ECET 4530

Industrial Motor Control

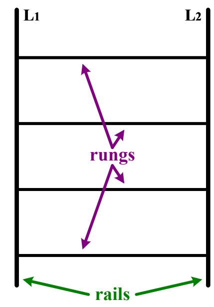
Introduction to Ladder Diagrams

1

Ladder Diagrams

Ladder Diagrams are a special type of schematic diagram that are often used to depict the electric circuits of an industrial control system.

They are called "ladder" diagrams because they resemble a ladder, having two **vertical rails** and multiple **horizontal rungs**.



<u>Of future interest</u>:
A **fundamental understanding of ladder diagrams** will also be very useful later in the course when PLCs are introduced because **PLCs are often programmed using "Ladder Logic"**, which is a graphical programming language that allows a programmer to graphically create the PLC's program by building a ladder structure that will closely resemble and have characteristics similar to the ladder diagrams that will be shown in this presentation.

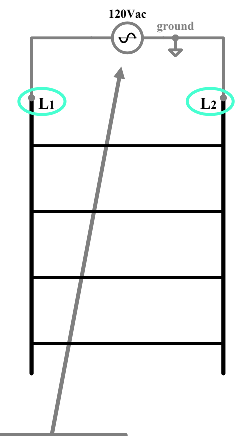
2

Ladder Diagrams – Vertical Rails

The vertical **rails** of the ladder provide a common connection to the control system's supply of electric power (voltage source).

The rails are often labeled "$\mathbf{L_1}$" and "$\mathbf{L_2}$" where:

- $\mathbf{L_1}$ is connected to the energized (ungrounded) conductor from the source, and
- $\mathbf{L_2}$ is connected to the grounded (neutral or negative) conductor from the source.



Although the control system requires a source of electric power in order to function, for simplicity's sake, the **voltage source is often omitted** from the ladder diagram, with the understanding that the proper voltage potential must exist across $\mathbf{L_1}$ and $\mathbf{L_2}$.

3

Choice of Control System Voltage

The **rated voltage** of the control system devices must be compatible with the supply voltage, the exact choice of which can depend on many factors, including:

- **Safety**
- **Convenience/Availability**
- **Component Size**

Low-Voltage AC/DC – Newer, state-of-the-art control systems often utilize $\mathbf{24V_{DC}}$. In addition to being safer to operate and maintain, the physical size of many of the system's components decreases with decreasing supply voltage, allowing for a smaller-sized or more compact control panel.

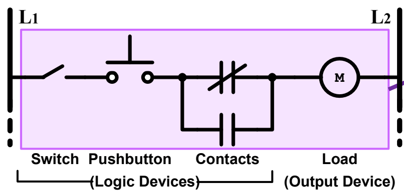
$\mathbf{120V_{AC}}$ – A large base of **120V** systems already exist within industry. $\mathbf{120V_{AC}}$ is readily available without the use either of a control transformer on an electronic supply. Additionally, the field coils of larger contactors often require higher supply voltages in order to minimize their current draw from the control system.

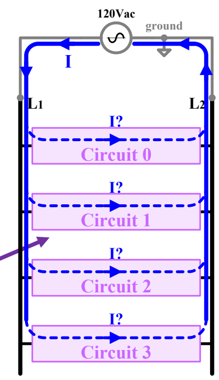
4

Ladder Diagrams – Horizontal Rungs

The horizontal **rungs** represent the individual circuits (potential closed-loop current paths) or functional elements of the control system.

A circuit on a typical rung contains at least one **output device** (load) along with one or more **logic devices** that control the flow of current on that rung.





Each rung **<u>must</u> contain at least one output device** because a rung without an output device could result in a short-circuit across the supply rails.

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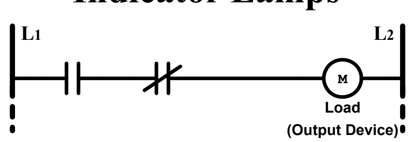
Output Devices

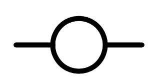
Output devices are the **electric loads** that are supplied by the various circuits that compose the rungs of the ladder.

When energized, an **output device performs a specific task** that is required as part of the overall system's operation.

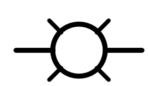
Two **output devices** that are often found within the ladder diagram of a control system are:

- **Field Coils**
- **Indicator Lamps**





Field Coil of a contactor or a relay



Indicator Lamp

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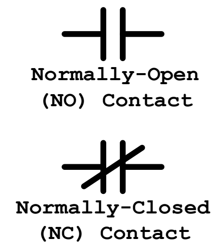
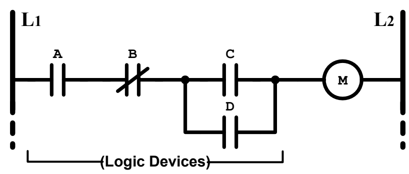
Logic Devices

A **logic device** is a device that, based on its operational state, will either permit or prevent the flow of current.

The fundamental logic device is a **contact**; either normally-open (NO) or normally-closed (NC), as found in a contactor or a relay.



Slight variations may exist in the **symbols** used to depict NO and NC contacts.



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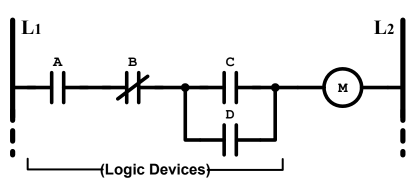
Contacts in Relays and Contactors

Note that **contacts** may be contained within a **relay** or a **contactor**, the field coil of which will also appear in the ladder diagram, or they may be contained within other devices such as **limit switches**, **pressure sensors**, **proximity detectors**, and **optical detectors**.

Although various devices contain contacts that can be utilized within a control system, the **basic symbol for a contact** may be **reserved** for those contained in **relays** and **contactors**.



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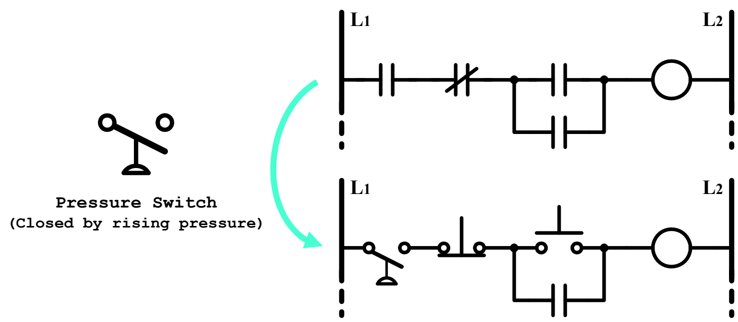
Contacts in other Electrical Components

Contacts contained in **other devices**, especially those that are not actuated by energizing an output device on one of the rungs, such as the contact contained within either a pushbutton or a pressure switch, **are often depicted by unique symbols** that can help clarify their operation within the control system.



Both rungs are logically equivalent, but the function of the circuit depicted on the lower rung is easier to visualize, even without any visible identifiers (labels).

I.e. – a **stop/start controller** with the addition of a pressure switch that prevents operation if the pressure is too low.

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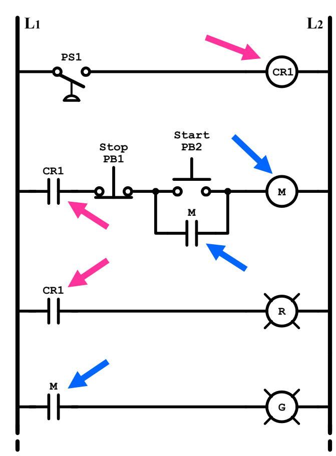
Device Identifiers

An **identifier** (label) must be included with each device shown in the ladder diagram in order to identify the device and, if part of a larger piece of equipment that contains multiple devices, to associate or link their operation.

For example, given the control circuit to the right that contains two field coils:

The **field coil** and **contacts** that are contained within a **control relay** are all labeled **CR1** in order to identify the contacts that actuate when field coil CR1 is energized, while **field coil** and **contacts** contained within the system's **main contactor** are all labeled **M** to associate their operation.



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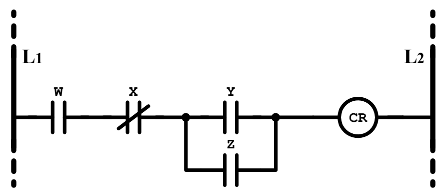
Rung Operation

The **operational state** of an **output device** on a specific rung is **determined** by the **conductive state** of that rung's **logic devices**.

In other words, the **load** on a rung is **energized** when the rung's **logic devices allow current to flow** from the source, down rail $\mathbf{L_1}$, **across the rung and through the load**, and then back up rail $\mathbf{L_2}$ to the source.

Note that the source that supplies rails $\mathbf{L_1}$ and $\mathbf{L_2}$ is not shown in the figure.



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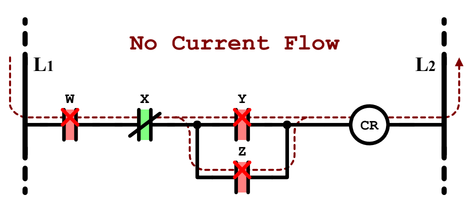
Rung Operation – Example

If the **contacts** on the following rung are in their **normal positions**, then **field coil CR** is **de-energized** because there is **no conductive path** for current to flow across the rung from rail $\mathbf{L_1}$ to rail $\mathbf{L_2}$.

A [green] behind a **logic device** denotes that the device will **<u>allow</u> current flow** (the contacts are closed) at the present time.

← **WITHIN THIS PRESENTATION** →

A [red] behind a **logic device** denotes that the device will **<u>prevent</u> current flow** (the contacts are open) at the present time.



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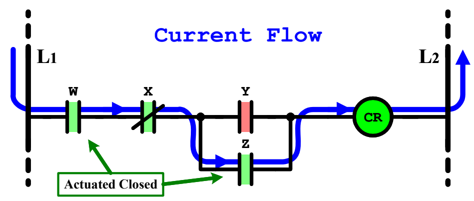
Rung Operation – Example

But, if:

- **contacts X** and **Y** remain in their **normal positions**, while
- **contacts W** and **Z** are **actuated** closed,

then **field coil CR** will be **energized** because a **conductive path** will exist from rail $\mathbf{L_1}$, through the load, to rail $\mathbf{L_2}$.



Note that the part of the **closed-loop path** from $\mathbf{L_2}$, through the source and then back to $\mathbf{L_1}$, is not shown in the figure.

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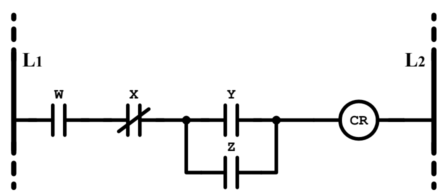
Rung Operation – Logic Statement

Thus, the **logic** required to **energize field coil CR** is:

- **contact W** must be **actuated (closed)**, <u>and</u>
- **contact X** must be in its **normal (open) position**, <u>and</u>
- either **contact Y** and/or **contact Z** must be **actuated (closed)**.



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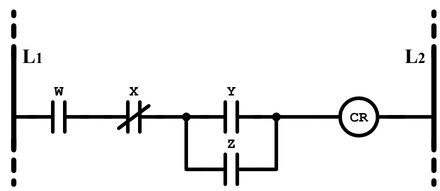
Rung Operation – Logic Statement

The **logic** required to **energize field coil CR** can also be expressed as:

- **contact W** must be **actuated (closed)**, and
- **contact X** must **not** be **actuated (open)**, and
- either **contact Y** and/or **contact Z** must be **actuated (closed)**.



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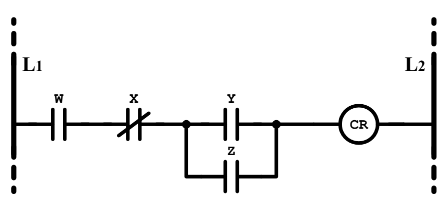
Rung Operation – Logic Statement

The **logic** required to **energize field coil CR** can also be expressed as:

- **field coil W** must be **energized**, and
- **field coil X** must **not** be **energized**, and
- either **field coil Y** and/or **field coil Z** must be **energized**.



Note - the **field coils** that control the state of contacts W, X, Y, and Z are not shown in the figure.

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Rung Operation – Logic Statement

The **logic** required to **energize field coil CR** can also be expressed as:

- **field coil W** must be **energized**, <u>and</u>
- **field coil X** must **<u>not</u>** be **energized**, <u>and</u>
- either **field coil Y** and/or **field coil Z** must be **energized**.

This can be expressed by the **Boolean expression**:

$$CR = W \cdot \bar{X} \cdot (Y + Z)$$

Not X

And

Or

This Boolean expression is provided for informational purposes only.
You will not be required to express or interpret logic statements expressed in this manner

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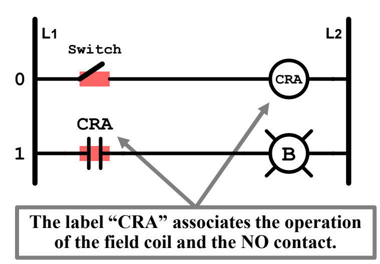
Basic Ladder Operation Example #1

Given the ladder diagram to the right:

- rung-0 contains a **switch** and the **field coil** of control relay CRA, and
- rung-1 contains a **NO contact** from control relay CRA and a **blue light**.



If the **switch** on rung-0 is initially **open (OFF)**, then:

- **field coil CRA** will be **de-energized**, and the **NO CRA contact** on rung-1 will be **open** (i.e. – in its "normal" position), and
- since the **CRA contact** on rung-1 is **open**, the **blue light** will be **de-energized (OFF)**.

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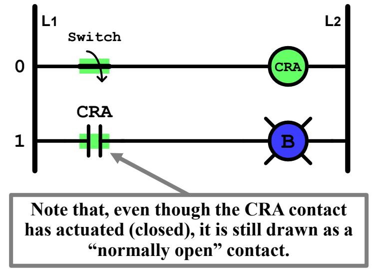
Basic Ladder Operation Example #1

Given the ladder diagram to the right:

- rung-0 contains a **switch** and the **field coil** of control relay CRA, and
- rung-1 contains a **NO contact** from control relay CRA and a **blue light**.

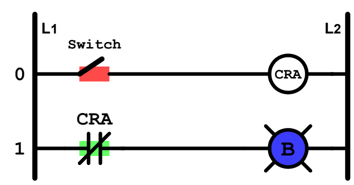


But, if the **switch** on rung-0 **closes (ON)**, then:

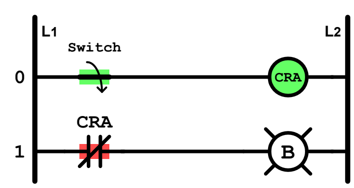
- **field coil CRA** will be **energized**, causing the **NO CRA contact** on rung-1 to actuate **closed**, and
- when **contact CRA closes**, the **blue light** will be **energized** (**ON**).

Basic Ladder Operation Example #2

But, what if the contact on rung-1 is replaced with a **NC contact**?



If the **switch** is **open**, then **field coil CRA** will be **de-energized**, the **NC CRA contact** will be **closed** (in its "normal" position), and the **blue light** will be **ON**.



But, if the **switch closes**, then **field coil CRA** will be **energized**, the **CRA contact** will actuate **open**, and the **blue light** will be **de-energized (OFF)**.

Sequential Rung Operations

When a field coil is (de)energized and its associated contacts actuate (dropout), those changes may cause other loads to become (de)energized, in-turn causing further (**sequential**) changes in the operational states of the various rungs in a ladder.

Note that, when the **field coil** of a relay or a contactor is **energized**, there is a **time-delay before its contacts change state** due to the time it takes for the electromagnet's field to build-up and for the armature to travel as it actuates the contacts.

And when a **field coil** is **de-energized**, there is a **time-delay before its contacts change state** due to the time it takes for the field to collapse and for the armature to travel as the contacts dropout.

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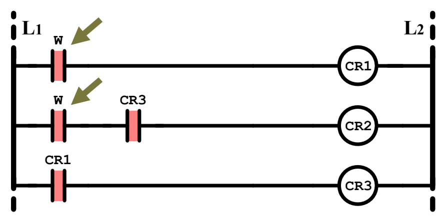
Sequential Rung Operation Example

Given the ladder to the right, in which all of the contacts are originally in their normal positions and all of the field coils are initially de-energized...



Determine the series of events that will occur if the **W contacts** are actuated **closed**.

Note that the specific means for actuating the W contacts, such as field coil W, is not shown in the figure.

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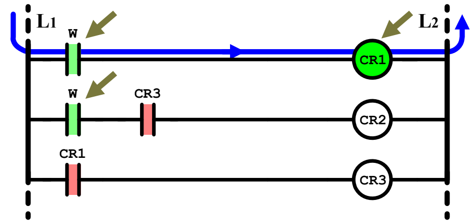
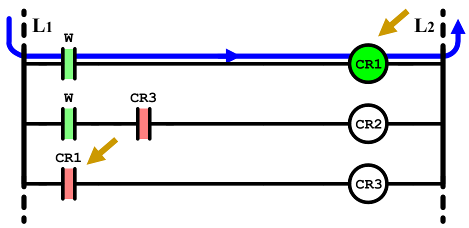
Sequential Rung Operation Example

When the **W contacts** are actuated **closed**, **field coil CR1** will be **energized**…





And when **field coil CR1** is **energized**, the **NO CR1 contact** will **actuate** closed **<u>after</u>** a short **delay***.

* – Due to the time delay, the contact is still shown to be in its open state. The effect of it actuating closed will be shown on the next slide.

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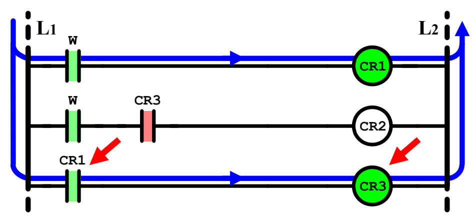
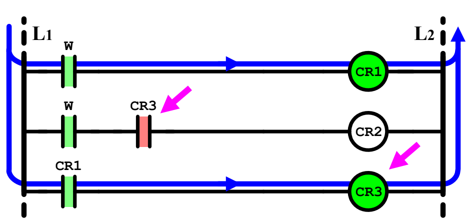
Sequential Rung Operation Example

When the **CR1 contact** is actuated **closed**, **field coil CR3** will be **energized**…





And when **field coil CR3** is **energized**, the **NO CR3 contact** will **actuate** closed **<u>after</u>** a short **delay**.

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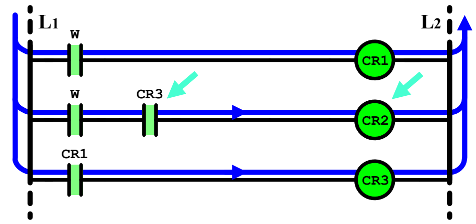
Sequential Rung Operation Example

When the **CR3 contact** is actuated **closed**, **field coil CR2** will be **energized**.

Since there are no CR2 contacts shown in the figure, no further operations can be predicted.



Thus, when the **W contacts** are actuated **closed**:

- **field coil CR1** is energized and the **CR1 contact actuates closed**, after which
- **field coil CR3** is energized and the **CR3 contact actuates closed**, after which
- **field coil CR2** is energized.

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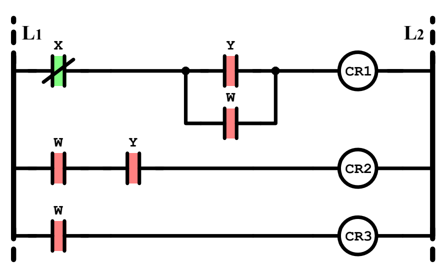
Simultaneous Rung Operation

When contacts actuate or dropout simultaneously on multiple rungs, the loads on those rungs might also be energized or **de-energized** simultaneously.

For example, determine the events that will occur if the **W contacts** are actuated **closed** in the following ladder:



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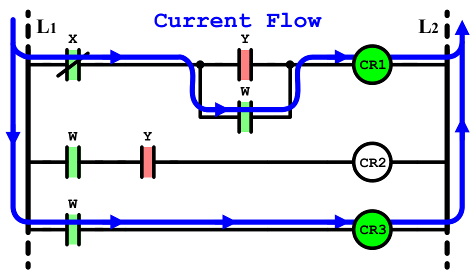
Simultaneous Rung Operation

When the **W contacts** are **actuated** (closed) while the **X** and **Y contacts** remain in their **normal positions**:

- **field coils CR1** and **CR3** will **simultaneously** be **energized** because **conductive paths** will simultaneously be created from rail L_1 to L_2 through <u>both</u> of those loads.



If multiple CR1 and CR3 contacts existed within the ladder, then the effects of those contacts actuating simultaneously would have to be investigated.

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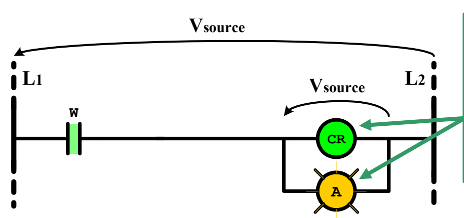
Multiple Output Devices on a Rung

Two (or more) loads may be connected in **parallel** on a single rung if their operation should always be based on the same conditional logic (i.e. – if they should always operate at the same time).



If placed on the same rung, they **must be placed in <u>parallel</u>** because each load will be **rated for the supply voltage**, and they will **require this voltage for proper operation**.

Note that, if additional logic devices are available, there are advantages to placing the loads on separate rungs that contain duplicate logic devices, especially if any modifications to the system's operational logic may be required in the future.

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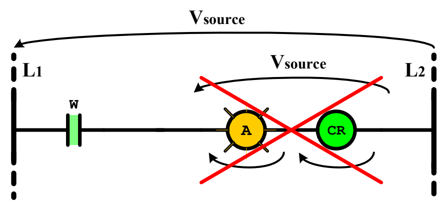
Multiple Output Devices on a Rung

Two (or more) loads should **never** be connected in **series** on a rung because the source **voltage will be split between the loads**, often causing one or both loads to **fail to operate** properly.



Do not wire multiple loads in series.

This is a **common mistake** that students often make when asked to modify or add components to an existing circuit, especially if the control circuit is not drawn as a ladder diagram!

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Introduction to Ladder Diagrams

Part II

Instructional Note

Safety should always be the **primary concern** in an industrial setting.

Part II briefly introduces the concept of **proper device placement** based on the location of the control circuit's **ground terminal**, along with some of the **safety issues** that arise from improper placement of the devices.

Note – the overall concept **System Grounding** is ***beyond the scope*** of this course due to its complexity and far-reaching implications. In fact, despite its importance, the topic is rarely discussed within any electrical engineering curriculum.

Thus, Part II of this presentation in intended to provide the students with a glimpse into the **field of grounding** and to encourage further study of this important topic. But, since this is a single semester course and limited time is available to cover all of the required topics, lectures will not be provided for part II of this presentation.

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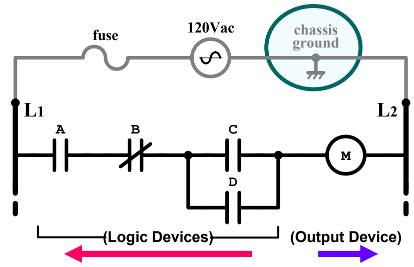
Proper Device Placement on a Rung

PROPER DEVICE PLACEMENT

Output devices (**loads**) should be placed on the **right-hand side of the rung**, closest to the <u>grounded</u> rail $\mathbf{L_2}$.

All of the **logic devices** that govern the operation of the loads are then placed on the **left-hand side of the load(s)**.



A "**chassis ground**" is an **electrical connection** to the **metal enclosure** of an electrical device.

The **metal enclosure** is also connected to the **earth ground** of the power distribution system; in-turn **holding the metallic enclosure at a 0-volt potential**.

Since only one point in the circuit is connected to the chassis (metal enclosure), the **chassis ground does not provide a closed-loop path for current to flow during normal operation**.

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Proper Device Placement on a Rung

PROPER DEVICE PLACEMENT

Output devices (**loads**) should be placed on the **right-hand side of the rung**, closest to the <u>grounded</u> rail $\mathbf{L_2}$.

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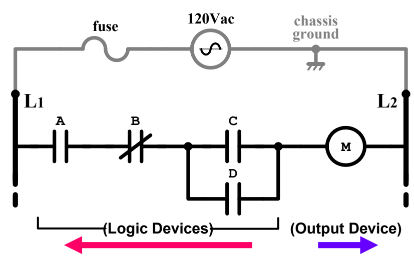

Note that most "**Ladder Logic**" editors that are used to create the programs that govern the operation of a **PLC** also adhere to the same standard:

Logic Devices → Left

Output Devices → Right

due to the order in which the editors interpret the devices (instructions) that are placed on the rungs within the programming environment.

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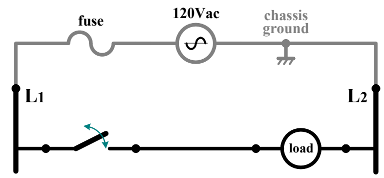
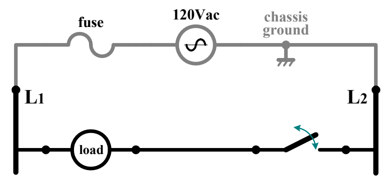
Device Placement on a Rung

Note that, **under normal conditions**, the **exact placement** of the devices on a rung **will not affect the load's overall operation** provided that the rung's operational logic is maintained.



Proper Device Placement



Improper Device Placement

In either case, the **load** will be **(de)energized** when the **switch** is **(opened) closed** under **normal conditions***.

* – in this case, **normal conditions** implies that all of the **system's components** are **functioning properly** and the there are **no faults** or other problems in the circuit.

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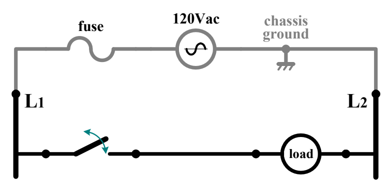
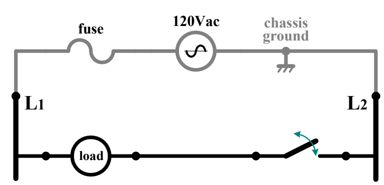
Device Placement on a Rung

Note that, **under normal conditions**, the **exact placement** of the devices on a rung **will not affect the load's overall operation** provided that the rung's operational logic is maintained.



Proper Device Placement



Improper Device Placement

But, **under abnormal conditions**, such as during the occurrence of a electrical fault within the control system, **improper placement** poses a **safety risk** that can result in possible electrocution as well as unexpected or uncontrollable system operation.

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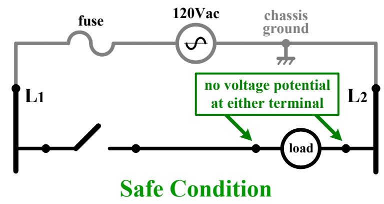
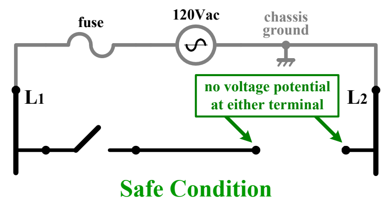
Proper Device Placement Example

SAFE OPERATION EXAMPLE

Under normal conditions, there will be **no voltage potential at** either of the **load terminals** while the **switch** is in the **OFF** (open) position.





There is always a **0-volt potential** at the **right-hand terminal of the load** since rail L_2 is **grounded**.

While the **switch** is **OFF**, a **0-volt potential** will also be present at the **left-hand terminal of the load** since the **potential difference** (voltage) **across the load is zero**.

And, if the **load is removed** while the **switch** is **OFF**, there will still be **no voltage** present on the **left-hand terminal** because wire that connects to the left-hand side is isolated (disconnected) from rail L_1 by the switch.

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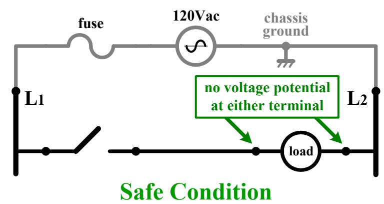
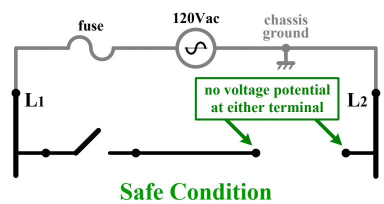
Proper Device Placement Example

SAFE OPERATION EXAMPLE

Under normal conditions, there will be **no voltage potential at** either of the **load terminals** while the **switch** is in the **OFF** (open) position.



Thus, if the load is a lamp, as long as the **switch** is **OFF**, a blown lamp could be removed from its socket and **replaced without risk** of shock or electrocution.



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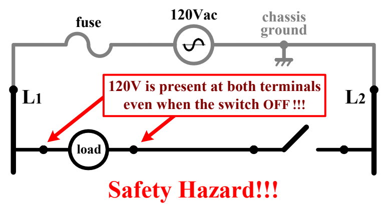
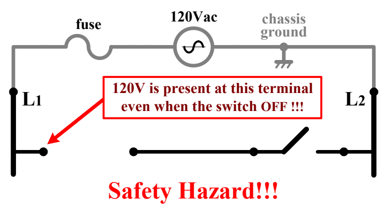
Improper Device Placement Example

UNSAFE OPERATION EXAMPLE

But, even under **normal conditions**, there will still be a **voltage potential** present at the **load terminals** while the **switch** is **OFF** since the load is directly connected to $\mathbf{L_1}$.





For **safety** reasons, **both load terminals** should be **held at a 0-volt potential** whenever **the load is de-energized**.

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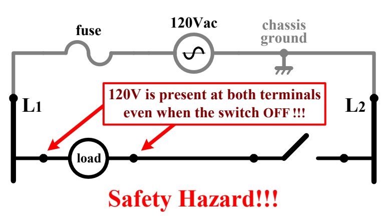
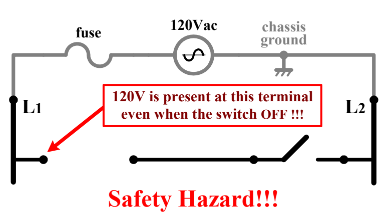
Improper Device Placement Example

UNSAFE OPERATION EXAMPLE

But, even under **normal conditions**, there will still be a **voltage potential** present at the **load terminals** while the **switch** is **OFF** since the load is directly connected to $\mathbf{L_1}$.

Thus, replacement of a blown lamp, even while the **switch** is **OFF**, could result in **electrocution** if accidental contact is made with the energized terminal of the empty lamp socket.





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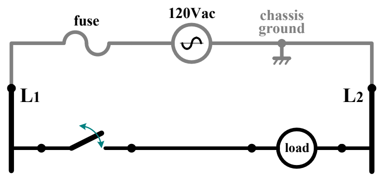
Proper Device Placement Example

SAFE OPERATION EXAMPLE

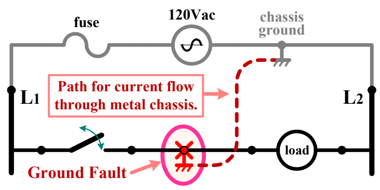
If a **ground fault*** occurs on the wire that connects the switch to the load…

Then the **metal enclosure** will provide an abnormal **short-circuit** (low resistance) **path for current flow** between the fault location and the connection point of the chassis ground.

* – A **ground fault** occurs whenever an **ungrounded circuit conductor** is **abnormally connected** to the **metal chassis**.



Proper Device Placement



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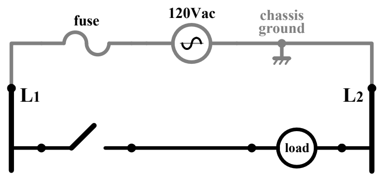
Proper Device Placement Example

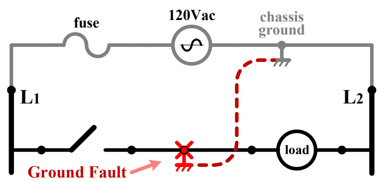
SAFE OPERATION EXAMPLE

Yet, even if a **ground fault** has occurred on the wire that connects the switch to the load, as long as the **switch is OFF**…

There is **no closed-loop path for current** to flow within the circuit, and thus the **circuit will remain de-energized** despite the existence of the fault.



Normal Operation



Safe Condition

Although the **fault** will remain **undetected** at this time, it creates **no adverse operational effects** in the system and poses **no immediate safety risk**.

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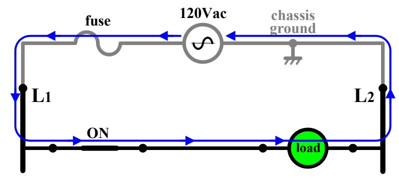
Proper Device Placement Example

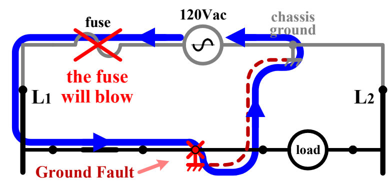
Safe Operation Example

But, if a **ground fault** has occurred on the wire that connects the switch to the load and the <u>**switch** is **ON**</u> (closed), then a **short-circuit** will be created **across the source terminals**.

The instant that the source becomes short-circuited, the **source current** will become **extremely large**, causing the **fuse to blow (**open-circuit**)**, in-turn **de-energizing the circuit**.



Normal Operation



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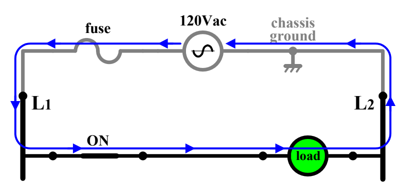
Proper Device Placement Example

Safe Operation Example

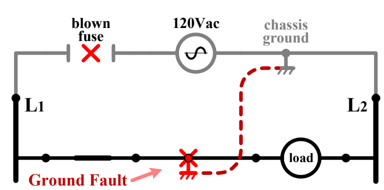
If the **fault occurs before** the **switch** is **flipped ON**, then the system will **fail to startup**.

But, if the **load** was **already energized when the fault occurred**, then the system will **unexpectedly shutdown***.

Either way, once the **fuse blows** and the system is de-energized, the cause of the failure can be **safely investigated**.



Normal Operation



Safe Condition

* – an **unexpected shutdown** can pose a **safety risk**, but **the alternative** is typically **more dangerous**.

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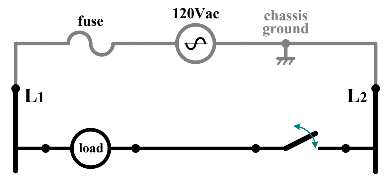
Improper Device Placement Example

Unsafe Operation Example

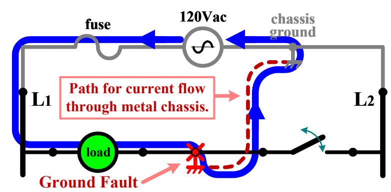
But, if the devices are **improperly placed** and a **ground fault** occurs on the wire that connects the switch to the load…

Then the metal chassis will provide a short-circuit (low resistance) path for current that **bypasses the switch**.

Thus, once the **ground fault** occurs, the **load will be energized regardless of the switch position**.



Improper Device Placement



Extreme Safety Hazard!!!

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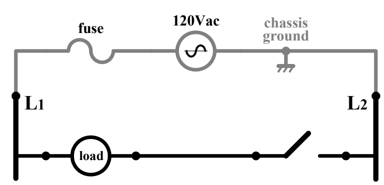
Improper Device Placement Example

Unsafe Operation Example

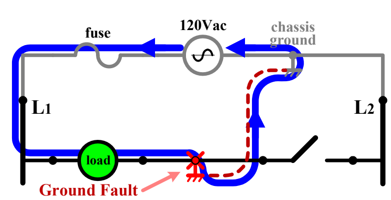
If the switch is OFF when the ground fault occurs, then the **load** would become **energized without warning**!

→ **This could be <u>extremely</u> <u>hazardous</u> depending on the type of system!**

Consider what could potentially happen if someone was cleaning debris from around the **shredding rotor** of a **chipper-shredder**, and the **main drive motor is unexpectedly energized due to a ground fault** that occurred when a vibration dislodged a loose wire.



Improper Device Placement



Extreme Safety Hazard!!!

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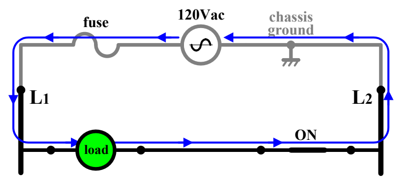
Improper Device Placement Example

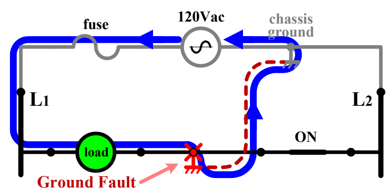
Unsafe Operation Example

But, **if the switch is ON** when the fault occurs, then the **system** would appear to continue **operating normally** until the operator <u>unsuccessfully</u> attempts to de-energize the system.

→ **This could be <u>extremely</u> <u>hazardous</u>, especially if an emergency occurs and the operator needs to shutdown the system, only to find out that the power switch has been rendered inoperative!**



Improper Device Placement



Extreme Safety Hazard!!!

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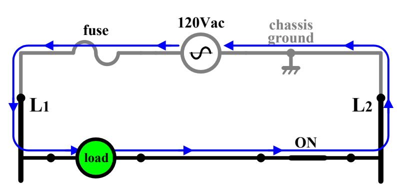
Improper Device Placement Example

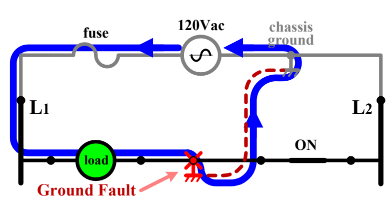
Unsafe Operation Example

But, **if the switch is ON** when the fault occurs, then the **system** would appear to continue **operating normally** until the operator <u>unsuccessfully</u> attempts to de-energize the system.

> Also note that, since the **ground fault** is only bypassing the switch and it **is not resulting in a short-circuit condition across the source** due to the improperly designed control circuit, the **fuse will not blow and de-energize the system**.
>
> Hopefully the **main disconnect** for the system is **readily accessible** or there was an additional **emergency stop** function also built into the system.



Improper Device Placement



Extreme Safety Hazard!!!

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