Programmable Logic Controllers:

An Emphasis on Design and Application

Second Edition

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Dedicated to Fran, Esther, David and Amanda

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PREFACE

The field of automatic control has been undergoing a transformation over the past twenty years. Twenty years ago, the engineering undergraduate had a course in feedback control theory and those interested in control engineering secured a position in the aerospace or chemical industries. Due to various factors, the number of control engineering positions in the aerospace industry has been declining, but the number of control engineering positions in manufacturing has been dramatically increasing to the point that the majority of control engineering positions is now in manufacturing and involves PLCs.

This book presents the subject of programming industrial controllers, called programmable logic controllers (PLCs) with an emphasis on the design of the programs. Many texts teach one how to program the PLC in its languages, but little, if any, attention is paid to how does one attack the problem: “Given a set of operational specifications, how does one develop the PLC program?” This book develops the design process: the tasks involved, breaking the program into manageable pieces, standard code for the various parts, and handling the sequential parts of the problem. The emphasis is toward those who will be programming PLCs.

Because of its popularity (now and in the future), ladder logic is the language that is used for the majority of the text. The industry trend is toward using the IEC 61131-3 (formerly IEC 1131-3) standard, and so it is the primary language. However, IEC 61131-3 is only a voluntary standard and individual manufacturers have some freedom in the implementation. Therefore, the Allen-Bradley ControlLogix, Modicon, Siemens S7, and GE implementations of the 61131-3 standard are covered. Because of their large installed base, the Allen-Bradley PLC-5/SLC-500 PLC languages are also covered.

Due to the limitations of ladder logic, the IEC 61131-3 standard defines four other languages: function block diagram, structured text, instruction list, and sequential function chart. These four languages will become more popular in the future. Therefore, this text also covers these languages.

Since a typical manufacturing plant may contain discrete, continuous, and batch processes, all of these applications are treated in this text, although the emphasis is on discrete and continuous processes. The emphasis is on a methodology that can be applied to any automation project, regardless of the size.

Throughout, the book contains example problems demonstrating good design practice. In addition, these problems are solved with each PLC covered in the book. The text culminates in two full-length case studies where the application of the design techniques to a large problem is illustrated.

This book takes a practical approach to the design of PLC control systems. Some mathematical theory is used to backup the presentation on PID controllers. However, the theory is not detailed and can be omitted.

Except for Chapters 1 and 13, every chapter begins with a scenario that reflects the experience of the author and his colleagues in the challenging world of factory automation.

These scenarios present a small problem and the solution and are intended to illustrate troubleshooting techniques.

Objectives

The main objectives of this text are to teach:

- PLC programming languages (with emphasis on IEC 61131-3)
- Approach to sequential problems
- Good program design practice
- Simple PID control tuning
- Introduction to sensors and actuators
- Factory communications
- Human-machine interface (HMI) concepts

Content Overview

The book starts by introducing programmable logic controllers (PLCs) and their distinguishing characteristics. Chapters 2 – 5 cover basic ladder logic programming: contact, timer, and counter instructions. As part of the basics, the memory structure of the five particular PLCs and installation topics are treated. Chapter 6 covers ladder logic program design for sequential applications, probably the most significant contribution of the text. Chapters 7 and 8 treat computation, comparison, and advanced ladder logic instructions. Alternate sequential implementations in ladder logic are covered in Chapter 9 and PID controller tuning is covered in Chapter 10. Chapters 11 – 14 cover the other four IEC programming languages: function block diagram, statement list, instruction list, and sequential function chart. PLC troubleshooting is covered in Chapter 15. Sensors and actuators appear in Chapter 16. Chapter 17 introduces factory communication networks. Operator interface, often called human-machine interface (HMI), issues are treated in Chapter 18. Control system security is addressed in Chapter 19 and PLC selection is introduced in Chapter 20. Chapter 21 presents the perspective of an entire automation project, bringing together the various pieces of PLC control design. Chapter 22 outlines two full-length project case studies. One case study is for a process that is primarily discrete and the other case study is for a process that is primarily continuous in nature. Details about number systems and drawing symbols are included as appendices, rather than interrupt the flow of the text material.

The Audience

This book primarily serves the academic market, at the junior or senior undergraduate electrical, mechanical, or industrial engineering or engineering technology level. This text is also suitable for the two-year technical school market. There is nothing in the material that requires a college degree, though the material will be more challenging than the typical PLC textbook for this level of student.

In addition, this text serves the professional market. Economic and regulatory pressures in the manufacturing, chemical, petrochemical, pharmaceutical, and food industries have forced control engineers to design new systems or retrofit existing control systems. Hence, there are many control engineers (primarily chemical and electrical) who need to rapidly educate themselves in an area of technology in which they are probably only somewhat familiar. This book is valuable to this audience.

Second Edition

The second edition primarily updates the Modicon, Siemens, and GE controllers to the current processors, but there are other changes throughout. The Modicon sections focus on the Modicon Unity processors. For the older Modicon Quantum/Momentum processors, see the first edition of this text. The Allen-Bradley material has been updated to focus on the ControlLogix processor, though the PLC-5/SLC-500/MicroLogix processors are also covered. Coverage of the ControlLogix add-on instruction (AOI) has been added. The Siemens S7-1200 has been added to the Siemens sections and the material on the S5-compatible timers and counters has been removed. The GE PACSystems processor has been added and the material focuses on this processor with references to the earlier processors as appropriate. The PLC history in Chapter 1 has been updated. In Chapter 2, the section about converting relay logic to ladder logic has been removed and replaced with a section on using the transitional contacts and coils. The examples in sections 9.2, 11.7 and 21.4 now utilize user-defined data types and user-defined function blocks. In addition, all of the chapter problems have been replaced with new problems. Lastly, the accompanying CD contains the PLC projects for each example problem and has an additional set of solved problems.

Acknowledgements

The author wishes to acknowledge the beneficial suggestions and comments of many colleagues. Steve Ingracia provided the sample panel specification in Chapter 4. Bill Bichler, Dean Ford, and Esther Erickson reviewed drafts of the first edition of this book and provided many suggestions and corrections to improve the final product. Ken Ball provided more information on the history of the PLC and John Crabtree provided helpful suggestions for the second edition. I especially thank Esther and Fran Erickson for correcting the entire manuscript for grammatical errors, and Fran for doing the initial typesetting.

Portions of this material were taught in industrial short courses and university courses and the students are acknowledged for their help in pointing out errors in the text and where the presentation was unclear.

Disclaimer

Information furnished herein is believed to be accurate and reliable; however no responsibility is assumed for any errors. The user assumes full responsibility for the accuracy and appropriateness of this information.

2 Basic Ladder Logic Programming

Chapter Topics:

- Basic ladder logic symbols
- Ladder logic diagram
- Ladder logic evaluation
- Start/stop logic

OBJECTIVES

Upon completion of this chapter, you will be able to:

- Understand basic ladder logic symbols
- Write ladder logic for simple applications

Scenario: A program with a long scan time may not detect short-duration events.

A manufacturer of small gasoline engines had an intermittent problem on the final assembly line. Sometimes, a defective engine would not be automatically removed from the line for repair at a “kick-out” station. If an operator noticed a problem with an engine, he/she inserted a bolt into a certain hole in the engine carrier. A proximity sensor before the kick-out station sensed the presence of the bolt, and the PLC activated a hydraulic solenoid to push the carrier (and engine) off the main conveyor and into the repair area. A view of this station is shown in Figure 2.1. Further investigation revealed that the duration of the **on** pulse of the proximity sensor was approximately 3/4 seconds. One PLC controlled all of the stations on the assembly line and its ladder logic program was quite large. As indicated in the PLC status, the time to scan the ladder logic program was slightly less than 1 second. Hence, it was very likely that a pulse from the proximity sensor could be undetected by the PLC processor. The proximity sensor could be **off** at the start of the ladder scan, generate an **on** pulse from a passing bolt in the carrier, and be **off** at the start of the next ladder scan.

Solution: Logic to examine the proximity sensor is placed in a ladder logic routine that is executed every ½ second. If the proximity sensor is detected to be on, an internal coil is turned on for at least 1.5 seconds. The main PLC program is changed to examine this internal coil to determine when to activate the hydraulic solenoid and push a carrier off the main conveyor.

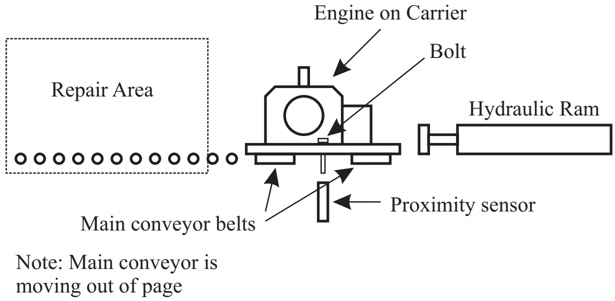


Figure 2.1. Kick-out station.

2.1 INTRODUCTION

Now that the PLC has been introduced, let us move on to programming the PLC. The first, and still most popular programming language, is ladder logic. Using examples, the language is developed from the electromechanical relay system-wiring diagram. After describing the basic symbols for the various processors covered by this text, they are combined into a ladder diagram. The subsequent section details the process of scanning a program and accessing the physical inputs and outputs. Programming with the normally closed contact is given particular attention because it is often misapplied by novice programmers. To solidify these concepts, the start/stop of a physical device is considered. Start/stop is a very common PLC application and occurs in many other contexts. An optional section on relay to PLC ladder logic conversion concludes the chapter.

2.2 SIMPLE LADDER LOGIC

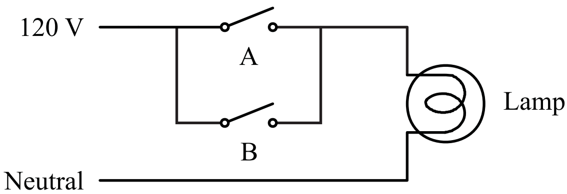
Ladder logic is the primary programming language of programmable logic controllers. Since the PLC was developed to replace relay logic control systems, it was only natural that the initial language closely resembles the diagrams used to document the relay logic. By using this approach, the engineers and technicians using the early PLCs did not need retraining to understand the program. To introduce ladder logic programming simple switch circuits are converted to relay logic and then to PLC ladder logic.

In all of the ladder logic examples used in this chapter, tags (symbols) are used for all inputs, outputs, and internal memory in the examples to avoid having to deal with input/output addressing. This addressing, treated in Chapter 3, is generally different for each PLC manufacturer.

Example 2.1. OR Circuit. Two switches labeled A and B are wired in parallel controlling a lamp as shown in Figure 2.2*a*. Implement this function as PLC ladder logic where the two switches are separate inputs.

Solution. The switch circuit action is described as, "The lamp is **on** when switch A is **on** (closed) or switch B is **on** (closed)." All possible combinations of the two switches and the consequent lamp action is shown as a truth table in Figure 2.2*b*.

To implement this function using relays, the switches A and B are not connected to the lamp directly, but are connected to relay coils labeled AR and BR whose normally-open



(a)

A	B	Lamp
off	off	off
off	on	on
on	off	on
on	on	on

(b)

Figure 2.2. Parallel switch circuit: *(a)* switch circuit; *(b)* truth table.

(NO) contacts control a relay coil, LR, whose contacts control the lamp, Figure 2.3*a*. The switches, A and B, are the inputs to the circuit. When either switch A or B is closed, the corresponding relay coil AR or BR is energized, closing a contact and supplying power to the LR relay coil. The LR coil is energized, closing its contact and supplying power to the lamp.

The output (lamp in this case) is driven by the LR relay to provide voltage isolation from the relays implementing the logic. The switches, A and B, control relay coils (AR and BR) to isolate the inputs from the logic. Also, with this arrangement, the one switch connection to an input relay can be used multiple times in the logic. A typical industrial control relay can have up to 12 poles, or sets of contacts, per coil. For example, if the AR relay has six poles (only one shown in Figure 2.3*a*), then the other five poles are available for use in the relay logic without requiring five other connections to switch A.

Before the PLC was developed, engineers had already developed a graphical electrical circuit shorthand notation for the relay circuit of Figure 2.3*a*. This notation was called a *relay ladder logic diagram*, shown in Figure 2.3*b*. The switches are shown as their usual symbol, the circles indicate the relay coils, and the NO relay contacts are shown as the vertical parallel bars.

The *PLC ladder logic* notation (Figure 2.3*c*) is shortened from the relay wiring diagram to show only the third line, the relay contacts and the coil of the output relay. The PLC ladder logic notation assumes that the inputs (switches in this example) are connected to discrete input channels (equivalent to the relay coils AR and BR in Figure 2.3*b*). Also, the actual output (lamp) is connected to a discrete output channel (equivalent to the normally open contacts of LR in Figure 2.3*b*) controlled by the coil. The label shown above a contact symbol is not the contact label, but the control for the coil that drives the contact. Also, the output for the rung occurs on the extreme right side of the rung and power is assumed to flow from left to right. The PLC ladder logic rung is interpreted as: "When input (switch) A is **on** OR input (switch) B is **on** then the lamp is **on**," which is the same as the statement describing the switch circuit in Figure 2.2*a*.

Notice that the original description of the switch circuit in Figure 2.2*a*,

The lamp is **on** when switch A is **on** <u>or</u> switch B is **on**.

translates into a relay circuit described as

A <u>parallel</u> connection of **normally-open contacts**,

which describes the PLC ladder logic in Figure 2.3*c*.

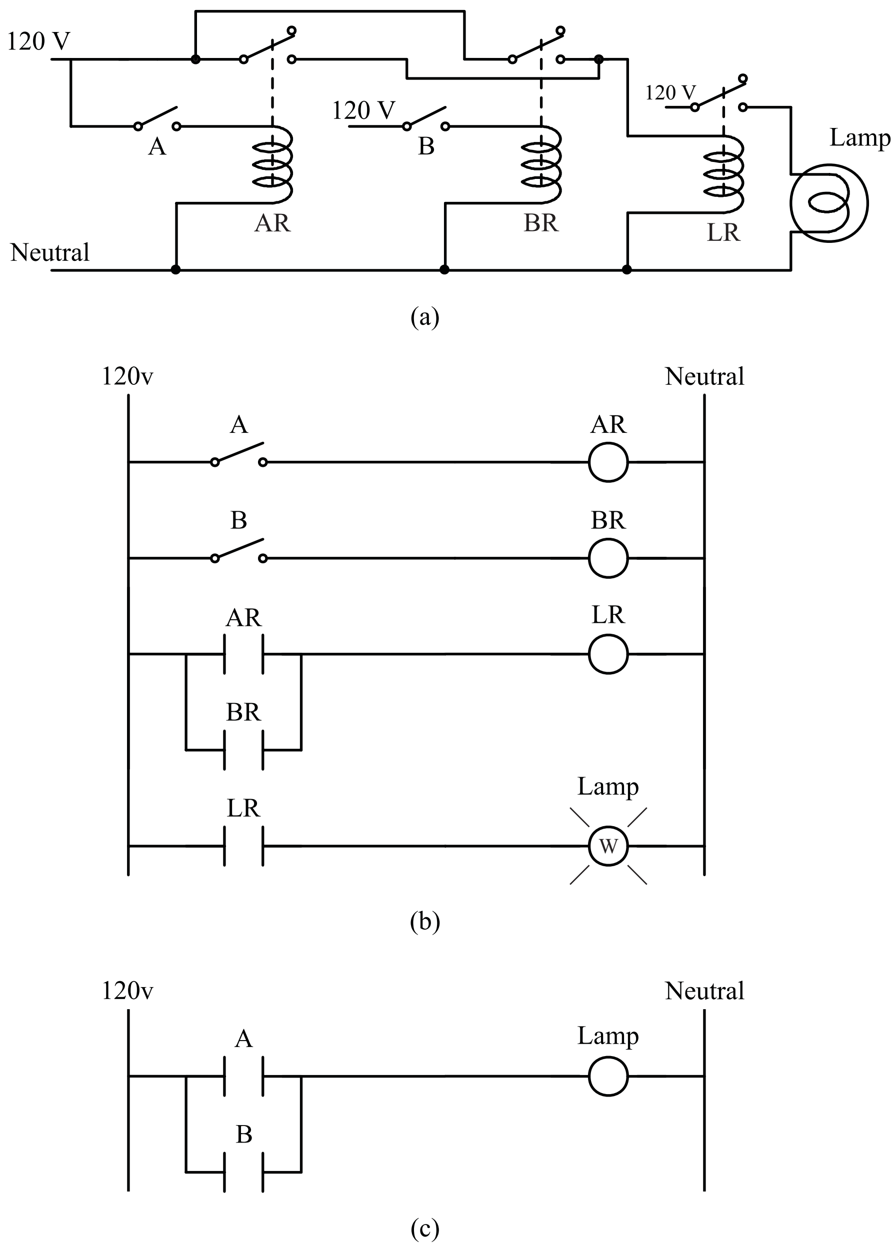
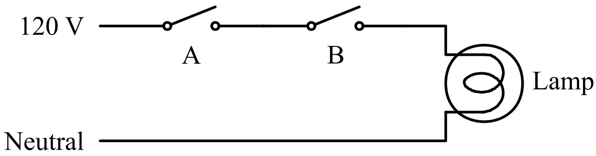


Figure 2.3. Parallel switch relay and ladder logic circuits: *(a)* equivalent relay circuit; *(b)* equivalent relay ladder logic circuit; *(c)* equivalent PLC ladder logic.

Example 2.2. AND Circuit. Two switches labeled A and B are wired in series controlling a lamp as shown in Figure 2.4*a*. Implement this function as PLC ladder logic where the two switches are separate inputs.



(a)

A	B	Lamp
off	off	off
off	on	off
on	off	off
on	on	on

(b)

Figure 2.4. Series switch circuit: *(a)* switch circuit; *(b)* truth table.

Solution. The switch circuit action is described as, "The lamp is **on** when switch A is **on** (closed) and switch B is **on** (closed)." All possible combinations of the two switches and the consequent lamp action is shown as a truth table in Figure 2.4*b*. To implement this function using relays, the only change from Example 2.1 is to wire the normally-open contacts of control relays AR and BR in series to control the light, Figure 2.5*a*. The wiring of switches A and B and the wiring of the lamp do not change. The relay circuit diagram, shown in Figure 2.5*b* is different from Figure 2.3*b* only in the third line. As for example 2.1, the PLC ladder logic notation (Figure 2.5*c*) is shortened from the relay wiring diagram to show only the third line, the relay contacts and the coil of the output relay. The PLC ladder logic rung is interpreted as: "When input (switch) A is **on** AND input (switch) B is **on** then the lamp is **on**."

Notice that the original description of the switch circuit in Figure 2.4*a*,

The lamp is **on** when switch A is **on** and switch B is **on**.

translates into a relay circuit described as

A series connection of **normally-open contacts**,

which describes the PLC ladder logic in Figure 2.5*c*.

Example 2.3. As a third example, consider the implementation of a logical NOT function. Suppose a lamp needs to be turned **on** when switch A is **on** (closed) and switch B is **off** (open). Implement this function as PLC ladder logic where the two switches are separate inputs.

Solution. Figure 2.6 shows the truth table, relay implementation and ladder logic for this example. The only difference between the relay implementation in Figure 2.6*b* and Figure 2.5*a* is the wiring of the relay BR contacts. The logical NOT for switch B is accomplished with the normally closed (NC) contact of relay BR. The PLC ladder logic rung in Figure 2.6*c* is different from Figure 2.5*c* only in the second contact symbol. The PLC ladder logic is interpreted as: "When input (switch) A is **on** (closed) and input (switch) B is **off** (open) then the lamp is **on**." This particular example is impossible to implement with a combination of only two normally open switches and no relays.

Notice that the original description of the Example 2.3,

The lamp is **on** when switch A is **on** and switch B is **off**.

translates into a relay circuit described as

A series connection of a **normally-open contact** and a **normally-closed contact**,

which describes the PLC ladder logic in Figure 2.6*c*.

Summarizing these three examples, one should notice that key words in the description of the operation translate into certain aspects of the solution:

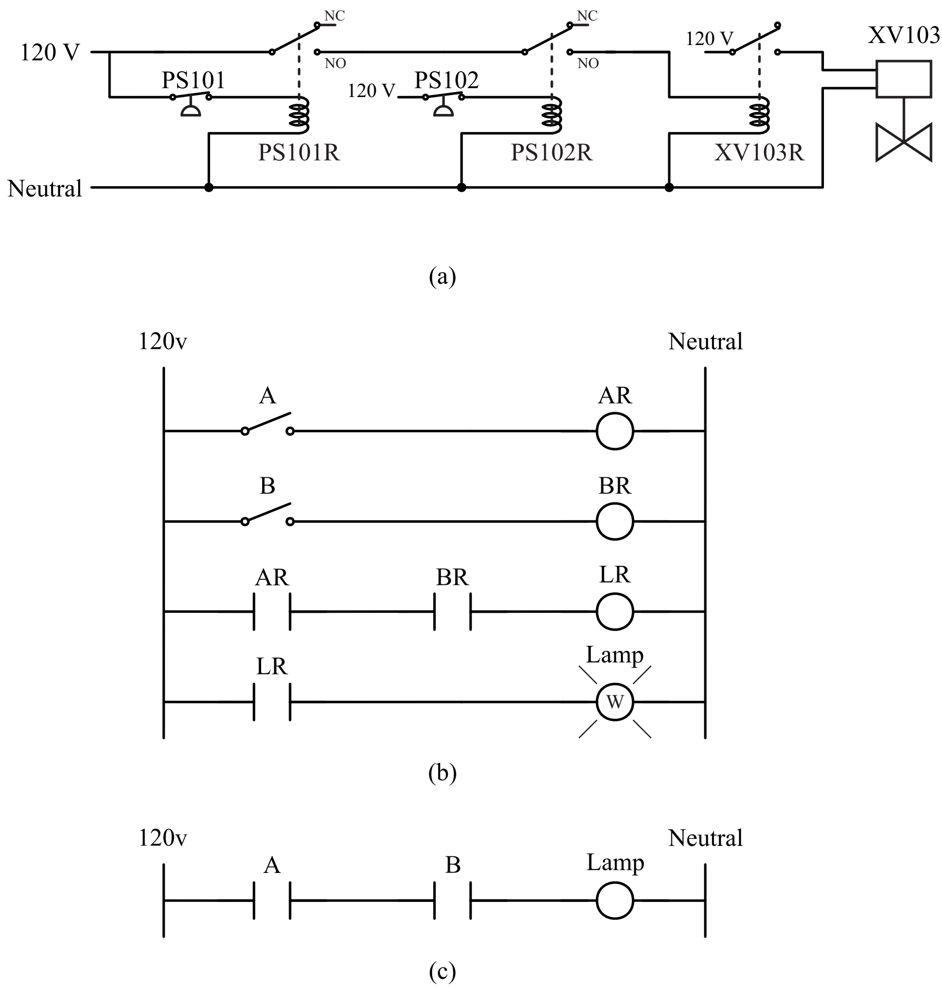


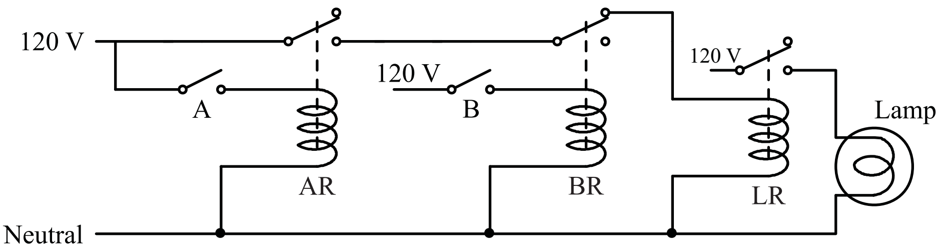
Figure 2.5. Series switch relay and ladder logic circuits: *(a)* equivalent relay circuit; *(b)* equivalent relay ladder logic circuit; *(c)* equivalent PLC ladder logic.

and	→	series connection of contacts
or	→	parallel connection of contacts
on	→	**normally-open** contact
off	→	**normally-closed** contact

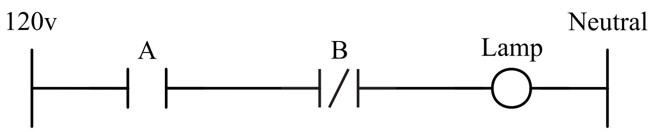
These concepts are key to being able to understand and write ladder logic. To many people these concepts appear strange and foreign at first. However, they will become more natural as one works problems. Ladder logic is a very visual and graphical language. It is very different from textual languages like C++, Fortran, Basic, and Java. In contrast, one can become proficient at ladder logic much quicker than with textual languages.

A	B	Lamp
off	off	off
off	on	off
on	off	on
on	on	off

(a)



(b)

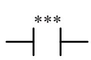


(c)

Figure 2.6. NOT function ladder logic circuits; *(a)* truth table; *(b)* equivalent relay circuit; *(c)* equivalent PLC ladder logic.

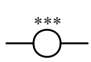
2.3 BASIC LADDER LOGIC SYMBOLS

At this point, one should start interpreting ladder logic directly and not think of its implementation with relays. As introduced by the examples in the previous section, the basic ladder logic symbols are



Normally open (NO) contact. Passes power (**on**) if *** is **on** (closed).

Normally closed (NC) contact. Passes power (**on**) if *** is **off** (open).



Output or *coil*. If any left-to-right path of contacts passes power, the *** output is energized. If there is no continuous left-to-right path of contacts passing power, *** is de-energized.

These symbols are ladder logic instructions that are scanned (executed) by the PLC. In order to avoid confusion, the contact symbols should be equated with certain concepts as follows:

—| |— = **on** = Closed = True = 1

—|/|— = **off** = Open = False = 0

This crucial point will be repeated later when the use of the NC contact is clarified. Figure 2.7 is an example ladder logic diagram with the basic instructions. The first line (also called a *rung*) that determines output labeled Out1 is interpreted as follows: Out1 is **on** if inputs A, B, and C are all **on**, or if inputs A and C are **on** and input D is **off**. For Out1 to be **on** there must be a continuous electrical path through the contacts.

Every PLC manufacturer uses the contact and coil symbols shown in the previous paragraph, though most vendors show the coil as two open parentheses. There are other contact and coil symbols, but there is no universal graphic representation for these other symbols among PLC vendors. The IEC 61131-3 standard has the most contact and coil symbols and many manufacturers do not implement the full set of symbols.

The industry trend is toward using the IEC 61131-3 (formerly IEC 1131-3) standard, and so it will be the primary language of this text. Since IEC 61131-3 is only a voluntary standard, individual manufacturers have some freedom in the implementation. Therefore, the Allen-Bradley ControlLogix, Modicon, and Siemens S7 implementations of the 61131-3 standard are covered. Because of their widespread use, Allen-Bradley PLC-5/SLC-500/MicroLogix and GE PLC languages are also covered.

For the remainder of the book, the languages will be presented in the following order:

IEC 61131-3 standard
Modicon (IEC compliant)
Allen-Bradley ControlLogix (IEC compliant)
Allen-Bradley PLC-5/SLC-500 (not IEC compliant)
Siemens S7 (IEC compliant)
GE (IEC compliant)

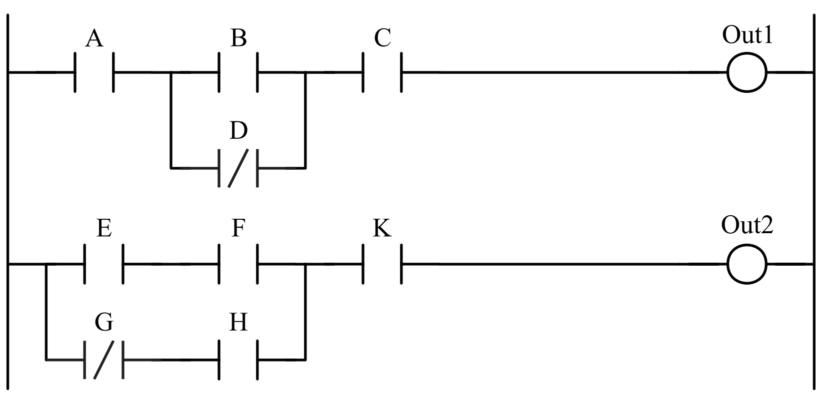


Figure 2.7. Ladder logic diagram with basic instructions.

The Modicon Concept ladder logic is presented first because it is closest to the IEC 61131-3 standard. The Allen-Bradley processors are presented next because of their widespread use in North America.

2.3.1 IEC 61131-3

The basic ladder logic contact symbols are

*** ─┤ ├─	*Normally open (NO) contact*. Passes power (**on**) if *** is **on** (closed).
*** ─┤/├─	*Normally closed (NC) contact*. Passes power (**on**) if *** is **off** (open).
*** ─┤P├─	*Positive transition sensing contact*. If the state of *** changes from **off** to **on**, this contact passes power for only one scan (until rung is scanned again).
*** ─┤N├─	*Negative transition sensing contact*. If the state of *** changes from **on** to **off**, this contact passes power for only one scan (until rung is scanned again).

The basic ladder logic coil (output) symbols are

*** ─( )─	Output or *coil*. If any left-to-right rung path passes power, the *** output is energized (**on**). If there is no continuous left-to-right rung path passing power, the *** output is de-energized (**off**).
/	*Negated coil*. If any left-to-right rung path passes power, the *** output is de-energized (**off**). If there is no continuous left-to-right rung path passing power, the *** output is energized (**on**).
*** ─(S)─	*Set coil*. If any rung path passes power, *** is energized and remains energized, even when no rung path passes power.
*** ─(R)─	*Reset coil*. If any rung path passes power, *** is de-energized and remains de-energized, even when no rung path passes power.
*** ─(P)─	*Positive transition sensing coil*. If conditions before this coil change from **off** to **on**, *** is turned **on** for one scan.
*** ─(N)─	*Negative transition sensing coil*. If conditions before this coil change from **on** to **off**, *** is turned **on** for one scan.

*** —(M)— *Retentive memory coil*. Like the ordinary coil, except the value of *** is retained even when the PLC is stopped or power fails.

*** —(SM)— *Set retentive memory coil*. Like the set coil, except the value of *** is retained even when the PLC is stopped or power fails.

*** —(RM)— *Reset retentive memory coil*. Like the reset coil, except the value of *** is retained even when the PLC is stopped or power fails.

Comments about the basic instructions

1. The transition sensing contacts and coils are useful for initialization and detecting input transitions, for example, a push button press.
2. The set and reset coils are used in conjunction with each other. Figure 2.8 is a short example using these two coils in conjunction to control a lamp.
3. The retentive memory coil instructions are used in a situation where the state of the output must be retained when the PLC is stopped or power fails. Normally, PLC outputs are turned **off** when the PLC is stopped or power fails. Depending on the system, it may be important that the state of an output be retained in order for the system to operate safely through a power failure of the PLC processor or when the PLC is stopped. For certain PLC manufacturers, this function is provided as part of the discrete output module.
4. The author discourages use of the negated coil for the following reason. In most systems the safe position is one in which the output from the PLC is **off**. Generally, contacts (often called permissives) are placed in series with the coil, indicating multiple conditions must be satisfied before the output is allowed to be energized. With the negated coil the rung conditions must be satisfied to turn **off** the output which is opposite to most safety concepts.

2.3.2 Modicon

The Modicon'Schneider M340 and QuantumPLC processors are programmed in ladder logic compatible with IEC 61131-3 compliant ladder logic. The IEC 61131-3 compliant ladder logic instructions are described here. The Modicon basic ladder logic contact symbols are the same as described in section 2.3.1.

The Modicon basic ladder logic coil symbols are similar to those described in section 2.3.1, except that Modicon does not support the following:

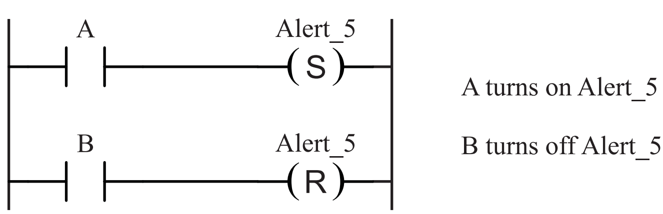
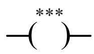


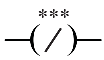
Figure 2.8. Set and reset coil example.

Retentive memory coil
Set retentive memory coil
Reset retentive memorpy coil

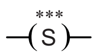
In addition, Modicon has a call and a halt coil. The coil symbols are:



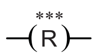
Output or *coil*. If any left-to-right rung path passes power, *** is energized (**on**). If there is no continuous left-to-right rung path passing power, the output is de-energized (**off**).



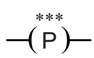
Negated coil. If any left-to-right rung path passes power, *** is de-energized (**off**). If there is no continuous left-to-right rung path passing power, the output is energized (**on**).



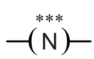
Set coil. If any rung path passes power, *** is energized and remains energized, even when no rung path passes power.



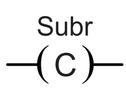
Reset coil. If any rung path passes power, *** is de-energized and remains de-energized, even when no rung path passes power.



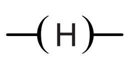
Positive transition sensing coil. If conditions before this coil change from **off** to **on**, *** is turned **on** for one scan.



Negative transition sensing coil. If conditions before this coil change from **on** to **off**, *** is turned **on** for one scan.



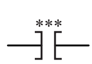
Call coil. If any rung path passes power, call subroutine. Section 8.3.4 has more details on this coil.



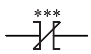
Halt coil. If any rung path passes power, halt program. Section 8.3.4 has more details on this coil.

2.3.3 Allen-Bradley ControlLogix and PLC-5/SLC-500

The Allen-Bradley PLC basic contacts and coils are not as numerous as for the IEC 61131-3 standard. In addition, for many of the instructions, a different symbol is used, though the function is the same as an IEC 61131-3 instruction. The Allen-Bradley basic ladder logic contact symbols are



Normally open (NO) contact. Passes power (**on**) if *** is **on** (closed). Also called XIC (eXamine If Closed).

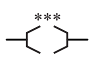


Normally closed (NC) contact. Passes power (**on**) if *** is **off** (open). Also called XIO (eXamine If Open).

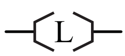
One-shot contact. If conditions before this contact change from **off** to **on**, this contact passes power for only one scan (ControlLogix, PLC-5, and certain MicroLogix only). It is analogous to the IEC positive transition sensing contact except that this contact <u>follows</u> the contact(s) whose transition is being sensed. The *** is a storage Boolean that retains the previous state of the contact input (left side).

One-shot rising contact. If conditions before this contact change from **off** to **on**, this contact passes power for only one scan (SLC-500 and certain MicroLogix only). Must immediately precede an output coil. It is analogous to the IEC positive transition sensing contact except that this contact <u>follows</u> the contact(s) whose transition is being sensed. The *** is a storage Boolean that retains the previous state of the contact input (left side).

For the Allen-Bradley PLCs, the basic ladder logic coil (output) symbols are

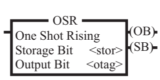


Output or *coil*. If any left-to-right rung path passes power, *** is energized (**on**). If there is no continuous left-to-right rung path passing power, the output is de-energized (**off**). Also called OTE (OuTput Energize).

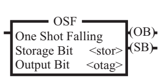


Latch coil. If any rung path passes power, output is energized and remains energized, even when no rung path passes power. It is analogous to the IEC set coil instruction. Also called OTL (OuTput Latch).

Unlatch coil. If any rung path passes power, output is de-energized and remains de-energized, even when no rung path passes power. It is analogous to the IEC reset coil instruction. Also called OTU (OuTput Unlatch).



One shot rising output. If conditions before this block change from **off** to **on**, the specified output bit is turned **on** for one scan (ControlLogix and enhanced PLC-5 only). This is more appropriately a function block because of its appearance. It is analogous to the IEC positive transition sensing coil. The storage bit retains the previous state of the block input .

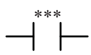


One shot falling output. If conditions before this block change from **on** to **off**, the specified output bit is turned **on** for one scan (ControlLogix and enhanced PLC-5 only). This is more appropriately a function block because of its appearance. It is analogous to the IEC negative transition sensing coil. The storage bit retains the previous state of the block input.

There are no retentive memory coil instructions. The retentive function is handled in the discrete output modules.

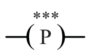
2.3.4 Siemens S7

The three types of S7 processors (S7-200, S7-300/400, and S7-1200) have the same basic instructions. The only exception is the midline output coil that is not valid for the S7-200 and S7-1200 processors and the negated and transitional coils valid only for the S7-1200. The basic ladder logic contact symbols are

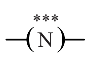


Normally open (NO) contact. Passes power (**on**) if *** is **on** (closed).

Normally closed (NC) contact. Passes power (**on**) if *** is **off** (open).



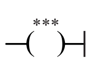
Positive transition sensing contact. If conditions before this contact change from **off** to **on**, this contact passes power for only one scan (until rung is scanned again). For S7-300/400, the *** is a storage Boolean that retains the previous state of the contact input (left side). For S7-200/1200 processors, this contact uses vertical bars, rather than parentheses. For S7-1200, if the state of *** changes from **off** to **on**, this contact passes power for only one scan (until rung is scanned again) and the storage Boolean is shown below the contact.



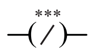
Negative transition sensing contact. If conditions before this contact change from **on** to **off**, this contact passes power for only one scan (until rung is scanned again). For S7-300/400, the *** is a storage Boolean that retains the previous state of the contact input (left side). For S7-200/1200 processors, this contact uses vertical bars, rather than parentheses. For S7-1200, if the state of *** changes from **on** to **off**, this contact passes power for only one scan (until rung is scanned again) and the storage Boolean is shown below the contact.

Invert power flow. If any left-to-right rung before this contact passes power, the power flow to succeeding elements is interrupted (turned **off**). If no left-to-right rung path before this contact passes power, the power flow to succeeding elements is turned **on**. Not valid for the S7-200 processors.

The basic ladder logic coil (output) symbols are

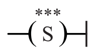


Output or *coil*. If any left-to-right rung path passes power, the *** output is energized (**on**). If there is no continuous left-to-right rung path passing power, *** is de-energized (**off**).

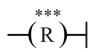


Negated coil (S7-1200 only). If any left-to-right rung path passes power, *** is de-energized. If there is no continuous left-to-right path of instructions passing power, *** is energized.

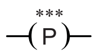
Midline output coil. Output coil in middle of rung. Other logic can occur to the right of this coil. Valid for S7-300/400 only.



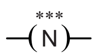
Set coil. If any rung path passes power, *** is energized and remains energized, even when no rung path passes power.



Reset coil. If any rung path passes power, *** is de-energized and remains de-energized, even when no rung path passes power.



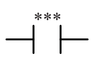
Positive transition sensing coil (S7-1200 only). If conditions before this coil change from **off** to **on**, *** is turned **on** for one scan.



Negative transition sensing coil (S7-1200 only). If conditions before this coil change from **on** to **off**, *** is turned **on** for one scan.

2.3.5 GE

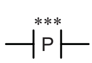
For the GE PLCs, the basic ladder logic contact symbols are



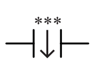
Normally open (NO) contact. Passes power (**on**) if *** is **on** (closed).

Normally closed (NC) contact. Passes power (**on**) if *** is **off** (open).

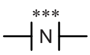
Positive transition sensing contact (POSCON). If *** changes from **off** to **on**, power is passed until *** is updated by a coil or input scan. Operational details are presented in section 2.8. Valid for PACSystems and 90-70 processors only.



Positive transition sensing contact (PTCON). If *** changes from **off** to **on**, power is passed for one scan (until rung is scanned again). Valid for PACSystems processors only.

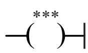


Negative transition sensing contact (NEGCON). If *** changes from **on** to **off**, power is passed until *** is updated by a coil or input scan. Operational details are presented in section 2.8. Valid for PACSystems and 90-70 processors only.

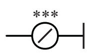


Negative transition sensing contact (NTCON). If *** changes from **on** to **off**, power is passed for one scan (until rung is scanned again). Valid for PACSystems processors only.

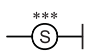
The PACSystems and 90-70 processors support fault, no fault, high alarm and low alarm contacts that are used to detect conditions in the I/O modules. Detailed descriptions of these contacts are contained in GE Fanuc Automation (2000) and GE Intelligent Platforms (2010). The basic ladder logic coil (output) symbols are



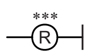
Output or *coil*. If any left-to-right rung path passes power, the *** output is energized (**on**). If there is no continuous left-to-right path of instructions passing power, the *** output is de-energized (**off**).



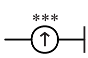
Negated coil. If any left-to-right rung path passes power, *** is de-energized. If there is no continuous left-to-right rung path passing power, *** is energized.



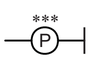
Set coil. If any rung path passes power, *** is energized and remains energized, even when no rung path passes power.



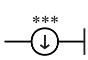
Reset coil. If any rung path passes power, *** is de-energized and remains de-energized, even when no rung path passes power.



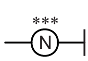
Positive transition sensing coil (POSCOIL). If conditions before this coil change from **off** to **on**, *** is turned **on** for one scan.There are some subtle differences between this coil and the PTCOIL, explained in section 2.8.



Positive transition sensing coil (PTCOIL). If conditions before this coil change from **off** to **on**, *** is turned **on** for one scan. PACSystems processors only.

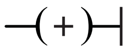


Negative transition sensing coil (NEGCOIL). If conditions before this coil change from **on** to **off**, *** is turned **on** for one scan.There are some subtle differences between this coil and the NTCOIL, explained in section 2.8.

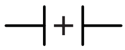


Negative transition sensing coil (NTCOIL). If conditions before this coil change from **on** to **off**, *** is turned **on** for one scan. PACSystems processors only.

If the variable being controlled by a coil is defined as a retentive variable, then the coil symbol includes an "M." A continuation coil and contact are used to handle ladder rungs with more than 10 columns:



Continuation coil. If any left-to-right path of instructions passes power, the next continuation contact is turned **on**. If there is no continuous left-to-right path of instructions passing power, the next continuation contact is turned **off**.



Continuation contact. Passes power (**on**) if preceding continuation coil is **on**.

2.4 LADDER LOGIC DIAGRAM

An example PLC ladder logic diagram appears in Figure 2.9. The vertical lines on the left and right are called the power rails. The contacts are arranged horizontally between the power rails, hence the term *rung*. The ladder diagram in Figure 2.9 has three rungs. The arrangement is similar to a ladder one uses to climb onto a roof. In addition, Figure 2.9

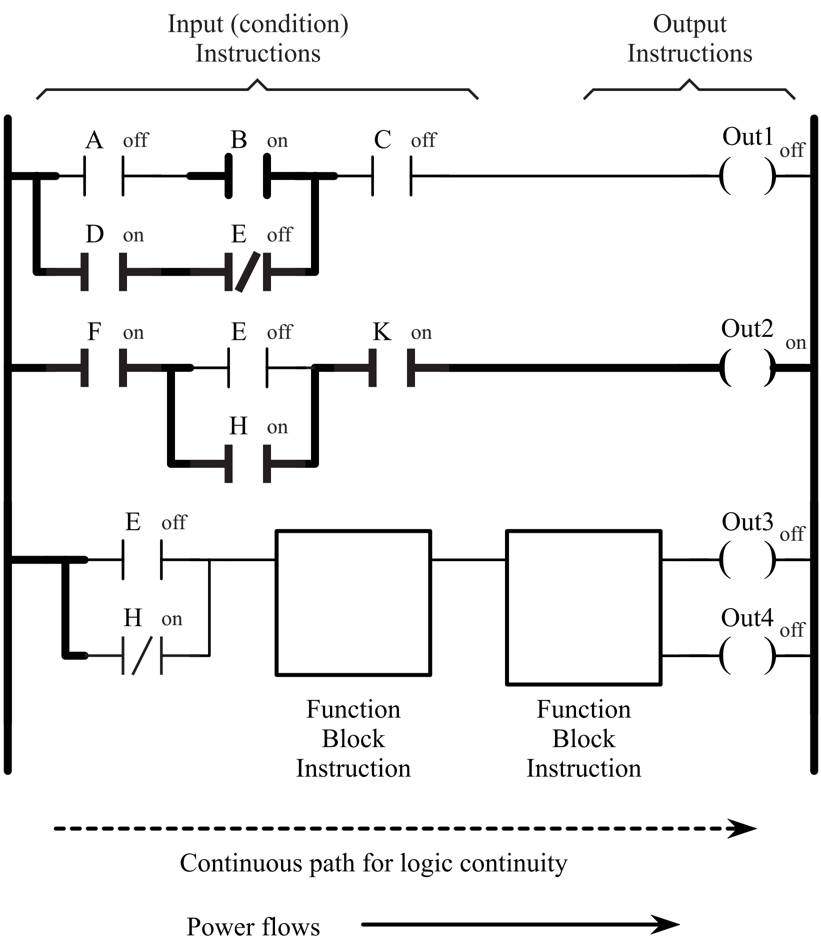


Figure 2.9. Sample ladder logic diagram.

shows an example diagram like one would see if monitoring the running program in the PLC. The thick lines indicate continuity and the state (**on**/**off**) of the inputs and outputs is shown next to the tag. Regardless of the contact symbol, if the contact is closed (continuity through it), it is shown as thick lines. If the contact is open, it is shown as thin lines. In a relay ladder diagram, power flows from left to right. In PLC ladder logic, there is no real power flow, but there still must be a continuous path through closed contacts in order to energize an output. In Figure 2.9 the output on the first rung is **off** because the contact for C is open, blocking continuity through the D and E contacts. Also notice that the E input is **off**, which means the NC contact in the first rung is closed and the NO contact in the second rung is open.

Figure 2.9 also introduces the concept of *function block instructions*. Any instruction that is not a contact or a coil is called a function block instruction because of its appearance in the ladder diagram. The most common function block instructions are timer, counter, comparison, and computation operations. More advanced function block instructions include sequencer, shift register, and first-in first-out operations.

Some manufacturers group the instructions into two classes: input instructions and output instructions. This distinction was made because in relay ladder logic, outputs were never connected in series and always occurred on the extreme right hand side of the rung. Contacts always appeared on the left side of coils and never on the right side. To turn on multiple outputs simultaneously, coils are connected in parallel. This restriction was relaxed in IEC 61131-3 and outputs may be connected in series. Also, contacts can occur on the right side of a coil as long as a coil is the last element in the rung. Of the ladder logic languages covered by this text, only the IEC 61131-3, Modicon, and Allen-Bradley ControlLogix allow coil instructions to be connected in series.

This text avoids using a series connection of coils for two reasons:

1. many PLCs do not allow it, and
2. it is counterintuitive to maintenance personnel who often interpret ladder logic in the context of an electrical diagram.

Also, in IEC 61131-3, all function block instructions are input instructions because the only output instructions are the coils. The Allen-Bradley PLC-5 and SLC-500 have function block output instructions (e.g., timer, counter, and computation) which must be remembered when constructing ladder logic programs for these PLCs.

Example 2.4. Draw a ladder diagram that will cause the output, pilot light PL2, to be **on** when selector switch SS2 is **closed**, push-button PB4 is **closed** and limit switch LS3 is **open**. (Note: no I/O addresses yet.)

Solution. The first question to answer is "What is the output?" The output is PL2, so the coil labeled as PL2 is put on the right side of the rung. Secondly, consider the type of connection of contacts to use. Since **all** three switches must be in a certain position to turn on the pilot light, a series connection is needed. Thirdly, the type of contact is determined by the switch position to turn on the pilot light:

SS2 closed → —| |—

PB4 closed → —| |—

LS3 open → —|/|—

Figure 2.10. Solution to Example 2.4.

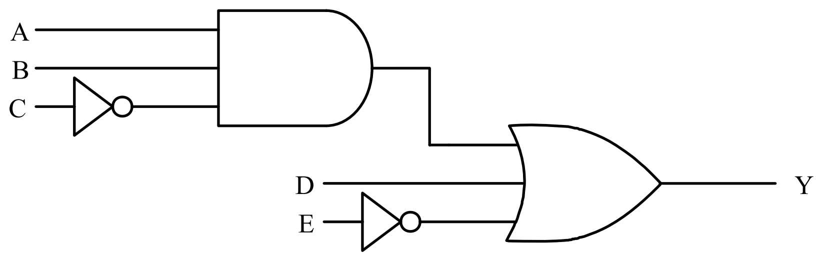


Figure 2.11. Digital logic for Example 2.5.

Putting all the pieces together, only one rung of ladder logic is needed, as shown in Figure 2.10.

> ## Design Tip
>
> The concept of placing the output on the rung first and then "looking back" to determine the input conditions is very important. Because of the way the diagram is configured, one has a tendency to consider the input conditions first and then position the output coil as the last step. As will be shown later, the coil or negated coil instruction referring to a particular output must only occur **once** in a ladder program. Considering the output coil first and the conditions for which it is active (on) will avoid repeating coils.

Example 2.5. Draw a ladder diagram that is equivalent to the digital logic diagram in Figure 2.11, which is the same as the following descriptions.

In words:

Y is **on** when (A is **on** and B is **on** and C is **off**) or D is **on** or E is **off**.

Boolean logic equation:

$$Y = AB\overline{C} + D + \overline{E}$$

Solution. First, answer, "What is the output?" The output is Y, so the coil labeled as Y is put on the right side of the rung. Secondly, consider the type of connection of contacts to use. For this problem, there is more than one type of connection. The three inputs within the parentheses (the AND gate in Figure 2.11) are connected with "and," so a series connection is required for these three contacts. The other two inputs (D and E) are connected with the three series contacts by "or" (the OR gate inputs), so a parallel connection is required. Thirdly, the type of contact is determined by the input state that turns **on** the output, Y:

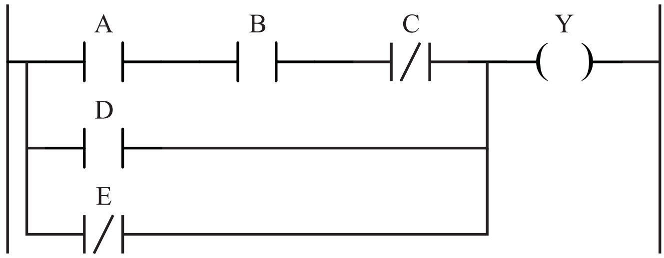


Figure 2.12. Solution to Example 2.5.

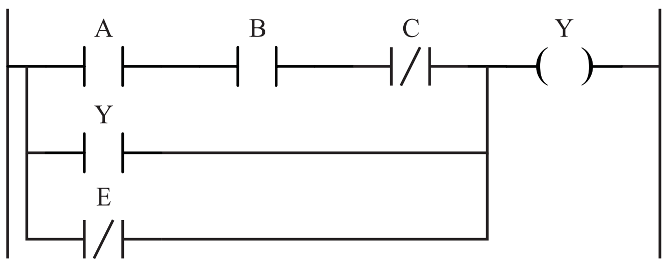
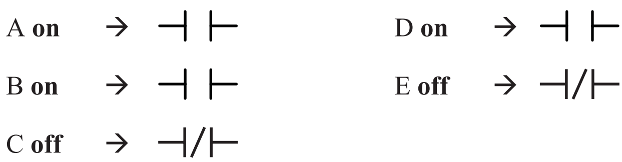


Figure 2.13. Output that appears as an input.



Putting all the parts together, only one rung of ladder logic is needed, as shown in Figure 2.12.

Suppose one changes the D contact in Figure 2.12 to refer to Y, the output (shown as Figure 2.13). Is this legitimate? Yes, it is legitimate, though probably not something one would want to do for this example. Even in relay ladder logic, it is legal and there is no wiring short because the coil for relay Y and its NO contact are not connected. This concept is called *sealing* or latching an output without using the set (or latch) coil instruction. In this example, it is not a good idea because once Y is sealed **on**, there is no provision to turn it off. Why?

There are some precautions to observe when programming in ladder logic:

1. **DO NOT** repeat normal output coils or negated coils that refer to the same tag. To illustrate what happens when this is done, consider the ladder logic diagram in Figure 2.14. This is the ladder of Figure 2.9, modified for this illustration. Note that the coils for both the first and second rung refer to Out1. When the first rung of the ladder is scanned, Out1 is turned **on**. However, when the second rung is scanned, Out1 is turned **off**, overriding the logic in the first rung. If all of these conditions are needed to turn on Out1, then they all should be placed in parallel, as in Figure 2.15. In this illustration, it was obvious there is a problem. Normally,

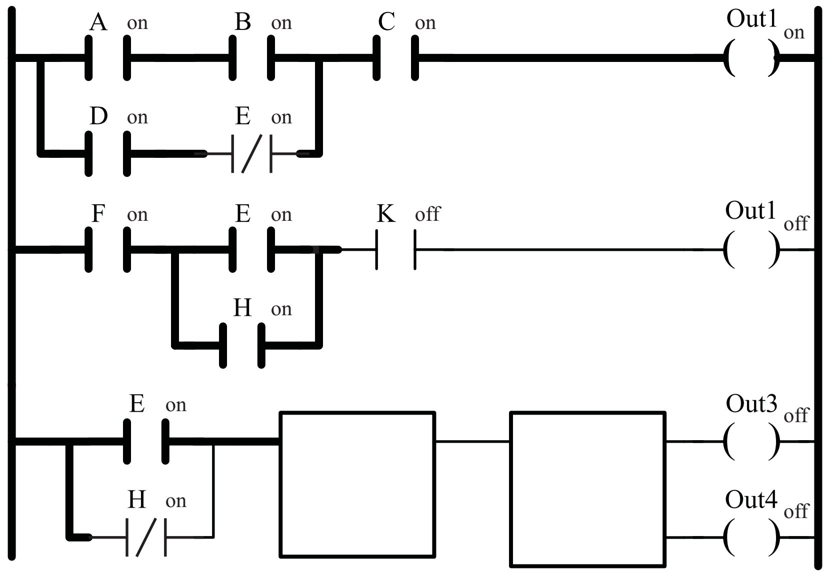


Figure 2.14. Ladder with repeated output.

when this problem occurs, the rungs are not adjacent, and it is not so obvious. Compounding the problem, not all PLC programming software checks for this situation. Therefore, the best way to prevent this problem is to consider the output coil **first** and then consider all of the conditions that drive that output.

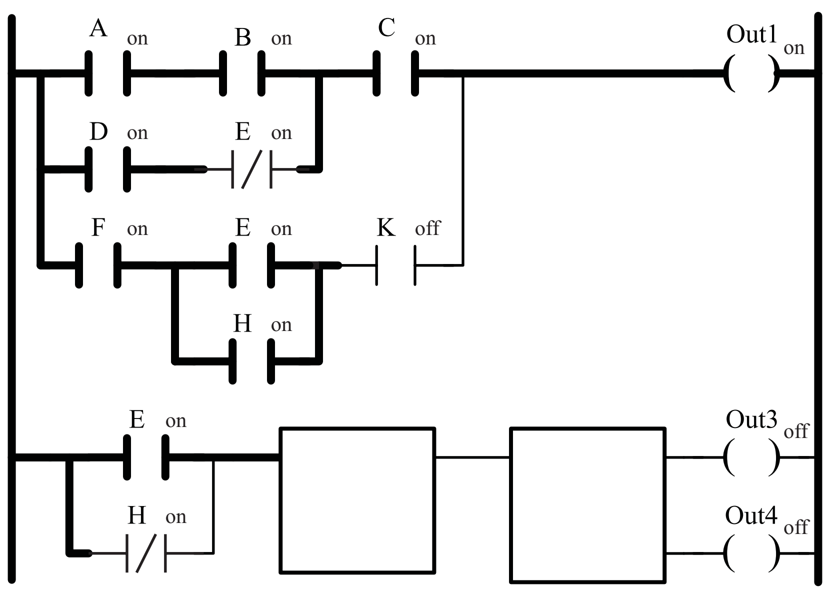


Figure 2.15. Repeated output corrected.

2. Use the set (latch) coil and reset (unlatch) coils together. If a set coil refers to an output, there should also be a reset coil for that output. Also, for the same reason that output coil and negated coils should not be repeated, do not mix the set/reset coils with an output coil or negated coil that refer to the same output.
3. Be careful when using the set/reset coils to reference PLC physical outputs. If the system involves safety and a set coil is used for a PLC physical output, simply interrupting the condition on the set coil rung **will not** turn off the physical output. All of the conditions that prevent the device from being turned on must also appear on a rung with a reset coil output. For this reason, some companies forbid the use of the set/reset coils.
4. Reverse power flow in the contact matrix is **not** allowed. When electromechanical relays implement ladder logic, power can flow either way through the contacts. For example, consider the ladder logic in Figure 2.16. If implemented with electromechanical relays, power may flow right-to-left through the SS2 contact. When solid state relays replaced electromechanical relays for ladder logic, power can flow only one way (left-to-right) through the contacts. This restriction was carried to PLC ladder logic. If the reverse power flow path is truly needed, then insert it as a separate path, where the power flows from left to right. The reverse power flow path in Figure 2.16 is added as a separate path in Figure 2.17.

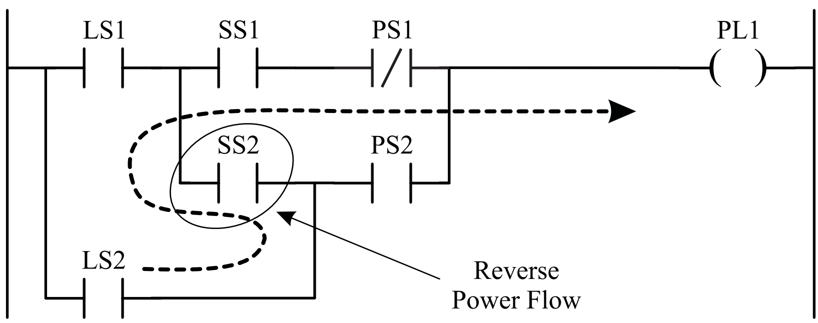


Figure 2.16. Reverse power flow in ladder logic.

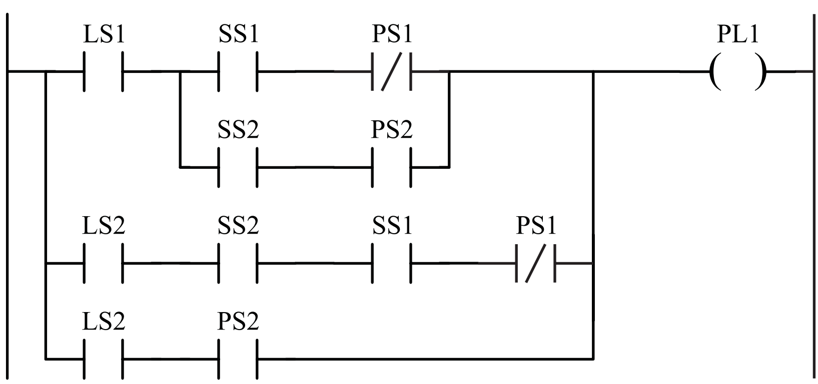


Figure 2.17. Reverse power flow in ladder logic corrected.

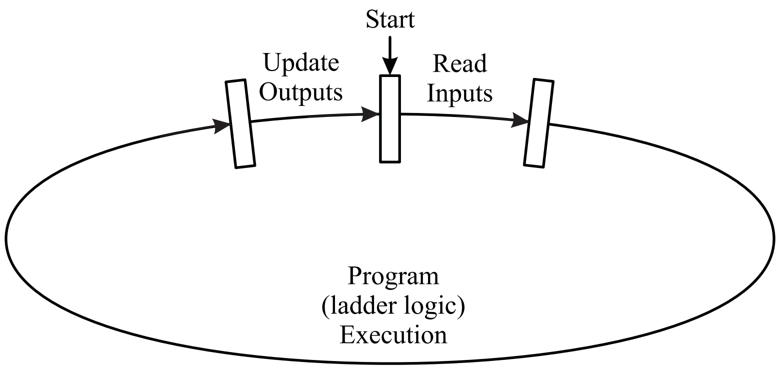


Figure 2.18. PLC processor scan.

2.5 PLC PROCCESSOR SCAN

Previously, the process that the PLC uses to scan the ladder logic has only been implied. Now it will be discussed in detail. In addition to scanning the ladder logic, the PLC processor must also read the state of its physical inputs and set the state of the physical outputs. These three major tasks in a PLC processor scan are executed in the following order:

Read the physical inputs
Scan the ladder logic program
Write the physical outputs

The processor repeats these tasks as long as it is running, as shown pictorially in Figure 2.18. The time required to complete these three tasks is defined as the *scan time* and is typically 1 - 200 milliseconds, depending on the length of the ladder logic program. For very large ladder logic programs, the scan time can be more than one second. When this happens, the PLC program may miss transient events, especially if they are shorter than one second. In this situation, the possible solutions are:

1. Break ladder logic into subroutines that are executed at a slower rate and execute the logic to detect the transient event on every scan.
2. Lengthen the time of the transient event so that it is longer than the maximum scan time. If the event is counted, both the on time and off time of the event must be longer than the scan time. A counter must sense both values to work correctly.
3. Place the logic examining the transient in a ladder logic routine that is executed at a fixed time interval, smaller than the length of the transient event.
4. Partition long calculations. For example, if calculating the solution to an optimization, do one iteration per scan cycle rather than execute the entire algorithm every scan.

Depending on the PLC processor, one or more of these solutions may be unavailable.

Normally, during the ladder logic program scan, changes in physical inputs cannot be sensed, nor can physical outputs be changed at the output module terminals. However, some PLC processors have an instruction that can read the current state of a physical input and another instruction that can immediately set the current state of a physical output, as shown in Figure 2.19. However, using the immediate input/output instruction incurs a severe time