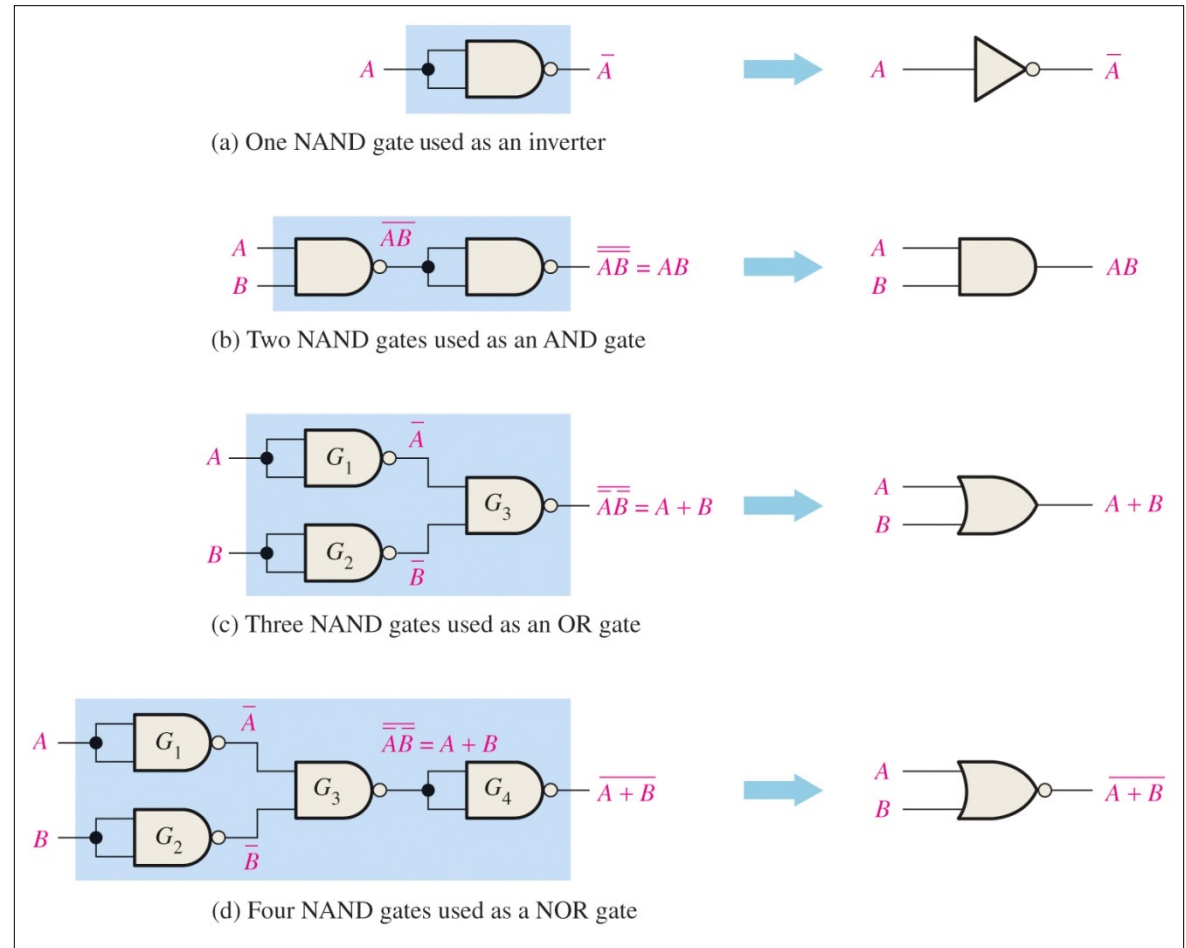
$$\overline{X + Y} = \overline{X} \cdot \overline{Y}$$





## Universal Gates

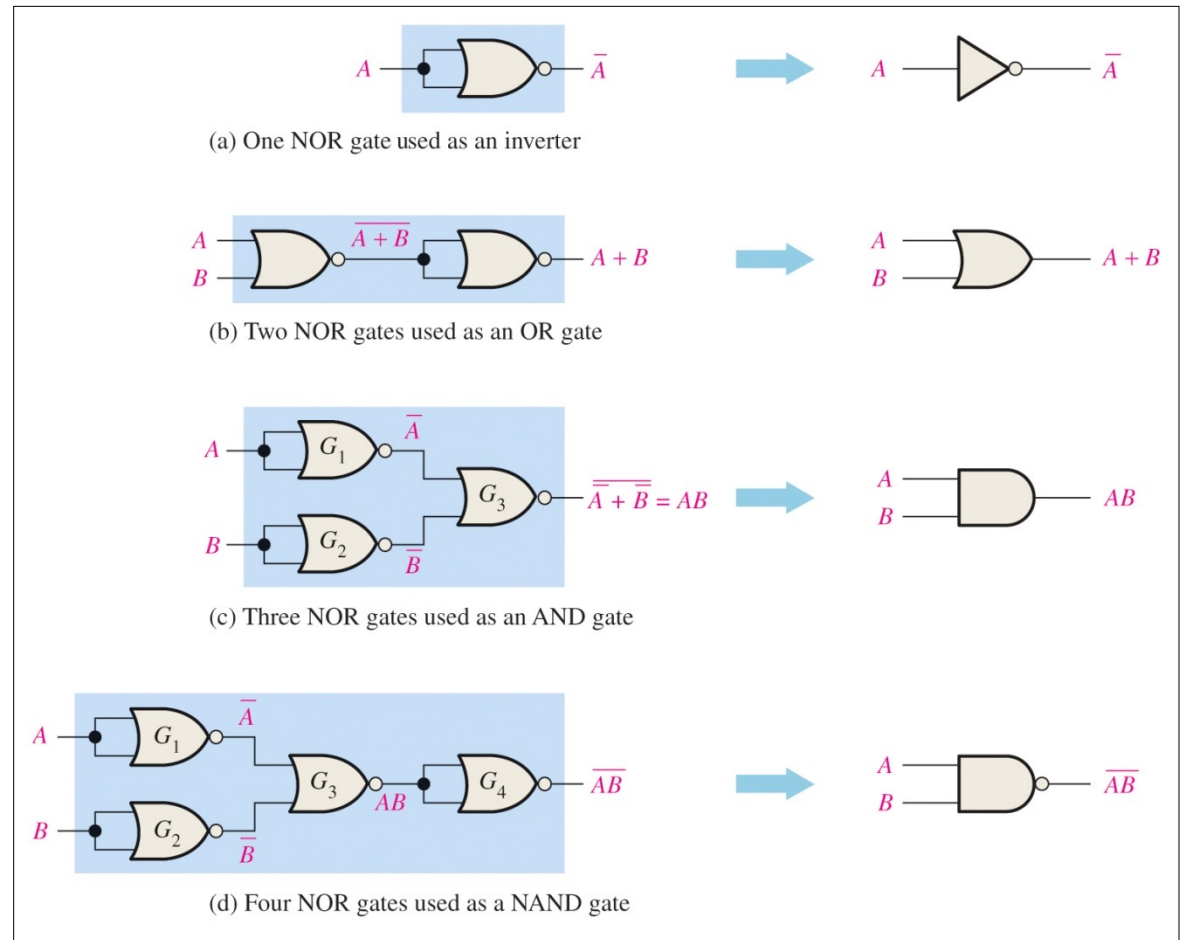
NAND gates are sometimes called **universal gates** because they can be used to produce the other basic Boolean functions.



# Ch.4 Summary

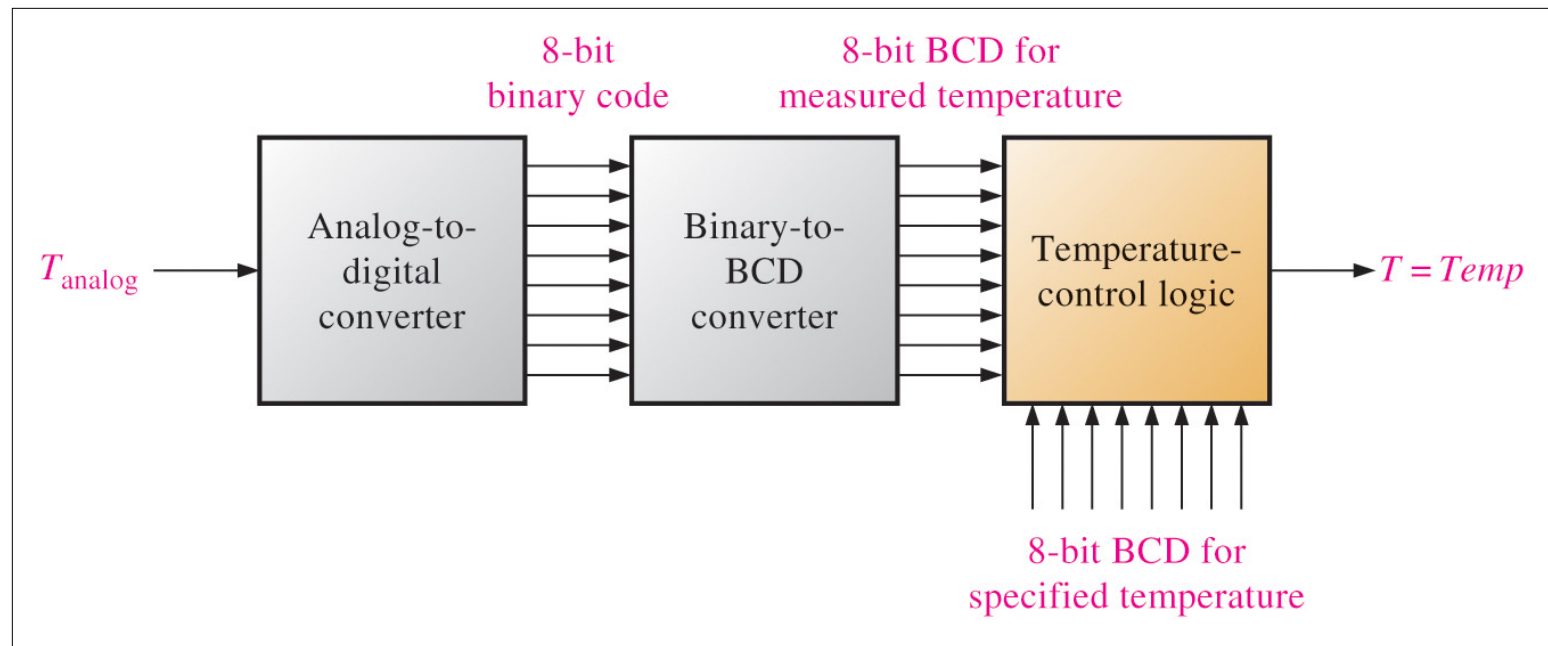
## Universal Gates

NOR gates are also called **universal gates** because they can be used to produce the other basic Boolean functions.



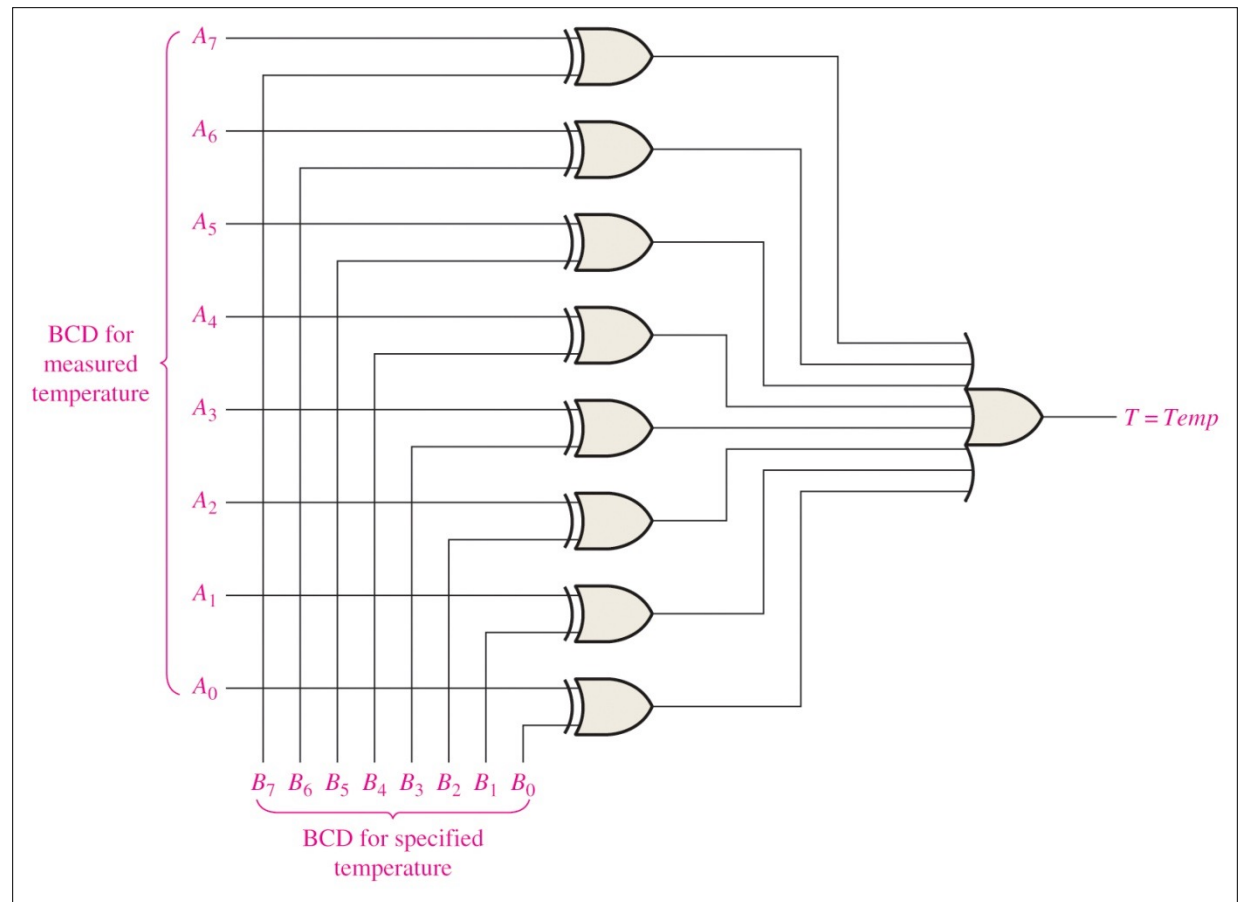
## Combinational Logic Application

### Temperature control circuit block diagram



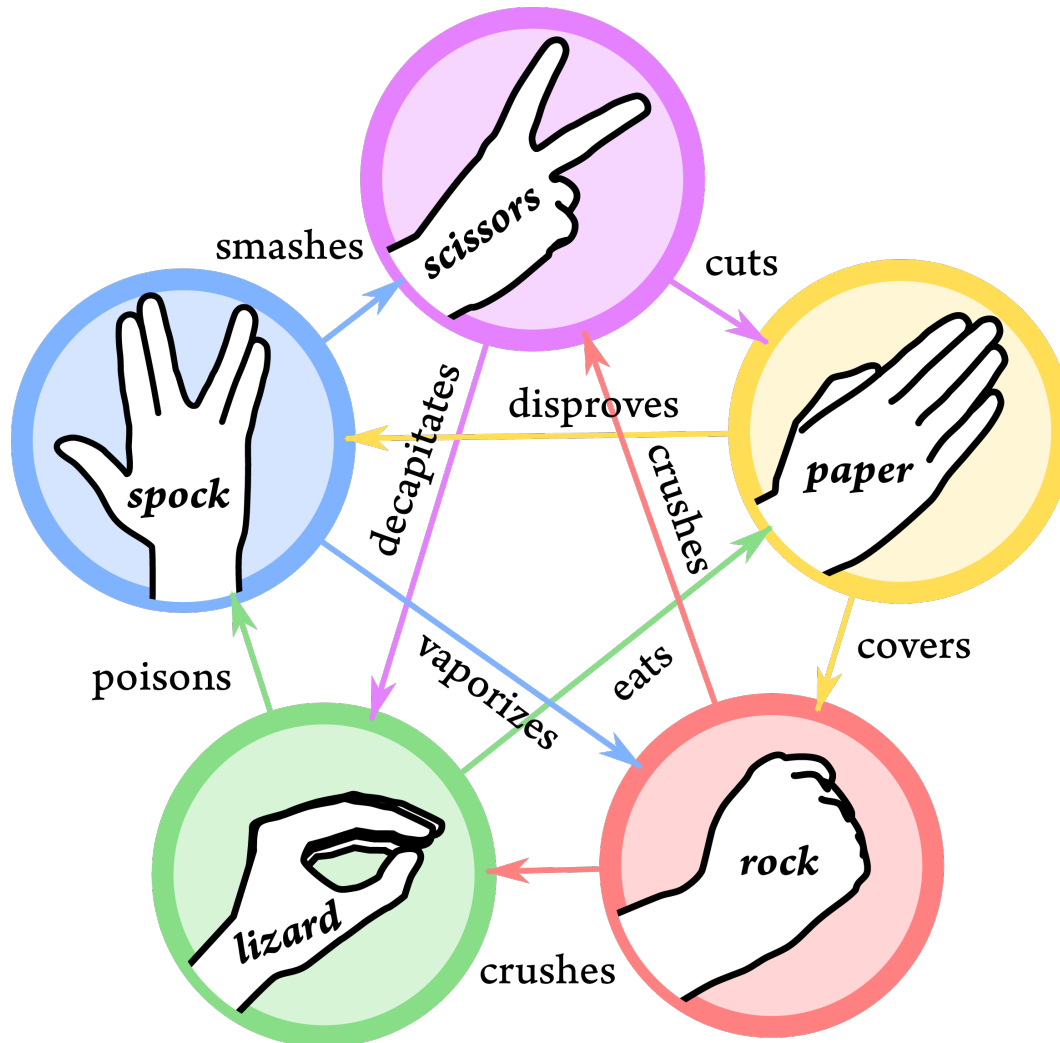
## Combinational Logic Application

Temperature control logic implementation



# BUILDING A SYSTEM FROM SCRATCH WITH TRUTH TABLES AND LOGIC





# Let's make a rock-scissors-paper game



# Inputs and outputs

- Inputs:
  - Player 1 can select rock, scissors or paper
  - Player 2 can select rock, scissors or paper
- Outputs:
  - Indication of winner





# Rock-scissors-paper truth table (1)

- Rock crushes scissors
- Scissors cuts paper
- Paper covers rock

Inputs		Outputs
Player 1	Player 2	Winner
Rock	Scissors	Player 1
Scissors	Rock	Player 2
Scissors	Paper	Player 1
Paper	Scissors	Player 2
Paper	Rock	Player 1
Rock	Paper	Player 2
Rock	Rock	No-one
Scissors	Scissors	No-one
Paper	Paper	No-one



# Rock-scissors-paper truth table (2)

- Represent paper with 1, scissors with 2, rock with 3
- Replace player 1 as winner with 1, player 2 as winner with 2, no-one / draw with 0

Inputs		Outputs
Player 1	Player 2	Winner
3	2	1
2	3	2
2	1	1
1	2	2
1	3	1
3	1	2
3	3	0
2	2	0
1	1	0



# Rock-scissors-paper truth table (3)

- Now convert to “binary”
- 3 -> 11
- 2 -> 10
- 1 -> 01
- 0 -> 00

Inputs		Outputs
Player 1	Player 2	Winner
11	10	01
10	11	10
10	01	01
01	10	10
01	11	01
11	01	10
11	11	00
10	10	00
01	01	00



# Rock-scissors-paper truth table (4)

- Split these into separate columns
- We now have a logic system with four inputs and two outputs (need two bits to represent each player choice, two bits to represent winner)

Inputs				Outputs	
A	B	C	D	X	Y
1	1	1	0	0	1
1	0	1	1	1	0
1	0	0	1	0	1
0	1	1	0	1	0
0	1	1	1	0	1
1	1	0	1	1	0
1	1	1	1	0	0
1	0	1	0	0	0
0	1	0	1	0	0



# Rock-scissors-paper truth table (5)

- This is only a partial table, as some input combinations are not used:
  - What if A, B, C and D are all zero?
    - Consider this to be a “don’t care” scenario as it does not happen in the game
- With this truth table we can find the “combinational logic” required to implement it

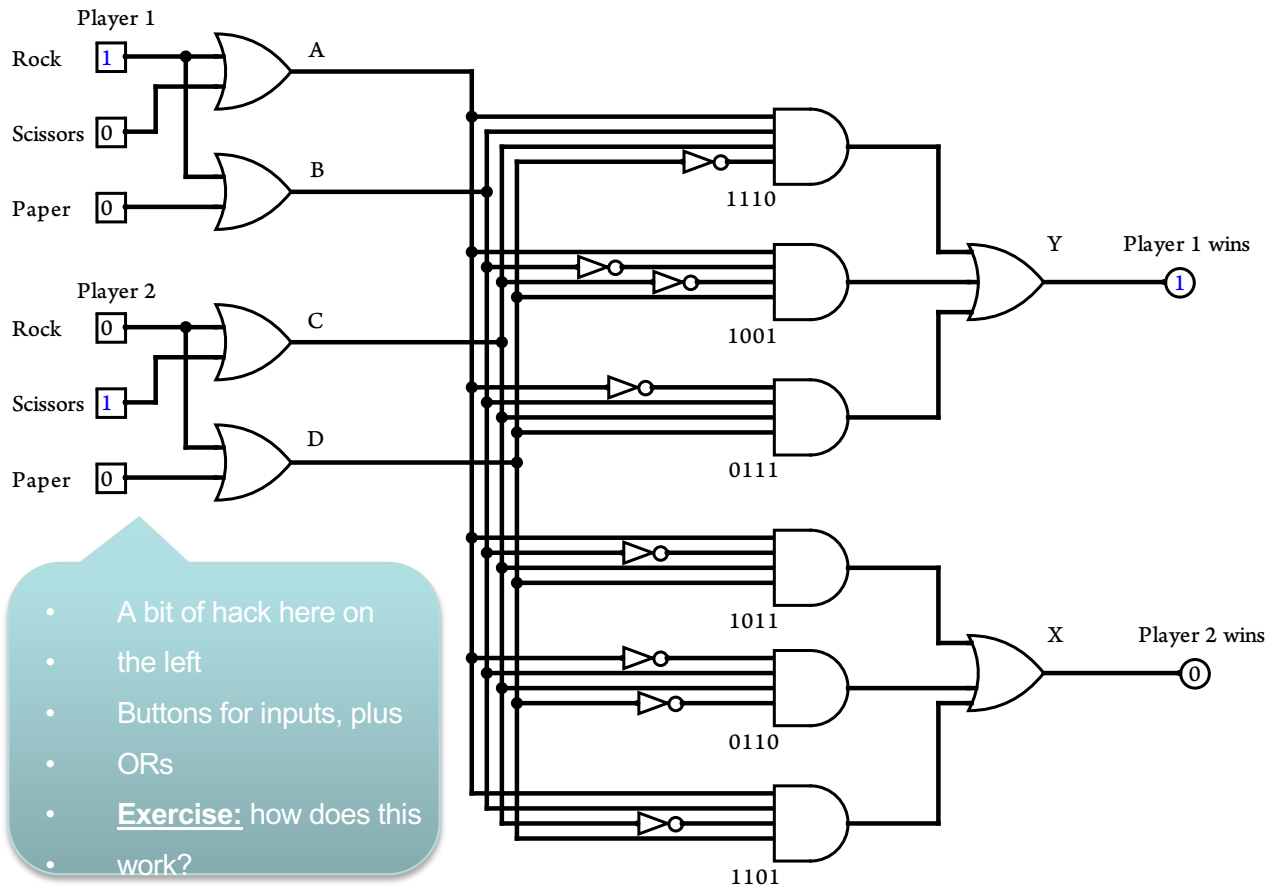


# Sum of products

- For every output line with a 1 in it, write out corresponding ABCD:
  - e.g. for Y, that is 1110, 1001, 0111
- Convert to sum-of-products form:
  - $Y = ABC\bar{D} + A\bar{B}\bar{C}D + \bar{A}BCD$
- Three ANDs, an OR, some NOTs
- Do same thing for X



# Complete circuit



# We can simplify using Boolean algebra, Karnaugh maps, etc. to reduce the complexity/number of gates used

## This is a Karnaugh map for X

		cd			
		00	01	11	10
ab	00	DC	DC	DC	DC
	01	DC	0	0	1
	11	DC	1	0	0
	10	DC	0	1	0

- The three cells with a 1 represent the following cases (from top to bottom) where player 2 wins (output X)
  1. Player 1's paper cut by player 2's scissors
  2. Player 1's rock covered by player 2's paper
  3. Player 1's scissors blunted by player 2's rock
- DC = Don't care (what happens in this case)

## Simplify to save money

- We can use Boolean algebra or a Karnaugh map (we won't explain in detail here) to simplify X from:
- $X = \bar{A}BC\bar{D} + AB\bar{C}D + A\bar{B}CD$
- to:
- $X = \bar{A}B\bar{D} + AB\bar{C} + \bar{B}CD$
- Gates with three inputs=cheaper





## Key Terms

### ***Universal gate***

Either a NAND or a NOR gate. The term universal refers to a property of a gate that permits any logic function to be implemented by that gate or by a combination of gates of that kind.

### ***Negative-OR***

The dual operation of a NAND gate when the inputs are active-LOW.

### ***Negative-AND***

The dual operation of a NOR gate when the inputs are active-LOW.



# Ch.4 Summary

## Quiz

1. Assume an AOI expression is  $\overline{AB} + \overline{CD}$ . The equivalent POS expression is

a.  $(A + B)(C + D)$

b.  $(\overline{A} + \overline{B})(\overline{C} + \overline{D})$

c.  $(\overline{A + B})(\overline{C + D})$

d. none of the above



# Ch.4 Summary

## Quiz

2. The truth table shown is for

- a. a NAND gate
- b. a NOR gate
- c. an exclusive-OR gate
- d. an exclusive-NOR gate

INPUTS		OUTPUT
<i>A</i>	<i>B</i>	<i>X</i>
0	0	1
0	1	0
1	0	0
1	1	1



# Ch.4 Summary

## Quiz

3. The truth table shown is for

- a. a NAND gate
- b. a NOR gate
- c. an exclusive-OR gate
- d. an exclusive-NOR gate

<i>A</i>	<i>B</i>	<i>X</i>
0	0	0
0	1	1
1	0	1
1	1	0



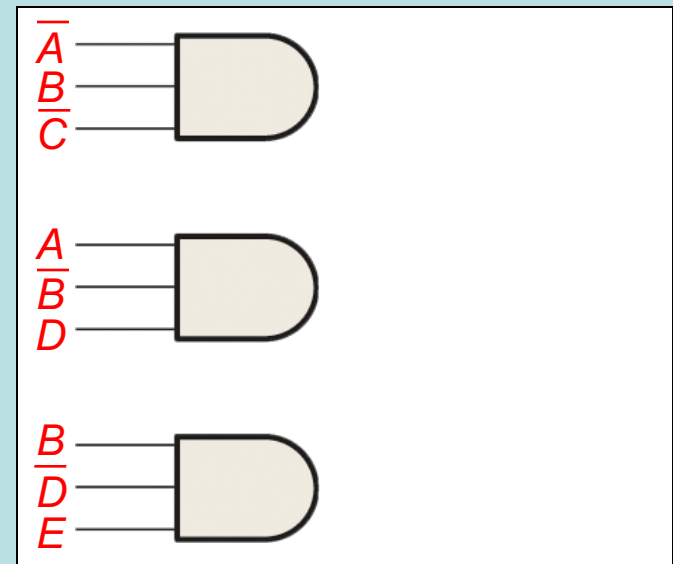
# Ch.4 Summary

## Quiz

4. What type of output gate is needed to implement the logic expression shown?

- a. 3-input AND gate
- b. 3-input NAND gate
- c. 3-input OR gate
- d. 3-input NOR gate

$$X = \bar{A}\bar{B}\bar{C} + A\bar{B}D + B\bar{D}E$$

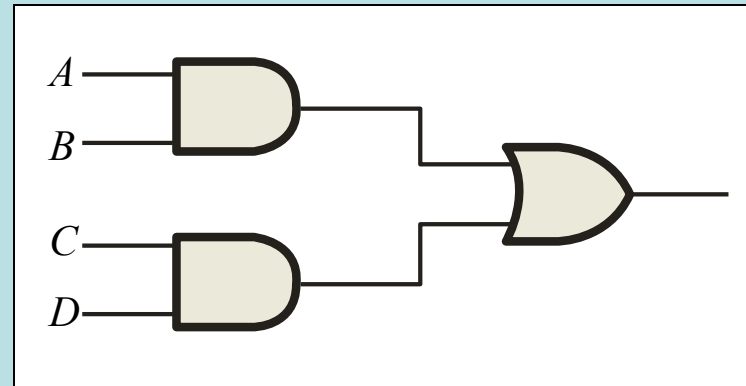


# Ch.4 Summary

## Quiz

5. The circuit shown will have identical logic outputs if all gates are changed to

- a. AND gates
- b. OR gates
- c. NAND gates
- d. NOR gates



## Ch.4 Summary

# Quiz

6. The expression  $(A+B)(C+D)$  can be implemented using only
- a. AND gates
  - b. OR gates
  - c. NAND gates
  - d. NOR gates



## Quiz

7. The two types of gates which are called *universal gates* are

- a. AND/OR
- b. NAND/NOR
- c. AND/NAND
- d. OR/NOR





# Ch.4 Summary

## Quiz

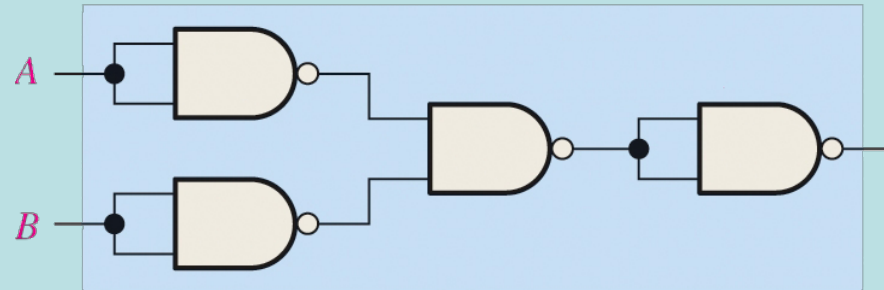
8. The circuit shown is equivalent to an

a. AND gate

b. XOR gate

c. OR gate

d. none of the above

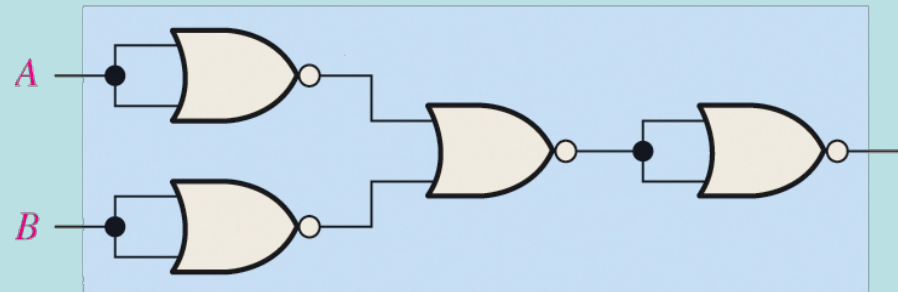


# Ch.4 Summary

## Quiz

9. The circuit shown is equivalent to

- a. an AND gate
- b. an XOR gate
- c. an OR gate
- d. none of the above

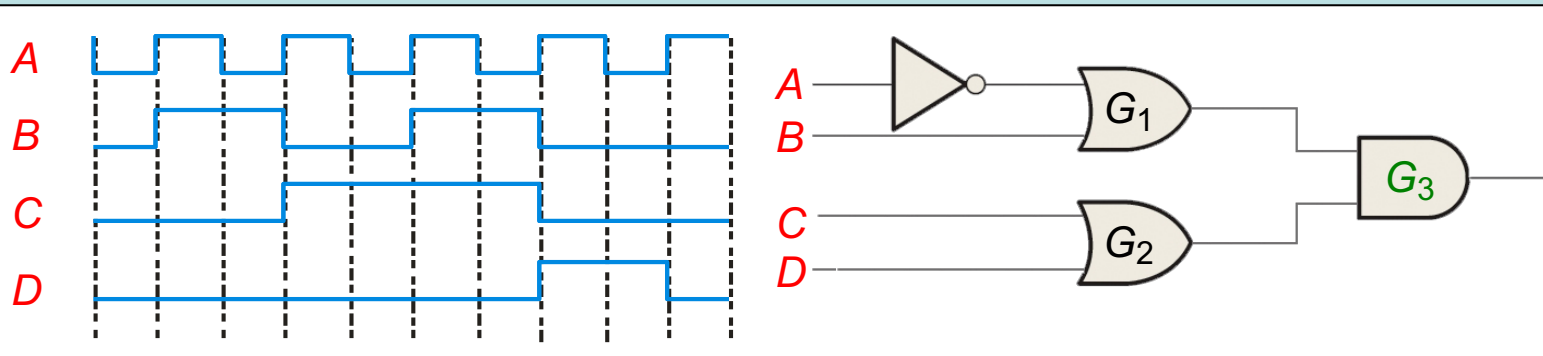


# Ch.4 Summary

## Quiz

10. During the first *three* intervals for the pulsed circuit shown, the output of

- a.  $G_1$  is LOW and  $G_2$  is LOW
- b.  $G_1$  is LOW and  $G_2$  is HIGH
- c.  $G_1$  is HIGH and  $G_2$  is LOW
- d.  $G_1$  is HIGH and  $G_2$  is HIGH



## Ch.4 Summary

# Answers

- |      |       |
|------|-------|
| 1. b | 6. d  |
| 2. d | 7. b  |
| 3. c | 8. c  |
| 4. c | 9. a  |
| 5. c | 10. c |

