Fundamentals of Electric Theory and Circuits

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Three and Two wire connections to single-phase equipment

Most single-phase domestic electric appliances built on a metal chassis like ironing boxes, washing machines and ovens use a 3-wire cord to make electrical connections to the single-phase power supply, which is usually 230VAC in Europe and 110VAC in USA and Japan.
In this article we will learn how electrical connections to single phase equipment can be made safe, unsafe wiring and operation of equipment and wiring practices to prevent unsafe operation.

The mains supply 230VAC is delivered to households using a three core wiring which run to receptacles in walls in electrical conduits usually buried in the walls at the time of construction. Fig. 1(a) shows a wall-mounting socket and a switch in a typical household wiring, and shown in Fig.1(b) is a line diagram of the incoming power supply and connection to a wall mounted outlet.

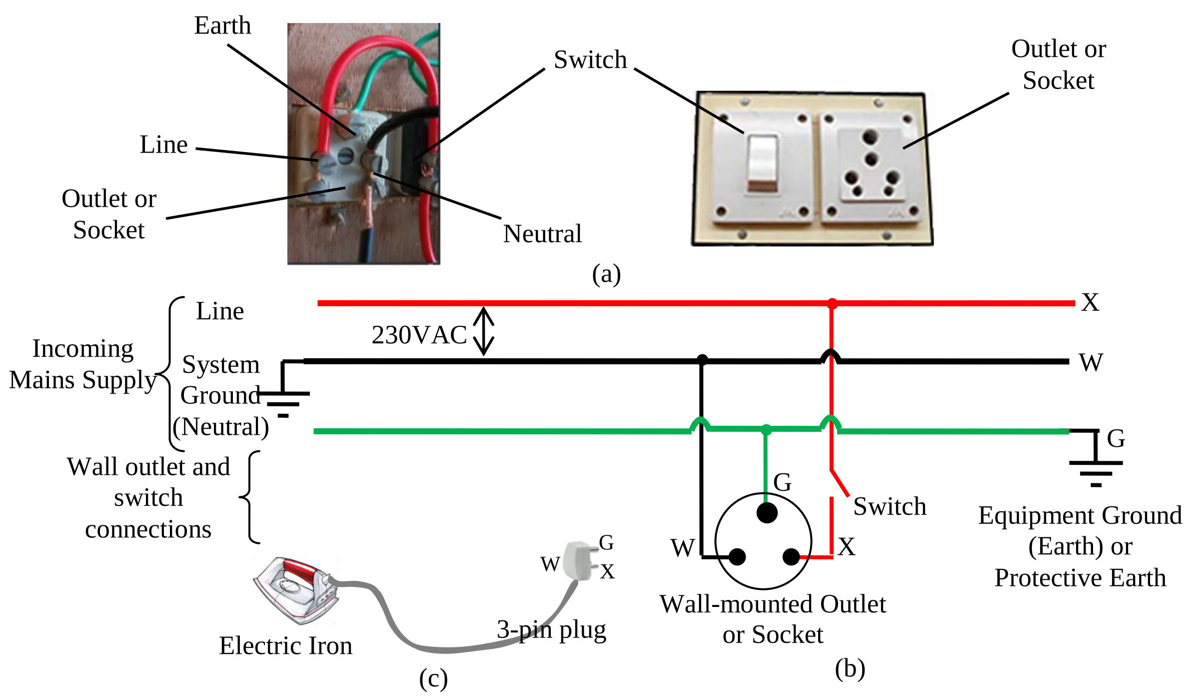

Fig. 1 (a) Front and rear view of a 3 pin outlet and switch combination. (b) Line diagram of power supply and socket connections. (c) An electric iron connected to a 3 pin plug.

The live wire is red in colour and the neutral is black colored. The earth is colored green or yellow. The earth wire is usually connected to a metal plate (labeled Equipment Ground (earth)

in Fig.1) buried deep in the earth close to residential buildings and near equipment in factory premises. It is a safety measure and does not in any way affect the supply.
Also, the neutral is grounded (or earthed) at the supply transformer end, labeled as system ground (neutral) in Fig.1, to a metal plate buried deep in the earth, usually separate from the plate used to ground the equipment.
If the neutral was *not* connected to the system ground, the potential of the neutral may attain a potential from a few volts to thousands of volts described in **Section 2.21** "How is there a voltage (or potential) for a single wire connected to one terminal of a battery ?" and the description related to Fig. 2.61 "Potential of a single wire connected to a battery having a net charge". Such potentials can cause gradual insulation damage leading to a breakdown. Therefore, it is safe practice to ground the neutral at the supply transformer end.
Accessible conductive parts of equipment like metal chassis of domestic electric appliances are connected to the protective earthing conductor in the fixed wiring of the installation. Connecting the chassis to earth ground keeps it at earth potential by spreading excess charge and also protects the user from an electric shock if there is a fault inside the device as we will soon learn.
The protective earth and the neutral conductors are at the same potential (See **Section 2.25** "What is Grounding"). The neutral wire carries the full load current providing the return path for the supply line or "hot" wire. The ground wire does not carry any current in normal operation but carries current during a fault and provides a conductive (sometimes called "leakage") path to the earth via the ground connection reducing its potential and prevents electric shock to the user.

Normal Operation (3-wire connection)

It will be useful for the reader to review the first few paragraphs which describe the operation of a sinusoidal voltage generator in **Section 2.9** "Application of a sinusoidal voltage (A.C.) to a capacitor".

Fig.1(c) also shows an electric iron wired to a 3-pin plug. The wires are labeled line X, Neutral W and Earth G. The iron incorporates an electric heating element and thermostat wired between the line and the neutral. The metal chassis is electrically isolated from the line and neutral terminals and this isolation is achieved by robust pvc insulated wires and porcelain isolation collars for the terminals. In a few irons, mica isolation strips are used between the terminals, the heating element and the metallic chassis and base which becomes hot when the iron is switched ON.
The metallic base and chassis are connected together and bonded to the G terminal of the iron as shown in Fig. 2 of an electric iron with a simplified view of the internal wiring of the heating element and the earth connection.

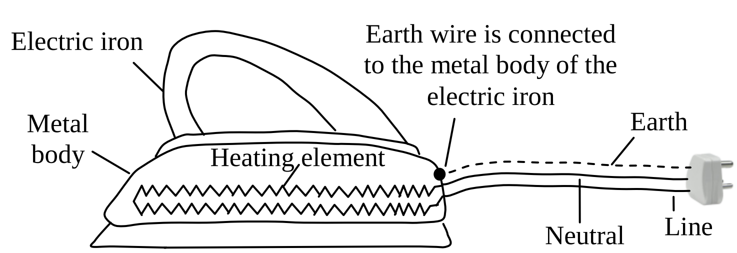

Fig. 2 Internal connection of an electric iron and external wiring with a 3 pin plug

When the electric iron is powered by inserting the 3-pin plug into the socket, and the switch is turned ON, a surface charge appears on the wires and the electric iron draws current, as shown in Fig. 3.

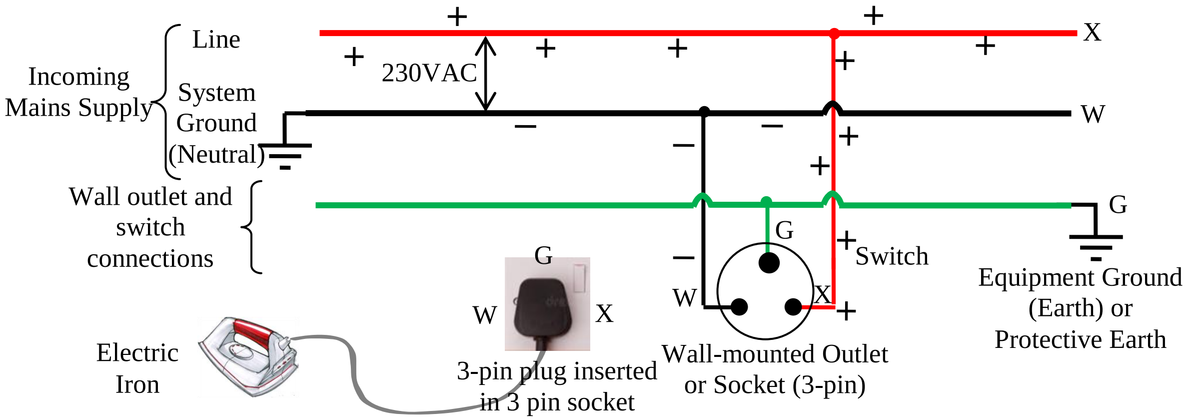

Fig. 3 Surface charge on the line and neutral during the half cycle when line is positive with respect to neutral. An electric iron with a 3 pin plug inserted in a 3 pin outlet and switch combo.

The surface charge, from the single-phase supply, is created by a very tiny number of conduction band electrons which produce a uniform electric field by a gradient of the surface charge density. The surface charge disperses and accumulates during every cycle on the wires to produce the electric field which pulsates at the line frequency. Electron dispersal on the surface causes the line to become positive with respect to neutral, and electron accumulation on the surface causes the line to become negative with respect to neutral. A surface charge appears even when the electric iron is not connected, which maintains the potential conditions of the line and neutral wires.

When the iron is switched ON, an electric field pulsates in alternate direction in the wires once every cycle. The field also pulsates in alternate directions in the heating element where it is powerful. The positive and negative charge accumulation on the neutral is minimized by the earth connection at the system ground by the action of charge spreading by the earth. When the line goes positive, a tiny amount of negative charge accumulates on the neutral and this is dispersed by the connection to the earth and by this action, which we learned in Section 2.25, maintains the neutral at near zero potential. Again, when the line goes negative, then a tiny amount of positive charge accumulates on the neutral and this is neutralized by electrons from the connection to the earth and by this action, which we learned in Section 2.25, maintains the neutral at near zero potential. The movement of charge on the earth wire and in the earth is due to mutual repulsion with a tendency for the system to attain minimum energy (See **Section 2.25** “What is Grounding?”).
Recollect from **Section 1.16** “The speed of surface charge build up” that tiny shifts by *infinitesimal* distances of the conduction band electron sea towards the surface nuclei and away from the surface nuclei produce the negative and positive surface charge, respectively.
The current in the line wire returns via the neutral wire to the power supply and there is no current in the G or earth green wire of the system.
There is also no current in the earth wire in the terminal marked G from the appliance to the system power supply. However, in the event of static charges accumulating on the accessible

conductive parts of equipment like the metal chassis and base of the electric iron which users may touch, then this charge will be distributed via the equipment earth (ground) terminal to the earth and the potential is kept safe from causing an electric shock to the user (See **Section 2.25** What is Grounding).

Unsafe Operation under fault conditions (3-wire connection)

If, the insulation between either the live or neutral terminals to the metallic chassis were to breakdown, termed a "fault" condition, then the potential of the body will rise to the system line voltage and the user operating the iron will experience an electric shock.
There will result a fault current from the live/neutral terminal to the earth terminal and this may be strong or mild depending upon the degree of insulation failure. Safety switches in the form of circuit breakers and earth-leakage detect breakers will trip and isolate the equipment but these should act fast enough, in the range of milliseconds, to prevent electric shock to the user.

Unsafe Operation of electric appliances using 2-wires

Because the neutral is connected to system ground at the incoming mains which could be a transformer, it is natural to think of connecting the neutral to the device's metal chassis so that both the neutral and the chassis would then be at zero potential. The protective earth is not connected to any part of the appliance. Fig. 4 shows a two-wire system (line and neutral) with the neutral connected to the chassis.

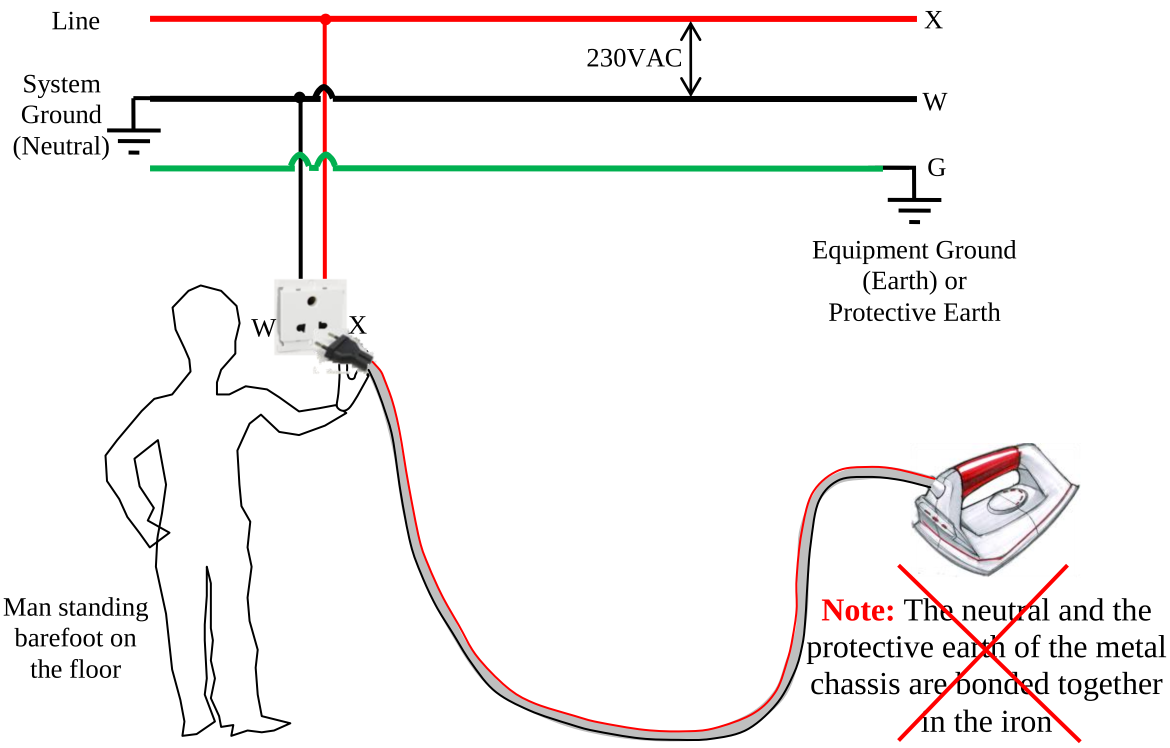

Fig. 4 Operating an electric appliance using 2 wires can be unsafe and dangerous.

The man shown standing barefoot on the floor (or he maybe touching a metal sink) would mean that he is effectively at the potential of the earth, near zero. He is shown inserting a 2 pin plug connected to an insulated twin wire cable to a wall-mounted socket. If the plug is inserted with its two prongs X and W making contact with the outlet terminals simultaneously, current will flow in the line wire X and return through the neutral wire W. Operation will be normal. However, there are **two scenarios** when unsafe and potentially dangerous operation can result which are described next.

Scenario 1

As seen in Fig. 5, a break can occur in the black neutral wire over a long period of usage, perhaps due to excessive flexing of the cable and the wires within (the red and black wires are shown for illustration in Fig. 5 but are not normally visible because of the outer insulation of the twin wire cable). If, with the plug inserted and the iron switched ON, the man touches the iron's metal chassis or plate, maybe to check its warmth, there will be an electric current. The current path is from the line X through the red wire, to the heating element in the iron and along the neutral to ground path through the man's body, because the neutral is connected to the metal chassis of the iron. This causes the man to receive a shock which can also prove fatal if the duration is longer than a few milliseconds.

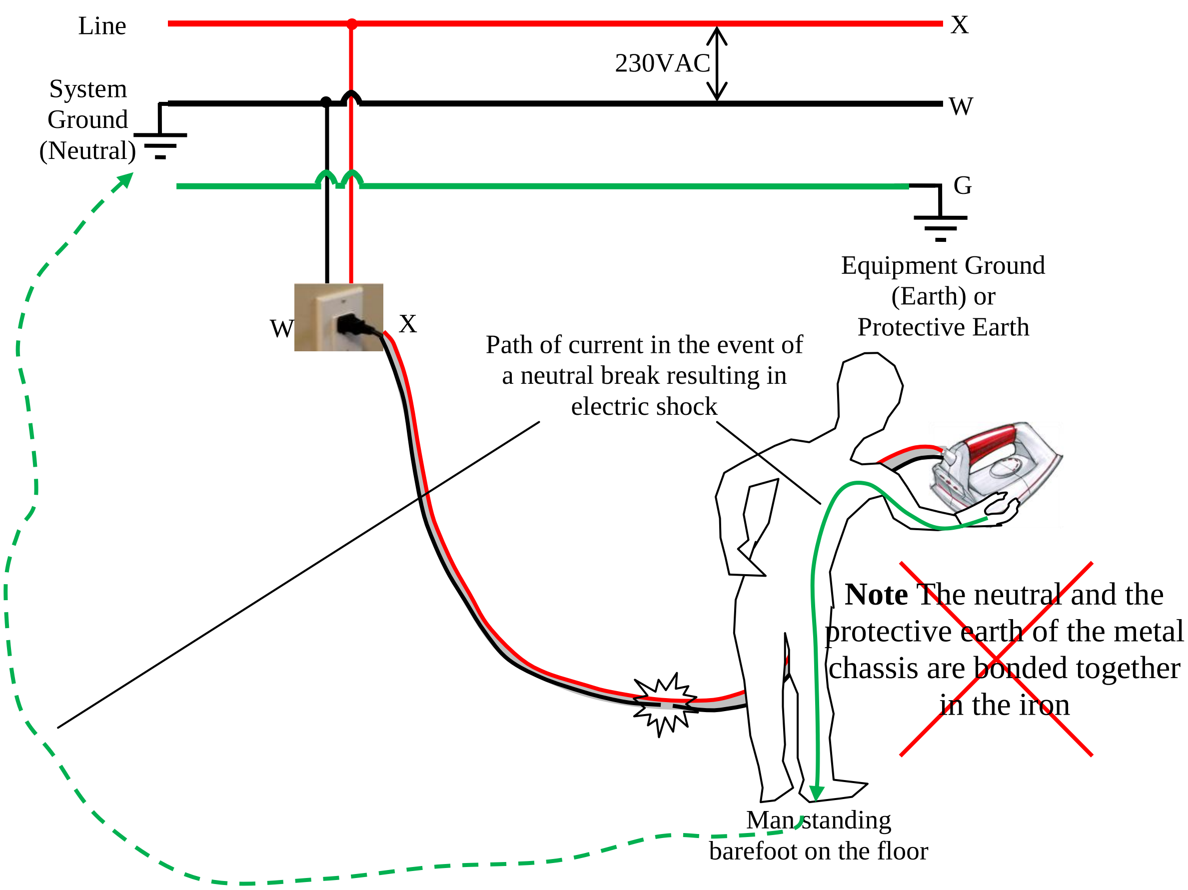

Fig. 5 Scenario 1 illustrating a dangerous operating condition should the neutral line break resulting in an electric shock to the user of an appliance with 2-wires with the neutral connected to the metal chassis of the appliance.

The path of the fault current through the user is shown by a long green arrow in Fig. 5. The fault current will find a return path to the system equipment ground buried in the earth via a ground path shown by the dashed green curving arrow.

Scenario 2

Scenario 2 is of a 2-wire connection which will result in a dangerous operation when a break occurs in the neutral line which is not as rare an occurrence as one would be led to think from the description of scenario 1 with reference to Fig. 5.
Temporary breaks in the neutral line occur whenever a 2-pronged plug is inserted into the wall outlet because there is no guarantee that the 2 pins make contact with the outlet's receptacles simultaneously. Fig. 6 shows a man standing barefoot on the floor, inserting a plug into a wall outlet while placing the other hand on the metal chassis of the iron.

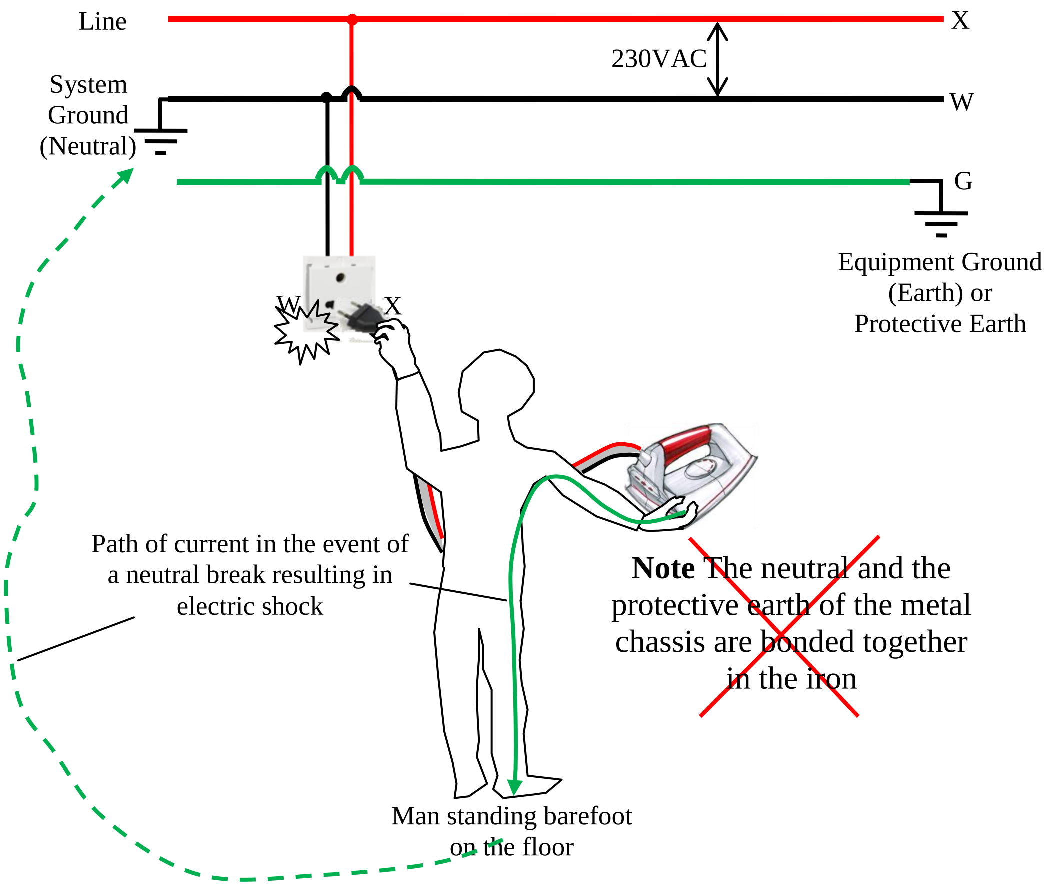

Fig. 6 Scenario 2 illustrating a dangerous operating condition should the line plug-pin make contact before the neutral plug-pin makes contact, resulting in an electric shock to the user of an appliance with 2-wires with the neutral connected to the metal chassis of the appliance.

Almost at every odd instance of the plug insertion, the line-pin makes contact a fraction of milliseconds before the neutral-pin makes contact with its corresponding receptacle. In this short duration, where only the line (or "hot") terminal is making contact at the plug/receptacle, and not the neutral, and with the neutral connected to the chassis of the electric appliance, if the user were touching the metal chassis of the electric iron (perhaps to check if its warming) while

inserting the plug in the receptacle, there will be a flow of current. The current path is from the line X through the red wire, to the heating element in the iron and along the neutral to ground path through the man's body (shown by a long green arrow) because the neutral is connected to the metal chassis of the iron. The fault current will find a return path to the system equipment ground buried in the earth via a ground path shown by the dashed green curving arrow. This causes the man to receive a shock which can also prove fatal if the duration is longer than a few milliseconds.
The notes in the Figs. 4, 5 and 6 are marked with a large red cross for the reasons described in Scenarios 1 and 2.

The way to prevent such dangerous operation is to use a third pin and to run a separate wire from the metal chassis to an equipment ground (protective earth terminal) labeled 'G', which is shown by the green colored wire in the Figs. 1, 2 and 3. The protective earth is connected to an earthing plate buried deep in the ground near the building premises where the appliance is in use.

There are a few devices which are considered safe for 2-wire use such as low power mobile battery chargers which use non-metal casing parts adequately insulated from live and neutral terminals and wires deemed safe for use by electrical standards UL, NEC, CE and carry labels of these standards.