UNITED STATES
NAVAL ACADEMY
Annapolis

PLC and Ladder Logic Basics Workshop

Brien Croteau, USNA, Cyber Science

DefCon 31, ICS Village, 12 Aug 2023

Link to these slides:
https://github.com/brienc23/Defcon31_workshop_materials

My Background

24-year Active Duty Naval Officer, EE Ph.D.
Assistant Professor, USNA Cyber Science Department
Military Deputy for the Dean of Math and Science

EA-6B Naval Flight Officer

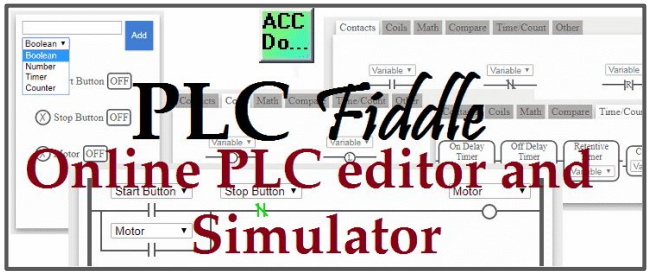
Research in Cyber-Physical Systems (CPS) Security: Detection of malicious sensors using side-channel power analysis, Alternate actuation paths, Actuation limits, Industrial Control Systems (ICS) security, Maritime Hull, Mechanical, & Electrical (HM&E) security

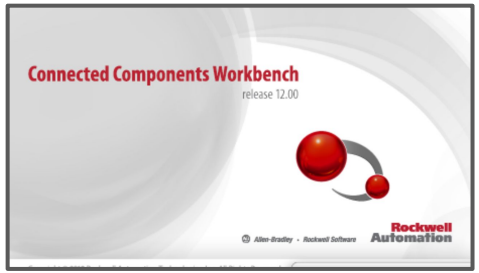
Workshop Outline

A gentle introduction to programming Industrial Controllers

Three Recommended Free Tools:

1. PLC Fiddle (browser-based Ladder Logic Simulator)
2. OpenPLC (open-source PLC software & hardware)
3. Rockwell/Allen-Bradley CCW (commercial micro800 PLCs)



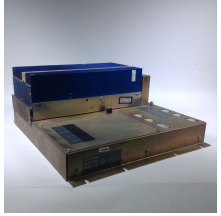


Disclaimer: None of these products are endorsed by: US Gov, US Navy, or USNA

What is a PLC?

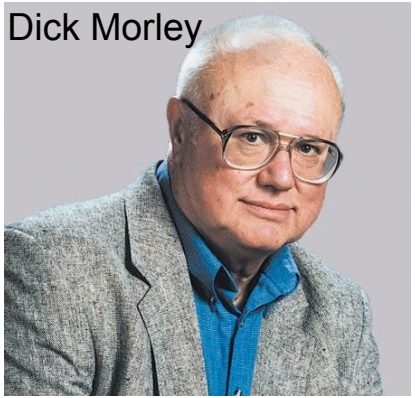
A programmable logic controller (PLC) or programmable controller is an industrial computer that has been ruggedized and adapted for the control of manufacturing processes, such as assembly lines, machines, robotic devices, or any activity that requires high reliability, ease of programming, and process fault diagnosis.

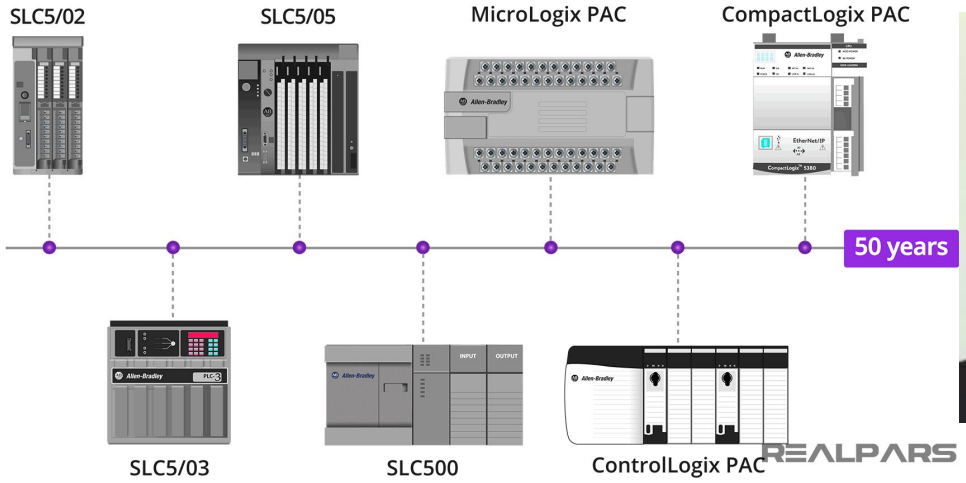
History



There are two men credited as being the "father" of the PLC.

- Richard E. Morley (1932-2017) was an American mechanical engineer who was involved with the production of the first PLC for General Motors, Modicon, and Bedford Associates in 1968.
- Odo Josef Struger (1931-1998) was involved in the invention of the Allen-Bradley programmable logic controller (PLC) and coined that term, during 1958 to 1960 based on a concept developed in his doctoral dissertation at the Vienna University of Technology.





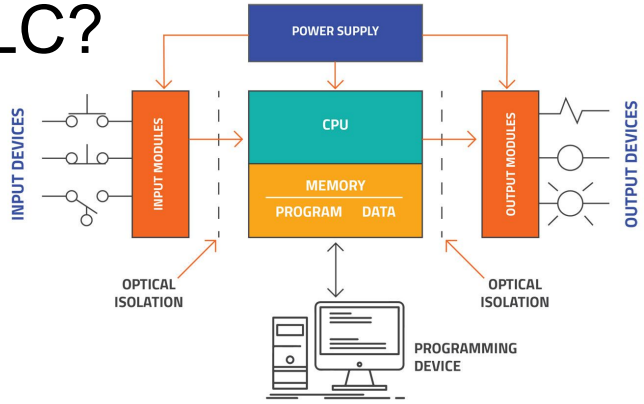
MODICON Schneider Electric

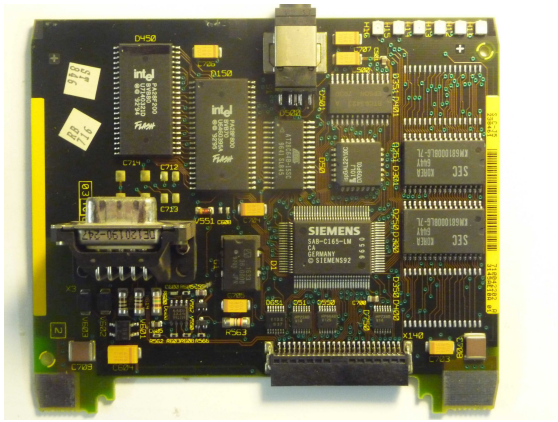
REALPARS

Allen-Bradley by ROCKWELL AUTOMATION

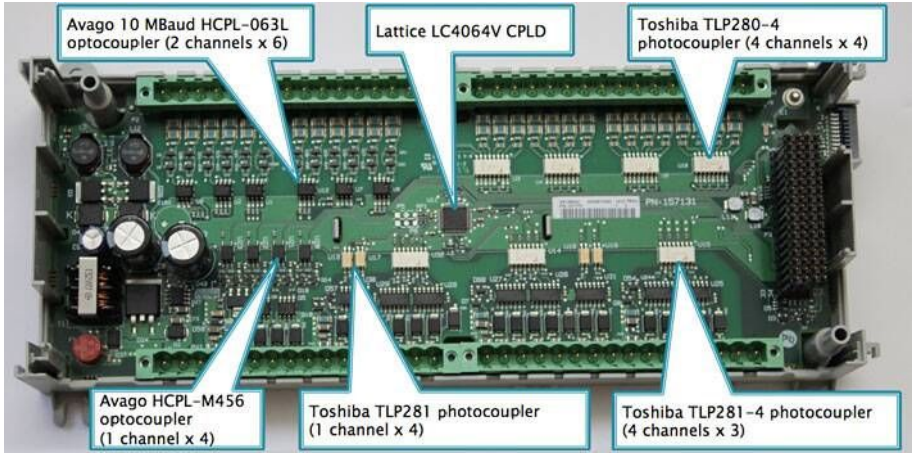
What is inside a PLC?

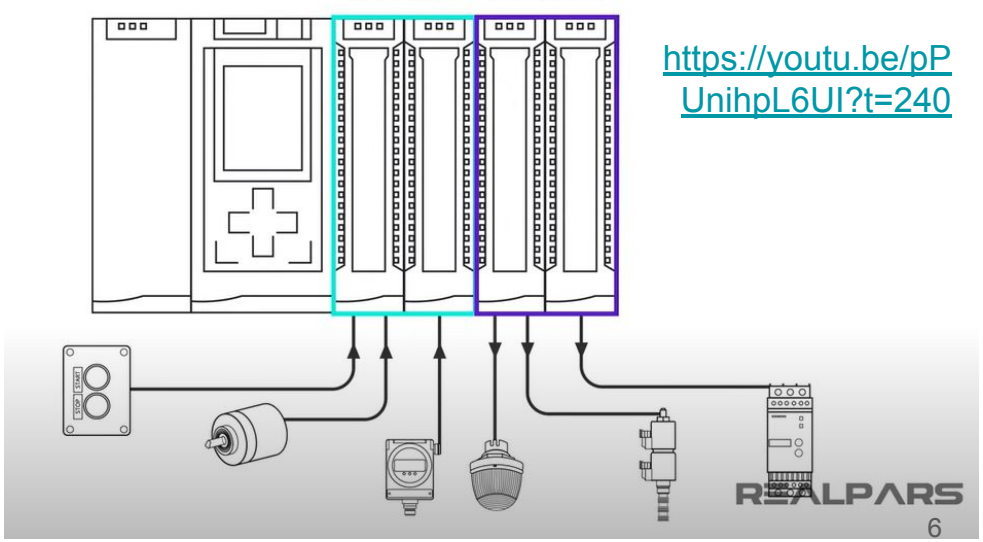
- Power Supply
- Processor
- Input Modules
- Output Modules
- Interface Modules
- Programming Interface





SIEMENS CPU314IFM with C165 series processor





https://youtu.be/pPUnihpL6UI?t=240

Simple PLC Example

"Figure 8 shows control of a manufacturing process being performed by a PLC over a fieldbus network. The PLC is accessible via a programming interface located on an engineering workstation, and data is stored in a data historian, all connected on a LAN."

https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-82r3.ipd.pdf

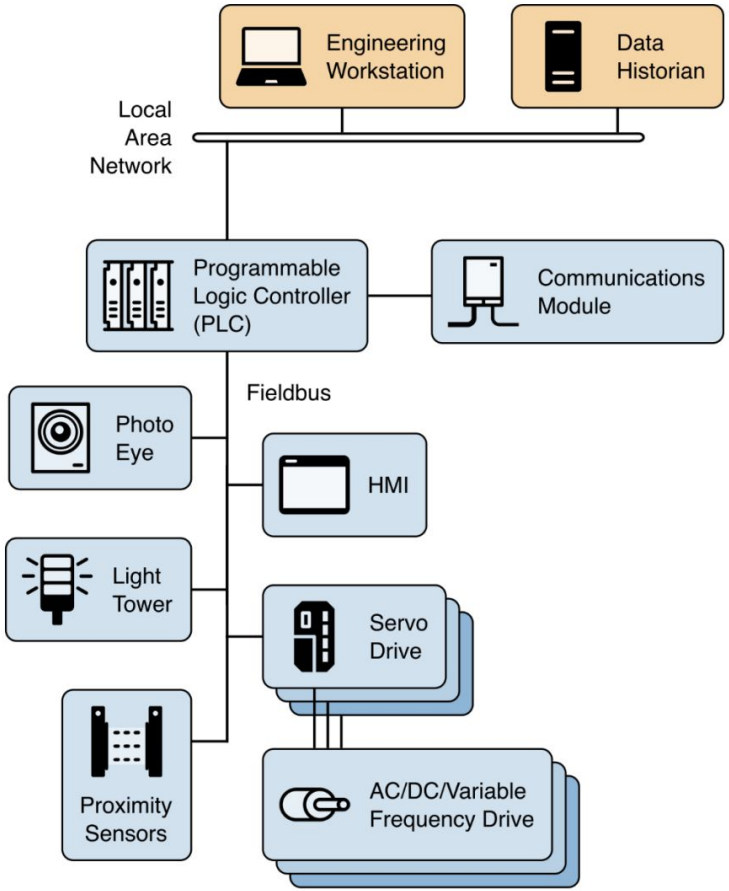
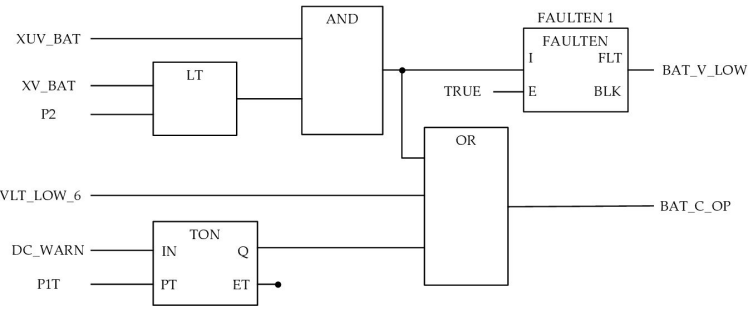


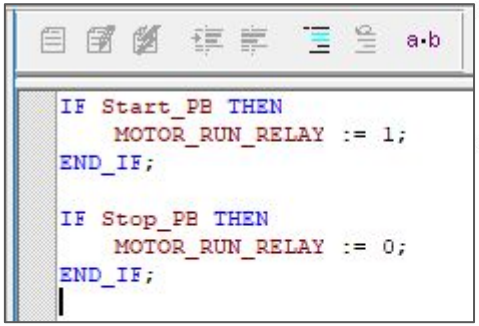
Figure 8: A PLC control system implementation example

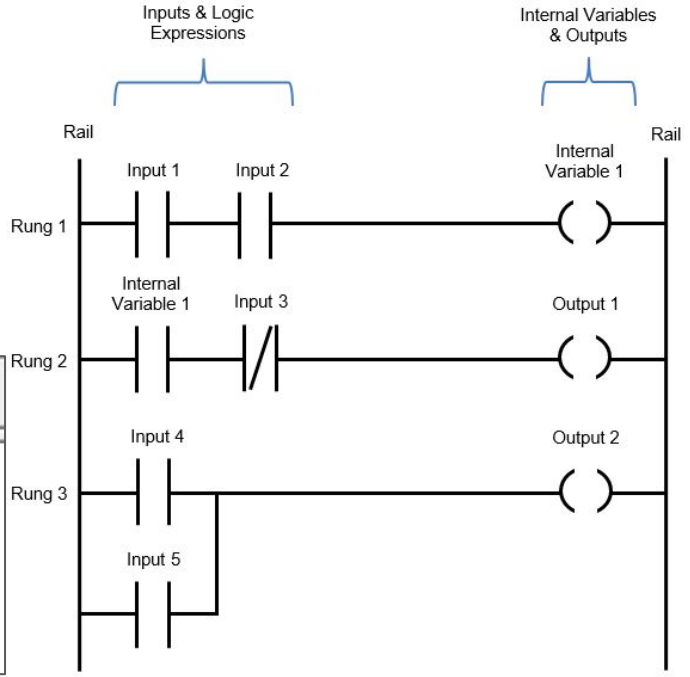
PLC Programming

Standardized with IEC 61131-3 which defines three graphical and two textual programming language standards:

- Ladder diagram (LD), graphical
- Function block diagram (FBD), graphical
- Structured text (ST), textual
- Instruction list (IL), textual (deprecated)
- Sequential function chart (SFC), graphical

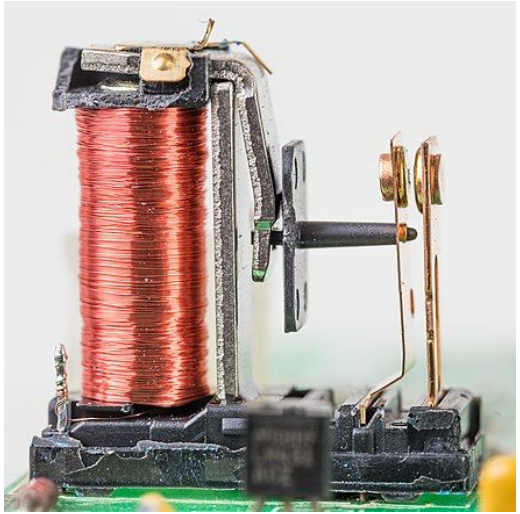


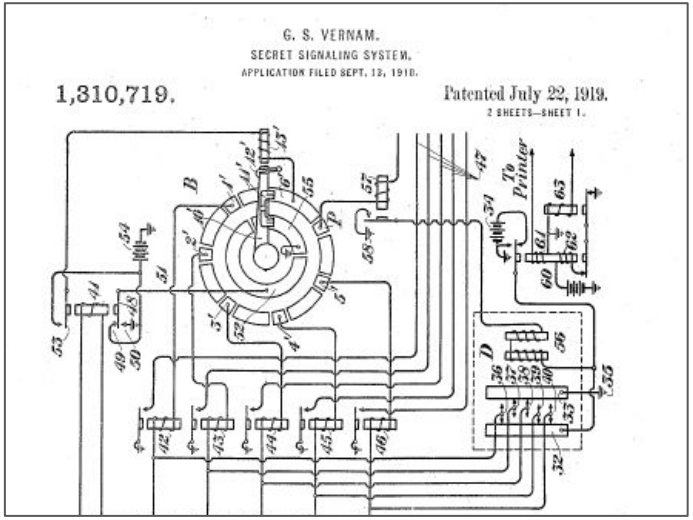


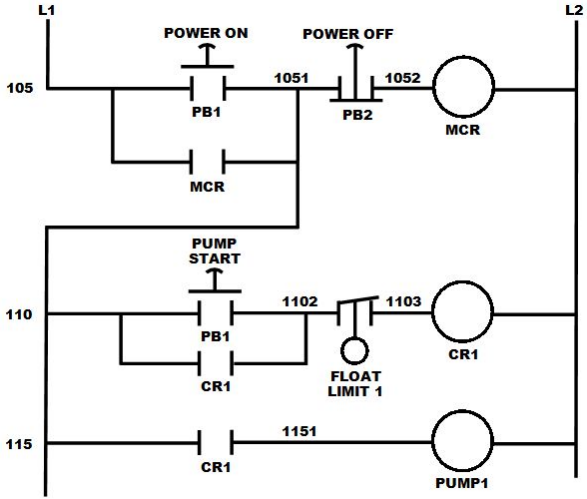


Where does LL come from?

Ladder logic was originally a written method to document the design and construction of relay racks as used in manufacturing and process control.[1] Each device in the relay rack would be represented by a symbol on the ladder diagram with connections between those devices shown. In addition, other items external to the relay rack such as pumps, heaters, and so forth would also be shown on the ladder diagram.

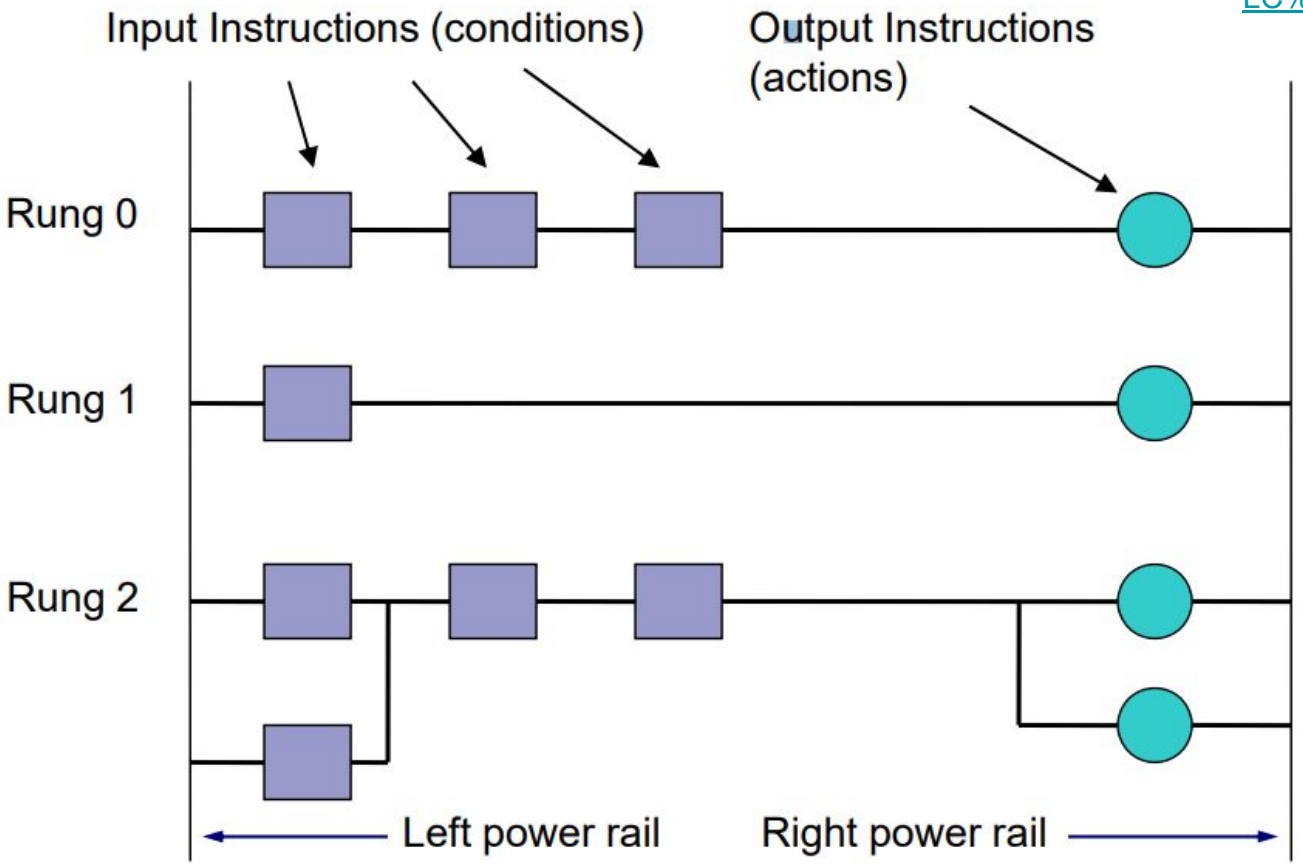






Anatomy of a Ladder Program

https://my.ece.utah.edu/~ece3510/Ladder%20Logic%20Fundamentals%20PLC%20tutorial.pdf



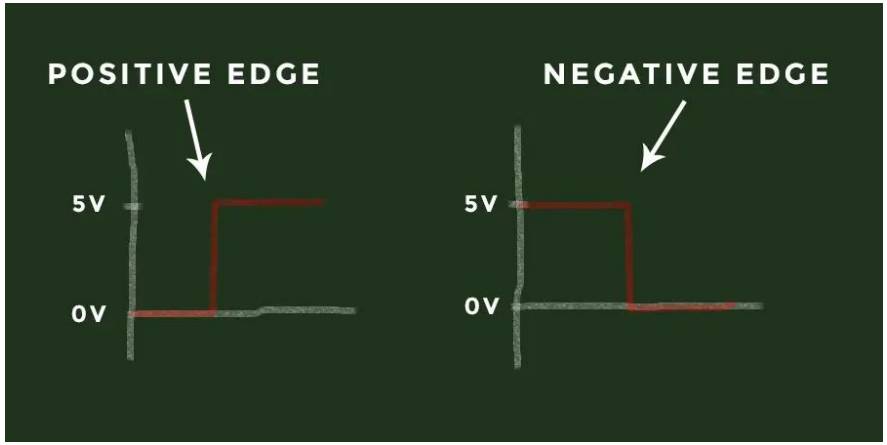
Typical Symbols

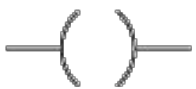
NO Contact

Positive Transition-Sensing Contact

NC Contact

Negative Transition-Sensing Contact

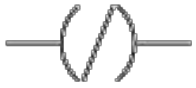




Coil

SET Latch Coil

Positive Transition-Sensing Coil



Negated Coil

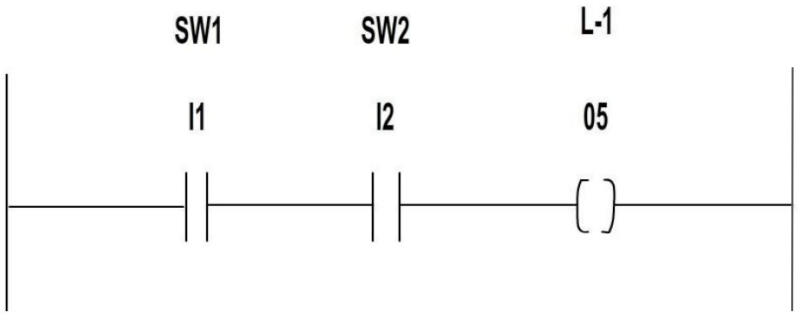
RESET Latch Coil

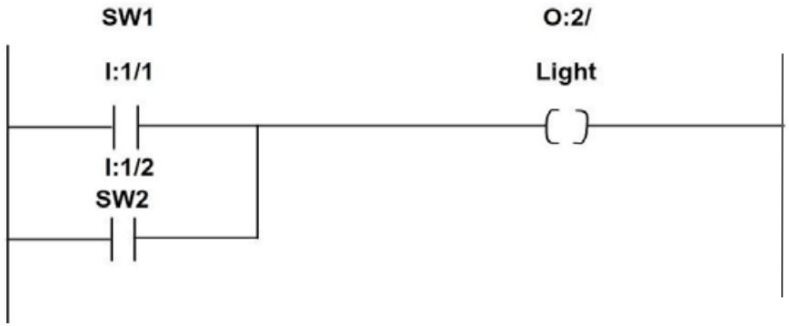
Negative Transition-Sensing Coil

https://www.plcacademy.com/ladder-logic-symbols/

Basic Logic

https://www.philadelphia.edu.jo/academics/waraydah/uploads/Introduction%20to%20PLC%20and%20Ladder%20Logic%20Programming.pdf



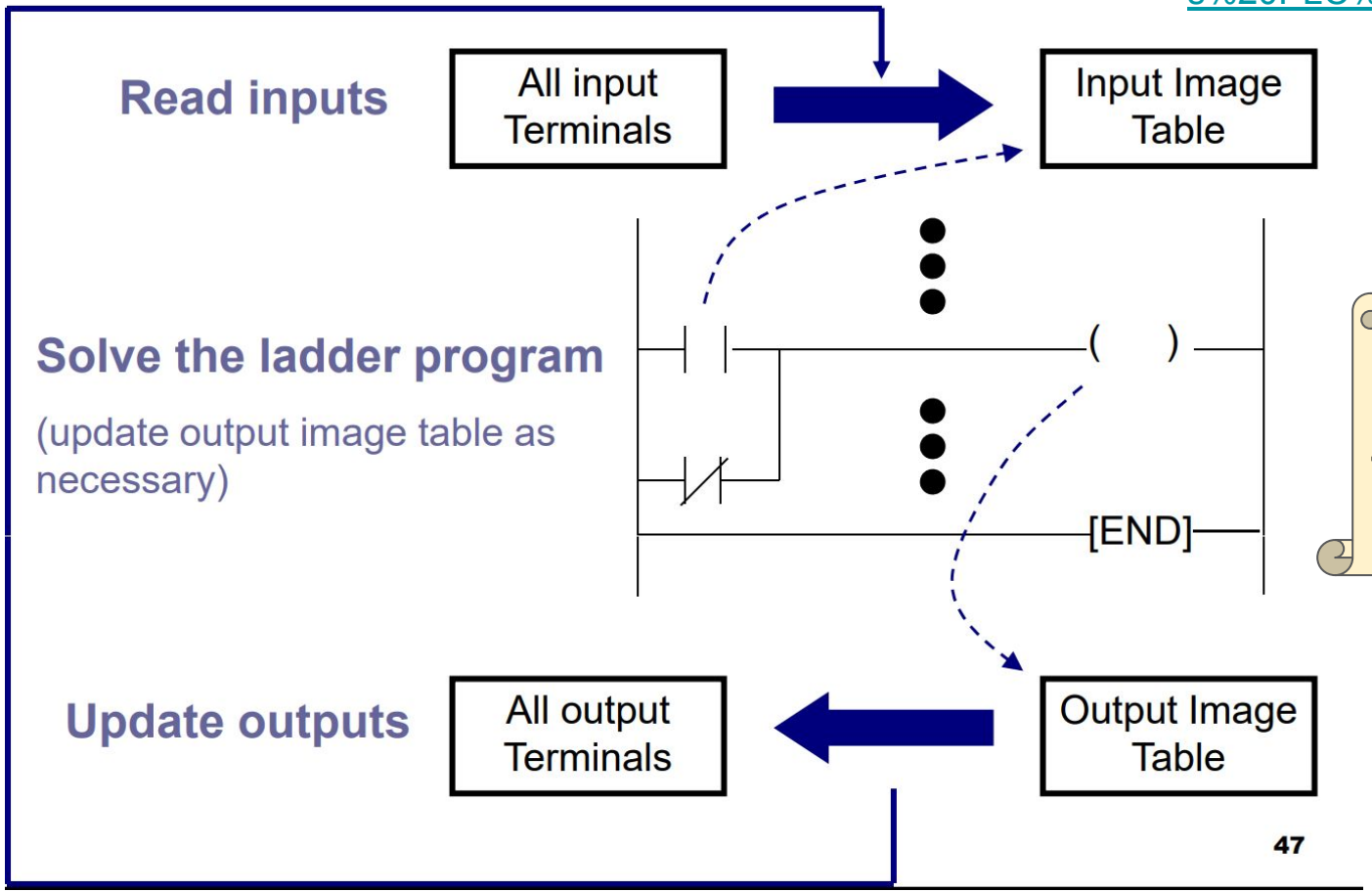


AND

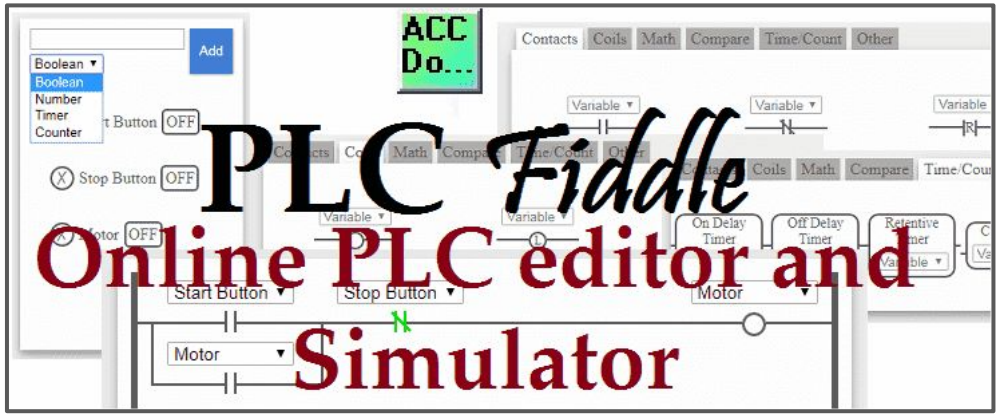
OR

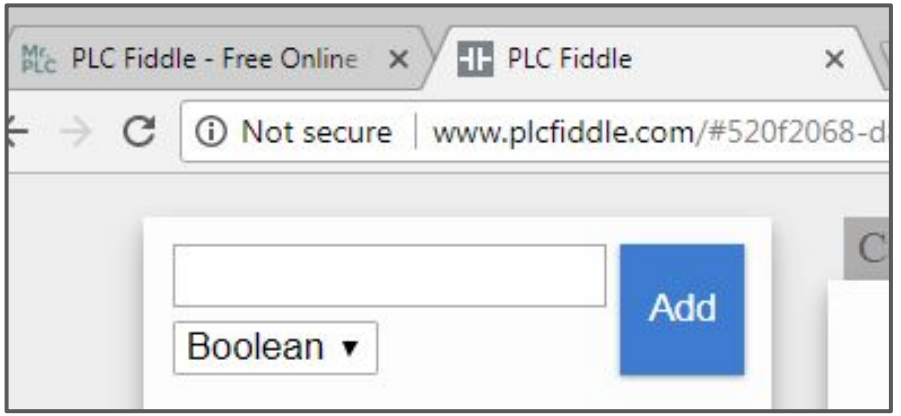
The Scanning Process

https://my.ece.utah.edu/~ece3510/Ladder%20Logic%20Fundamentals%20PLC%20tutorial.pdf



Left to Right
Top to Bottom


PLC Fiddle
Online PLC editor and
Simulator
Add
Boolean
Number
Timer
Counter
Contacts
Coils
Math
Compare
Time/Count
Other
Start Button
Stop Button
Motor
On Delay Timer
Off Delay Timer


PLC Fiddle - Free Online
PLC Fiddle
Not secure
www.plcfiddle.com/#520f2068-d
Add
Boolean

1. PLC Fiddle

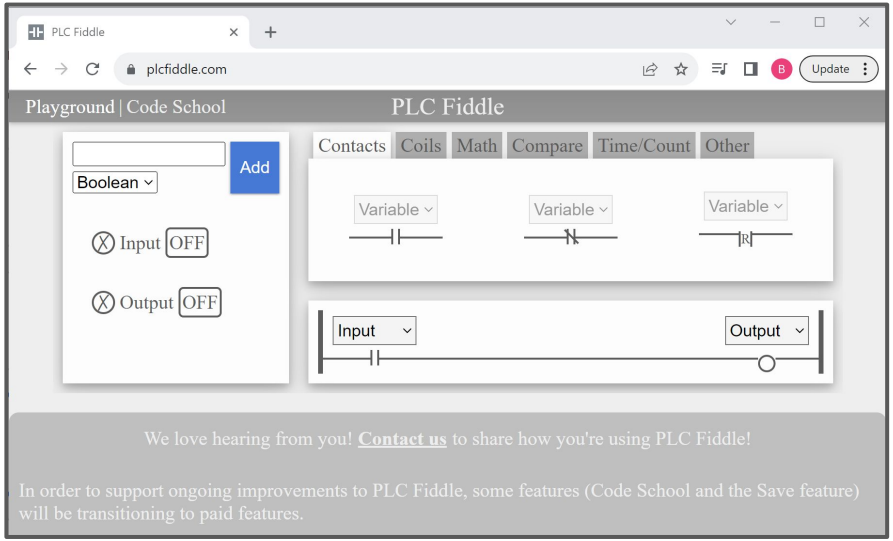
About PLC Fiddle

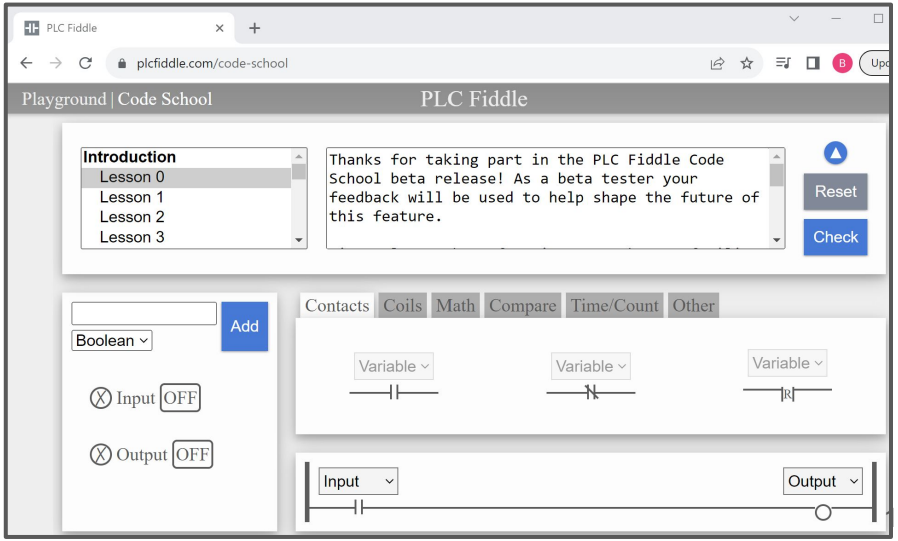
https://www.plcfiddle.com/

PLC Fiddle is a free online PLC Ladder Logic Editor and Simulator that works in your browser.

It includes:

1. Sandbox-like simulator = "Playground"
2. Interactive Tutorial/Lessons = "Code School"



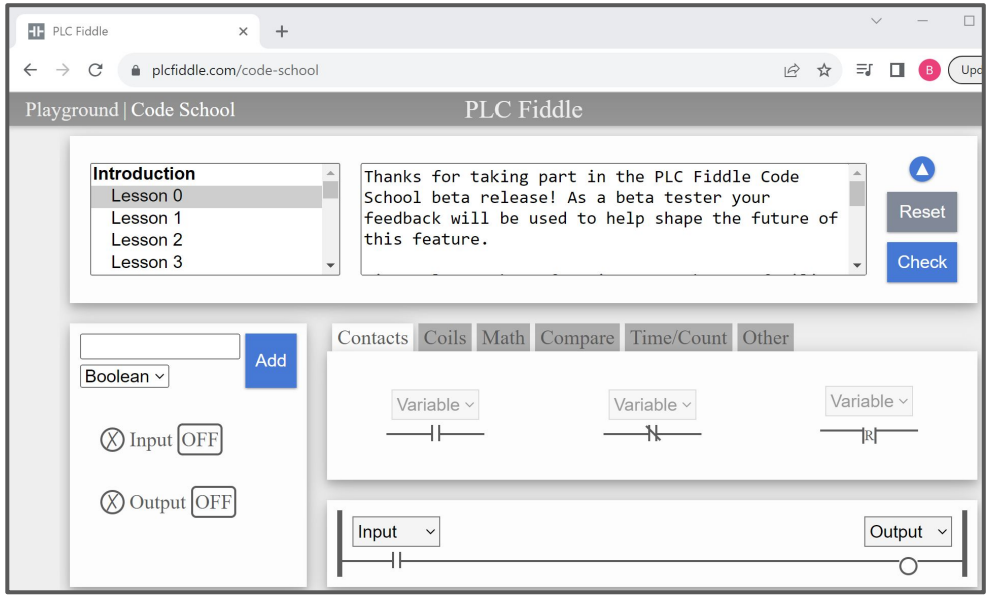


https://www.plcfiddle.com/code-school

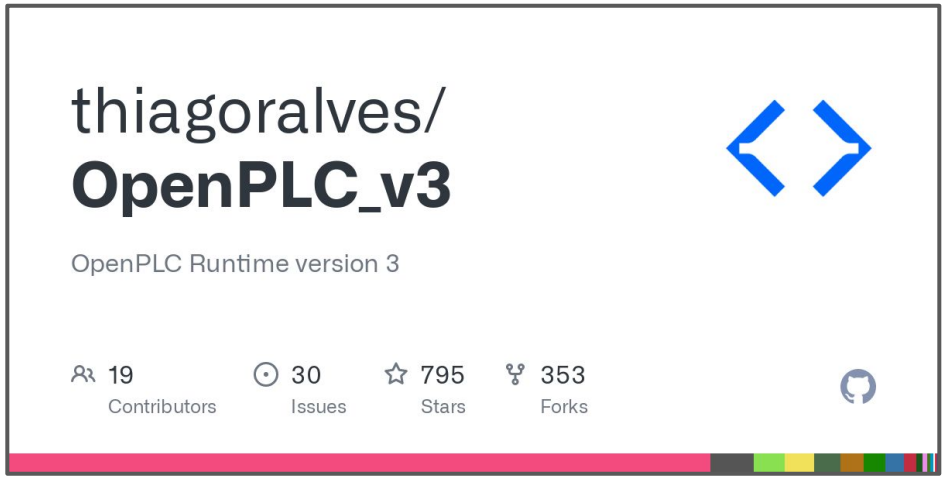
PLC Fiddle "Code School" Topics

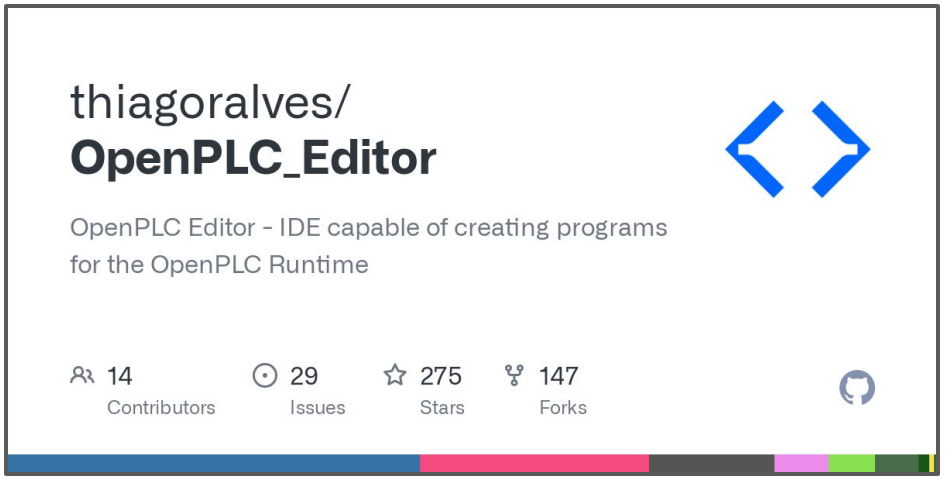
Here is a list of the topics the Code School covers:

1. Introduction (to the Interface)
2. Boolean Logic Basics
3. Intro to Counters
4. Intro to Timers
5. Working with Numbers



PLC Fiddle Demo


thiagoralves/
OpenPLC_v3
OpenPLC Runtime version 3
19
Contributors
30
Issues
795
Stars
353
Forks


thiagoralves/
OpenPLC_Editor
OpenPLC Editor - IDE capable of creating programs
for the OpenPLC Runtime
14
Contributors
29
Issues
275
Stars
147
Forks

2. OpenPLC

OpenPLC Project Overview

https://github.com/thiagoralves/OpenPLC_v3

"OpenPLC is an open-source Programmable Logic Controller that is based on easy to use software. Our focus is to provide a low cost industrial solution for automation and research. OpenPLC has been used in many research papers as a framework for industrial cyber security research, given that it is the only controller to provide the entire source code."

The OpenPLC Project consists of two sub-projects:

1. Runtime
2. Programming editor

https://openplcproject.com/docs/openplc-overview/

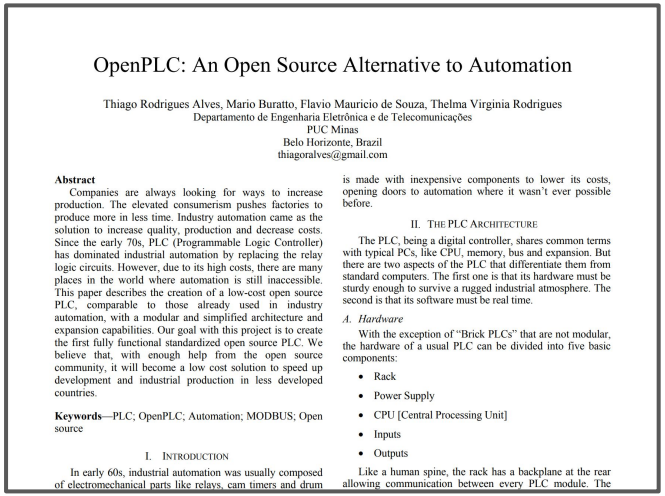
"It is the first fully-functional standardized open-source PLC, both in software and in hardware. The OpenPLC project was created in accordance with the IEC 61131-3 standard, which defines the basic software architecture and programming languages for PLCs."

History and Documentation

Developed by a group of Brazilian ICS security researchers in 2014

Undergone significant updates

Open Source = Free (as in speech [and beer])



OpenPLC: An Open Source Alternative to Automation

Thiago Rodrigues Alves, Mario Buratto, Flavio Mauricio de Souza, Thelma Virginia Rodrigues
Departamento de Engenharia Eletrônica e de Telecomunicações
PUC Minas
Belo Horizonte, Brazil
thiagoralves@gmail.com

Abstract

Companies are always looking for ways to increase production. The elevated consumerism pushes factories to produce more in less time. Industry automation came as the solution to increase quality, production and decrease costs. Since the early 70s, PLC (Programmable Logic Controller) has dominated industrial automation by replacing the relay logic circuits. However, due to its high costs, there are many places in the world where automation is still inaccessible. This paper describes the creation of a low-cost open source PLC, comparable to those already used in industry automation, with a modular and simplified architecture and expansion capabilities. Our goal with this project is to create the first fully functional standardized open source PLC. We believe that, with enough help from the open source community, it will become a low cost solution to speed up development and industrial production in less developed countries.

Keywords—PLC; OpenPLC; Automation; MODBUS; Open source

I. Introduction

In early 60s, industrial automation was usually composed of electromechanical parts like relays, cam timers and drum is made with inexpensive components to lower its costs, opening doors to automation where it wasn't ever possible before.

II. The PLC Architecture

The PLC, being a digital controller, shares common terms with typical PCs, like CPU, memory, bus and expansion. But there are two aspects of the PLC that differentiate them from standard computers. The first one is that its hardware must be sturdy enough to survive a rugged industrial atmosphere. The second is that its software must be real time.

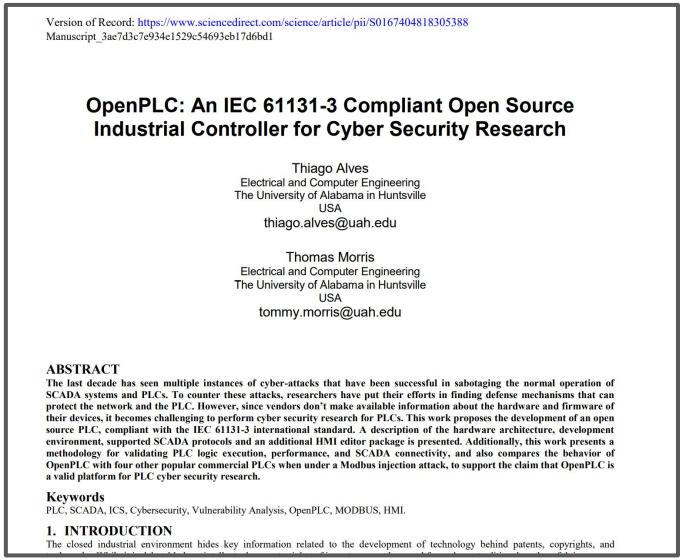
A. Hardware

With the exception of "Brick PLCs" that are not modular, the hardware of a usual PLC can be divided into five basic components:

- Rack
- Power Supply
- CPU [Central Processing Unit]
- Inputs
- Outputs

Like a human spine, the rack has a backplane at the rear allowing communication between every PLC module. The

https://ieeexplore.ieee.org/document/6970342



Version of Record: https://www.sciencedirect.com/science/article/pii/S0167404818305388
Manuscript_3ae7d3c7e934e1529c54693eb17d6bd1

OpenPLC: An IEC 61131-3 Compliant Open Source Industrial Controller for Cyber Security Research

Thiago Alves
Electrical and Computer Engineering
The University of Alabama in Huntsville
USA
thiago.alves@uah.edu

Thomas Morris
Electrical and Computer Engineering
The University of Alabama in Huntsville
USA
tommy.morris@uah.edu

ABSTRACT

The last decade has seen multiple instances of cyber-attacks that have been successful in sabotaging the normal operation of SCADA systems and PLCs. To counter these attacks, researchers have put their efforts in finding defense mechanisms that can protect the network and the PLC. However, since vendors don't make available information about the hardware and firmware of their devices, it becomes challenging to perform cyber security research for PLCs. This work proposes the development of an open source PLC, compliant with the IEC 61131-3 international standard. A description of the hardware architecture, development environment, supported SCADA protocols and an additional HMI editor package is presented. Additionally, this work presents a methodology for validating PLC logic execution, performance, and SCADA connectivity, and also compares the behavior of OpenPLC with four other popular commercial PLCs when under a Modbus injection attack, to support the claim that OpenPLC is a valid platform for PLC cyber security research.

Keywords
PLC, SCADA, ICS, Cybersecurity, Vulnerability Analysis, OpenPLC, MODBUS, HMI.

1. INTRODUCTION

The closed industrial environment hides key information related to the development of technology behind patents, copyrights, and

https://www.sciencedirect.com/science/article/abs/pii/S0167404818305388

OpenPLC Runtime v3 Target Platforms

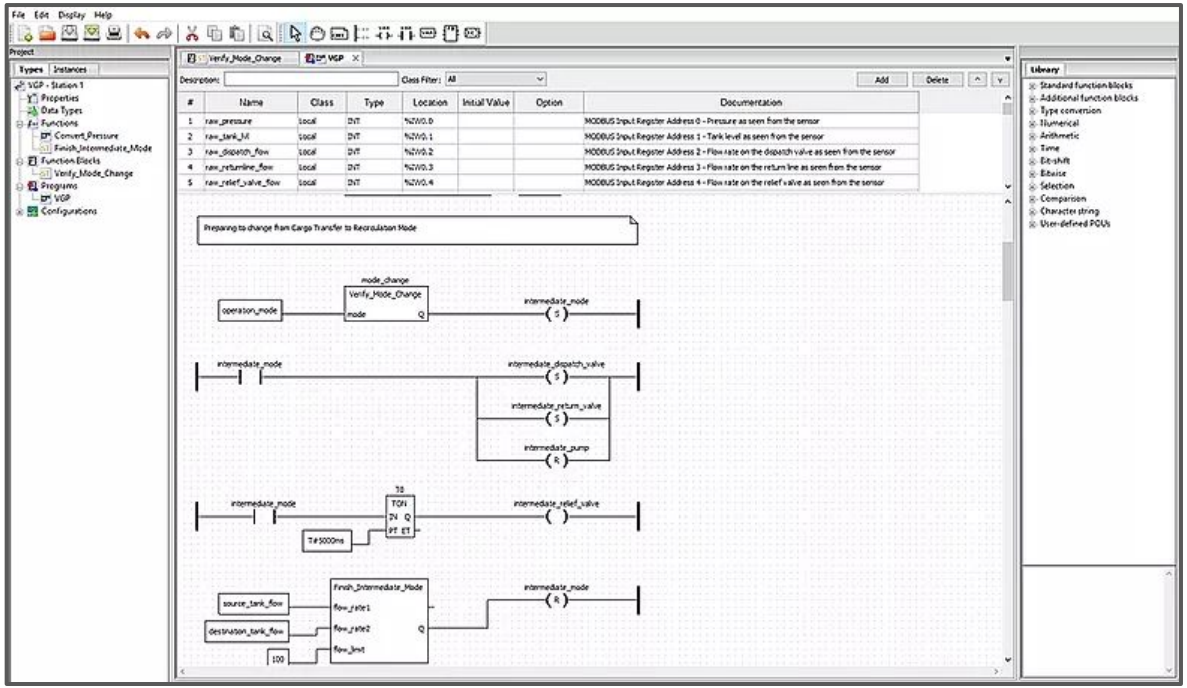
- Arduino Uno / Nano / Leonardo / Micro
- Arduino Mega / Due
- Arduino Nano Every / IoT / BLE
- Arduino RB2040 Connect
- Arduino Mkr / Zero / WiFi
- Arduino Pro (Machine Control and EDGE)
- Controllino Maxi / Automation / Mega / Mini
- Productivity Open P1AM
- ESP8266 (nodemcu)
- ESP32
- **Raspberry Pi 2 / 3 / 4**
- PiXtend
- UniPi Industrial Platform
- Neuron PLC
- FreeWave Zumlink
- FreeWave ZumIQ
- Windows (generic target as a soft-PLC)
- Linux (generic target as a soft-PLC)

OpenPLC Editor

https://openplcproject.com/docs/3-1-openplc-editor-overview/

v3.0+ uses the python-based Beremiz IDE

Writes programs according to IEC-61131-3 and conforms to PLCopen XML



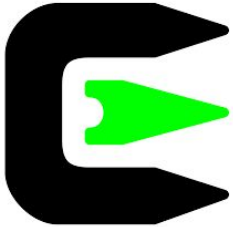
OpenPLC Runtime

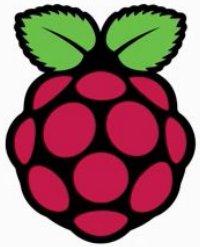
https://openplcproject.com/docs/2-1-openplc-runtime-overview/

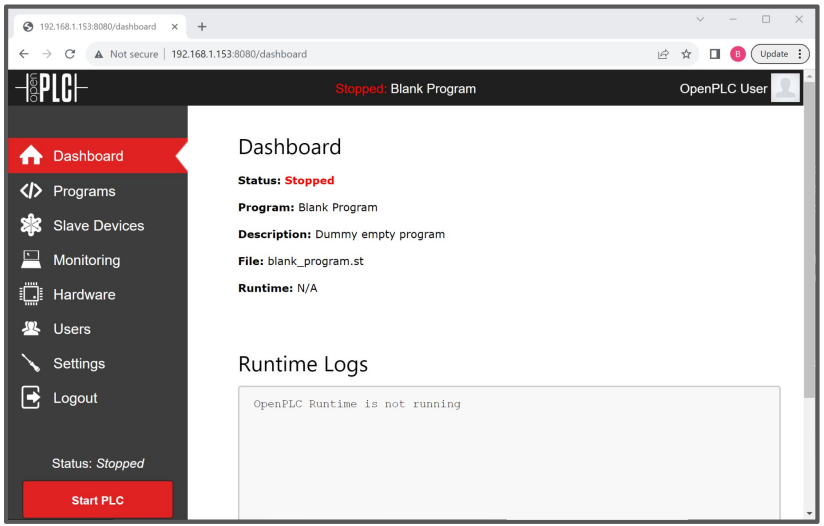
Runs PLC programs created on the OpenPLC Editor.

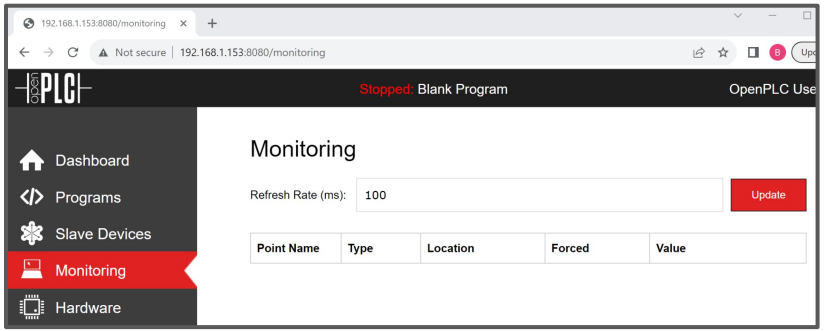
The main runtime has a built-in webserver that allows configuration & control.

A soft PLC can be run from Windows (via Cygwin) or Linux

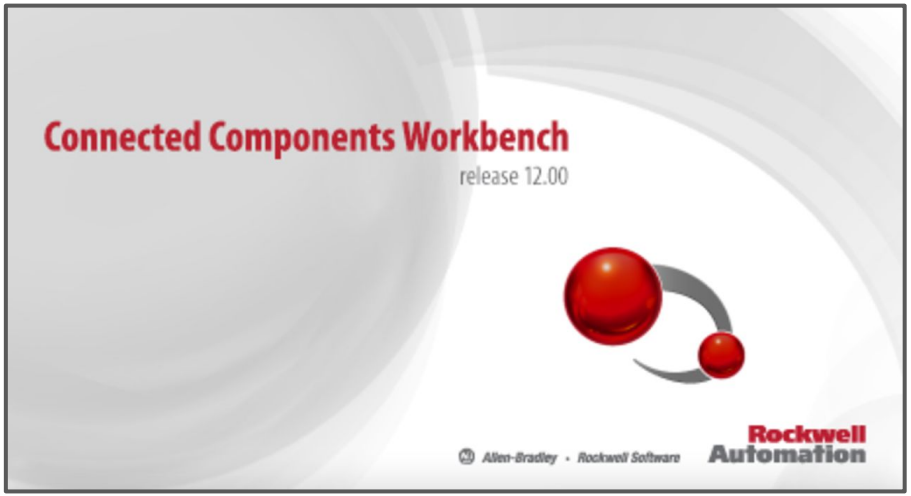








OpenPLC Demo



Rockwell Automation

Allen-Bradley
by ROCKWELL AUTOMATION

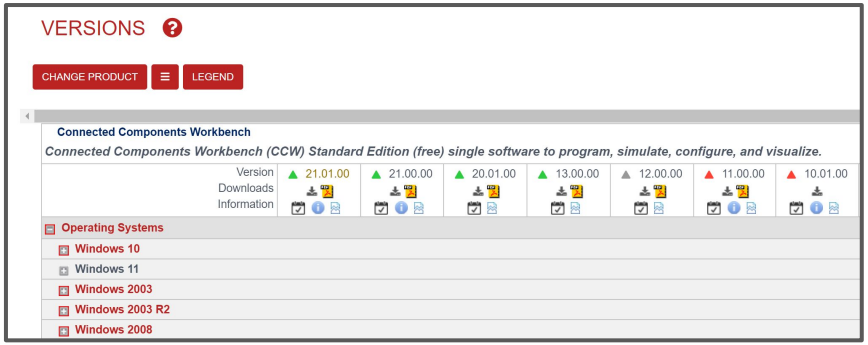
3. Rockwell/Allen-Bradley CCW

Connected Components Workbench (CCW) Overview

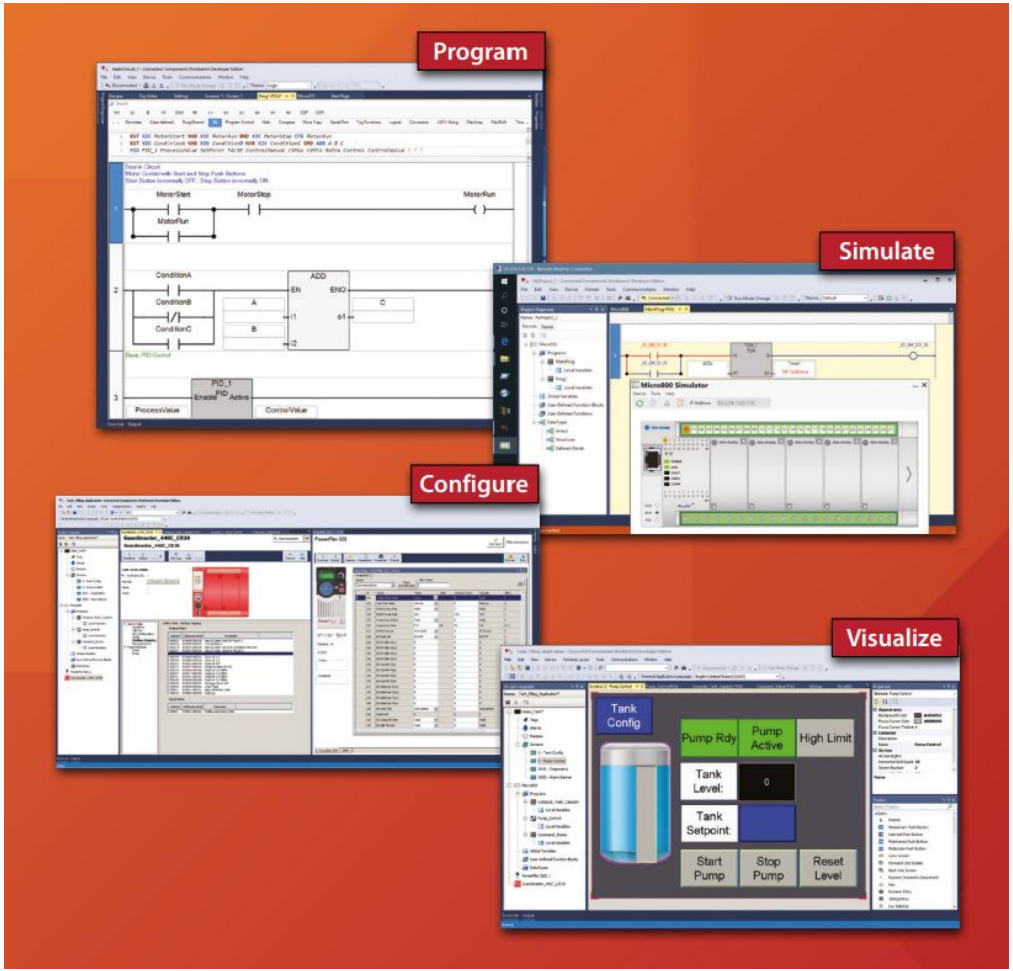
Standard Edition is Free (as in beer)

Program and run their newest low-cost line of PLC micro8X0

You need to sign up for an account on the Rockwell Automation website

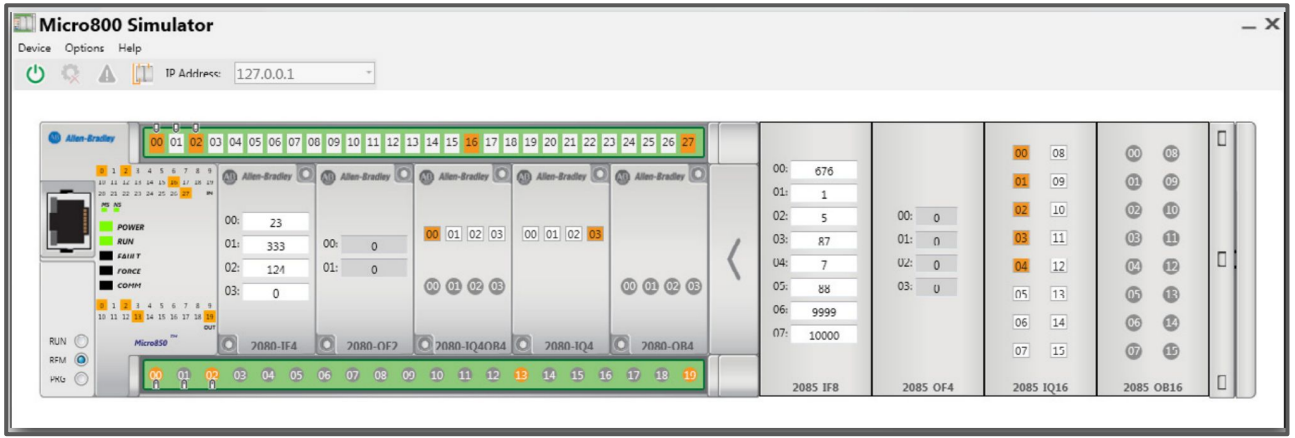


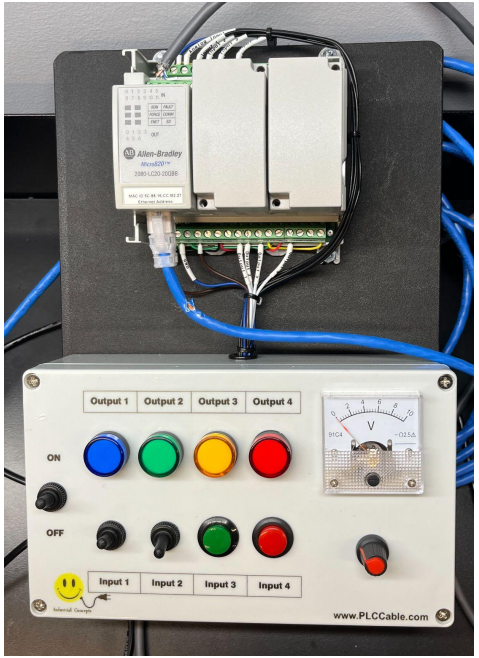
https://compatibility.rockwellautomation.com/Pages/ProductReplacement.aspx?crumb=101&restore=1&vid=62094



https://literature.rockwellautomation.com/idc/groups/literature/documents/pp/9328-pp001_-en-p.pdf

Built-in Simulator -or- Real-World Hardware

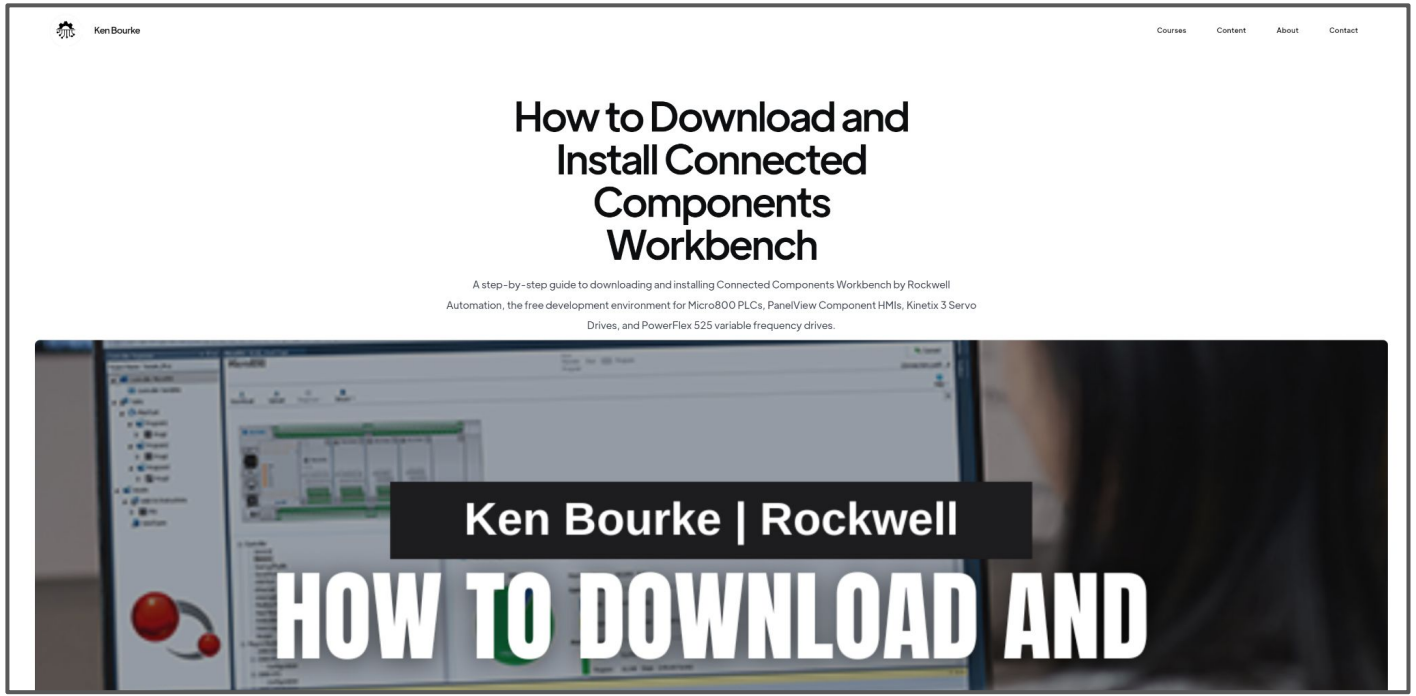




https://www.plccable.com/allen-bradley-micro820-analog-ccw-plc-trainer-micro800-training-kit/

How to Install

https://www.kenbourke.me/posts/how-to-download-and-install-connected-components-workbench



Plenty of other Online Resources

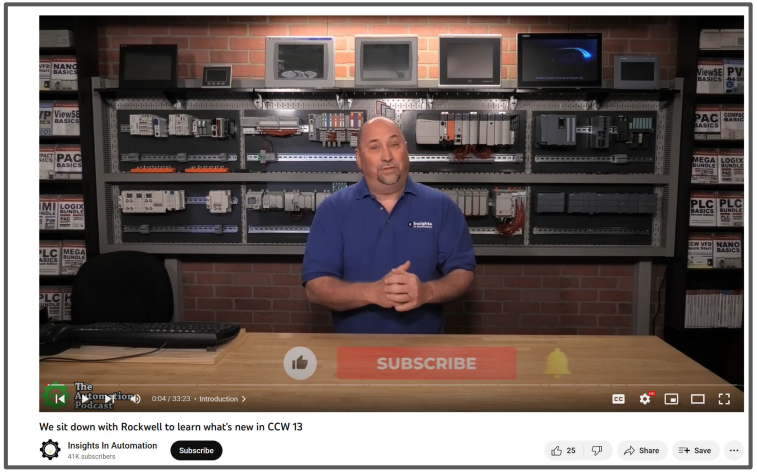
Allen Bradley Micro800 Connected Components Workbench CCW

Tim Wilborne

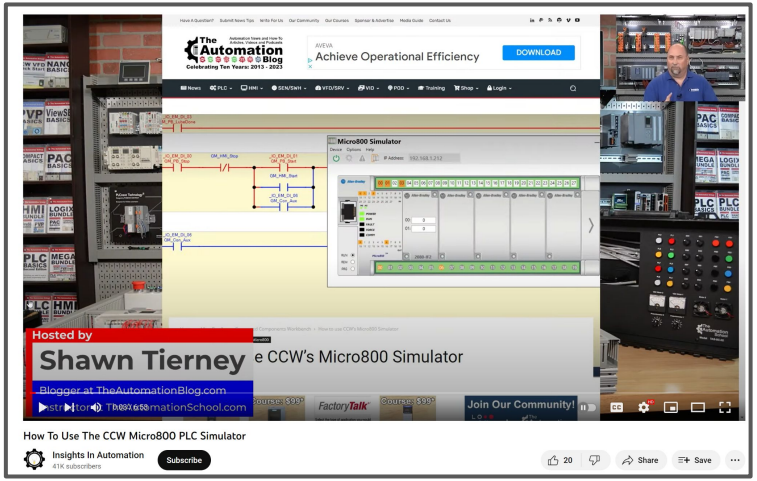
53 videos 54,980 views Last updated on Feb 2...

In this lesson series we show you how to download you software, go through the PLC programming instru ...More

https://www.youtube.com/playlist?list=PLUi5cdVq3wTCjGF-QqwyVLDejTLhHrvAT



https://www.youtube.com/watch?v=j0uWjQD0PIY

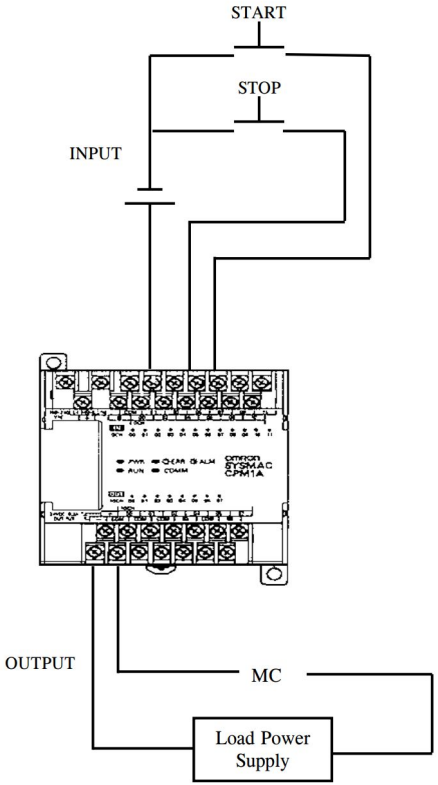


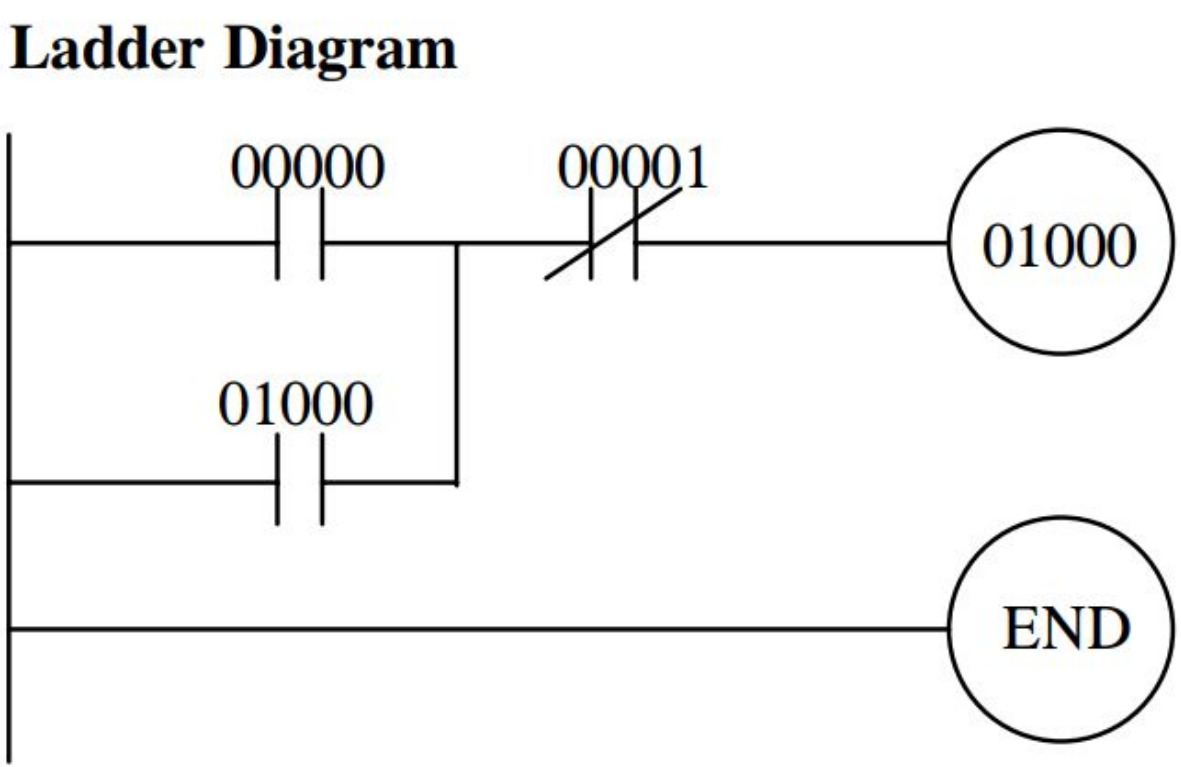
https://www.youtube.com/watch?v=s6dRL-8meFs

CCW Demo

Example Circuits

Latch / Self Holding Circuit

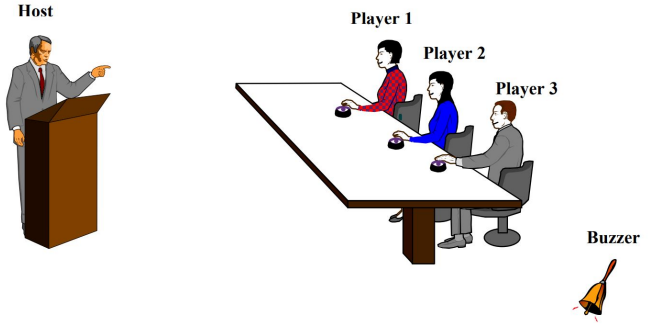




Example - Quiz Show

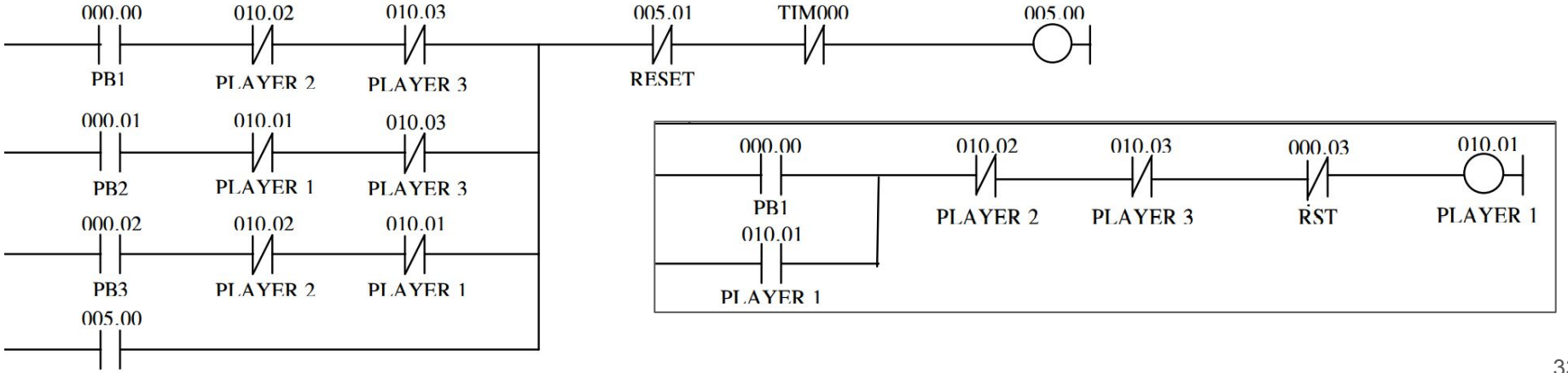
The game buzzer control requirement:

1. After the Host has finished with question.
2. The 3 players will press the switch in front of them to fight to be first to answer the question.
3. The buzzer will sound for 10 sec after any one of the players has touched the switch.
4. The light indicator in front of each player will light-up and only reset by the Host switch.



Input	Device
00000	PB1
00001	PB2
00002	PB3
00003	RST (reset)

Output	Device
01000	Buzzer
01001	Player 1 light
01002	Player 2 light
01003	Player 3 light



Backup Slides

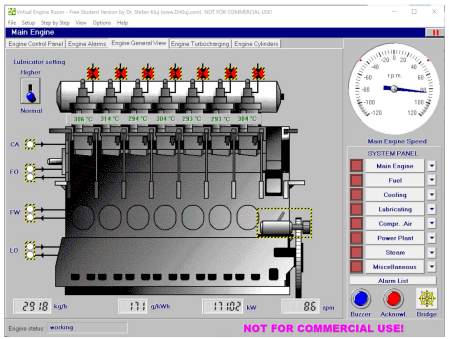
MICS Course Offering

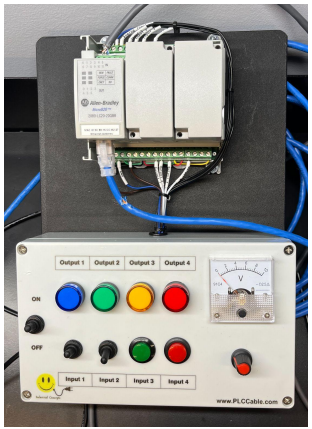
Spring 2023, SY486K Maritime Industrial Control Systems Cybersecurity

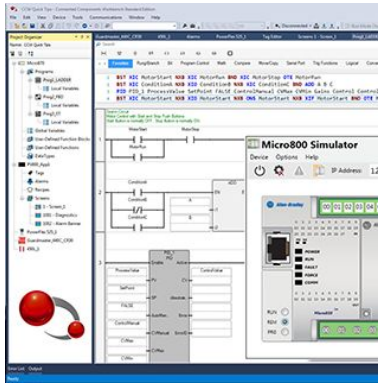
Three-credit technical elective

Lectures, Labs, Student Presentations, and YP Project

Topics included: Maritime Systems, PLC, Ladder Logic, Modbus, CIP, Attacking ICS





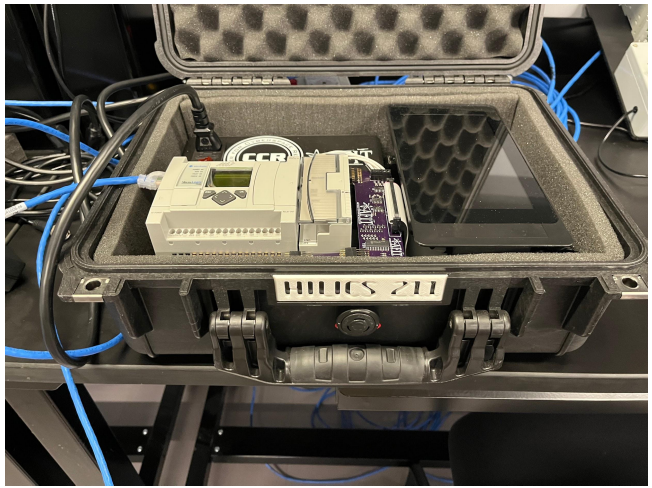


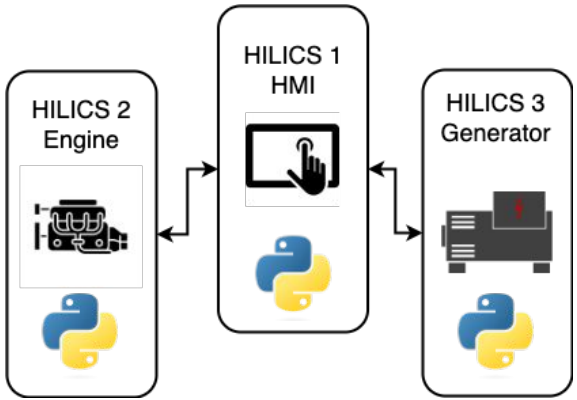
https://github.com/brienc23/MICS_Course_Materials

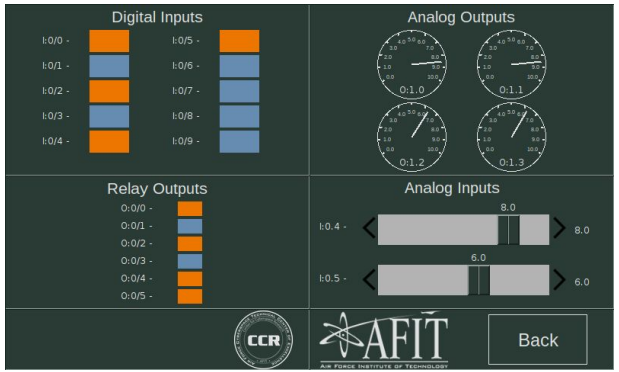
Hardware-in-the-Loop ICS (HILICS)

Produced by Air Force Institute of Technology (AFIT)
AB microLogix 1100+RasPi (with touchscreen HMI) in a Pelican case

https://github.com/sdunlap-afit/hilics







The Scanning Process

https://my.ece.utah.edu/~ece3510/Ladder%20Logic%20Fundamentals%20PLC%20tutorial.pdf

- The scan sequence can be broken into two functional parts:
  - The **Program Scan**
    - Scan the ladder program
  - The **I/O Update Scan**
    - Write outputs, Read inputs

https://my.ece.utah.edu/~ece3510/Ladder%20Logic%20Fundamentals%20PLC%20tutorial.pdf

The Program Scan:

- For each rung executed, the PLC processor will:
  - Examine the status of the input image table bits,
  - Solve the ladder logic in order to determine logical continuity (is the rung true?),
  - Update the appropriate output image table bits, if necessary.

  Note: The output will not actually be energized until the I/O update part of the scan.

https://my.ece.utah.edu/~ece3510/Ladder%20Logic%20Fundamentals%20PLC%20tutorial.pdf

The I/O Update Scan:

- Copy the output image table status to the ALL of the output terminals (discrete output circuits)
  - Power is applied to the output device if it's output image table bit has been previously set to a 1.
- Copy the status of ALL of the input terminals to the input image table
  - If an input is active (i.e., there is electrical continuity), the corresponding bit in the input image table will be set to a 1.