Ollscoil Teicneolaíochta na Mumhan
Munster Technological University

COMP6043 Physical Computing

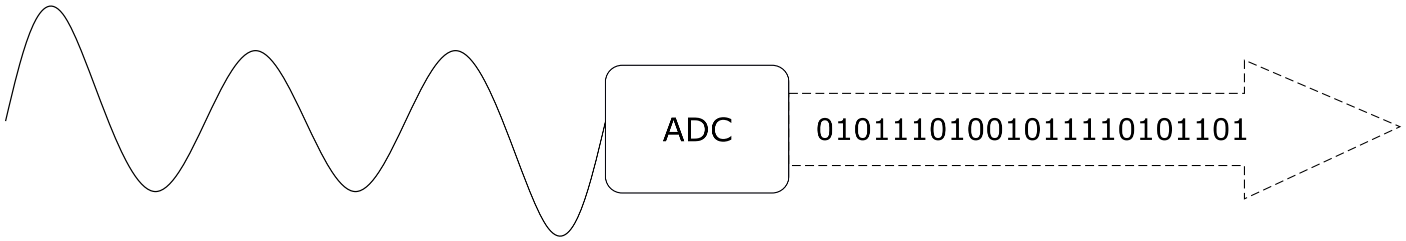
MCQ Revision

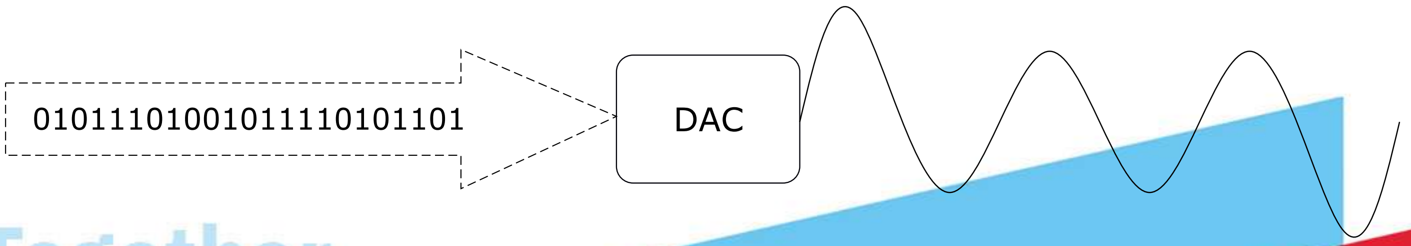
What is Physical Computing?

- Physical computing refers to computer systems that can sense and respond to the analog world.
- Key elements of physical computing systems:
  - Sensors
  - Actuators
  - Processors
  - Memory
  - Communication protocols

Analog & Digital Signals

- An analog signal is a signal that has continuous time varying quantities.
- Digital signals are discrete in both time and value.
- ADC: Analog to Digital Converter.
- DAC: Digital to Analog Converter.

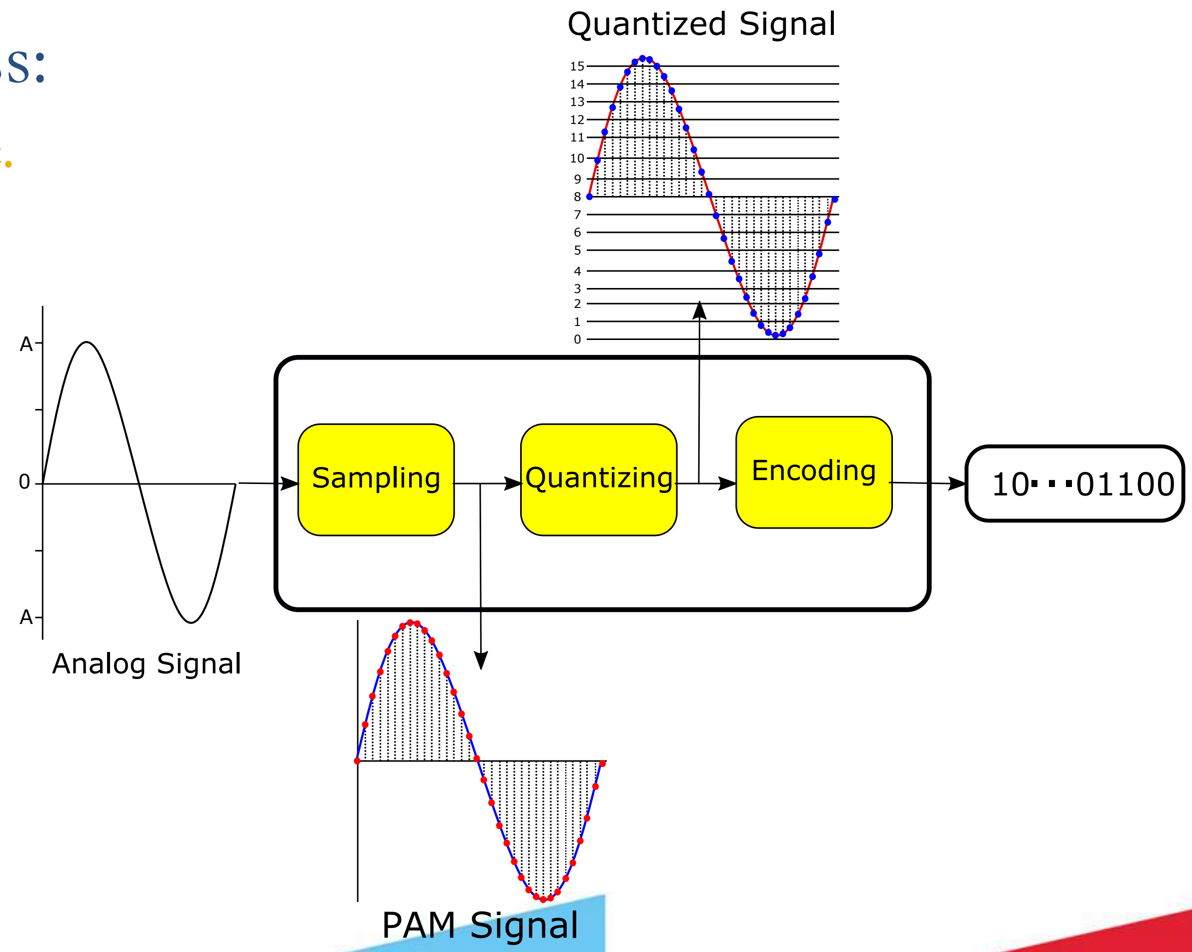




Analog ↔ Digital Signals

MTU
Ollscoil Teicneolaíochta na Mumhan
Munster Technological University

- There are three steps to the ADC process:
  - Sampling - makes the signal discrete in time.
  - Quantization - makes the signal discrete in amplitude.
  - Encoding - maps quantised values to digital words.



Analog ↔ Digital Signals

MTU
Ollscoil Teicneolaíochta na Mumhan
Munster Technological University

- An n-bit ADC has 2^n quantisation levels → a sampled value will be mapped to an integer in the range 0 to 2^n - 1, e.g. a 4-bit ADC has 16 quantisation levels, 0 to 15.
- Consider a temperature sensor which produces a voltage from 0 to 5 V according to: voltage = 0.5 + temperature / 100
- If this voltage is inputted to a 10-bit ADC, we have:

INTEGER	BINARY	VOLTAGE
0	0000000000	0
1	0000000001	0.0049
2	0000000010	0.0098
…	…	…
511	0111111111	2.4975
512	1000000000	2.5024
…	…	…
1022	1111111110	4.9951
1023	1111111111	5

$$V = V_L + \frac{(V_U - V_L)i}{2^n - 1}$$

$$= \frac{5i}{1023}$$

Analog ↔ Digital Signals

- Consider again the temperature sensor outlined previously.
- Suppose an integer value of 193 is read from the ADC (0011000001).
- This reading is of little use unless we can find the temperature it corresponds to.
- This may be easily done by mapping the
  - Sensor reading (integer) back to the voltage.
  - Voltage back to the temperature.

$$\text{voltage} = 5 \times \text{sensor value} \,/\, 1023$$

$$\text{temperature} = (\text{voltage} - 0.5) \times 100$$

$$193 \rightarrow 0.9433\ \text{V} \rightarrow 44.33°\text{C}$$

Analog ↔ Digital Signals

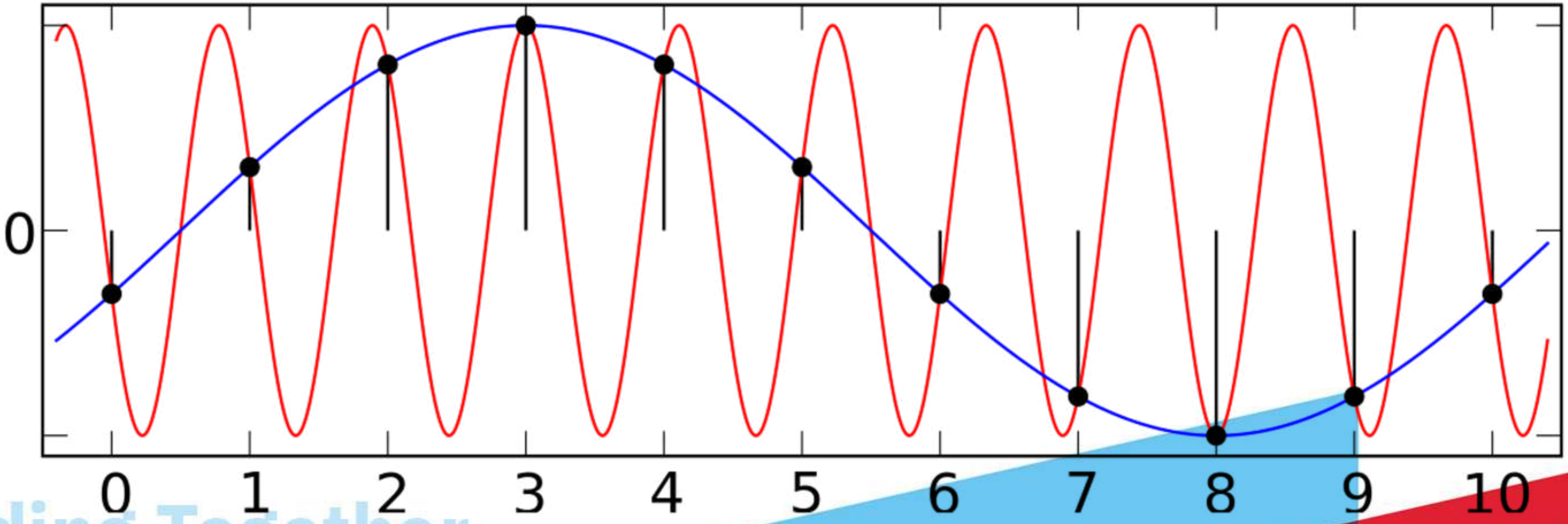
In summary:

- Sensor produces a voltage between 0 and 5 V corresponding to the temperature.
- This analog voltage signal is continuous in time and amplitude.
- The sensor voltage is sampled and quantised.
- Each sample is encoded to a 10-bit digital word, which corresponds to an integer between 0 and 1023.
- In order to interpret/process the ADC output, your code needs to map the (integer) reading back to the corresponding temperature:

$$\text{Sensor reading} \rightarrow \text{voltage} \rightarrow \text{temperature}$$

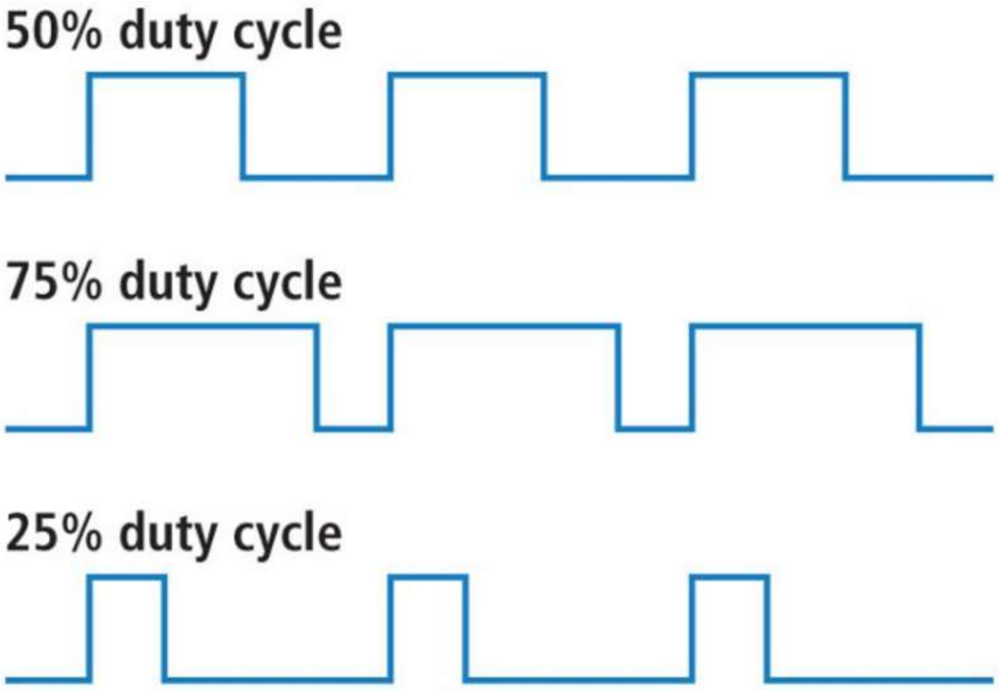
Nyquist Rate and Aliasing

- Nyquist rate: the minimum sampling rate such that an analog signal can be successfully reconstructed is twice the signal bandwidth (max frequency).
- Aliasing: if the sampling rate is too low, the signal being sampled will have a lower frequency alias, i.e. a signal that produces the same set of samples for a given sampling rate.



Pulse Width Modulation

- PWM rapidly turns an output pin high and low over a fixed period of time, varying "intensity" according to the duty cycle of the periodic waveform.
- Duty cycle represents the percentage of time that a periodic signal is HIGH.



(e.g. 50% duty cycle: HIGH for half of the period, LOW for the other half)

PWM with the Arduino

- The Arduino Uno does not have an integrated DAC.
- Therefore, it cannot vary the output voltage on its pins, it can only output 0 or 5 V.
- In order to give the illusion of an analog output, the Arduino uses PWM.
- The Arduino Uno has six pins set aside for PWM (digital pins 3, 5, 6, 9, 10, and 11), which can be identified by the ~ next to their number on the board.
- The function that writes an "analog" value (more accurately, a PWM wave) to a pin is analogWrite().
- This function can be used to change the brightness of an LED or drive a DC motor at various speeds.

PWM with the Arduino

MTU
Ollscoil Teicneolaíochta na Mumhan
Munster Technological University

- The function that writes an "analog" value (more accurately, a PWM wave) to a pin is analogWrite().

- This function can be used to:
  - change the brightness of an LED
  - drive a DC motor at various speeds
  - Control the angle of a servo motor

- It takes two arguments:
  - The pin to write to.
  - A value between 0 - 255 representing the duty cycle (0: constant LOW; 255: constant HIGH).

PWM with the Arduino

How would you make the light emitted from an LED connected to pin 9 one-third of its full capability?

Answer: analogWrite(9, 85);

Arduino Programming

The basic structure of the Arduino programming language consists of two required functions, **setup** and **loop**:

```
void setup() {
    statements; // preparation code
}

void loop() {
    statements; // execution code
}
```

setup is the first function to run. It is run only once and is used to initialise pin modes and/or serial communication.

loop runs after setup and includes code to be executed continuously - reading inputs, triggering outputs, etc.

I/O

Function	Purpose
pinMode(pin,mode)	Configures a specified pin as an INPUT or an OUTPUT.
digitalRead(pin)	Reads HIGH/LOW value from specified digital pin.
digitalWrite(pin,value)	Outputs logic level HIGH or LOW to specified digital pin.
analogRead(pin)	Reads value from specified analog pin with 10-bit resolution (0 - 1023).
analogWrite(pin,value)	Writes a pseudo-analog value using PWM to a specified pin. Duty cycle is specified by value parameter as an integer 0 - 255.

Functions

```
int led = 2;
void setup() {
   pinMode(led, OUTPUT);
}
void loop() {
   int d = delayVal(A0); // custom function: delayVal ... (A0: analog input 0)
   flash(led,d);         // custom function: flash
}
int delayVal(int in) { // note that the datatype is required for the parameters
   int v = analogRead(in);
   int d = map(v,0,1023,100,1000); // re-map v from 0 - 1023 to 100 - 1000
   return d;
}
void flash(int pin, int d) {
   digitalWrite(pin, HIGH);
   delay(d);
   digitalWrite(pin, LOW);
   delay(d);
}
```

Variables

```
int s1 = 2; // global variable - visible to all functions
void setup() {
   pinMode(s1, INPUT); // note that s1 is visible here
   for(int i = 3; i < 5; i++) { // i is only visible inside for loop
      pinMode(i, OUTPUT);
   }
}
void loop() {
   int i = digitalRead(s1); // i is only visible inside loop function
   if(i == LOW) {            // this i is different to previous i (in setup)
      digitalWrite(3,HIGH); // note also that s1 is visible here too
      digitalWrite(4,LOW);
   }
   else {
      digitalWrite(3,LOW);
      digitalWrite(4,HIGH);
   }
}
```

Note:

`i++` increments the counter by 1.

`i++` is equivalent to `i=i+1`

Python does not support `i++` or `i--` but most other languages do.

Succeeding Together

Misc. functions

Function	Purpose
delay(ms)	Pause program for specified amount of time (time specified in milliseconds).
millis()	Returns number of milliseconds since the Arduino board began running the current program (return type is unsigned long).
min(x,y)	Returns minimum of two numbers.
max(x,y)	Returns maximum of two numbers.
map()	Re-maps a number from one range to another. map(value,fromLow,fromHigh,toLow,toHigh)
randomSeed(seed)	Set a value, or seed, as the starting point for the random() function.
random(max)	Returns a pseudo-random number between 0 and max.
random(min,max)	Returns a pseudo-random number between min and max.

Serial Communication

Function	Purpose
Serial.begin(rate)	Opens serial port and sets the baud rate for serial data transmission (usually 9600 bps).
Serial.print(data)	Prints data to the serial port.
Serial.println(data)	Prints data to the serial port, followed by a carriage return, i.e. newline character.

Note: when using serial communication, digital pins 0 (RX) and 1 (TX) cannot be used at the same time.

```
void setup() {
   Serial.begin(9600);
}
void loop() {
   Serial.println(analogRead(A0)) ; // send analog value
   delay(1000);                      // pause for 1 second
}
```

Voltage, Current and Resistance

- Current is the rate of electric charge motion through a conductor.

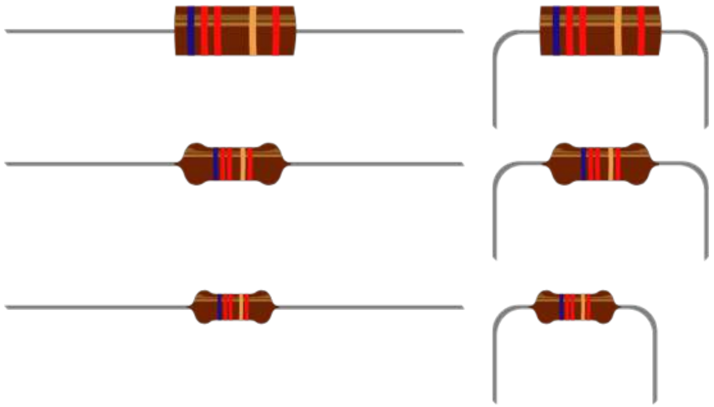
- The force motivating electrons to "flow" in a circuit is called voltage.

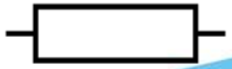
- When we speak of a certain amount of voltage being present in a circuit, we are referring to the measurement of how much potential energy exists to move electrons from one particular point in that circuit to another particular point.

- Free electrons tend to move through conductors with some degree of friction, or opposition to motion.

- This opposition to motion is more properly called resistance.

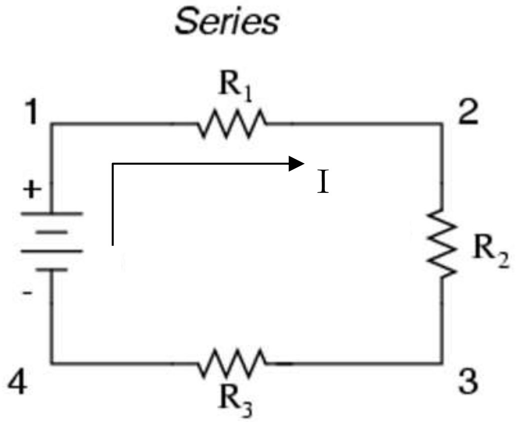
Resistors



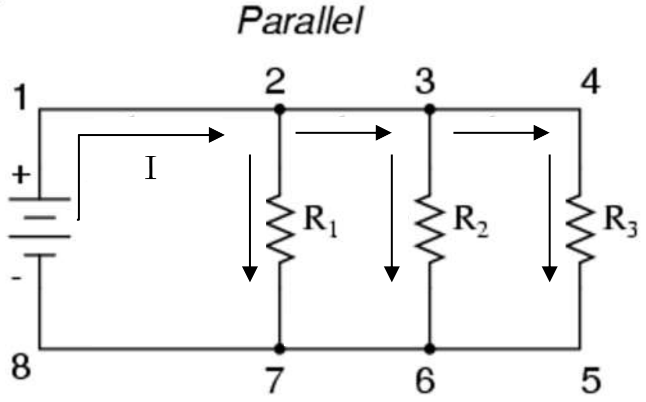
- Factors affecting the resistance of a conductive component include its material, size and shape.
- Resistors are made for the purpose of creating a precise quantity of resistance for insertion into a circuit.
- Schematic symbol for a resistor: 
- An alternative symbol sometimes used is: 

Series and Parallel Circuits

- There are two basic ways in which to connect more than two circuit components, series and parallel.



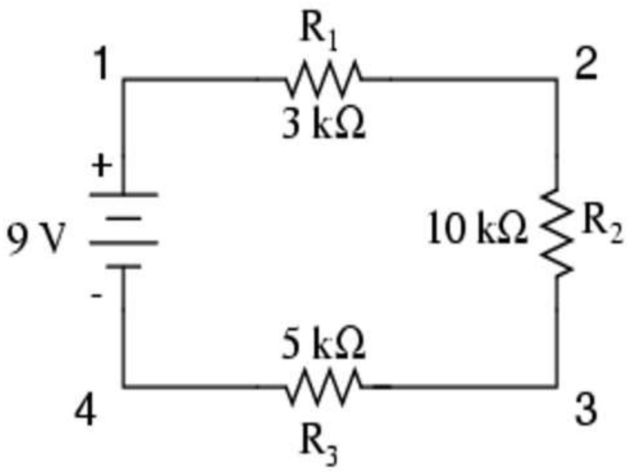
- Only one path for current to flow.

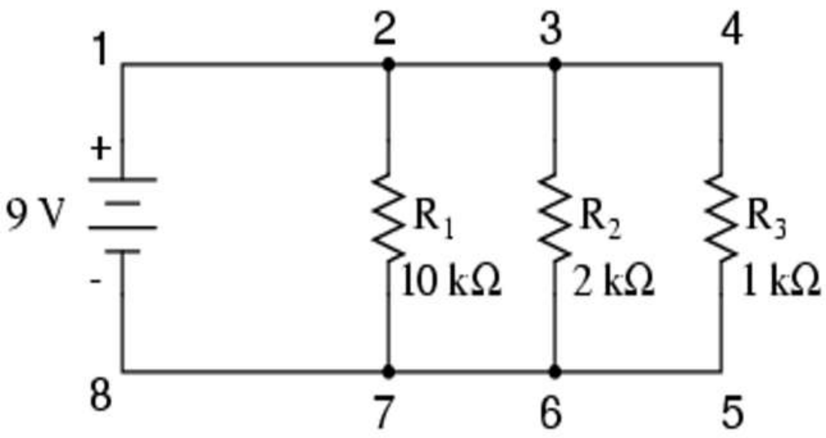


- Multiple paths for current to flow.
- Each individual path (through R_1, R_2, and R_3) is called a branch.
- Points 1, 2, 3, and 4 are all electrically common, as are points 5, 6, 7, and 8.
- All components are connected between the same set of electrically common points.

Series and Parallel Circuits

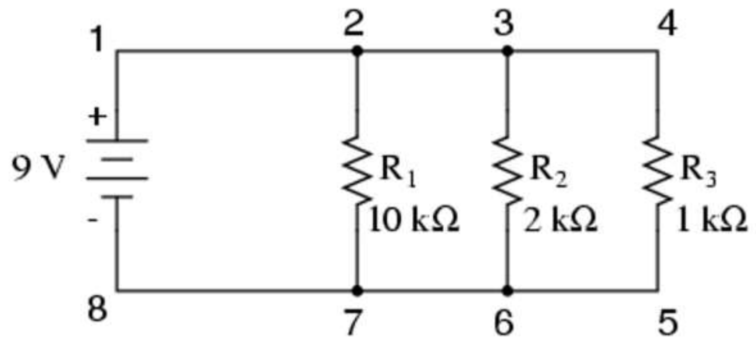
- Given the following circuits, what is:
  - The total equivalent resistance?
  - The total current?
  - The current through each resistor?
  - The voltage across each resistor?





Series and Parallel Circuits

- Consider the following parallel circuit:



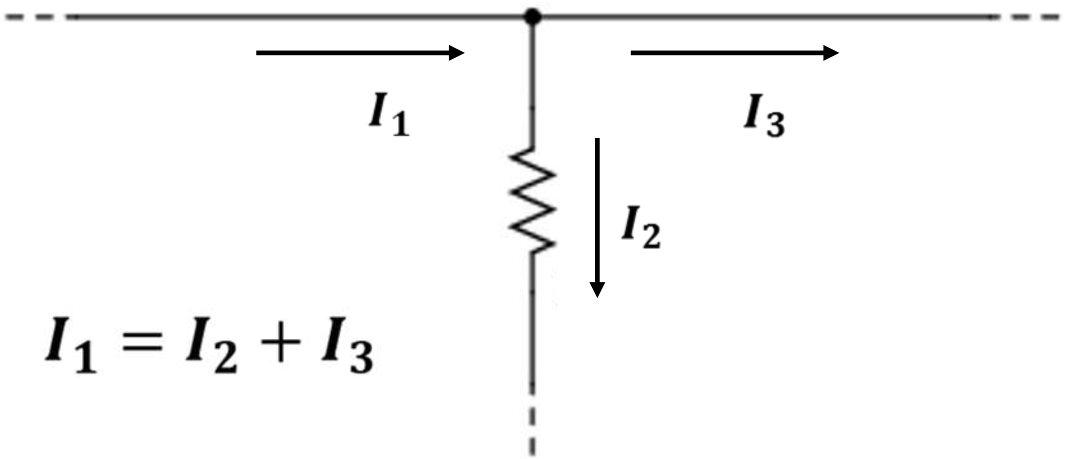
- Voltage is equal across all resistors.

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I					Amps
R	10k	2k	1k		Ohms

Series and Parallel Circuits

- Apply Ohm's law to individual resistor columns:

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	**0.9m**	**4.5m**	**9m**		Amps
R	10k	2k	1k		Ohms
	↑ Ohm's Law	↑ Ohm's Law	↑ Ohm's Law		



$$I_1 = I_2 + I_3$$

Series and Parallel Circuits

- Therefore, the total circuit current is equal to the sum of the individual branch currents.

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	0.9m	4.5m	9m	**14.4m**	Amps
R	10k	2k	1k		Ohms

Rule of parallel circuits

$I_{total} = I_1 + I_2 + I_3$

- Applying Ohm's law

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	0.9m	4.5m	9m	14.4m	Amps
R	10k	2k	1k	**625**	Ohms

$$R_{total} = \frac{E_{total}}{I_{total}} = \frac{9\ V}{14.4\ mA} = 625\ \Omega$$

Ohm's Law

Series and Parallel Circuits

- In general, for a parallel circuit:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}$$

- In summary:
  - Series: $RT = R1 + R2 + \ldots + RN$
  - Parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}$
  - Kirchhoff's Voltage Law: $\sum V\text{n} = 0$ around loop
  - Kirchhoff's Current Law: $\sum I\text{n} = 0$ through node

Voltage Divider Circuits

MTU
Ollscoil Teicneolaíochta na Mumhan
Munster Technological University

- A series circuit is often called a voltage divider for its ability to proportion (i.e. divide) the total voltage into fractional portions of constant ratio.

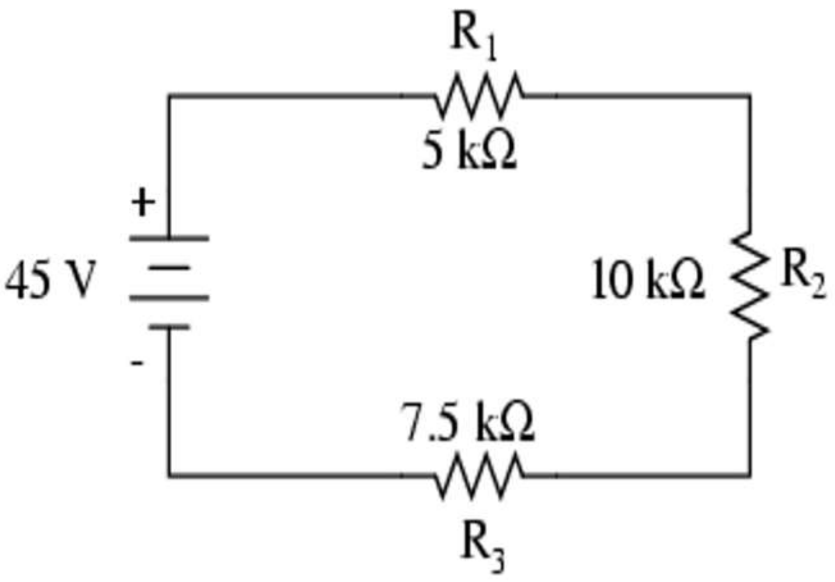
- In a voltage divider circuit, the ratio of individual resistance to total resistance is equal to the ratio of individual voltage drop to total supply voltage:

$$V_n = V_T \frac{R_n}{R_T}$$

- This is known as the voltage divider formula.

Voltage Divider Circuits

- Applying to the following series circuit:



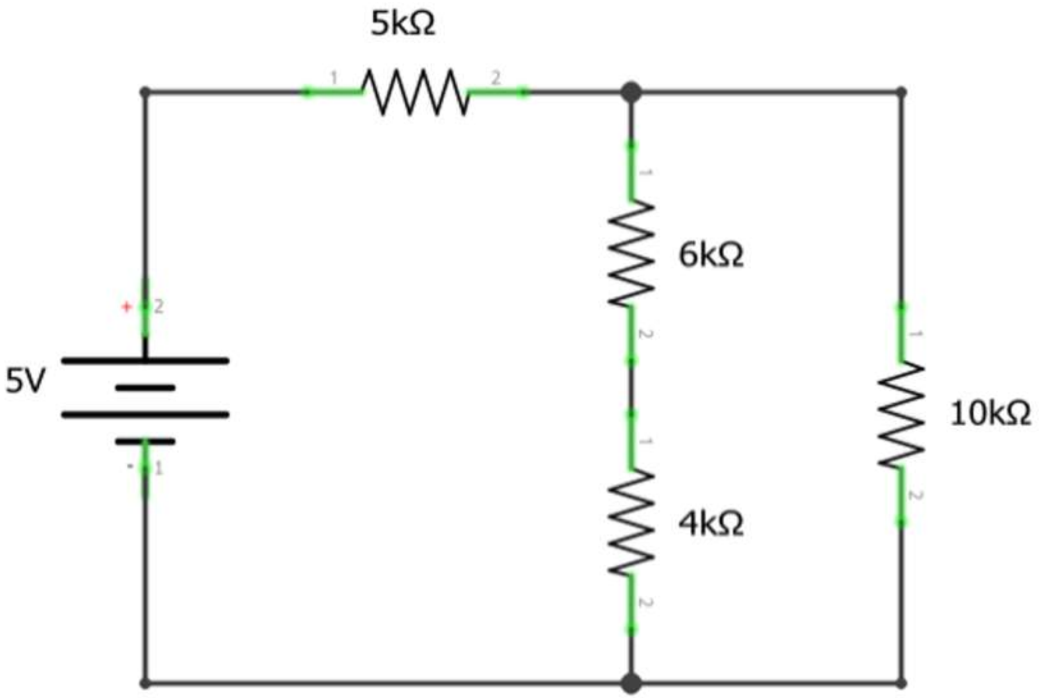
$$V_{R_1} = 45\ \frac{5}{22.5} = 10\text{ V}$$

$$V_{R_2} = 45\ \frac{10}{22.5} = 20\text{ V}$$

$$V_{R_3} = 45\ \frac{7.5}{22.5} = 15\text{ V}$$

Exercise

- What is the equivalent total resistance in the following circuit?
- Calculate the current in each branch and the total current.



Voltage-current relationship for a capacitor

- A capacitor does not behave like a resistor, i.e. Ohm's law does not apply to a capacitor.
- Instead,

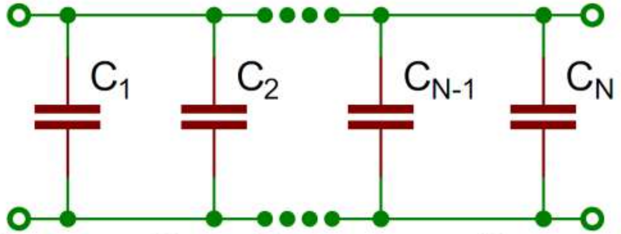
$$i(t) = C\frac{dv(t)}{dt}$$

- Note that if the voltage across a capacitor is steady and unchanging, no current will flow through it, i.e. current cannot flow through a capacitor holding a steady DC voltage.

Capacitors in series/parallel

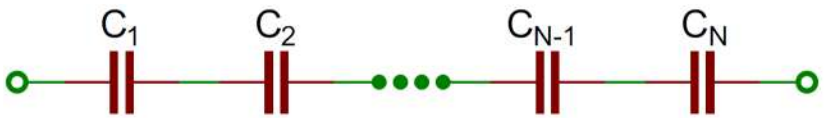
- Like resistors, multiple capacitors can be combined in series or parallel to create a combined equivalent capacitance.
- Capacitors, however, add together in a way that's completely the opposite of resistors.

Parallel:



$$C_{Tot} = C_1 + C_2 + \ldots + C_{N-1} + C_N$$

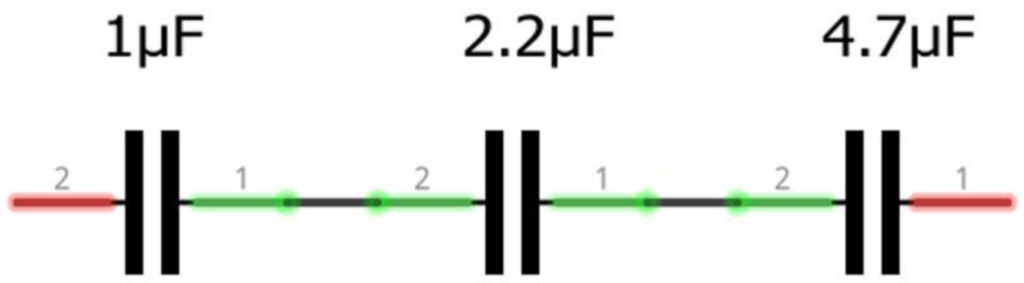
Series:



$$\frac{1}{C_{Tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_{N-1}} + \frac{1}{C_N}$$

Exercise

- What is the total equivalent capacitance in the following circuit?



- Draw the parallel arrangement using the capacitors above. What is the total equivalent capacitance of the parallel circuit?

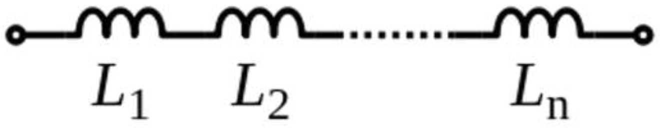
Inductors

- An inductor will resist changes in an electric current flowing through it:
  - According to Faraday's law of electromagnetic induction, when the current flowing through an inductor changes, the time-varying magnetic field induces a voltage in the conductor.
  - According to Lenz's law, the direction of induced electromotive force (emf) is always such that it opposes the change in current that created it.
- Voltage-current relationship:

$$v(t) = L\frac{di}{dt}$$

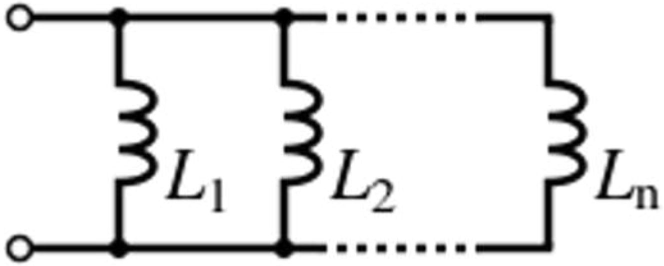
Inductors in series/parallel

Series



$$L_{eq} = L_1 + L_2 + \cdots + L_n$$

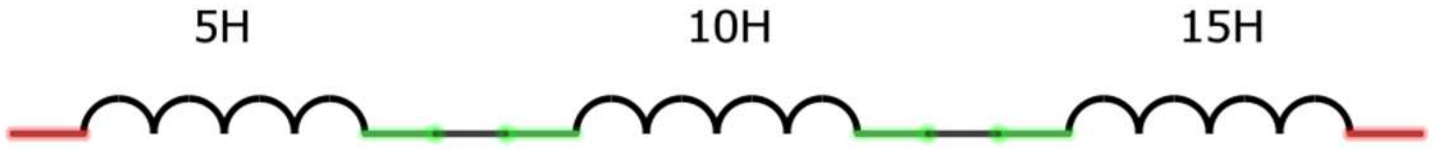
Parallel



$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}$$

Exercise

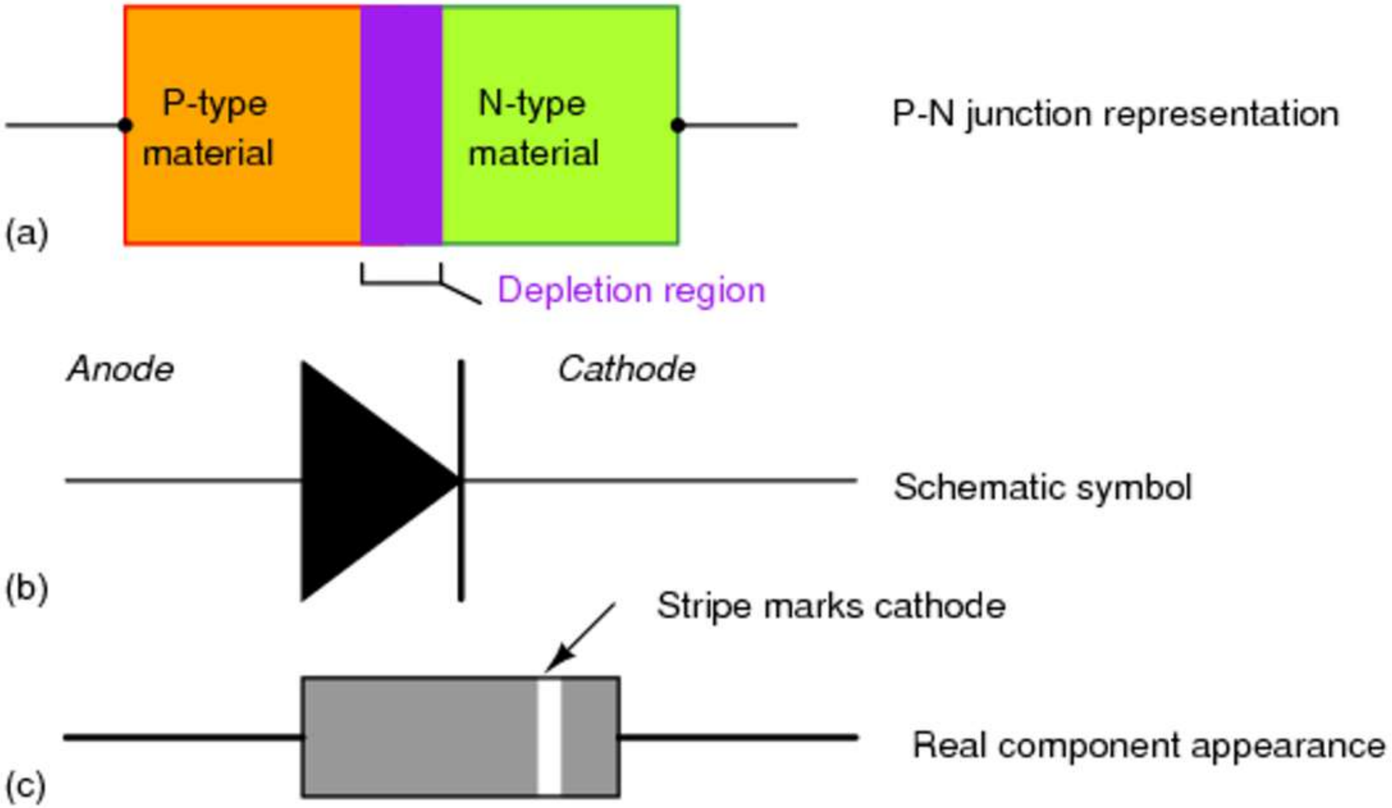
- What is the total equivalent inductance in the following circuit?



- Draw the parallel arrangement using the inductors above. What is the total equivalent inductance of the parallel circuit?

Semiconductor Diode

- A diode is an electrical device allowing current to move through it in one direction with far greater ease than in the other.



Semiconductor Diode

- A diode may be thought of as like a switch: “closed” when forward-biased and “open” when reverse-biased.

- However, there is a small voltage drop across the diode even when forward-biased (compare this to a mechanical switch).

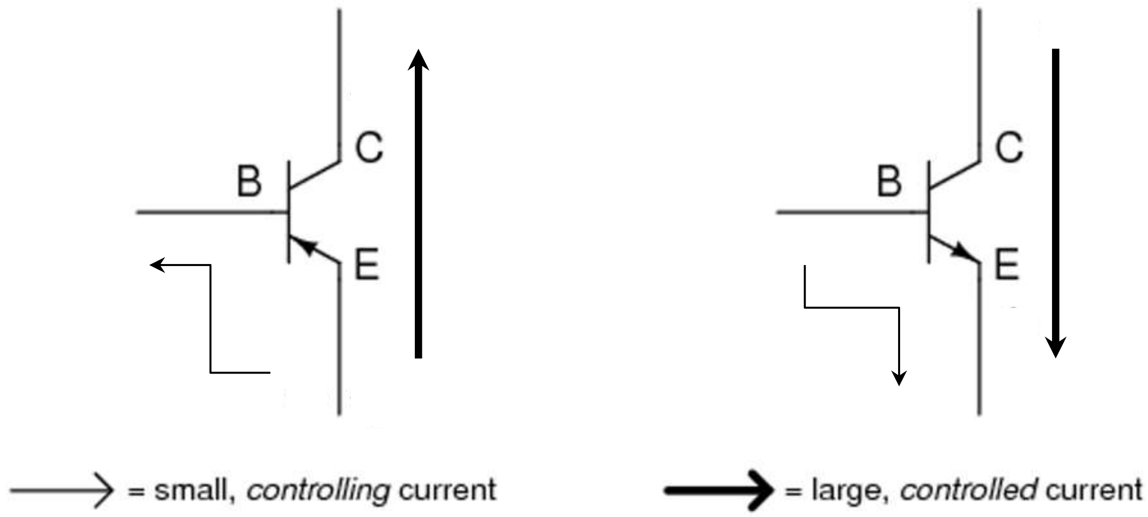
- This voltage drop is called the forward voltage.

- It is the minimum voltage required to turn the diode on and allow a sustained current to flow.

Transistors

- Transistors are used primarily as either:
  - An electrically controlled switch where a small input signal can switch on a larger signal.
  - An amplifier to amplify the small input signal.
- Transistors may be roughly grouped into two major divisions: bipolar and field-effect.

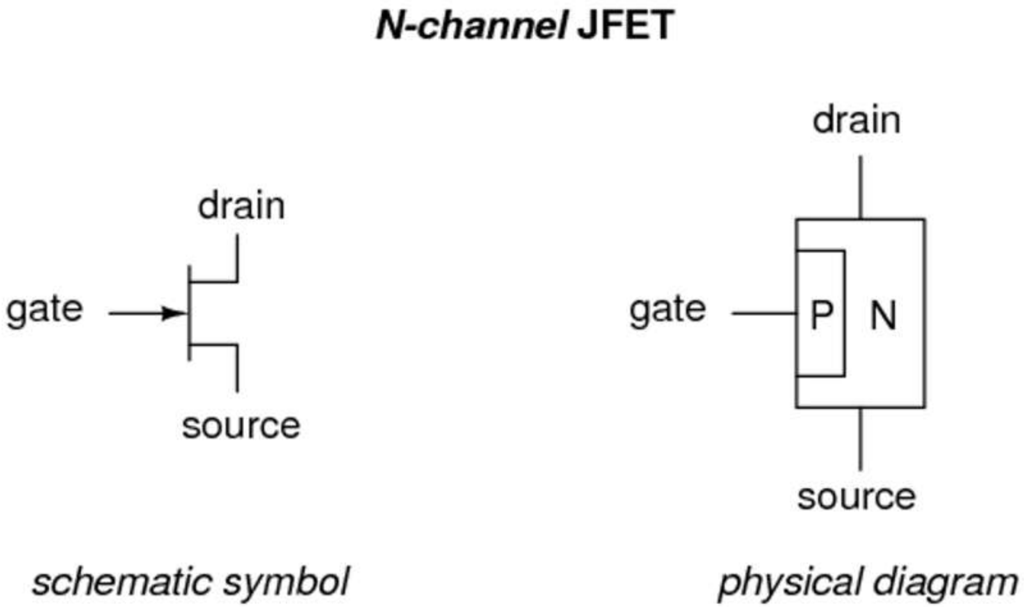
Bipolar Junction Transistor (BJT)



- Small base-emitter current controls large collector-emitter current.
- No current through the base of the transistor, shuts it off like an open switch and prevents current through the collector.
- A base current turns the transistor on like a closed switch and allows a proportional amount of current through the collector.
- "Current-controlled switch"

Field Effect Transistors

- Unlike BJTs which use a small base current to control a much larger collector/emitter current, **field-effect transistors use a small voltage to control current**.



- Essentially, a voltage applied to the gate (input element) controls the resistance of the channel.

Field Effect Transistors

- With no voltage applied between gate and source, the channel is a wide-open path for electrons to flow.
- However, if a voltage is applied between gate and source of such polarity that it reverse-biases the PN junction, the flow between source and drain connections becomes limited, or regulated.
- Maximum gate-source voltage "pinches off" all current through source and drain, thus forcing the JFET into cutoff mode.

Questions

- What is the SI unit for capacitance?
- How do capacitors store energy?
- What is the voltage-current relationship for a capacitor?
- What is the SI unit for inductance?
- How do inductors store energy?
- What is the voltage-current relationship for an inductor?

Questions

- What two conditions are necessary for a diode to conduct?
- Run the BJT animation at the following site to understand its operation: http://www.learnabout-electronics.org/Semiconductors/bjt_04.php
- Name the three terminals of a BJT.
- Fill in the blanks: In an NPN BJT, a small ________ current controls a much larger ________ current.
- Is a BJT a current or voltage controlled device?
- Name the three terminals of a JFET.
- Is a JFET a current or voltage controlled device?