CS2507 Computer Architecture

Lecture 5

Buses

The function of a bus is to carry data from one point to another. Rather than connecting every possible pair of points with individual data paths, a bus runs past all the points and each point is allowed either to put data on the bus or copy data from it at the appropriate intersections.

Buses are used within the CPU to connect registers, the ALU and the external environment.

Buses are used outside the CPU to connect the CPU, Memory and Input-Output devices in a single printed circuit board (pcb).

Buses are used on backplanes or motherboards to connect several pcbs together.

Buses are used outside computers to connect computers to external peripherals or to other computers.

There are many types of bus, but the main divisions are Parallel buses and Serial buses.

In a parallel bus, there is one conductor for each data bit and several data bits may be transmitted on the bus simultaneously. The length of the bus is limited by electrical and timing considerations and is of the order of 1 metre.

In a serial bus, there is only one conductor and the data bits are transmitted one at a time. The length of the bus is limited by electrical considerations but the limit is usually higher than that of a parallel bus.

Parallel/Serial issues can be temporarily ignored while considering the transmission of a bit of data from one point to another.

The bit is transmitted by an electrical signal. A material which is a good conductor of electricity a conductor is needed to carry the signal. A copper wire could be used, for instance.

The presence or absence of a bit is indicated by a voltage level on the copper wire.

However, properly speaking, voltage is a measure of the difference in electrical potential between two points, so that a second conductor is needed to provide a reference voltage. We call the reference voltage "ground" and arbitrarily assign it a potential of zero volts (0V).

Let us refer to the copper wire carrying the data bit as a data line.

It is possible for the data line to be connected to the ground line or to a positive voltage source. There are several possible values for this source, but we will use +5V as the positive voltage level here.

When there is no difference in electrical potential between the data line and the ground line, then the data line voltage is 0V and it can be said to be at a low potential, signified by LO.

When there is a difference in electrical potential between the data line and the ground line, then the data line voltage is 5V and it can be said to be at a high potential, signified by HI.

Boolean logic values 1 and 0 can be assigned to HI and LO in that order (active-HI) or conversely (active-LO).

Independent of the number of data lines, only one ground line is used in any system, although it may have numerous branches in order to carry the LO level to many locations in the system.

For the purpose of discussion, assume that the data line is active-HI. In order to transmit a 1 bit, the data source places the line at +5V. Considered graphically, this results in a step waveform on the data line. This step takes some time to propagate from the source to the receiver, although the time is really short, of the order of 5 nanoseconds per metre (ns = 10^{-9} s).

As the wave meets the ends of the bus, reflections may occur. These are undesirable, as they interfere with the voltage level on the line and postpone the time instant at which the data destination can sample the data line meaningfully. In order to prevent these reflections, the ends of a bus have a resistance connected between each data line and ground. This resistance is provided by a terminating resistor.

When the data bit arrives at its destination, reception of the bit causes an electrical

current to flow. The flow of current causes power to be dissipated in the electrical circuit due to resistance in the circuit paths. The loss of power is manifested as heat.

Bypass Capacitors

Rapid switching in a digital circuit creates high-frequency signals that can be radiated from and received by bus lines. These, in turn, can give rise to spurious voltages that augment the difficulties caused by inductance and capacitance effects between data lines. Minimising these unwanted signals (noise) is referred to as signal conditioning. Capacitors are often connected between data lines and ground in order to nullify high-frequency noise. These are called bypass capacitors.

Pullup Resistors

The inputs to digital devices have to be connected to some logic level at all times: the input cannot be left to "float", meaning being in a state in which no input exists. If inputs are left to float, electrical noise could cause an incorrect input to occur. Therefore, it is desirable to "tie" circuit inputs to some definite voltage level.

One idea would be to make a direct connection from VCC (the +5V source) to the device input. However, a LO input to the device would then cause a short circuit, which is highly undesirable.

The solution is to connect a resistor between VCC and the input line. When there is no logic input or the input is HI, this has the same effect as when there is no resistor in the circuit. When the logic input is LO, a current flows through the resistor but a short circuit is prevented. Resistance values of 5k to 50k are commonly used.

Circuit Components

Resistors

Resistance is provided in circuits by resistors. The leads of a resistor can be axial or radial. Traditionally, resistor values are colour coded. There are two systems: Body-Tip-Spot and End-to-Centre. The systems only influence the order in which the values are read, not the actual colour codes.

Colour	Number	Colour	Number	Colour	Tolerance
Black	0	**Green**	5	**Gold**	5%
Brown	1	**Blue**	6	**Silver**	10%
Red	2	**Violet**	7	**No Colour**	20%
Orange	3	**Grey**	8	**Other**	% as for code
Yellow	4	**White**	9		

These values are read in order from end to centre or in the order body-tip-spot.

The first value gives the first significant digit, the second value gives the second significant digit and the third value gives a multiplier specifying a power of ten (or, more simply, the number of zeros).

There are several mnemonics for remembering the resistor colour code. One of these is "Bye-bye Rosie, on you go to Birmingham via Great Western".

Examples

Red-Orange-Black = 2-3-No zeros = 23Ω

Brown-Green-Black = 1-5-No zeros = 15Ω

Green-Red-Orange = 5-2-000= 52kΩ

Red-Green-Yellow = 2-5-0000 = 250kΩ

Orange-Orange-Orange = 3-3-000 = 33kΩ

Ohm's Law

The current that flows in an electric circuit is directly proportional to the emf (voltage) applied and inversely proportional to the resistance of the circuit.

I = E/R

From this, we get R = E/I and E = IR

In these equations, current is always expressed in Amps, emf in Volts and resistance in Ohms.

Examples

1.

A device is connected to the terminals of a battery. By measurement, the voltage across the ends of the wire is 12V and the current flowing in the circuit is 3A. What is the resistance of the device?

Answer: R = E/I = 12/4 = 3 Ω

2.

What is the voltage across a 25Ω resistor when a current of 200mA is flowing through it?

Answer: E = IR = 25*0.2 = 5V

3.

A voltage drop of 60V is measured across a resistance of 12kΩ. What current is flowing?

Answer: I = E/R = 60/12000 = 5mA

4.

If the resistance in 3. above is provided by a resistor with bands coloured Brown-Red-Orange and Silver, what are the limits of the current that may be flowing through the resistor?

Answer (a) Lower Limit: R = 12000 + 10% = 13200 ohms. I = E/R = 60/13200 = 4.5mA approximately.

(b) Upper Limit: R = 12000 - 10% = 10800 ohms. I = E/R = 60/10800 = 5.5mA approximately.

Exercises

1.

A bulb from your car headlamp has a rating of 12V and 4A. What is its resistance?

2.

An electric kettle draws 2.5A from the 240V mains supply when it is switched on. What is the resistance of its element?

3.

What value of resistance is required to limit a current driven by a voltage source of 12V to a flow of 6mA?

The Series Circuit

When resistors are connected in series, the total resistance equals the sum of the individual resistances.

Rt = R1 + R2 + R3 + ... + Rn

The same current flows through every resistance.

Kirchoff's Second law

The sum of the voltage drops across series resistances in a closed circuit equals the total voltage applied to the circuit.

Example

A closed circuit powered by a 12V battery consists of three resistors with values of 2Ω, 4Ω and 6Ω connected in series. What is the voltage drop across each resistor?

Consider what you know:

Rt = R1 + R2 + R3

It = I1 = I2 + I3

Vt = V1 + V2 + V3

So an equivalent circuit comprises a resistance of 12 ohms connected across a 12V source.

Thus the current flowing is I = E/R = 12/12 = 1A

The voltage drops across the individual resistors are given by

V1 = IR1 = 1*2 = 2V

V2 = IR2 = 1*4 = 4V

V3 = IR3 = 1*6 = 6V

It can be seen that the sum of the voltage drops equals the applied voltage.

Example

A circuit contains three resistors connected in series across a 100V source. The current flow is 2A. Resistors R1 and R2 have known values of 5Ω and 10Ω respectively.

Calculate (i) the resistance of the entire circuit, (ii) the value of resistor R3 and (iii) the voltage drop across each of the three resistors.

Step 1

Sketch the circuit. Fill in the known values and leave the unknown values blank.

Thus,

It = 2A

Vs = 100V

Rt = ?

I1 = It = 2A

V1 = ?

R1 = 5 ohms

I2 = It = 2A

V2 = ?

R2 = 10 ohms

I3 = It = 2A

V3 = ?

R3 = ?

Step 2

It = 2A

Vs = 100V

Rt = ?

So Rt = Vs/It = 100/2 = 50 ohms

Rt = R1 + R2 + R3

50 = 5 + 10 + R3

R3 = 50 - 15 = 35 ohms

V1 = ItR1 = 2*5 = 10V

V2 = ItR2 = 2*10 = 20V

V3 = ItR3 = 2*35 = 70V

Exercises

1.

A circuit branch consists of three resistors, R1, R2 and R3, with values of 10Ω, 20Ω and 60Ω respectively, connected in series between points A and B. Due to the tight design of the equipment chassis, you can only get your voltmeter probes across R1, where you measure a voltage drop of 5V. Calculate the voltage drops across R2 and R3. Hence give the total voltage applied across points A-B.

2.

You have received a present of a car spotlight rated at 2A, designed to work with a 6V battery. However, your car has a 12V battery. What value of resistance must you connect in series with the spotlight before you can safely switch it on?

Potential Divider

A potential divider chain is a circuit designed to provide current at a reduced voltage. Input voltage is divided between 2 resistors, R1 and R2. Output voltage is taken across R2.

Assume the input voltage is Vin, output voltage is Vout and a current I flows in the circuit.

Then the voltage drop across R1 is IR1, voltage drop across R2 is IR2 and total voltage across the resistors is I(R1+R2).

So, Vin = I(R1+R2), Vout = IR2 and Vout/Vin = R2/(R1+R2) or Vout = VinR2/(R1+R2)

Kirchoff's First Law

The sum of all the currents flowing towards a junction always equals the sum of all the currents flowing away from the junction.

To use Kirchoff's First Law on a circuit:

- Draw the circuit
- Show the current flow through every resistance in the circuit
- Determine which currents flow towards or away from every junction in the circuit
- The value and direction of unknown currents can often be determined by applying Kirchoff's First Law.

Example

R_1, IN, A

R_3, A, B

R_2, A, C

R_4, B, C

R_6, B, D

R_5, C, D

R_7, D, OUT

I_1 = ?

I_2 = 7A, A->B

I_3 = 3A, A->B

I_4 = ?

I_5 = 5A, C->D

I_6 = ?, I7 = ?

Resistance in Parallel Circuits

Assume R1 and R2 are connected in parallel across a voltage source V from which a current I is drawn.

From Kirchoff's First Law,

I = I1 + I2

Let Rt represent the joint resistance presented by R1 and R2 in parallel.

By Ohm's Law,

I = V/Rt

I1 = V/R1

I2 = V/R2

So V/Rt = V/R1 + V/R2

1/Rt = 1/R1 + 1/R2

This is often written as Rt = R1R2/(R1 + R2)

In general, 1/Rt = 1/R1 + 1/R2 + 1/R3 + ... + 1/Rn

for any n resistors connected in parallel.

Note that the result of putting resistors in parallel is to create a total resistance that is lower in value than any of the individual resistances.

Power

The rate at which work is done in an electrical circuit is called power. It corresponds to the rate of energy dissipation due to resistance presented to current flowing in the circuit.

The unit of electric power is the Watt.

One Watt is the rate at which work is being done in a circuit in which a current of one ampere is flowing when an emf of one volt is applied.

The power consumed in a resistor is determined by the voltage measured across it multiplied by the current flowing through it.

P = VI

Since V = IR, P = I^2R

Since I = V/R, P = V^2/R

Many devices have a wattage rating to indicate the rate of power dissipation they can withstand. Thus, for instance, resistors of the same resistance are available in a range of wattage ratings.

Alternating Current

Alternating voltage and alternating current (AC) take the form of a sinusoidal wave about a zero voltage level.

The mains electricity supply voltage alternates at a frequency of 50 cycles per second, or 50Hz (Hertz).

The effective value of alternating voltage or current, in relation to its peak value, is its root mean square value (RMS).

$I_{rms} = I_{max}/sqrt(2) = 0.707I_{max}$

$V_{rms} = V_{max}/sqrt(2) = 0.707V_{max}$

In AC circuits containing only resistance, current and voltage are in phase. The same laws apply as for DC circuits.

Average power = $[V_{max}/sqrt(2)]$ * $[I_{max}/sqrt(2)]$ = $V_{max}I_{max}/2$ = half maximum power

Inductors

When the current in an electric circuit changes, the circuit opposes the change. One of the circuit properties that opposes the change is called inductance.

As current flow in a conductor increases, it gives rise to an increasing magnetic field around the conductor.

The direction of the magnetic force can be seen by pointing the thumb of the right hand in the direction of current flow (from positive to negative) and wrapping the fingers around the conductor. The direction of the magnetic field follows the fingers.

When a magnetic field moves across a conductor, it induces an emf in the conductor. As the magnetic field increases, it creates a counter-emf in the conductor that

opposes the emf giving rise to the current. This is self-induction, and its effect is magnified if the conductor is coiled so that its magnetic fields overlap many points on the conductor.

Inductance affects DC circuits whenever the current is switched on or off. Collapsing fields in DC circuits can generate very high induced emf.

In an inductive circuit, when current increases, energy is stored in the magnetic field. When current decreases, the circuit gives up energy from the magnetic field.

In an inductor coil, inductance depends on the number of turns, the spacing between turns, the shape and diameter of the coil, the core material, wire size and the number of layers of windings.

Inductive Rise Time

In a resistive circuit, current rises to its maximum value almost immediately when power is switched on. In an inductive circuit (which will always contain a certain amount of resistance), there is a delay in the rise to maximum current due to self-inductance. The time for the current to rise to 63.2% of its maximum is called the *time constant* and is given by **L/R**. A similar effect occurs when power is switched off. In this case, the time constant gives the time for current to fall to 36.8% of its maximum value. In these calculations, L is expressed in Henries, R in Ohms and time in seconds.

Inductive Reactance

Due to inductance in an AC circuit, peak current levels are lower than they would be if the circuit was only resistive in nature. This is because current has less time to rise to its maximum before it has to drop again. The higher the frequency, the more exaggerated this effect becomes.

Inductive reactance is the opposition offered by an inductor to current flow. It depends not just on the inductance, but also on frequency.

Inductive reactance is given by $\mathbf{X_L = 2\pi fL}$

Here X_L is in ohms, L in Henries, f in Hertz

Furthermore, the current waveform lags behind the voltage waveform so that the two

waves are out of phase.

In the case of pure inductance, current will lag voltage by 90 degrees or $\pi/2$ radians.

In general, the angle by which current lags voltage is called the *phase angle*, denoted by Φ.

The phase angle can be calculated from the formula

tan Φ = X_L/R

Power in circuits containing inductors

In a circuit containing only pure inductance, current lags voltage by 90 degrees, or $\pi/2$ radians. The power wave for a circuit can be obtained by multiplying together the current and voltage values at each instant. In the case of a purely resistive circuit, the current and voltage waveforms are in phase and the power waveform is entirely positive. In a circuit containing reactance, however, current will lag voltage and there will be some time intervals for which voltage is positive when current is negative and vice versa. During these intervals, the power waveform will be negative. Positive power represents power being stored and/or dissipated in a circuit. Negative power represents power being returned to the power source. The power dissipated (used up) in a circuit can be found by subtracting the negative power from the positive power.

In a circuit containing an inductor, some of the power supplied to the circuit is used to build up a magnetic field in the inductor. When this field collapses, it returns power to the power source as negative power.

Power Factor

In a purely resistive circuit, current and voltage are in phase and power is always positive. The rms power is given by $P_{rms} = V_{rms}I_{rms}$, giving power measured in Watts, as for DC circuits.

In a circuit with some inductance, multiplying the rms current and voltage together does not give the true power dissipation, since the waveforms are out of phase. However, the formula $P_{rms} = V_{rms}I_{rms}$ can be used to give the Apparent Power, which is then measured in Volt-Amperes (VA) rather than watts.

The true power dissipation can be calculated as $P_{rms} = I2_{rms}R$ and will be less than

or equal to the Apparent Power.

The ratio of True Power to Apparent Power is called the *Power Factor*.

In a purely resistive circuit consisting of a power supply of 12V rms, a current of 1.2A rms and a resistance of 10 ohms, the True Power is I^2R = 14.4W, the Apparent Power is $P_{rms} = V_{rms}I_{rms}$ = 14.4 VA and the resulting power factor will be $P_{true}/P_{apparent}$ = 1.

In a purely reactive circuit consisting of a power supply of 12V rms, a current of 1.2A rms and a reactance of 10 ohms, the True Power is I^2R = 0W, the Apparent Power is $P_{rms} = V_{rms}I_{rms}$ = 14.4 VA and the resulting power factor will be $P_{true}/P_{apparent}$ = 0.

Capacitors

Just as inductors tend to oppose changes in current flow in electric circuits, there are also elements that oppose changes in voltage. These elements are called capacitors.

Consider two parallel metal plates A and B connected in a circuit with a 5V battery (the negative terminal of which connected to ground) and two switches, SW1 and SW2, so that SW1 lies between Plate A and +5V and SW2 lies between plate B and ground.

Let both switches be initially open.

Before any switch is closed, the voltage across the battery terminals is 5V. The voltage between Plate A and ground is 0V. The voltage between plate B and ground is 0V.

If SW1 is closed at time t1, plate A's potential is 5V. Plate B will reach 5V after a time interval during which the charge on Plate A pushes electrons away from Plate B. Suppose Plate B reaches 5V at time t2.

If SW2 is then closed at t3, Plate B's potential changes to 0V with respect to ground over an interval terminating at time t4.

Current flow between VCC and Plate A can be viewed as a spike at t1 diminishing to 0 at t2.

Current flow between Plate B and GND can be viewed as a spike at t3 diminishing to

0 at t4.

If SW1 and SW2 are now opened, plates A and B will be isolated. A 5V charge remains across AB.

If the terminals of plates A and B are now reversed in the circuit and the switches closed again, a temporary current flow will result, in the opposite direction.

If this entire procedure is repeated at, for example, a rate of 50 times per second, then bursts of current will flow 50 times in a positive direction and 50 times in a negative direction during each second.

Thus, although the parallel plates A and B represent an open circuit to a DC source, they allow current to flow when connected across an AC source.

Factors affecting capacitance

Capacitors consist of parallel plates separated by an insulating material that is referred to as a dielectric.

- Increasing the plate area increases the capacitance.
- Increasing the distance between the plates decreases the capacitance.
- Changing the dielectric material changes the capacitance.

When capacitors are connected in series, the total capacitance is obtained by using a formula similar to that describing resistors in parallel.

$1/C_t = 1/C_1 + 1/C_2 + 1/C_3 + ... +1/C_n$

Capacitors connected in parallel have the effect of increasing the total plate area:

$C_t = C_1 + C_2 + C_3 + ... + C_n$

Time Constant

When a capacitor is connected to a voltage source, the voltage across the terminals of the capacitor does not instantly reach the value of the applied voltage. This is because every circuit contains some resistance, and this resistance slows down the charging of the capacitor plates. The larger the resistance in the circuit, the longer it takes the capacitor to charge. The time taken to charge a capacitor to 63.2% of its final value is called the time constant of the circuit and equals RC, where R is

expressed in ohms and C in Farads.

Capacitive Reactance

A capacitor allows current to flow in an AC circuit.

- Current flow is highest when the capacitor plates begin to charge and lowest as the charge reaches its maximum.

- Switching the polarity of the voltage applied to the capacitor allows the highest value of current to flow more frequently.

- Thus, the AC current flowing through a capacitor increases with the frequency of the applied voltage.

Therefore, the reactance of a capacitor is inversely proportional to frequency.

- For a fixed voltage frequency, current through a capacitor increases with increasing capacitance.

Therefore, the reactance of a capacitor is inversely proportional to its capacitance.

The formula for capacitive reactance is given by

$X_C = 1/2\pi fC$

where f is the frequency in Hertz, C is the capacitance in Farads and X_c is in ohms.

Phase angle in a capacitive circuit

Since current has to flow in a capacitive circuit before the capacitor charges, current is said to lead the voltage in this circuit. In a purely capacitive circuit, current will be at its peak when voltage is zero and current will be zero when voltage is at its peak. This means that voltage lags behind current by 90 degrees ($\pi/2$ radians) in a purely capacitive circuit.

When resistance is added to the circuit, the amount by which voltage leads current is reduced and the phase angle is given by

$\tan \Phi = X_C/R$

Power in a capacitive circuit

As in the case of inductive circuits, the power wave for a pure capacitive circuit can be obtained by multiplying together the current and voltage values at each instant. The resulting power wave has the same zero axis as voltage and current, and oscillates at twice the frequency of either voltage or current.

The ratio of true power to apparent power gives the *power factor*. As for inductive circuits, it can be calculated as $\mathbf{I^2_{rms}R/V_{rms}I_{rms}}$.

Clearly, in a purely capacitive circuit the power factor is 0 since the resistance is 0 and power used to charge the capacitor in the positive cycle is returned to its source in the negative cycle.

If resistance is added to the circuit, the phase angle between voltage and current decreases and some power is dissipated in the circuit. In that case, the power factor lies somewhere between 0 and 1.

Semiconductors
Diodes
Transistors
BJT
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Voltage Sources
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