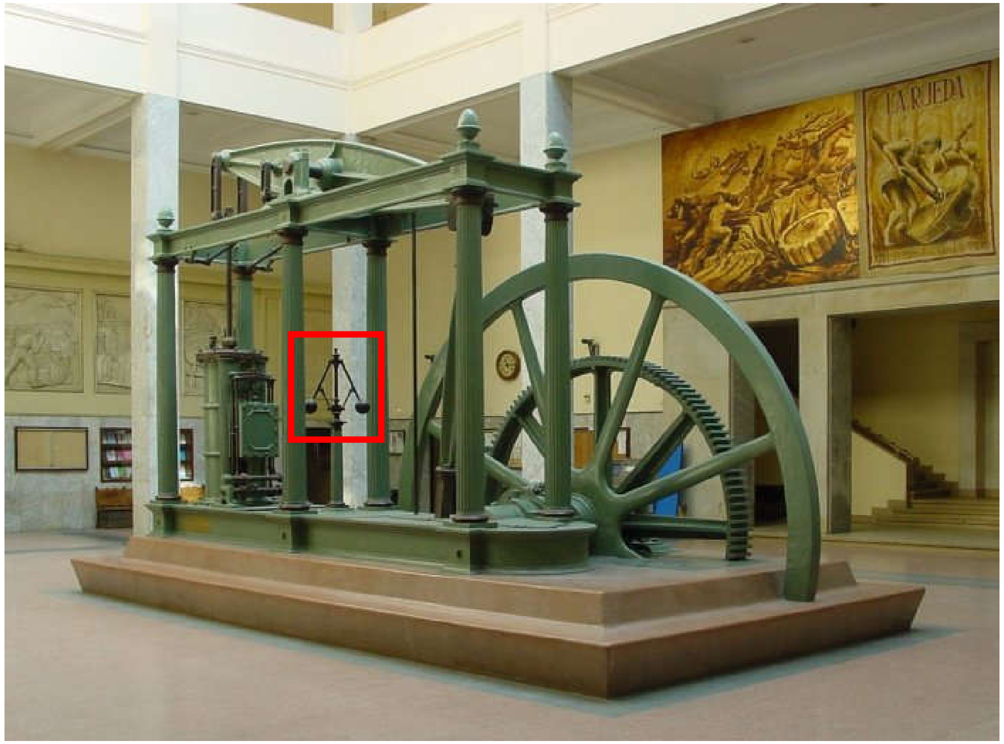
Modeling and Automation of Industrial Processes

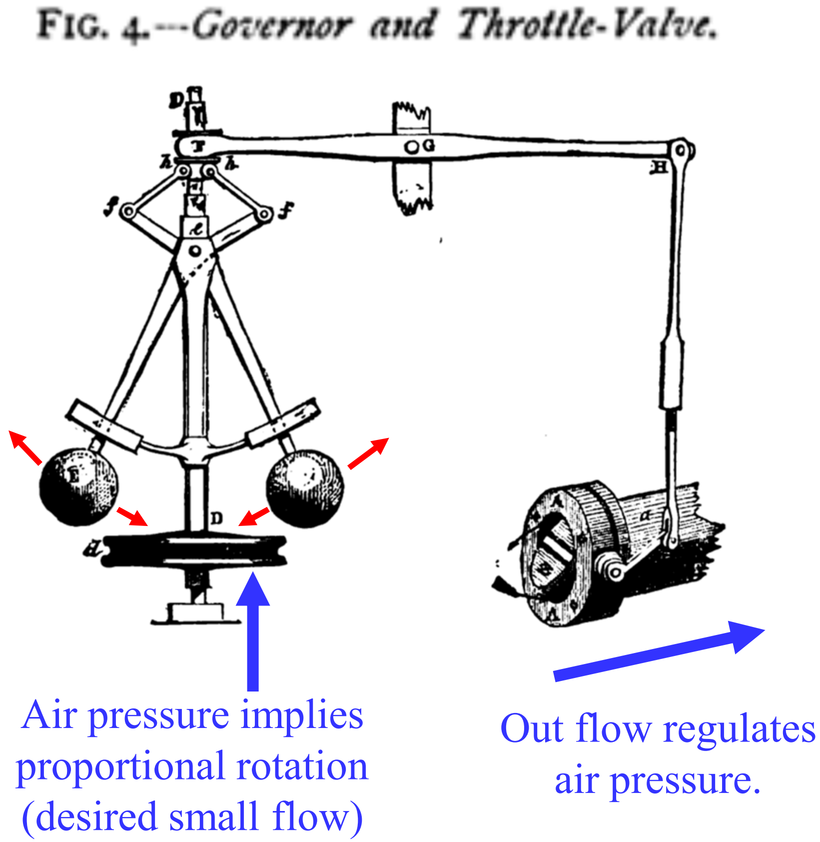
Modelação e Automação de Processos Industriais / MAPI

http://www.isr.tecnico.ulisboa.pt/~jag/courses/mapi2223

Prof. José Gaspar, rev. 2022/2023

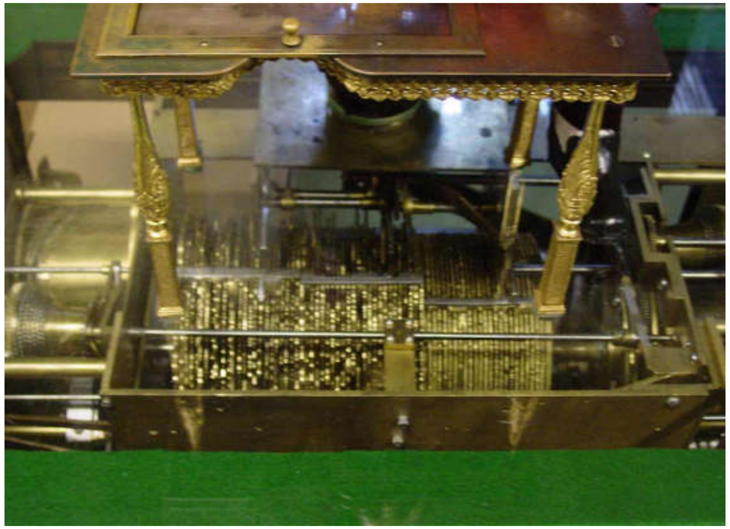
Industrial Revolution 1760/80 – 1820/40 (historians E. Hobsbawm, T. S. Ashton)

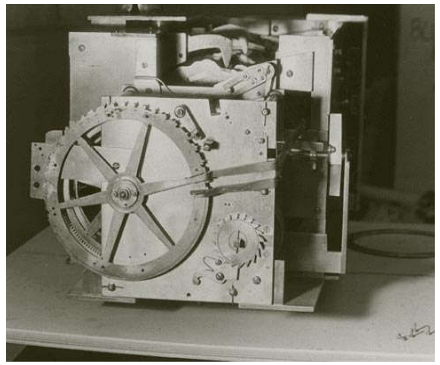




Steam engine and detail of the governor, James Watt's [Wikipedia].

A jewel: Maillardet's Automaton, 18th century, the largest known mechanical memory

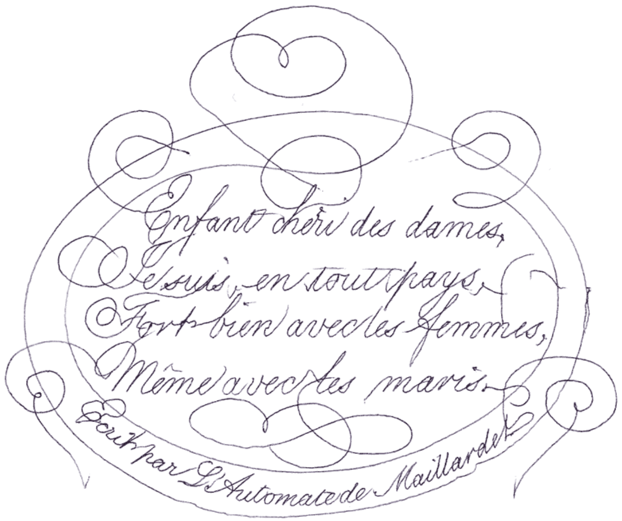


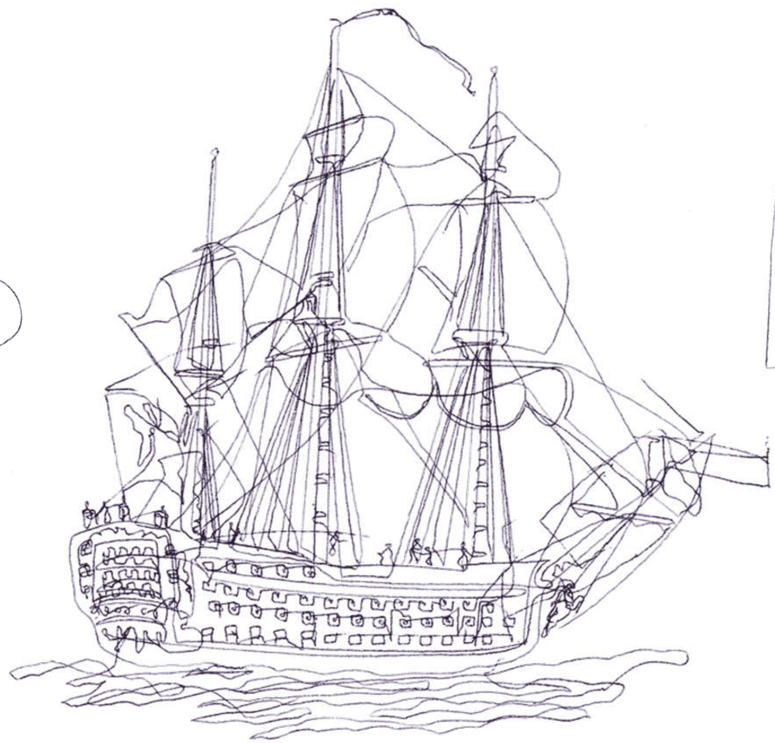


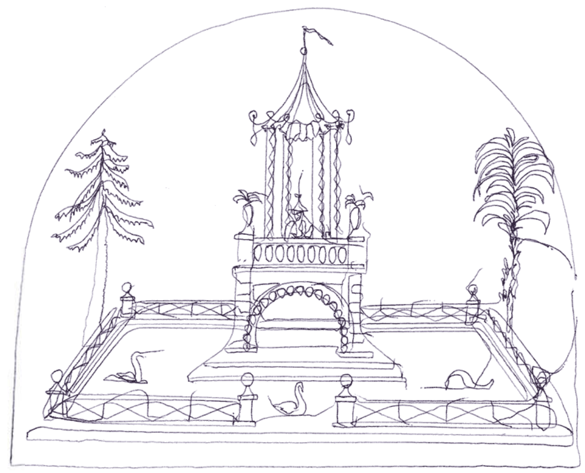
https://www.fi.edu/history-automaton

Maillardet's Automaton, 18th century: the largest known mechanical memory

Four drawings and three poems

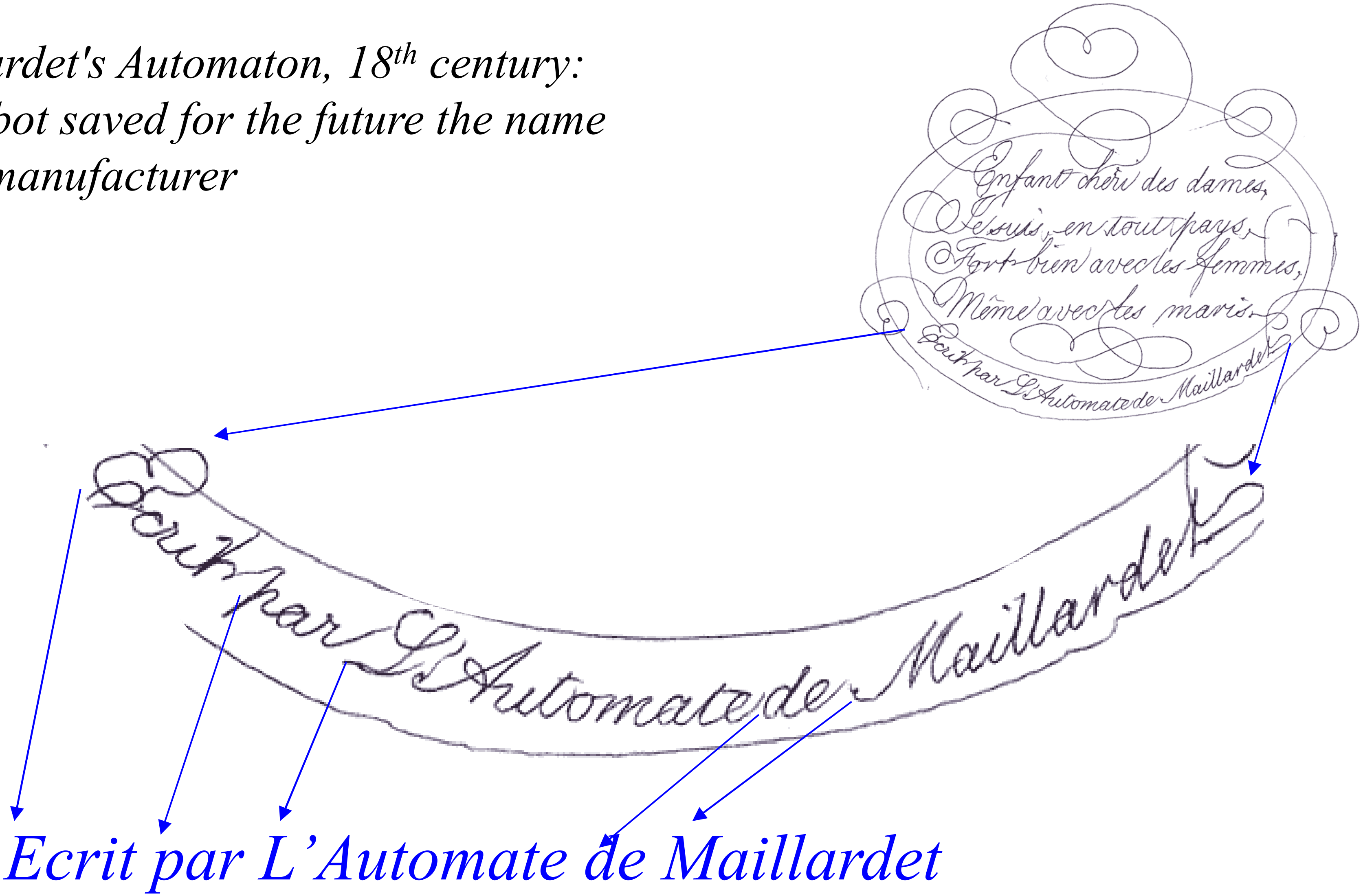






https://www.fi.edu/history-automaton

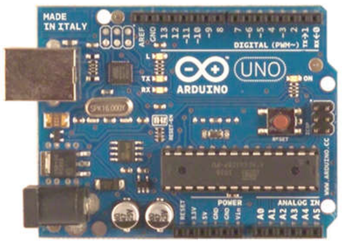
Maillardet's Automaton, 18th century: the robot saved for the future the name of its manufacturer



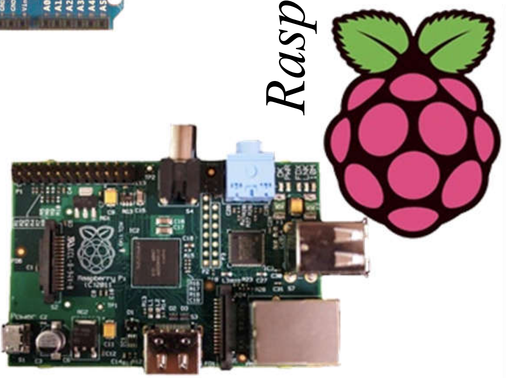
https://www.fi.edu/history-automaton

Microcontrollers

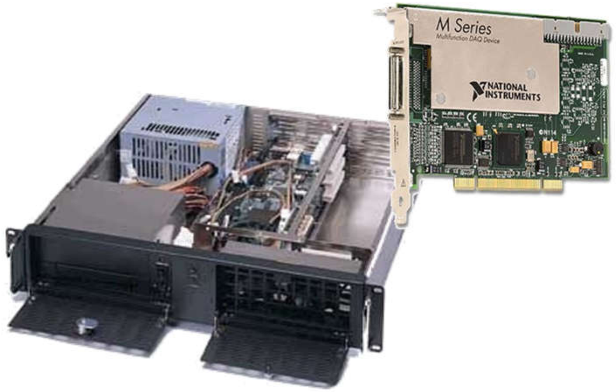
Arduino



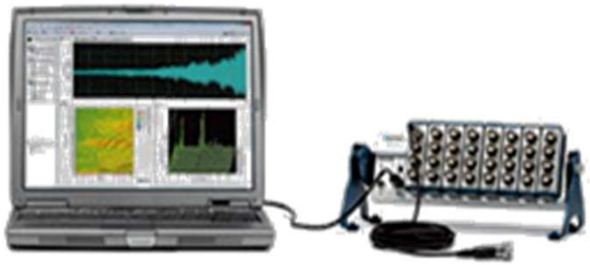
Raspberry-pi



Computer + IO

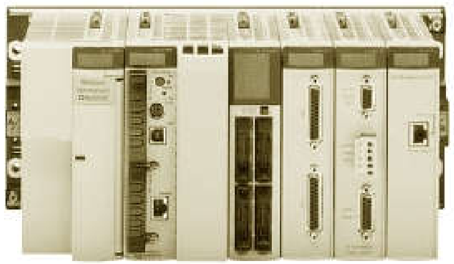


National Instruments AD/DA



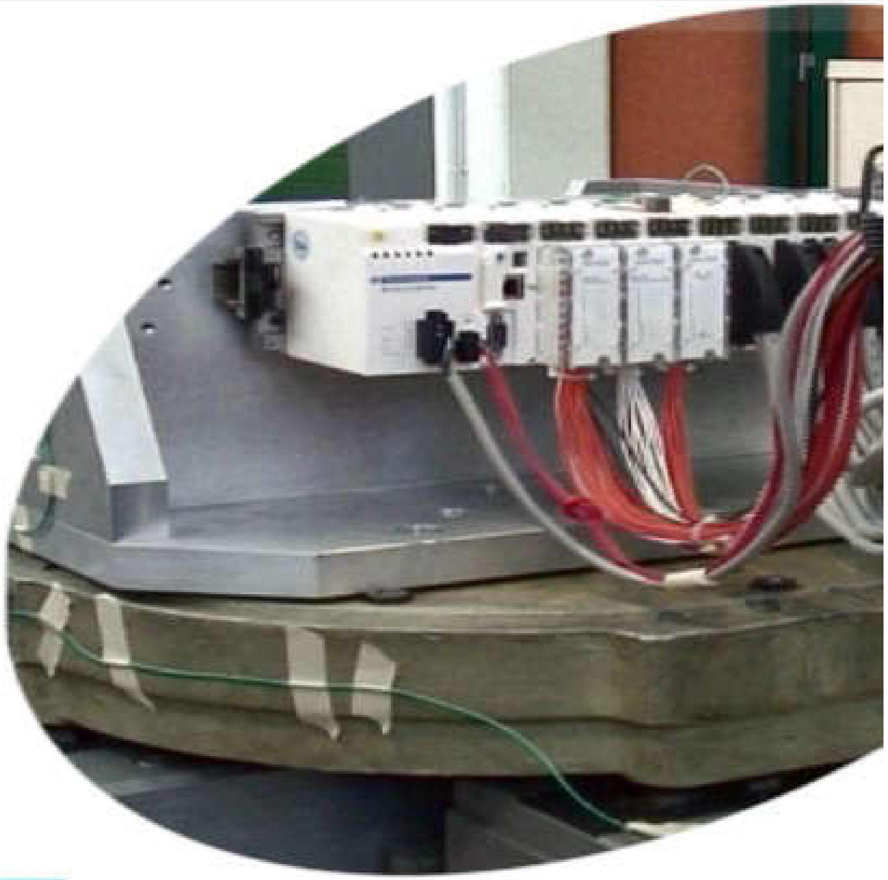
PLC

Premium P57



Many options for controlling real world devices! Why PLCs?

Robustness
is not an Option



a brand of Schneider Electric

Telemecanique

Program at a glance:

1a. Introduction to PLCs
Components of Programmable Logic Controllers (PLCs). Architecture, functional structure, IO.

1b. PLCs Programming Languages
Standard languages (IEC-61131-3): Ladder Diagram and Structured Text.

1c. GRAFCET (Sequential Function Chart)
Norm, elements of the language, modelling.

2. Discrete Event Systems
Modeling of discrete event systems (DESs). Automata. Petri networks. State and dynamics of PNs.

3. Stochastic models
4. Stochastic analysis
Stochastic Petri Nets (SPN). Stochastic Queuing Networks (SQN). Markov chain modelling of SPN and SQN

5. Control (MDPs in continuous time)
6. Supervisors and Fluid models
Methodologies for supervision. Synthesis based on invariants. Examples of application.

7. Case studies (connection to Industry and Services)

Assessment and grading:

- ***1 Quiz (MAP)*** *at the middle of the 7-weeks classes-period (15%)*

- ***2 Laboratory assignments*** *(15%+15% of the final grade). Groups of 3/4 students.*

  Need one volunteer to help with lab registrations

- ***1 Seminar*** *(10% of the final grade). Topics to be selected with each group.*

- ***1 Exam*** *(45% of the final grade).*

  Depending on the number of students, the second exam can be oral.

- *Minimum grade: 9.0/20.0 val. for labs, 7.5/20.0 val. for the exam.*

Final *= 0.15*MAP +0.15*L1 +0.15*L2 +0.1*A +0.45*E*

A= Apresentação / Seminar

Bibliography :

--- References mostly found in the slides :

• **Introduction to discrete event systems**, Christos Cassandras Christos Cassandras and Stéphane Lafortune, Springer 2008.

• **Programmable Logic Controllers,** Frank D. Petruzella, McGraw-Hill, 1996 (recent version 2022).

• **Supervisory Control of Discrete Event Systems**, Moody and Antsaklis, Kluwer Academic Publishers, 1998.

• **Petri Net Theory and the Modeling of Systems**, James L. Peterson, Prentice-Hall,1981.

• **Automating Manufacturing Systems with PLCs**, Hugh Jack (available online).

--- Complementary :

• **Supervisory Control of Concurrent Systems: A Petri Net Structural Approach**, Marian V. Iordache, Panos J. Antsaklis, Birkhauser, 2006.

• **Manufacturing Systems Modeling and Analysis**, G. Curry, R. Feldman , 2nd Edition, Springer 2011

• **Processing Networks - fluid models and stability**, J. Dai, J. Harrison, available online, 2019

• **Manufacturing Systems Control Design: A Matrix Based Approach**, S. Bogdan, F. Lewis, Z. Kovacic, J. Meireles Jr., Springer, 2006

• **Técnicas de Automação**, João R. Caldas Pinto, Lidel Ed. Técnicas Lda, 2010 (3ª Edição)

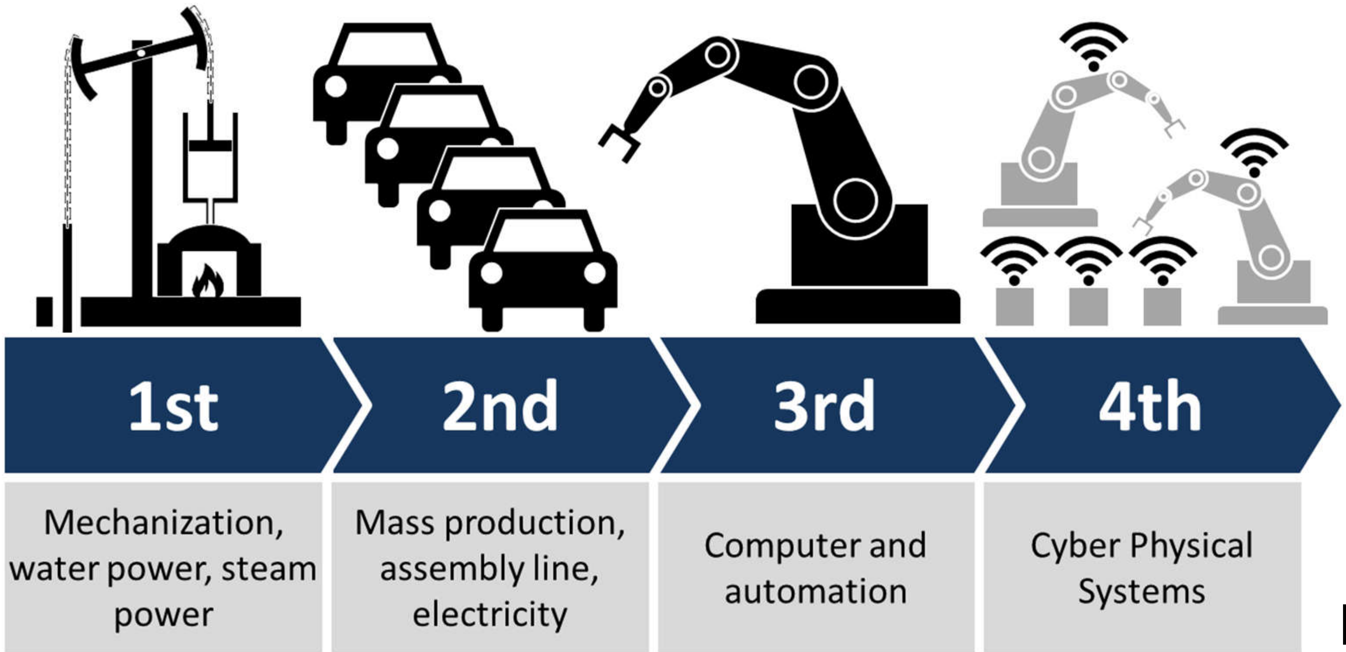
Modeling and Automation of Industrial Processes

Modelação e Automação de Processos Industriais / MAPI

Introduction to Automation

Prof. Paulo Jorge Oliveira, original slides
Prof. José Gaspar, rev. 2021/2022

Industrial Automation - Industry 4.0



[Wikipedia]

1760-1840 Industrial Revolution

1913 Assembly line by Henry Ford

1955 NC/CNC 1968 Bedford / GM PLC

2011 Industry 4.0 term revived at the Hannover Fair

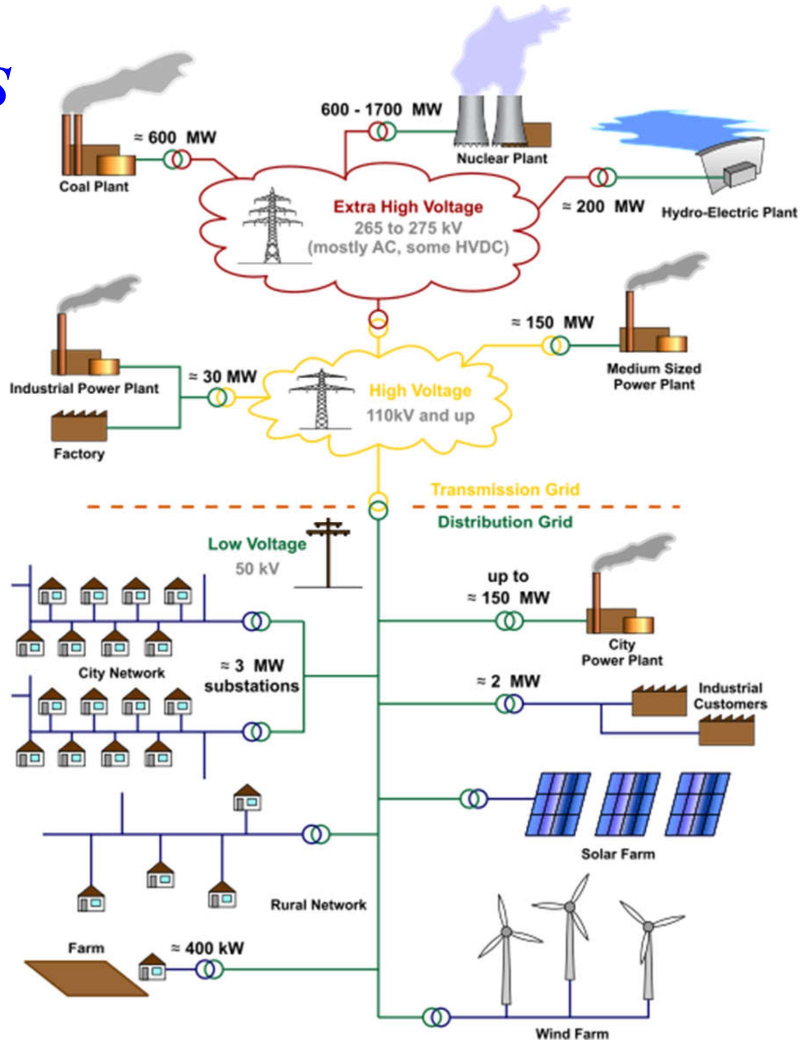
1807-1811 *French invasions, 1821 Independence of* ***Brasil***

1974-1975 *Independence of Guiné-Bissau, Moçambique, Cabo Verde, São Tomé e Príncipe,* ***Angola***

Industrial Automation - Industry 4.0

Cyber physical systems (CPS), Internet of things (IoT) and Visual computing (VC)

CPS

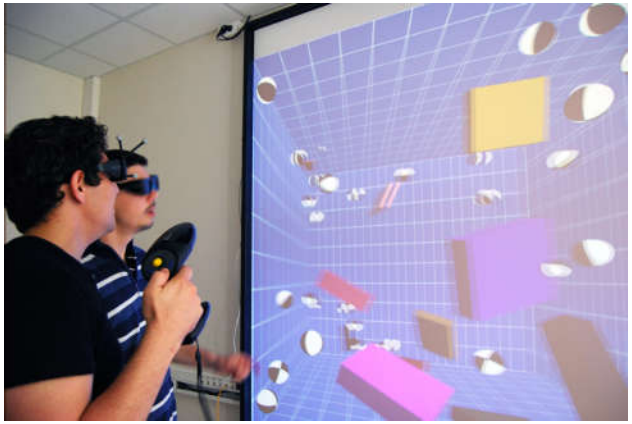


https://en.wikipedia.org/wiki/Electric_power_distribution

IoT

https://medium.com/datadriveninvestor/the-internet-of-things-90263f7b1249

VC

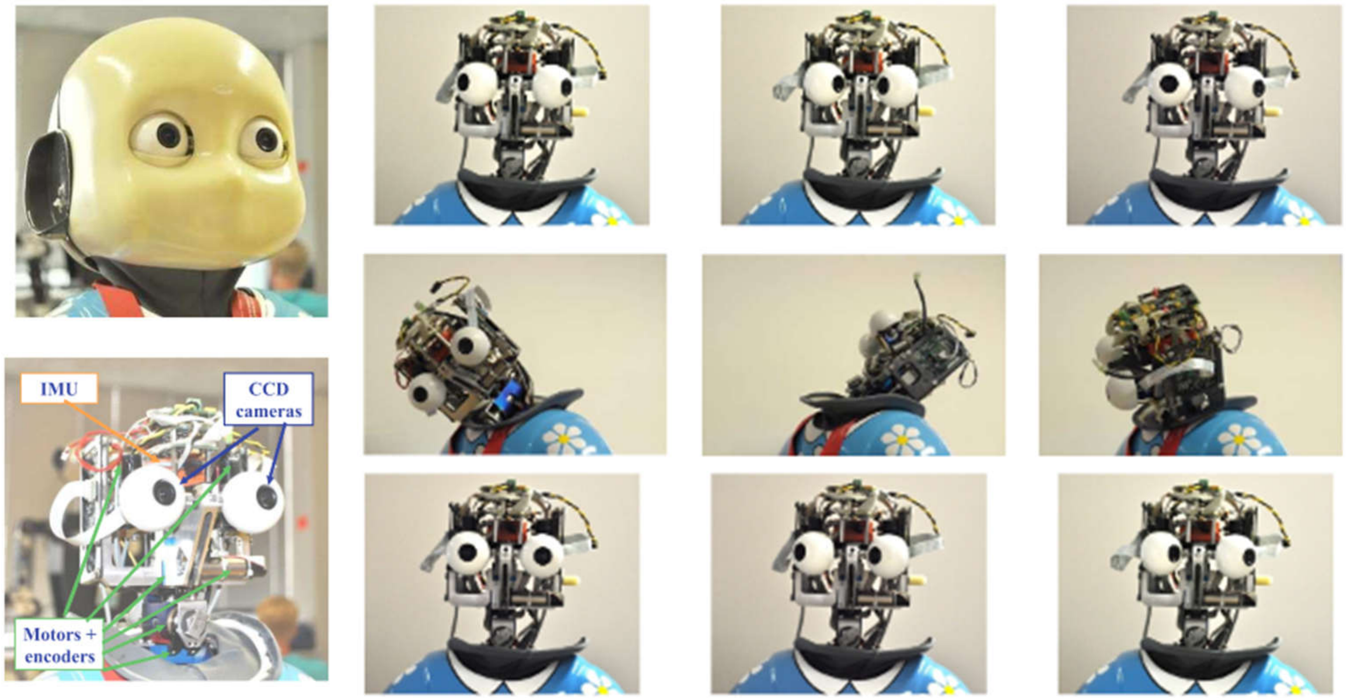


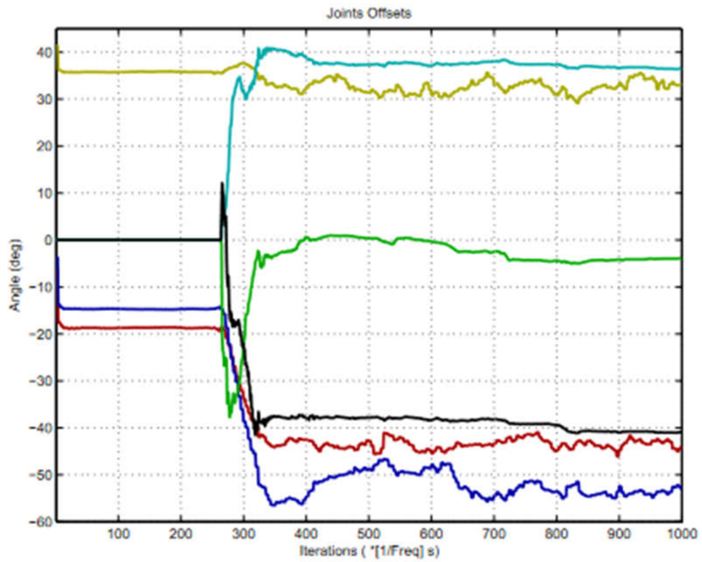
https://eisti.fr/en/formation/visual-computing-option

Industrial Automation - Industry 5.0

While ***Industry 4.0 is still under implementation****, the European Union is already launching what will be the foundation of* ***Industry 5.0*** *[1]:*

Transition to a ***sustainable****,* ***human-centric*** *and* ***resilient*** *European industry*





Humanoid Robot Head Continuous Calibration for Active Stereo Vision, using Non-Linear Filtering Techniques [2]

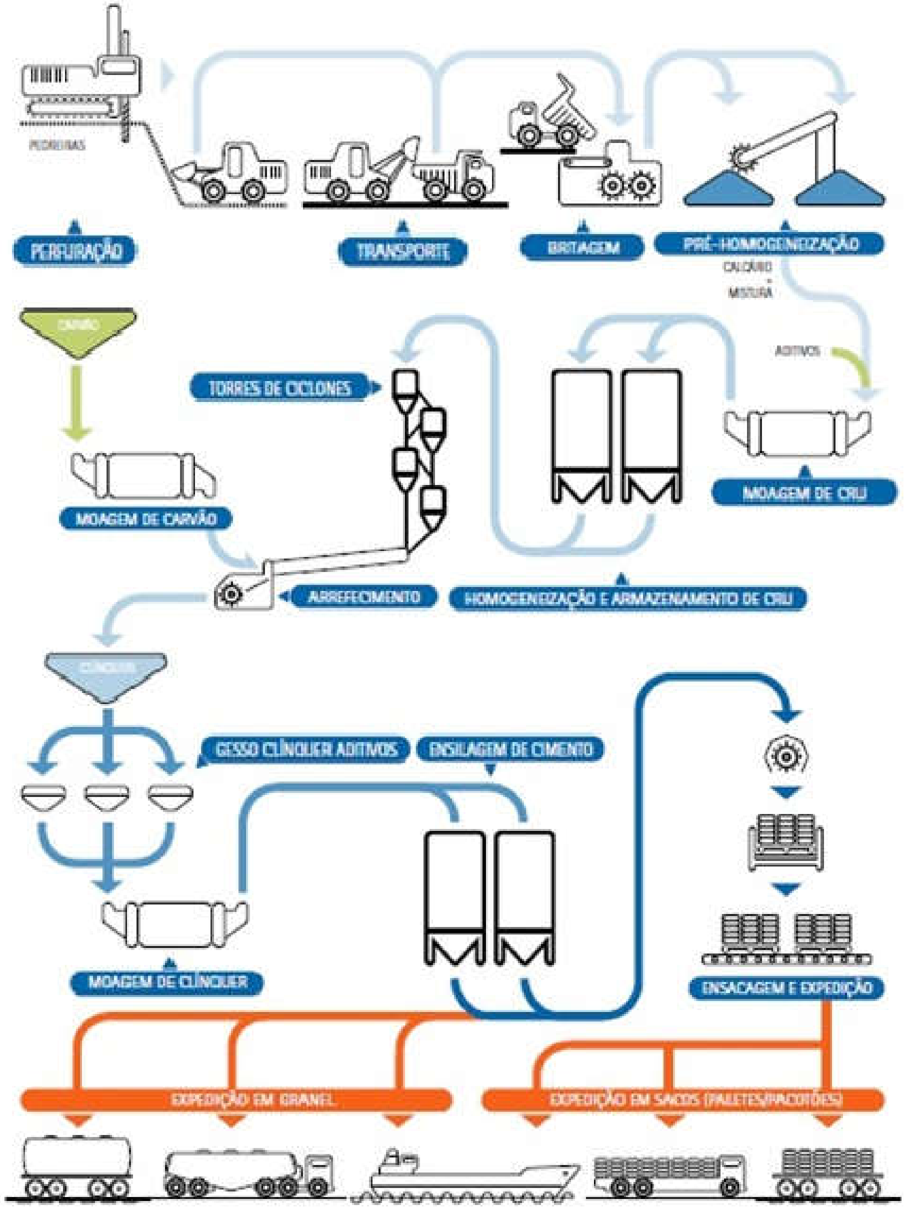
1 https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en
2 PhD thesis, Nuno Moutinho, Instituto Superior Técnico 2017

Industrial Process:

Making Cement

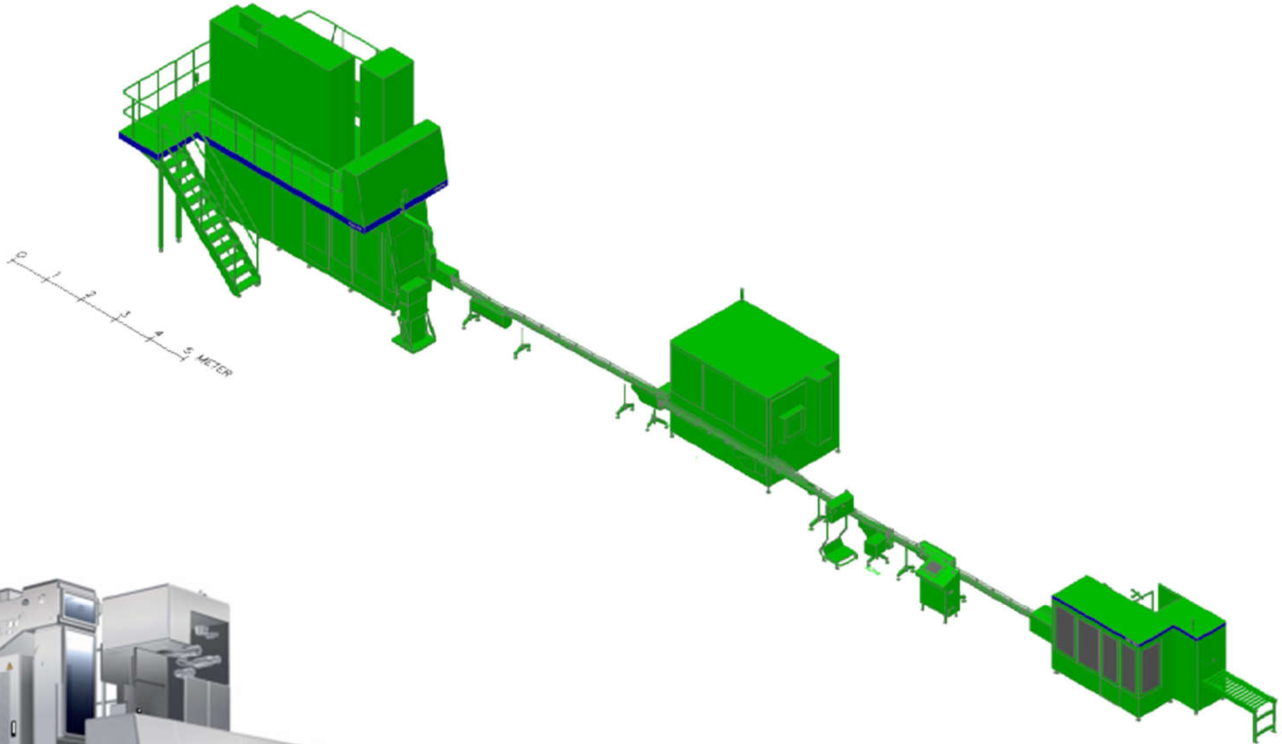
[Outão / Setúbal / Portugal]

Some systems are very ***large and complex*** *but still need to "work like a clock"*



Industrial Process:

Tetra Pak / Parmalat

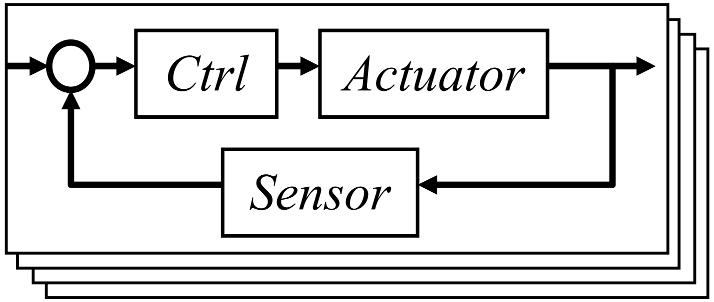


*Complexity handled with **modularity**.*
Filling machine, complete line:

- *200 ml slim 20000 TP/h*
- *Straw Applicator*
- *Beverage Carton Film Wrapper*
- *Conveyors*
- *Carboardpacker*

Complex Systems based on Local and Global Controllers

Subsystem +Subsystem +Subsystem + … + Global Controller = Automated Industrial Process



Other courses as e.g. Control

*Subsystems **sequencing, synchronization**, …*

***Start and stop** digital (binary) signals and events.*

The subject of this course.

Ch. 1 – Introduction to Automation

1.1 Introduction to **components** in industrial automation.

1.2 **Cabled** logic versus **programmed** logic versus **networked** logic.

1.3 Introduction to **methodologies** for problem modeling. Methodologies of work.

1.1 Components used in industrial automation

Computerized CNC Machines
– specialized workers

Handling materials (1)
– specialized load and unload

Handling (2) Robotic Manipulators
– generic load, unload, handle, work

How it is done:
– Low level actuation and sensing
– Motors and sensors, local and global integration

Computerized Numerical Controlled (CNC) Machines

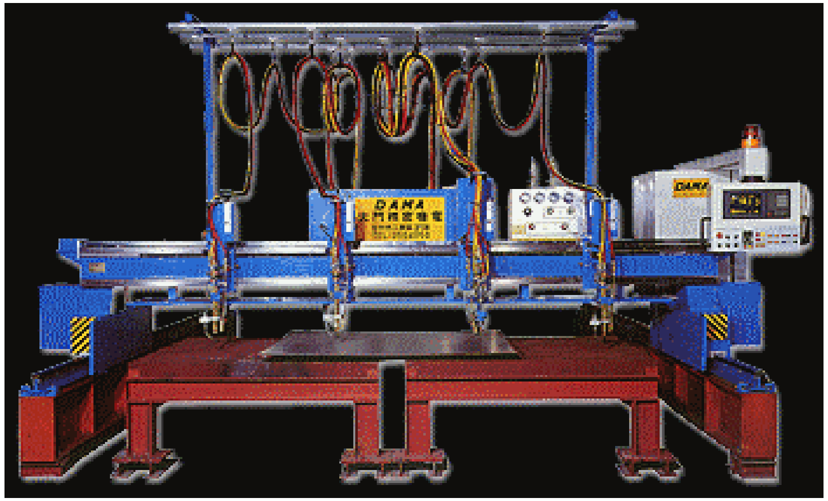
Major characteristics:

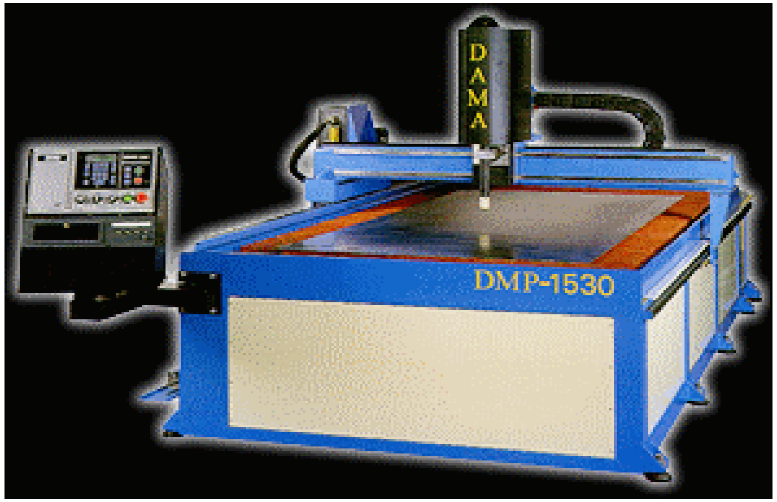
• Number of degrees of freedom
• Interpolation methods
• Load/unload automation, and also in tool change
• Programming (high level languages, teach pendent, ...)
• Workspace
• Accuracy, reliability
• Payload and robustness
• Interface
• Synchronization with exterior

Examples:
Milling, Lathes, ...

MITSUI SEIKI Machining Center

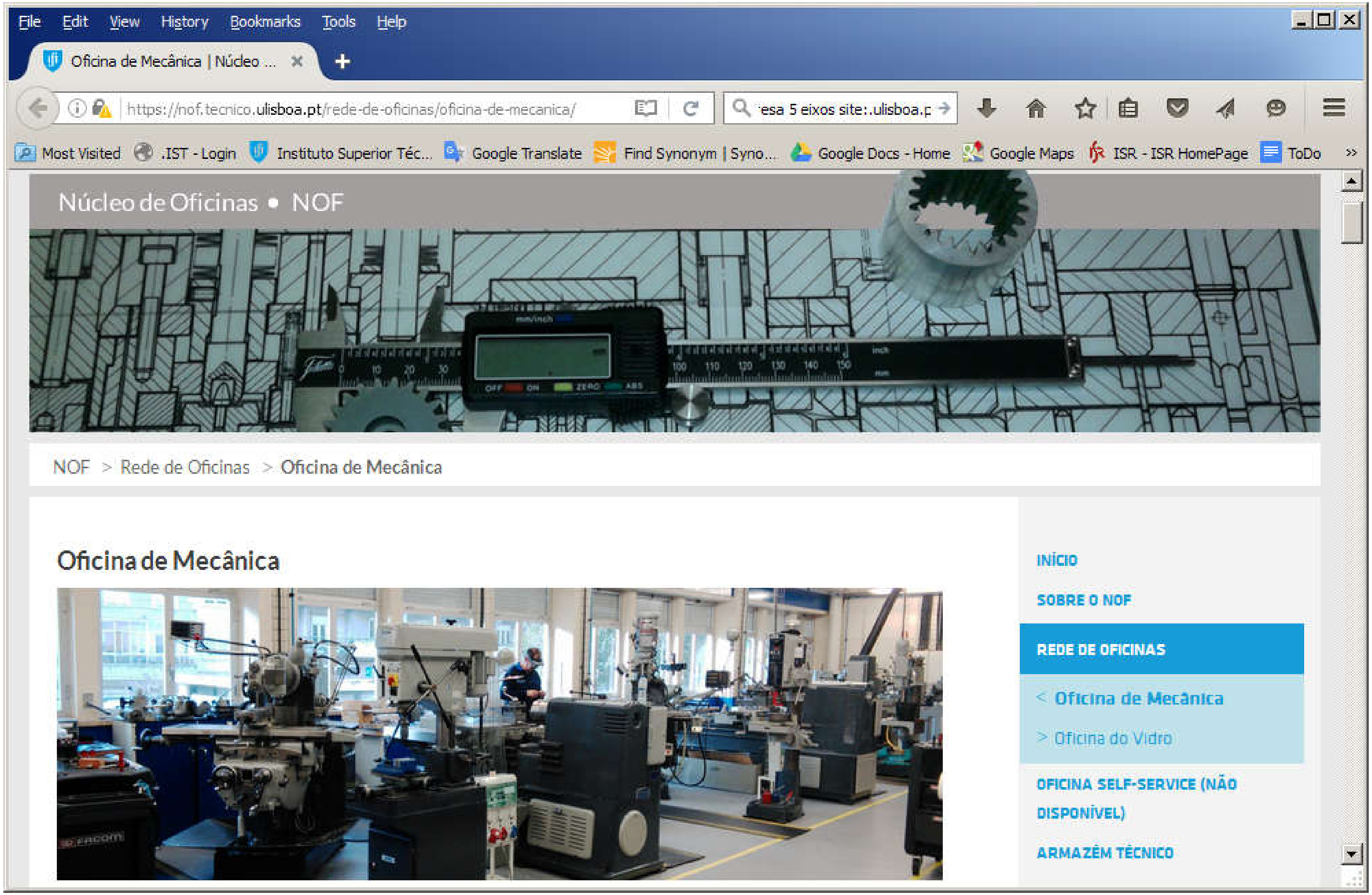
Computerized Numerical Controlled (CNC) Machines





Compact CNC plasma cutting machine
Effective cutting :1.5 m X 3 m
Plasma torch cutting capacity up to 5cm (mild steel), Gas torch option allows up to 10cm.

Computerized Numerical Controlled (CNC) Machines



Solutions for Handling Materials

Transport

Conveyors, wheels on the ground

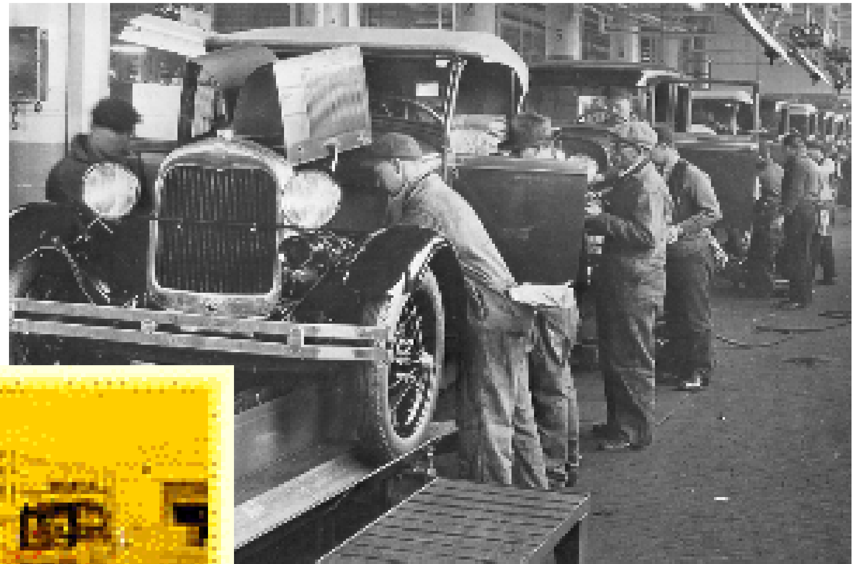
Major characteristics:
- Load / unload automation
- Accuracy, reliability
- Payload and robustness
- Interface
- Synchronization with exterior

Automatic Guided Vehicles (AGVs)

Major characteristics:
- Load/unload automation
- Accuracy, reliability
- Payload and robustness
- Interface
- Synchronization with exterior

Solutions for Handling Materials

Automatic Guided Vehicles (AGVs)



Example of fleet operating in industry

Solutions for Handling Materials

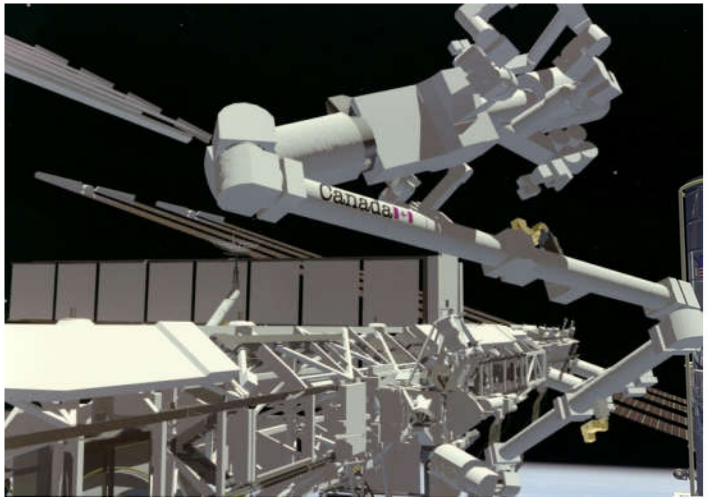
Automatic Guided Vehicles (AGVs)

Kiva Systems Inc
- warehouse automation
- used by Staples, Toys R Us, ...
- 2012 bought by *Amazon, $ 775 million*

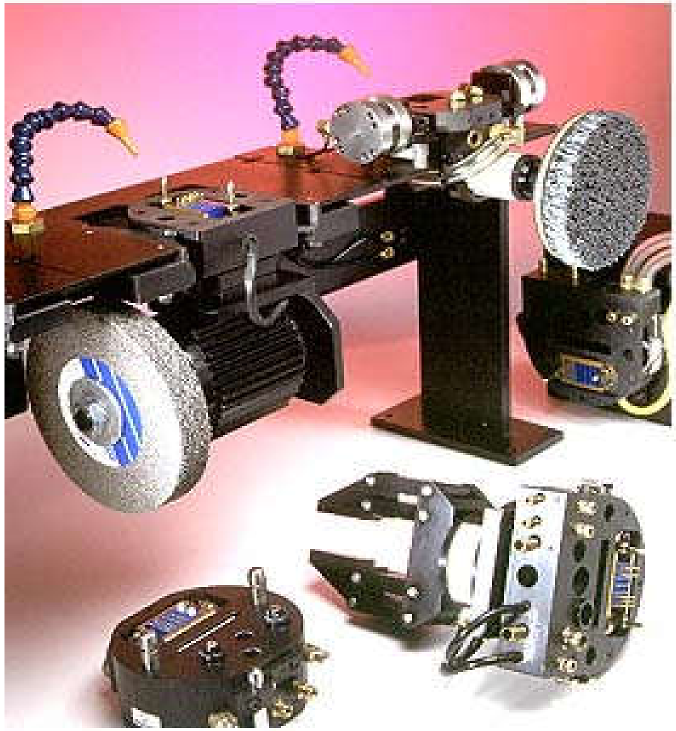
Solutions for Handling Materials

AGVs (Automatic Guided Vehicles) Kiva Systems Inc, warehouse automation

Solutions for Handling Materials
Robotic Manipulators



Robotic Manipulators - End Effectors

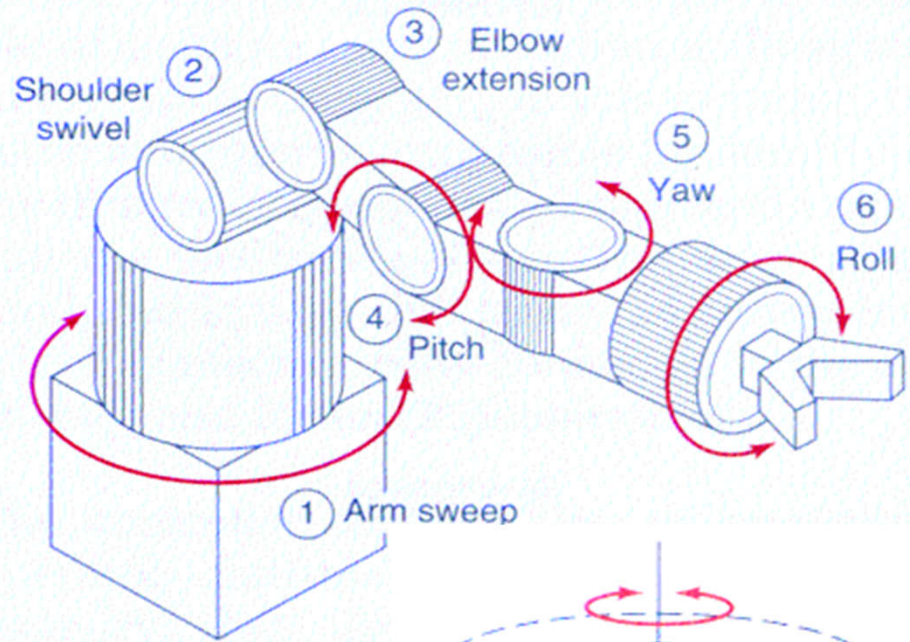





Robotic Manipulators

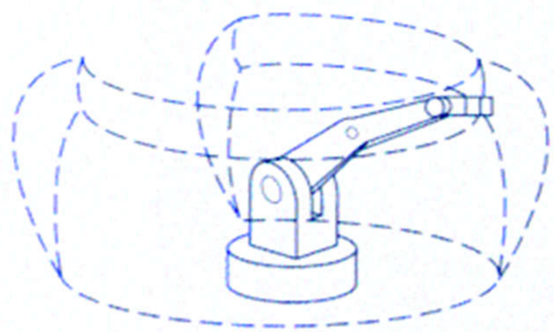
Major characteristics:

- Number of degrees of freedom
- Types of joints (prismatic/revolution)
- Programming tools and environments (high level languages, teach pendent, ...)
- Workspace
- Accuracy, reliability
- Payload and robustness

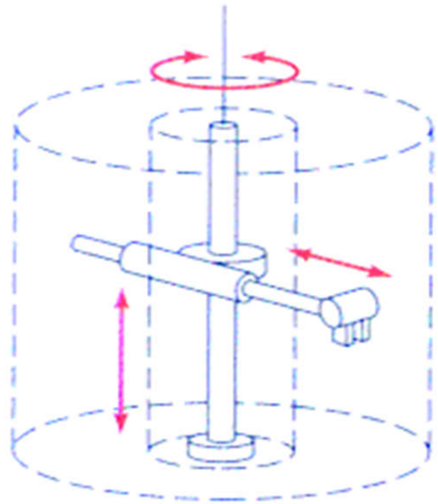


Workspace, examples:

- Spherical
- Cylindrical
- …



(b) Articulated



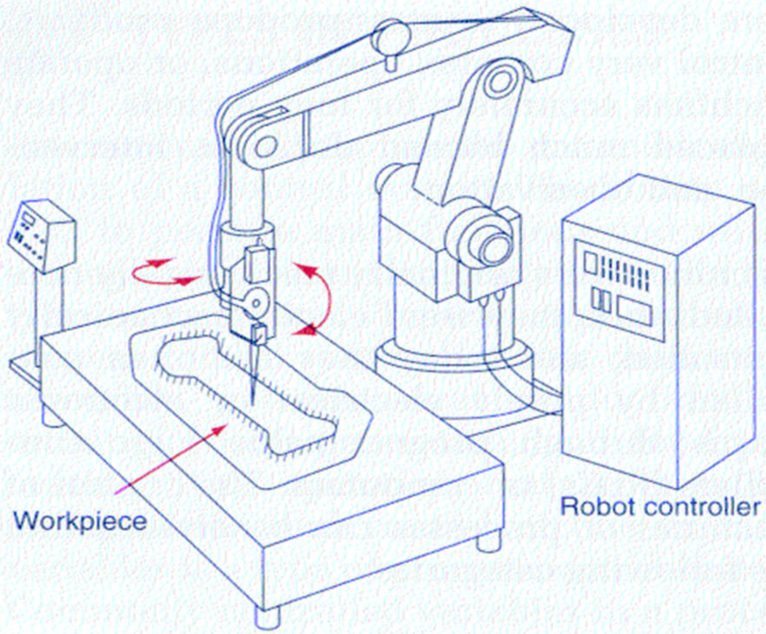
(a) Cylindrical

Fig. 15-23 Robot work envelope.

Robotic Manipulators

Central problems to address and solve:

- Direct / Inverse kinematics
- Trajectory generation / Trajectory following
- Coordinate frames where tasks are specified
- Level of abstraction of the programming languages



Industrial robot used in an individual item process

Fig. 14-3 Individual product production.

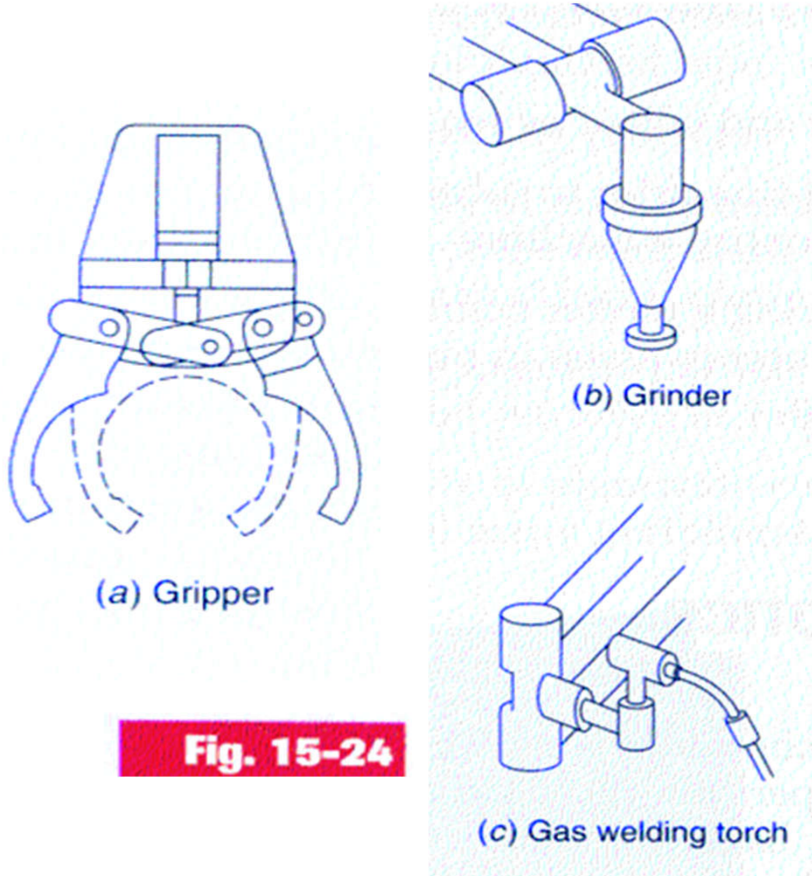


Fig. 15-24

Use in Flexible Cells of Fabrication:

it is required that the manipulators have correct interfaces for the **synchronization** and inputs for **external** commands.

Robotic Manipulators

Riding an ABB IRB 6600 Robot 1 [Youtube]

MAPI Note: please understand the power, ***and do not do this!*** *keep always the safety!*

Ch. 1 – Introduction to Automation

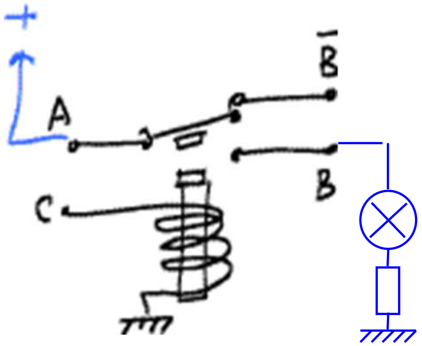
1.1 Introduction to **components** in industrial automation.

1.2 **Cabled** logic versus **programmed** logic versus **networked** logic.

1.3 Introduction to **methodologies** for problem modeling. Methodologies of work.

1.2 Cabled Logic

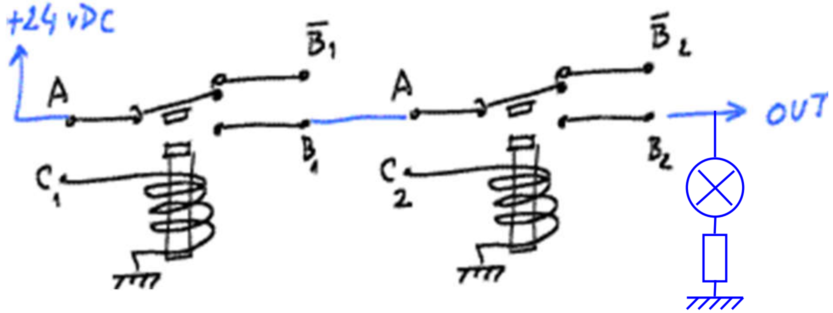
One ***relay***
NOT gate



$$B = C$$

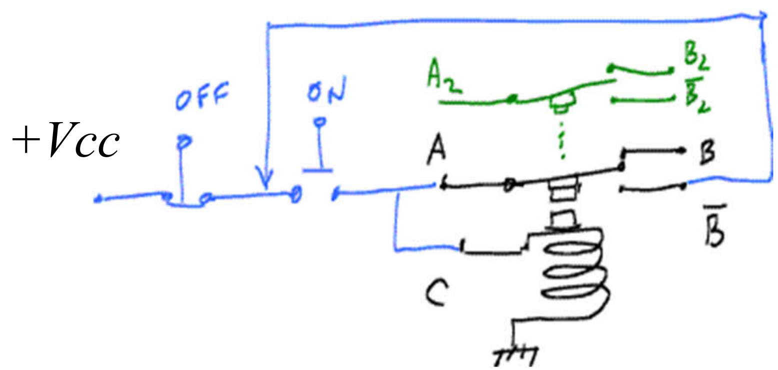
$$\overline{B} = \overline{C}$$

Two ***relays*** *making one AND gate*



$$B_2 = C_1 \wedge C_2$$

One relay ***Latch*** *circuit example*



Press once the ON button, and you can go away till you change your mind and press the OFF.

1.2 Cabled Logic versus ...

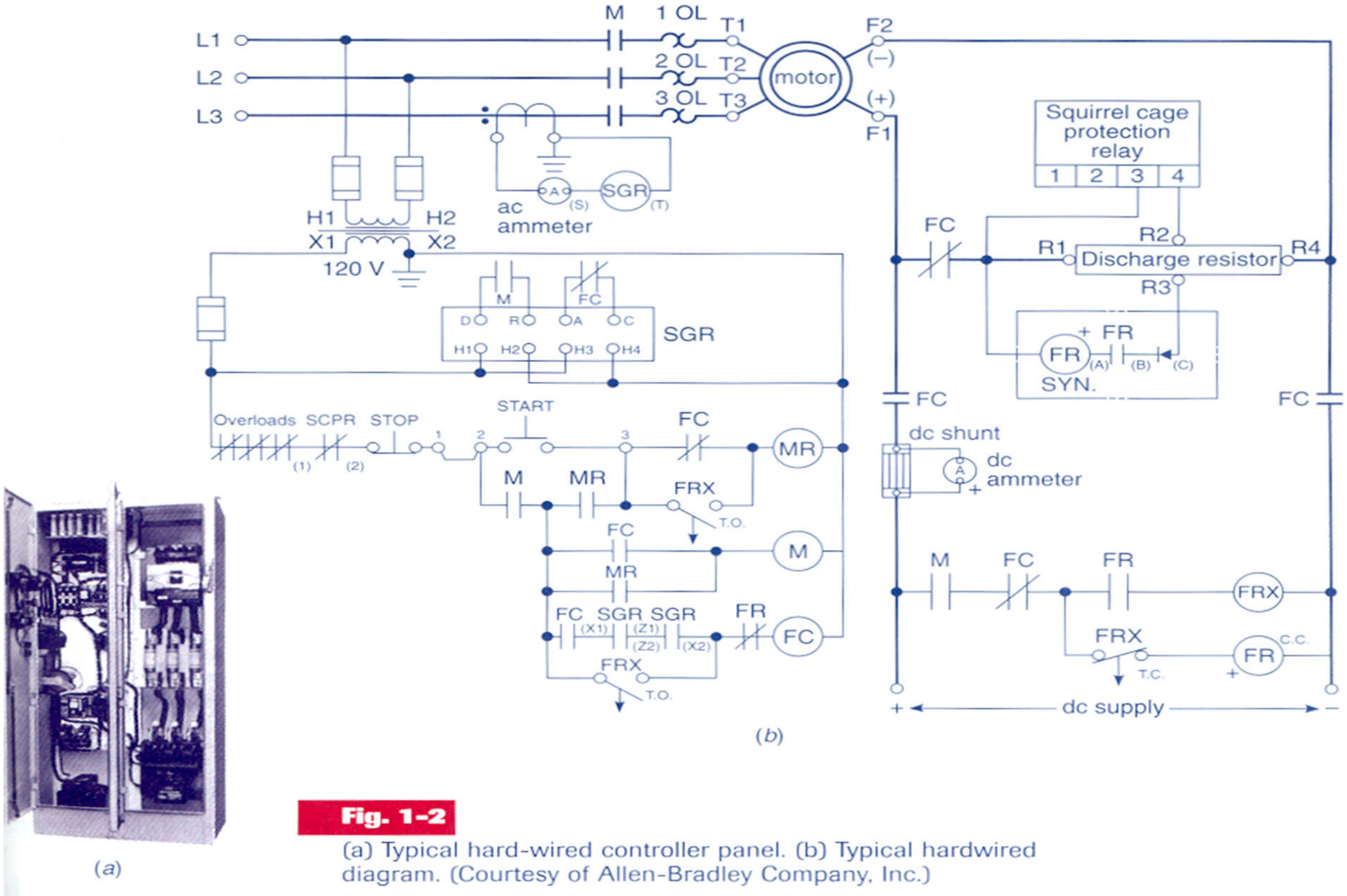
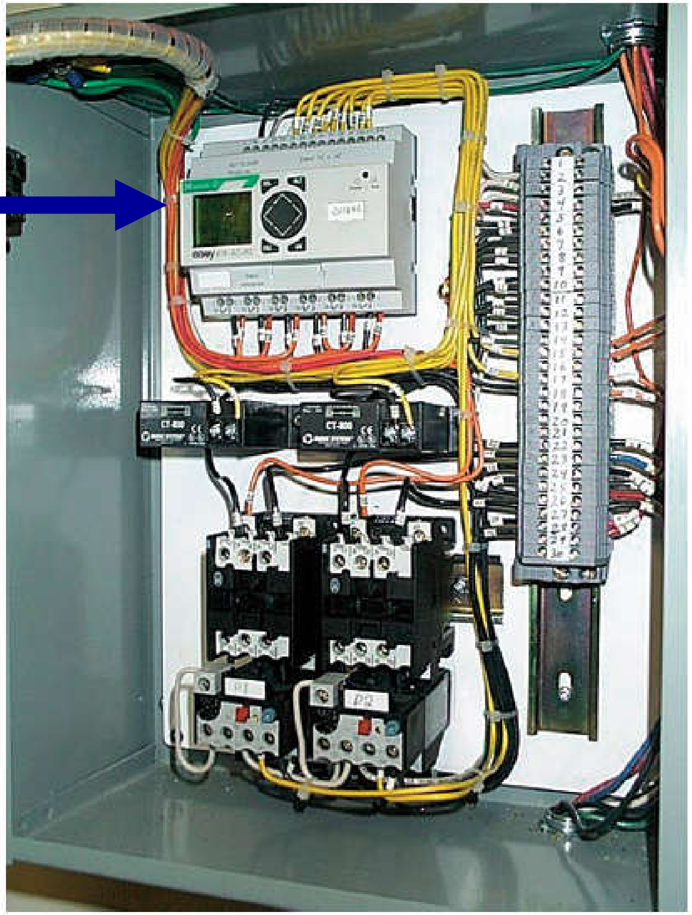


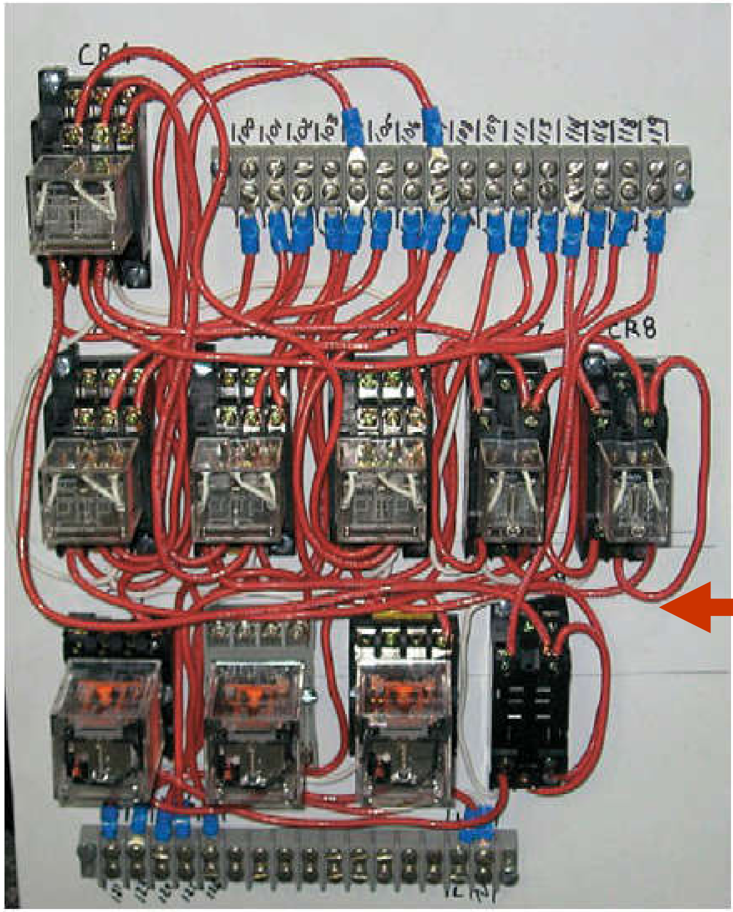
Fig. 1-2
(a) Typical hard-wired controller panel. (b) Typical hardwired diagram. (Courtesy of Allen-Bradley Company, Inc.)

Cabled Logic versus ...

... versus Programmed Logic …

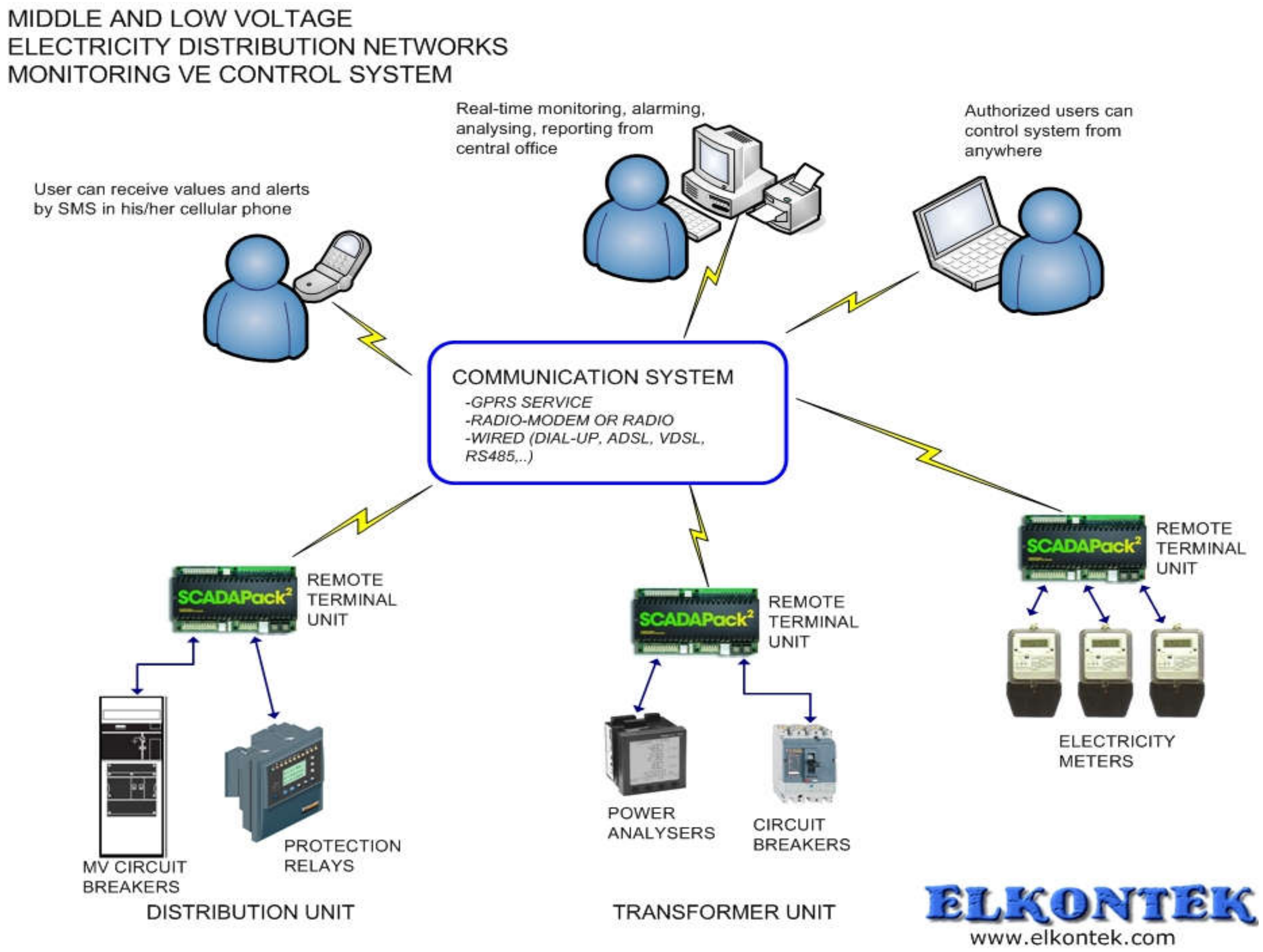


PLC control panel



Relay control panel

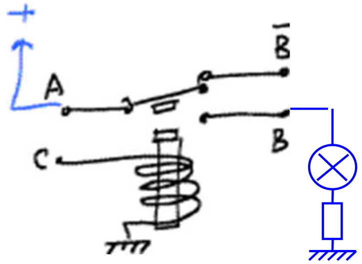
... versus Networked Logic



Hardware is getting common: Internet of Things (IoT) and Industrial Internet of Things (IIoT)

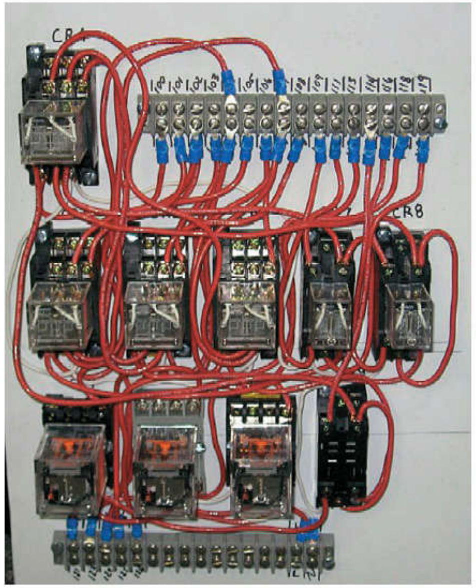
Cabled Logic

*One **relay** NOT gate*



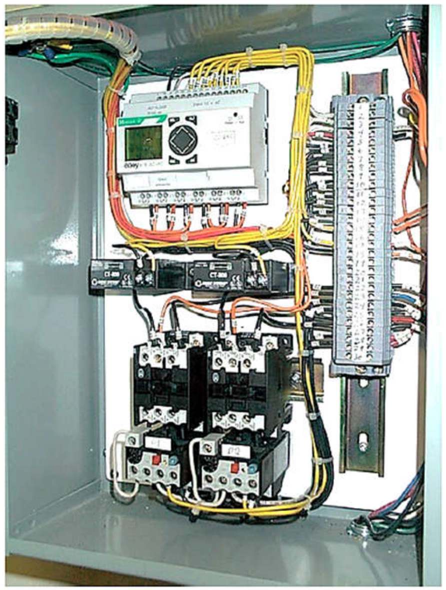
$B = C$

$\overline{B} = \overline{C}$



Relay control panel

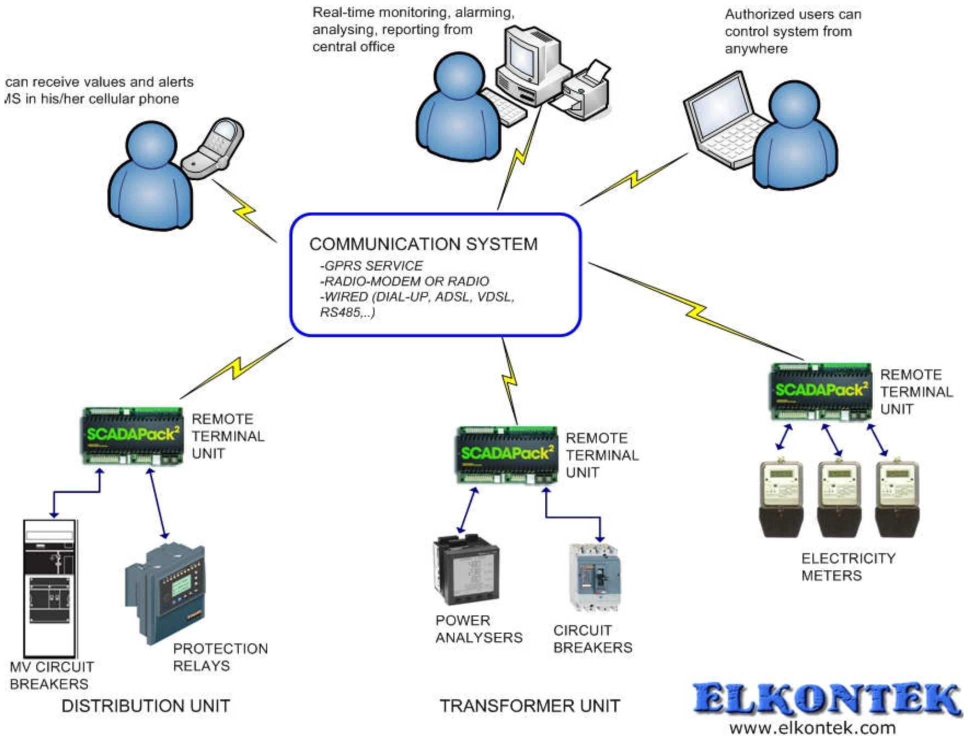
PLC control panel



Programmed Logic

*Rule of thumb: if using **more than 6 relays** then a **PLC** is already lesser expensive*

Networked Logic



Hardware is getting standard for:
- *Internet of Things* (IoT) and
- *Industrial Internet of Things* (IIoT)

Ch. 1 – Introduction to Automation [1 week]

1.1 Introduction to **components** in industrial automation.

1.2 Cabled logic versus **programmed logic** versus networked logic.

1.3 Introduction to **methodologies** for problem modeling.
Methodologies of work.

Relay or Ladder diagram, design methodology:

- identify the main hardware, **actuators & sensors**, to build the system
- break the system into **subsystems**; tune hardware selection
- **integrate** hardware, logic and sequencing, locally and globally.

Actuators

Motors
Solenoid valve
Command relay
Pneumatic cylinder / Electro pneumatic

Sensors

Pressure switch
Temperature sensors
Proximity sensors

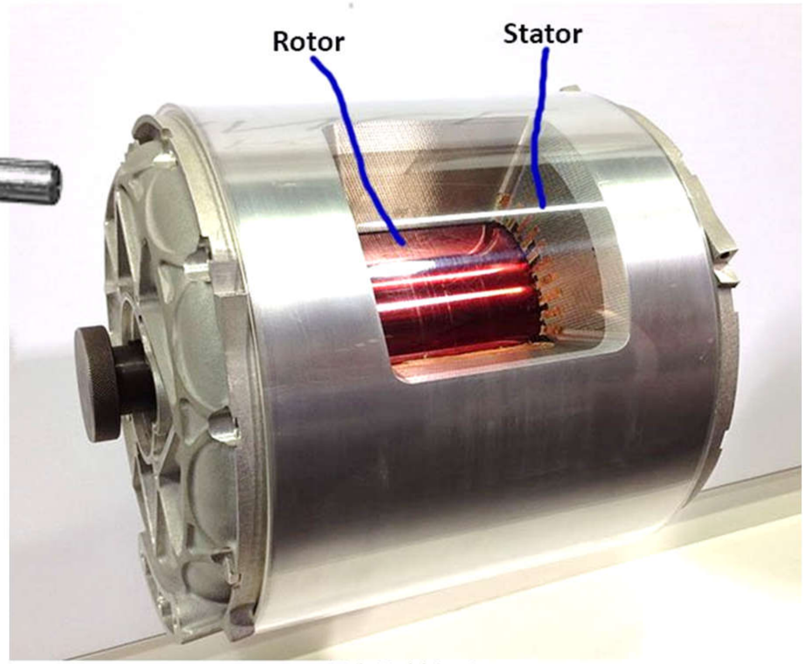
Ref: Programmable Logic Controllers, Frank D. Petruzella, McGraw-Hill, 1996.

Actuation

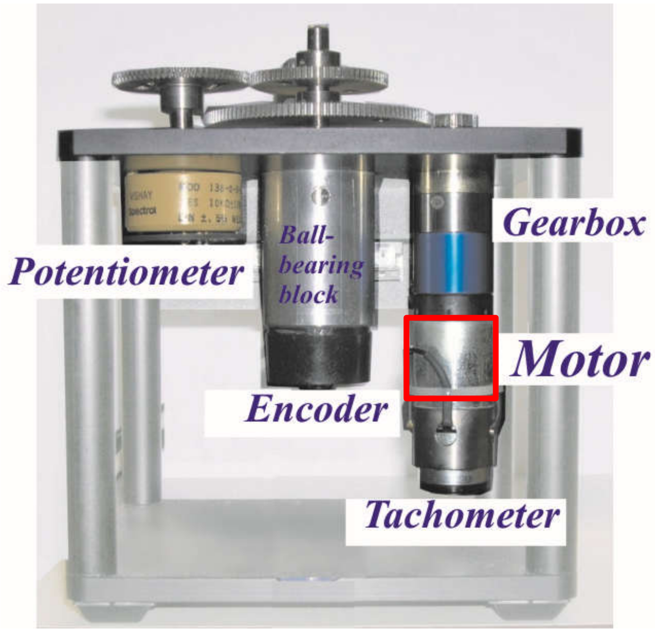
Motors

Major characteristics:

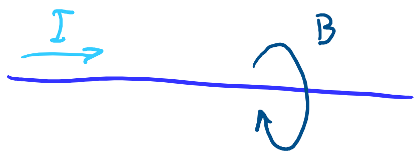
- Type of start
- Type of control
- Accuracy, reliability
- Payload and robustness
- Interface with exterior
- Synchronization



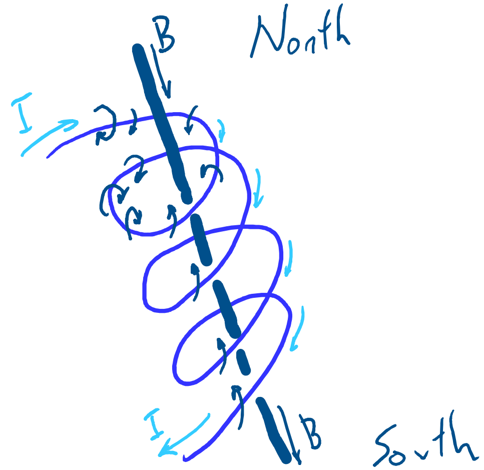
Tesla Model S motor



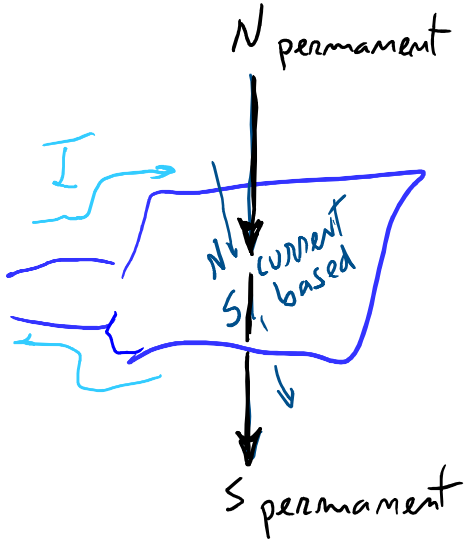
Current in a wire makes a magnetic field

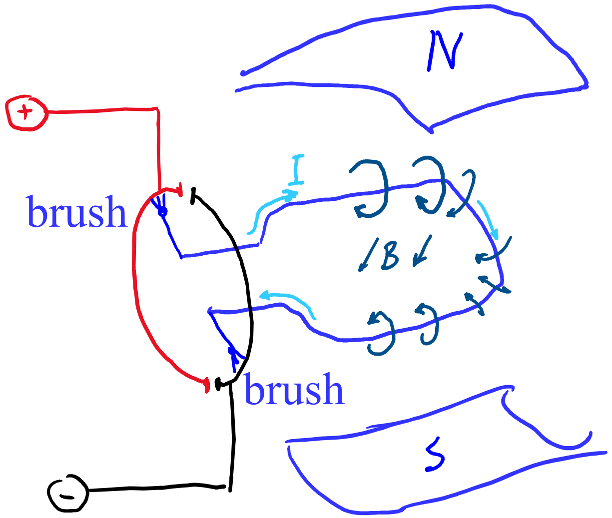


Current spinning around a core makes a larger magnetic field

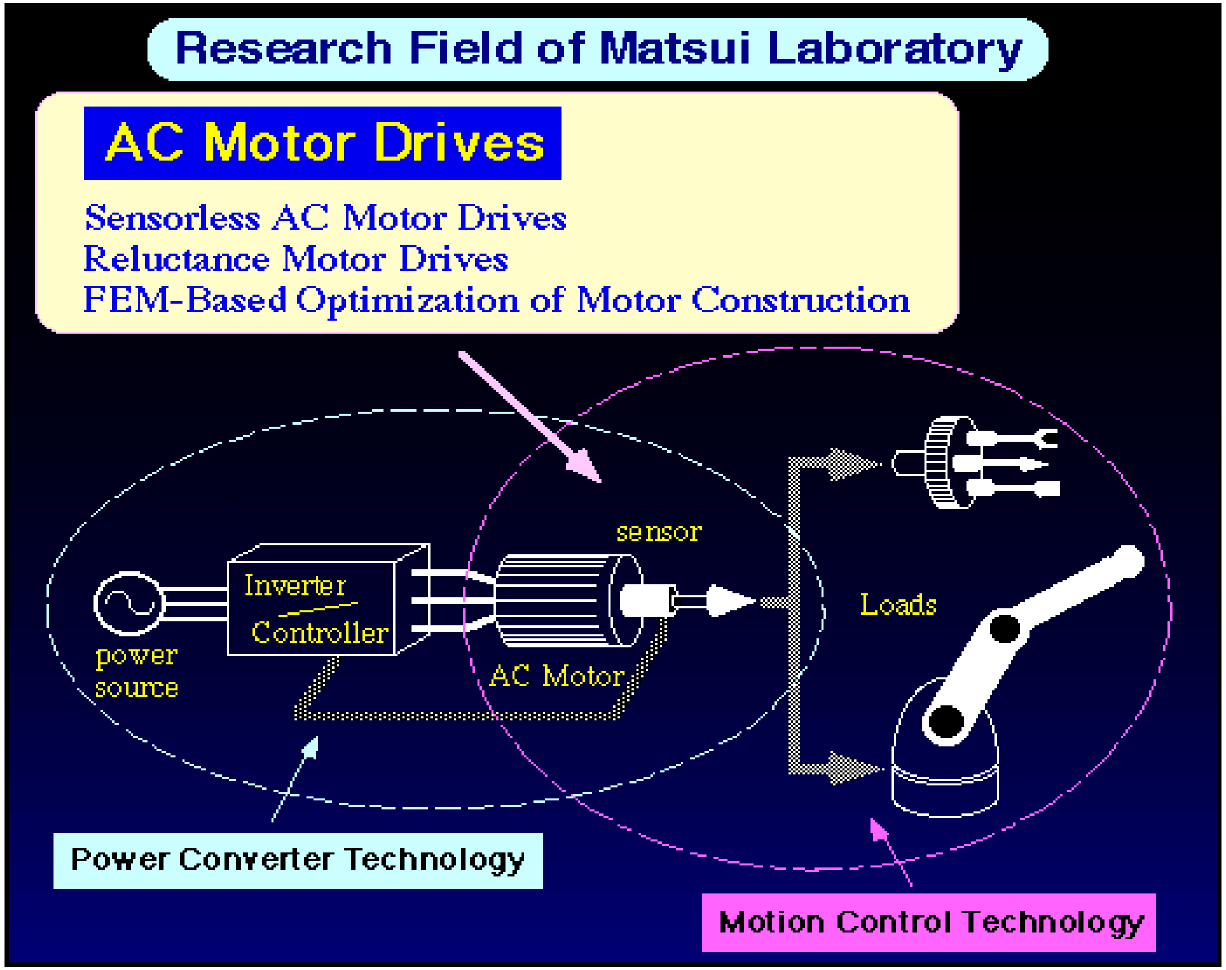


A permanent magnet motor works by almost always having mismatch current based B (rotor) vs magnets B (armature)





Example of AC motor, with driver



Solenoid Valve

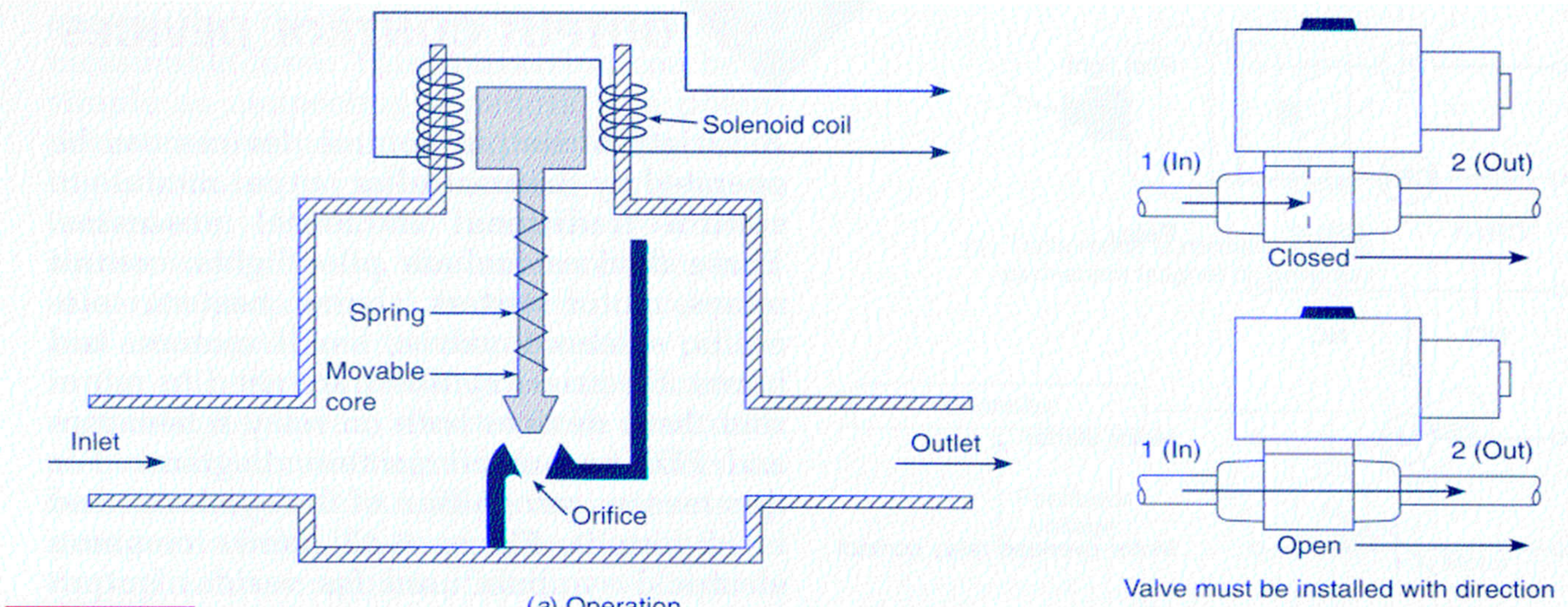


Fig. 6-45
Solenoid valve.

Command Relay

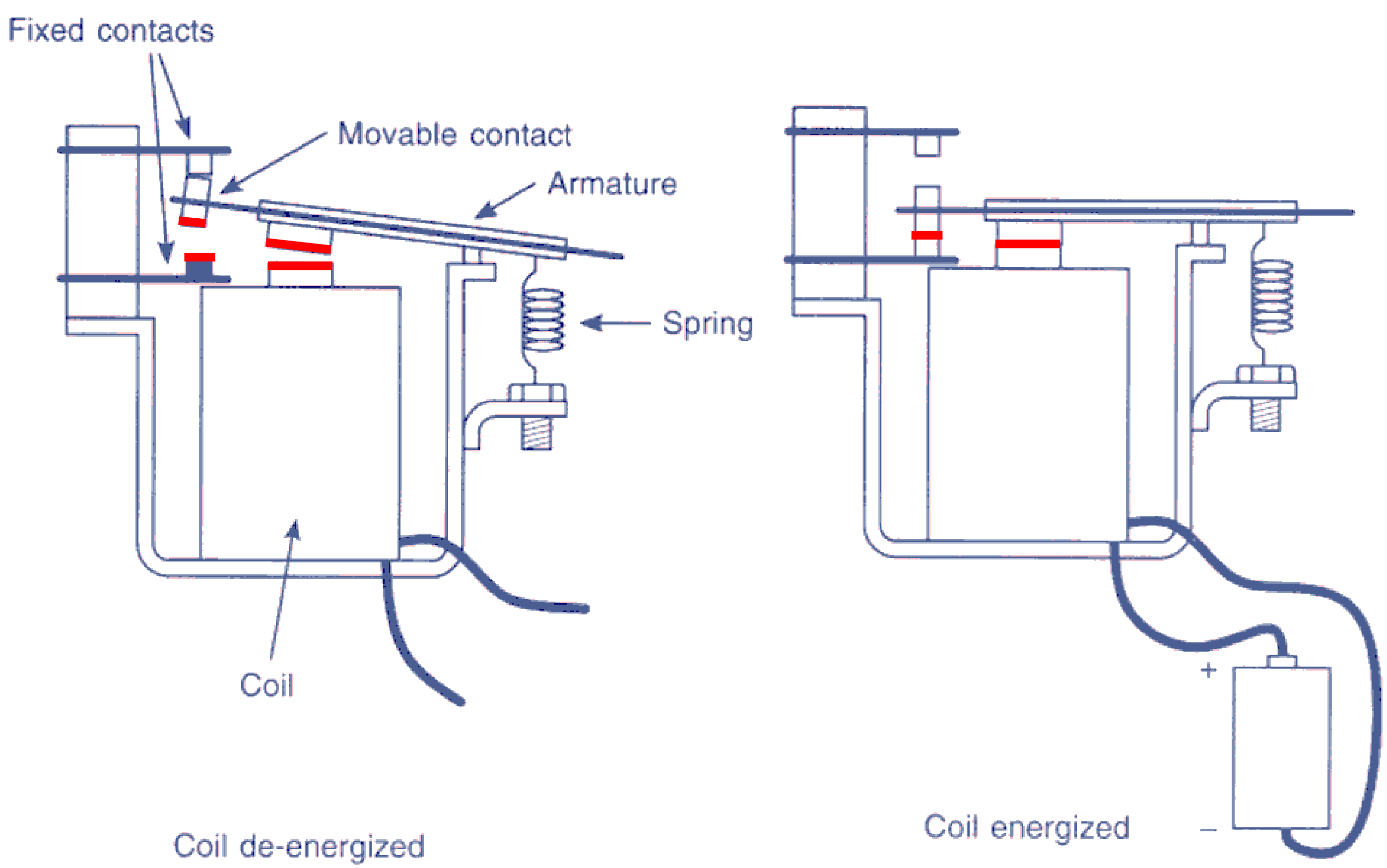
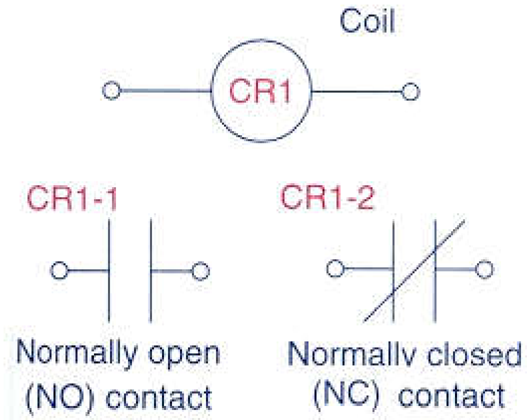
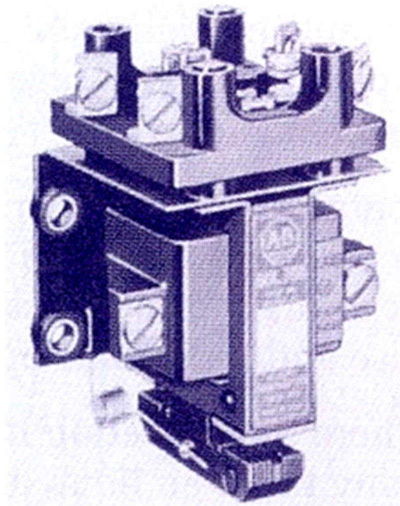


Fig. 6-1

Electromagnetic control relay operation.



(*a*) Control relay symbol

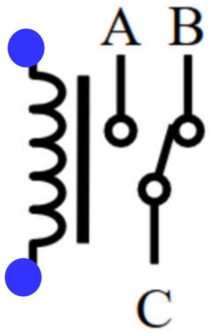


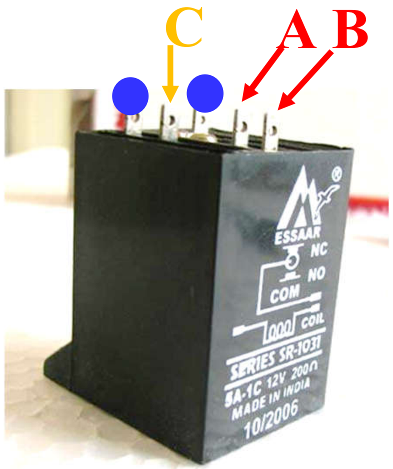
(*b*) Typical industrial control relay. *(Courtesy of Allen-Bradley Company, Inc.)*

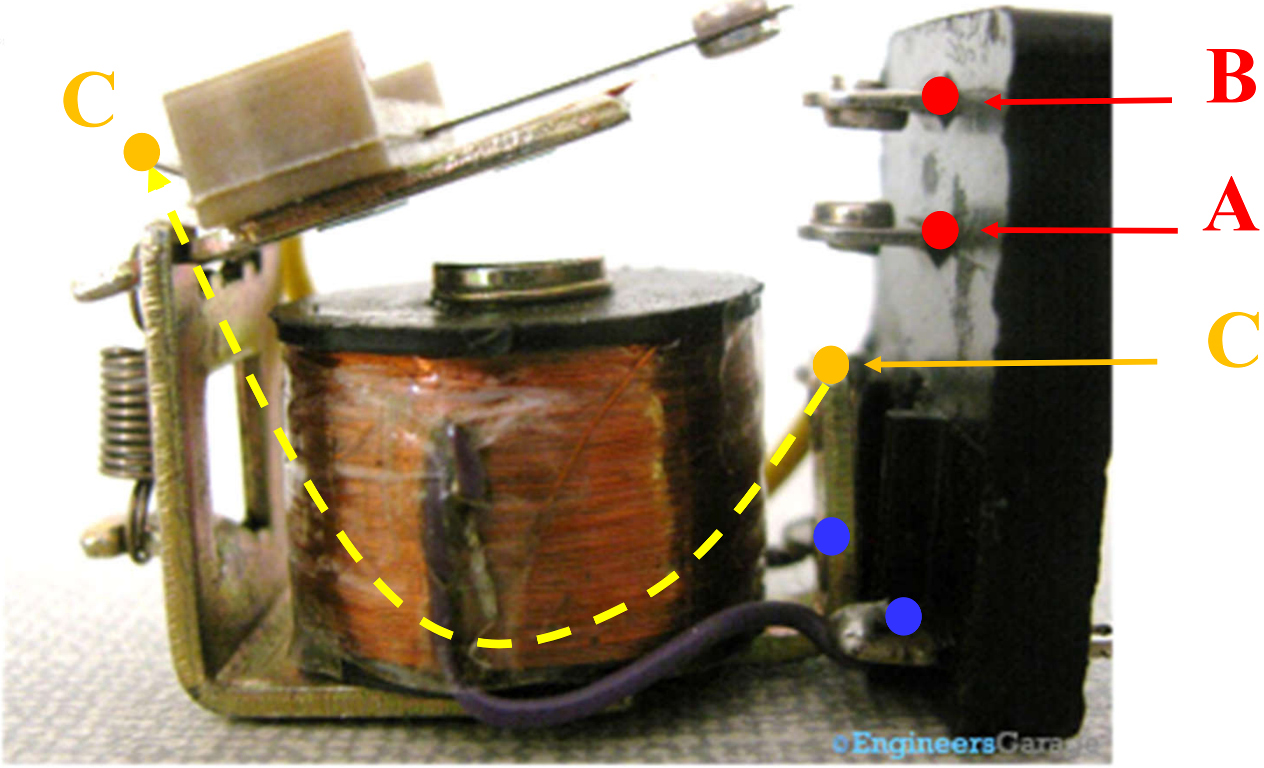
Fig. 6-2

Control relay.

Command Relay

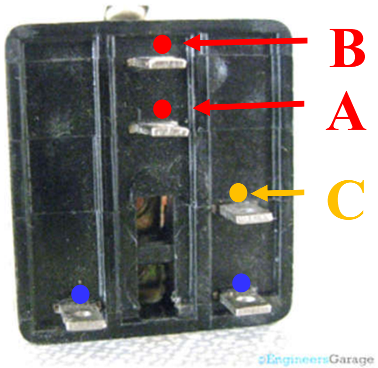


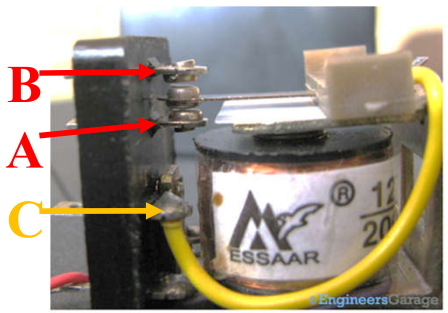




A *= NO = Normally Open*

B *= NC = Normally Closed*



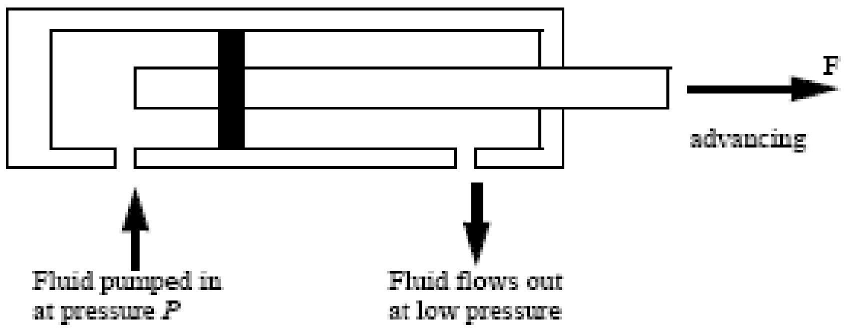


DC off

DC on

from: http://www.engineersgarage.com/insight/how-relay-switch-works

Cylinders (Pneumatics)



Force: $$P = \frac{F}{A} \qquad F = PA$$

where

P = the pressure of the hydraulic fluid

A = the area of the piston

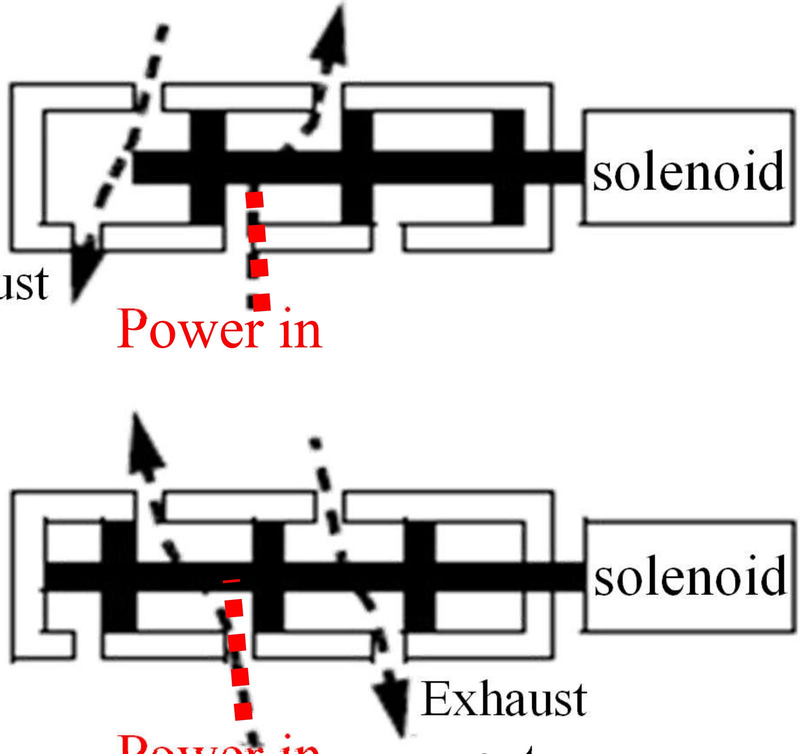
F = the force available from the piston rod

Air flow in or out

https://www.smctraining.com/en/webpage/indexpage/1108

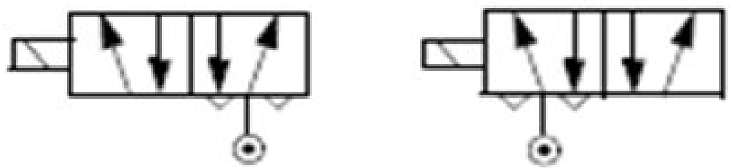
Solenoid Valves (Electrovalves, Electro-pneumatics)

The solenoid has 2 positions. Each position implies one direction of fluid flowing:

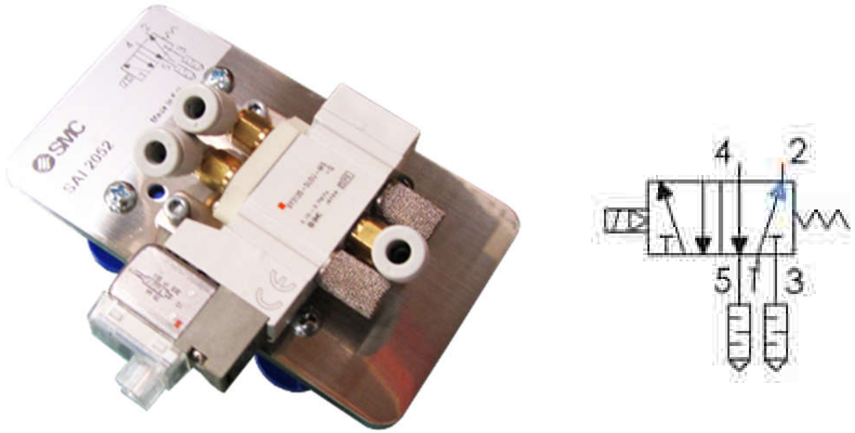


Two types: ON/OFF valves, Proportional Valves

Symbols commonly used to represent the two cases:



Example of a commercial valve:

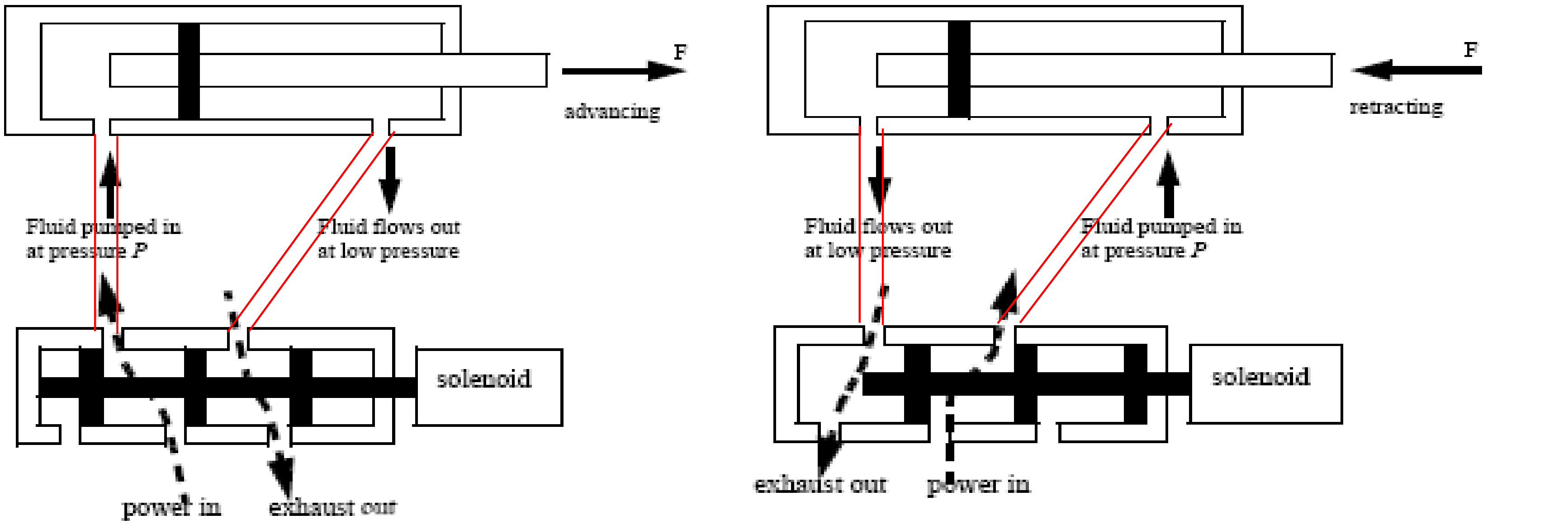


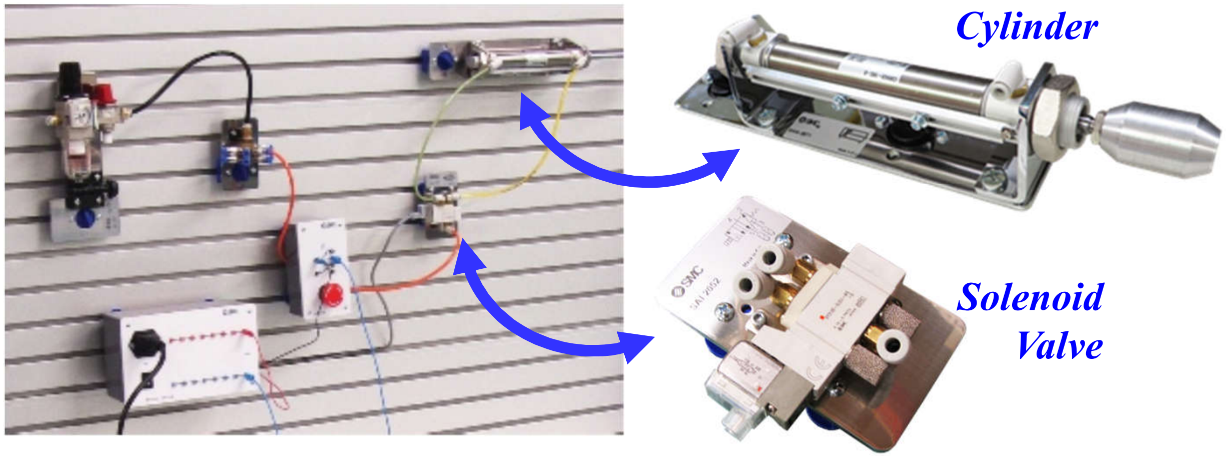
https://www.smctraining.com/en/webpage/indexpage/354

Solenoid Valves and Cylinders

Cylinder

Solenoid Valve



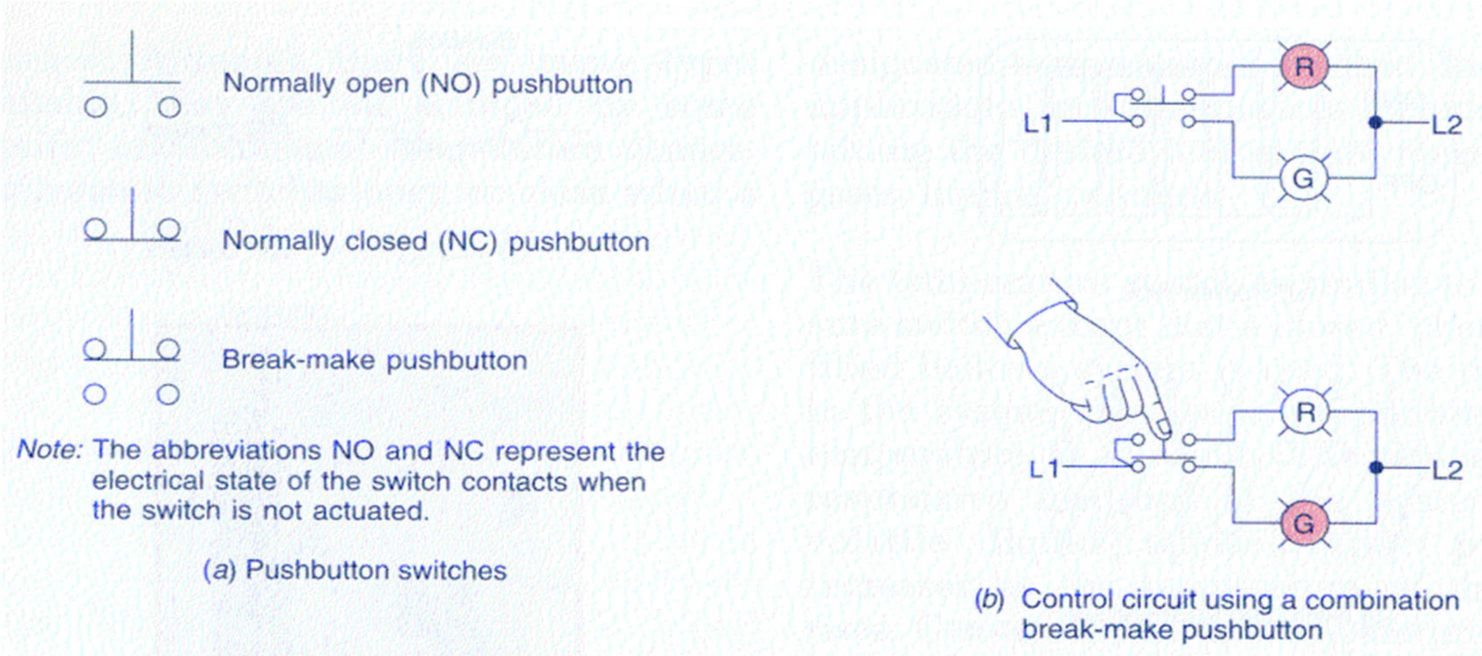


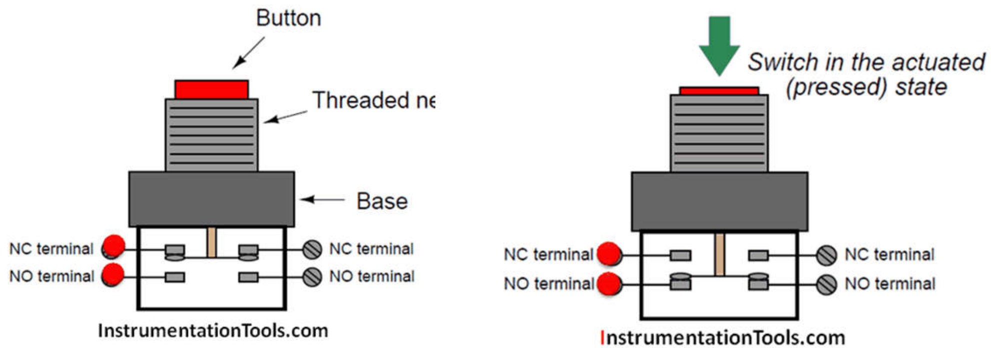
https://www.smctraining.com/webpage/indexpage/341/

Note about the most flexible systems:
- Proportional pneumatics (proportional valve),
- Servo-pneumatics (e.g. feedback of the position of the piston).

Sensors

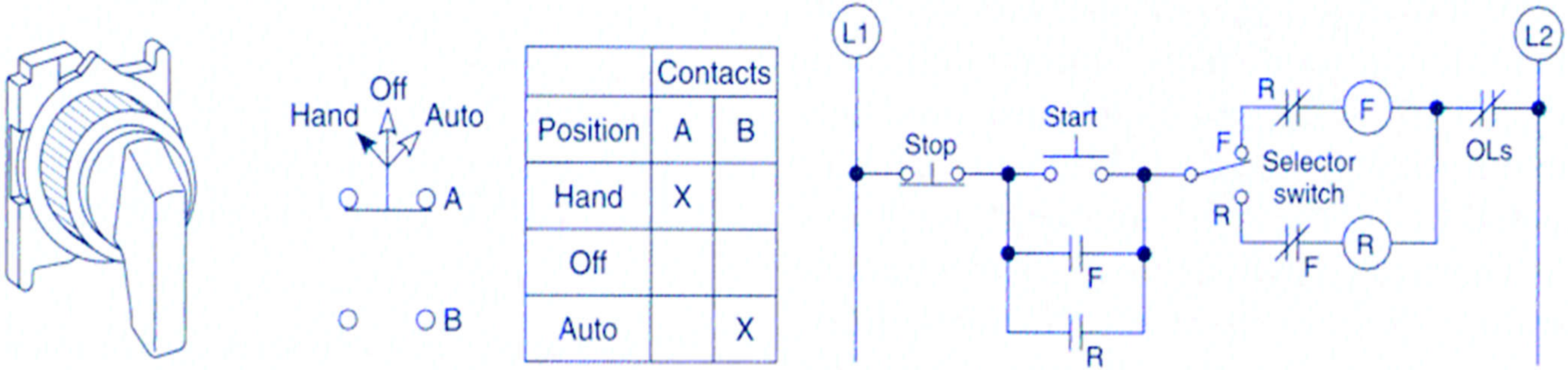
Push buttons





Break-make pushbutton

Selector with three positions



	Contacts	
Position	A	B
Hand	X	
Off		
Auto		X

(*a*) Selector switch operator

(*b*) Three-position selector switch and truth table

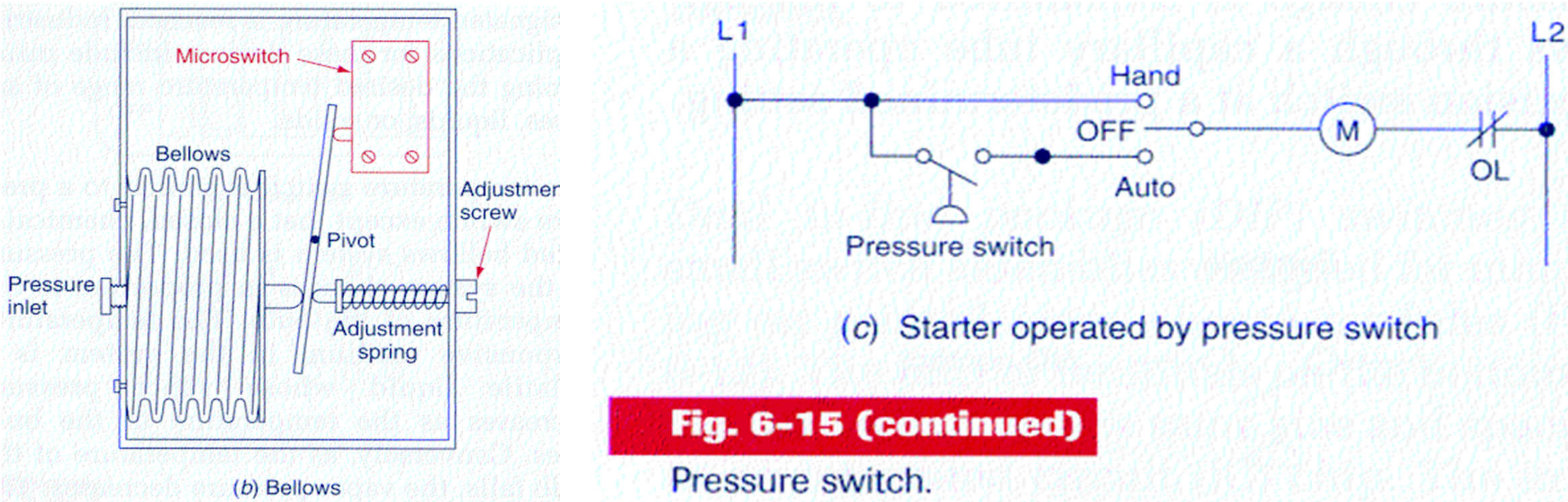
(*c*) Selector switch used in conjunction with a reversing motor starter to select forward or reverse operation of the motor

Fig. 6-11

Selector switch.

Sensors

Pressure Switch



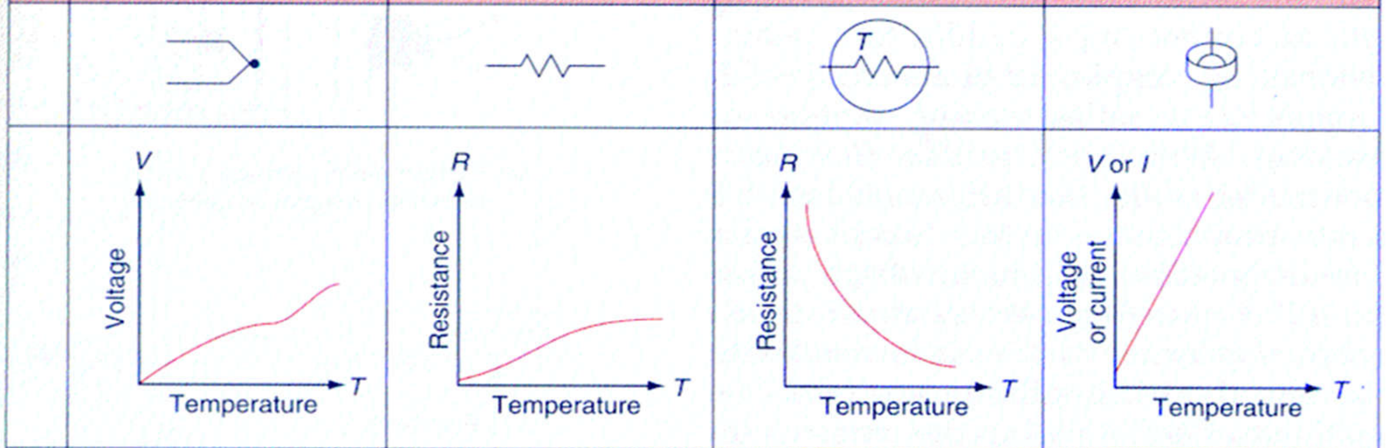
(c) Starter operated by pressure switch

Fig. 6-15 (continued)

Pressure switch.

Temperature

Sensors



	Thermocouple	RTD	Thermistor	IC Sensor
Advantages	• Self-powered • Simple • Rugged • Inexpensive • Wide variety • Wide temperature range	• Most stable • Most accurate • More linear than thermocouple	• High output • Fast • Two-wire ohms measurement	• Most linear • Highest output • Inexpensive
Disadvantages	• Nonlinear • Low voltage • Reference required • Least stable • Least sensitive	• Expensive • Power supply required • Small ΔR • Low absolute resistance • Self-heating	• Nonlinear • Limited temperature range • Fragile • Power supply required • Self-heating	• $T < 200°C$ • Power supply required • Slow • Self-heating • Limited configurations

Fig. 6-38
Common temperature sensors.

RTD = Resistance Temperature Detector
IC = Integrated Circuit

Thermocouple

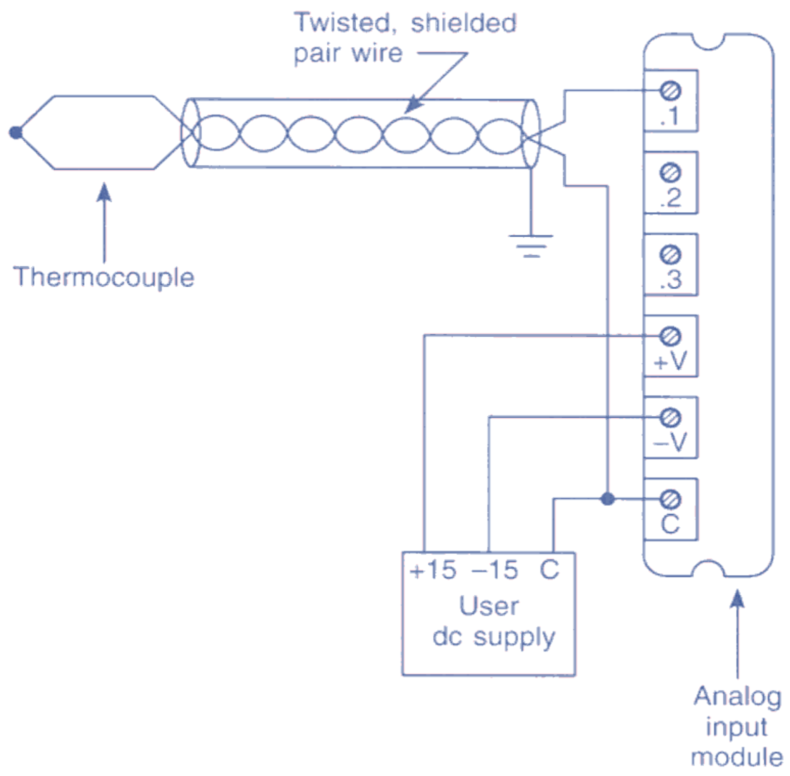


Fig. 2-12
Typical thermocouple connection to an analog input module.

Proximity detector

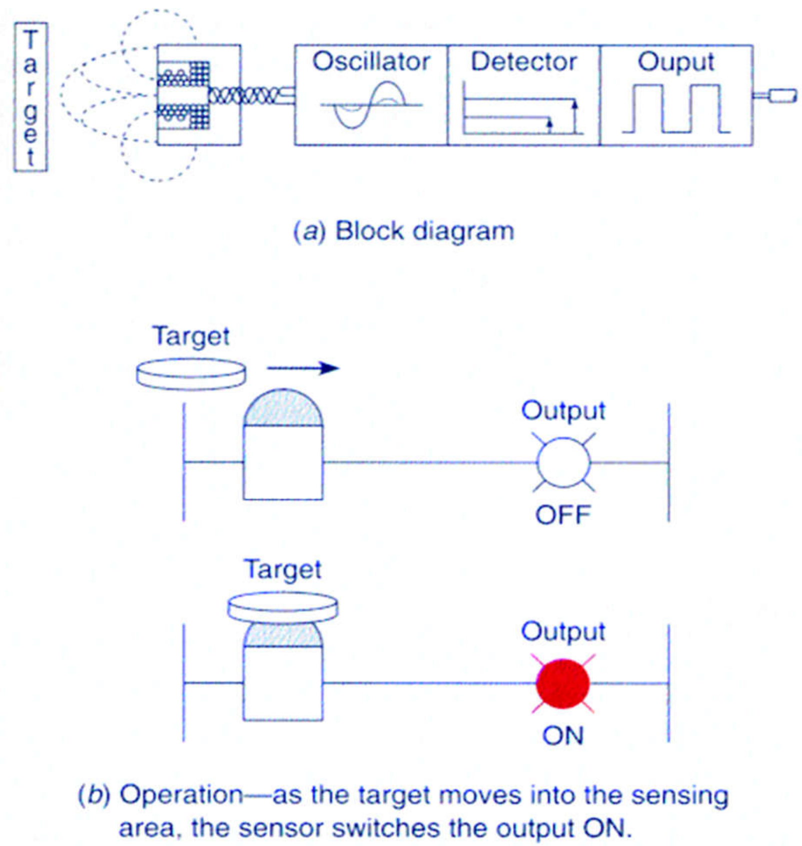


Fig. 6-20
Inductive proximity sensor.

Magnetic detector

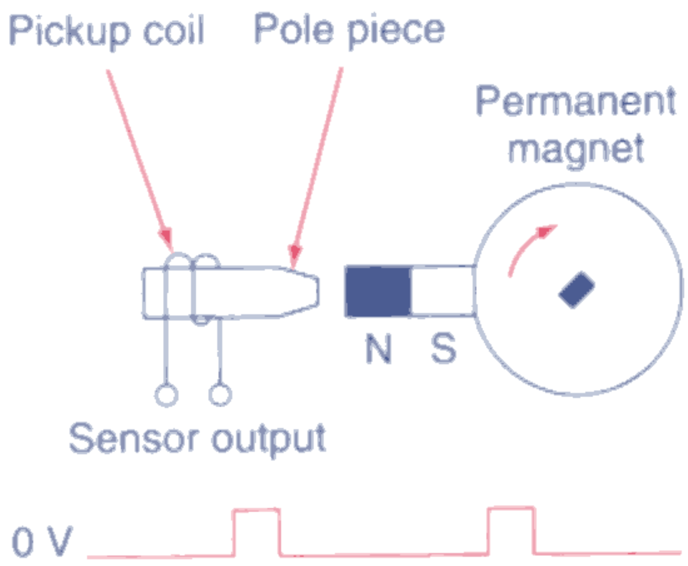


Fig. 6-42
Magnetic pickup sensor.

Magnetic switch

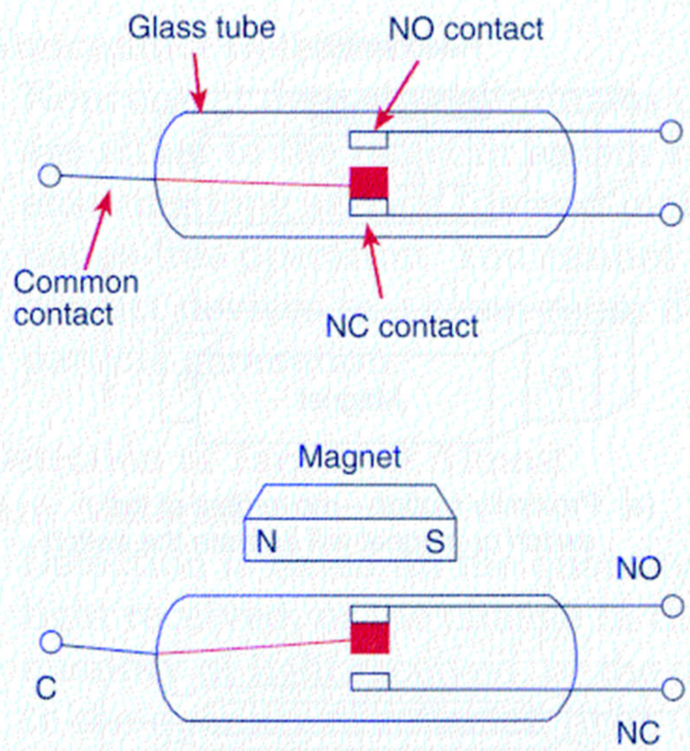


Fig. 6-25
Magnetic switch (reed switch).

Symbols associated to all components

Standards - Joint International Committee (JIC) Wiring Symbols

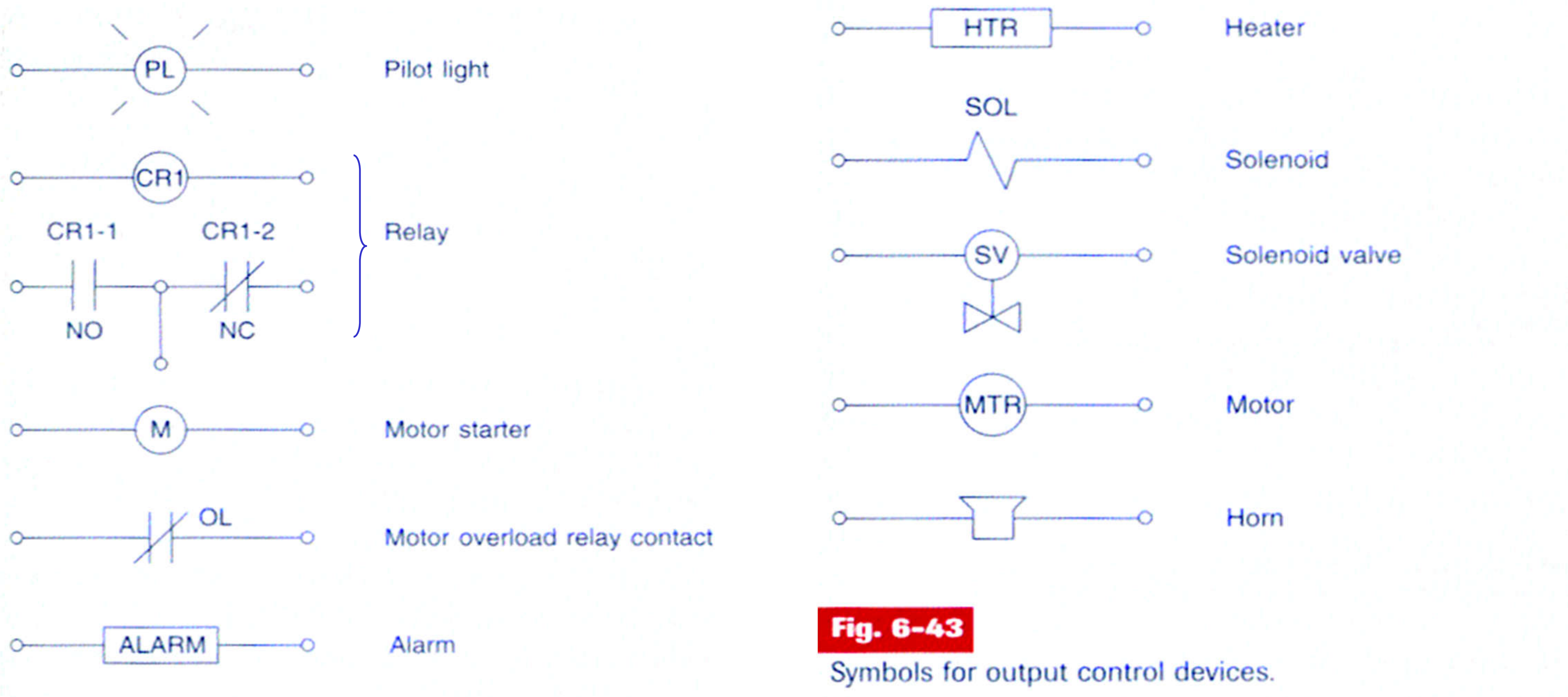
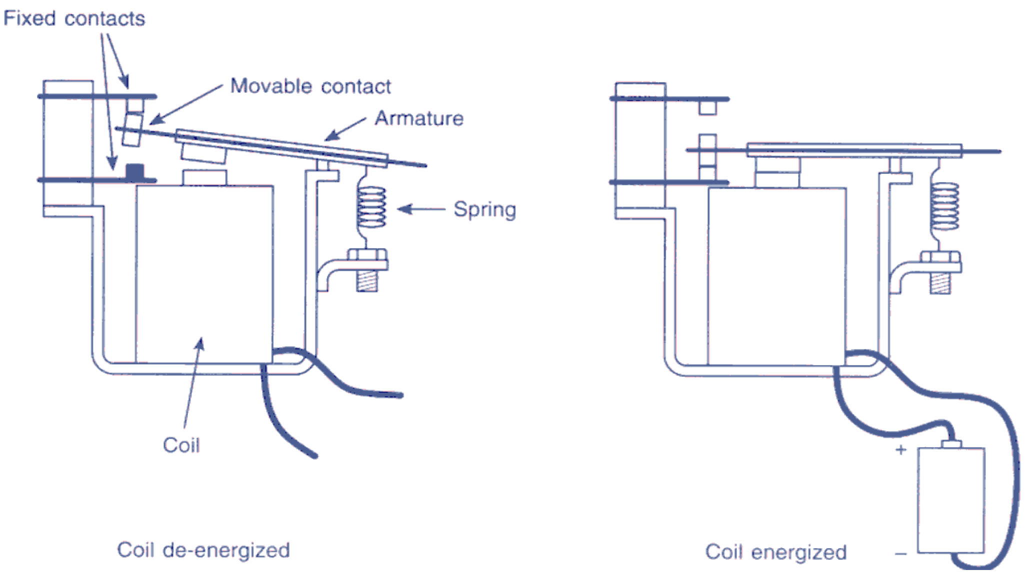


Fig. 6-43
Symbols for output control devices.

Methodologies for the implementation of solutions in industrial automation

Device: Relay



Contact Diagram or *Ladder Diagram*

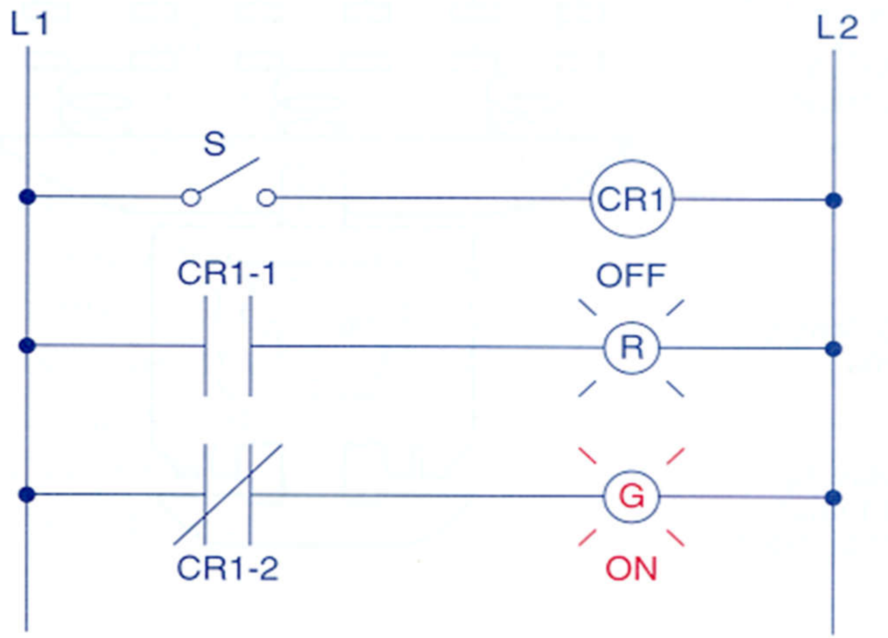


Fig. 6-3
Relay circuit—switch open.

Example of relay and ladder diagrams:

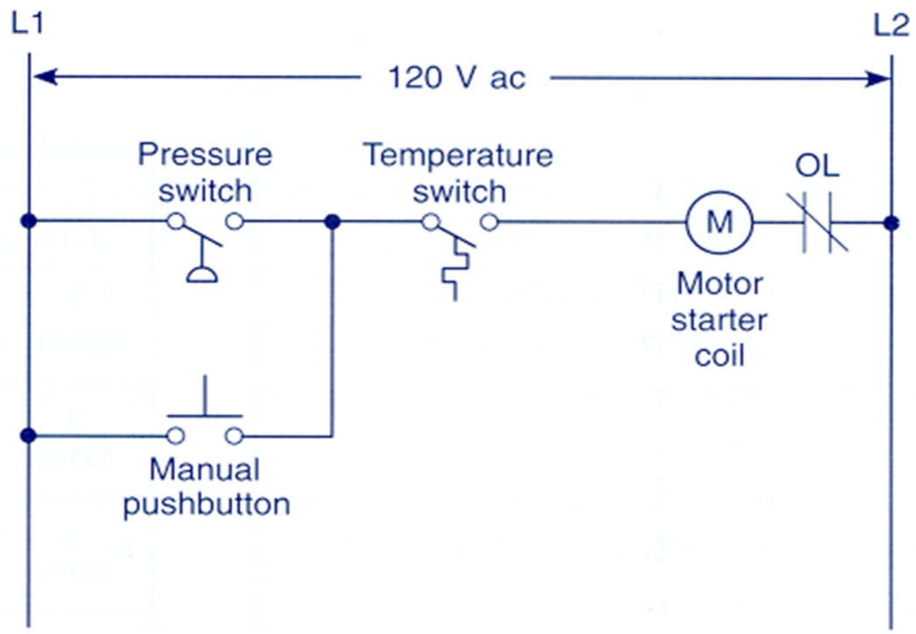


Fig. 1-13
Relay ladder diagram for modified process.

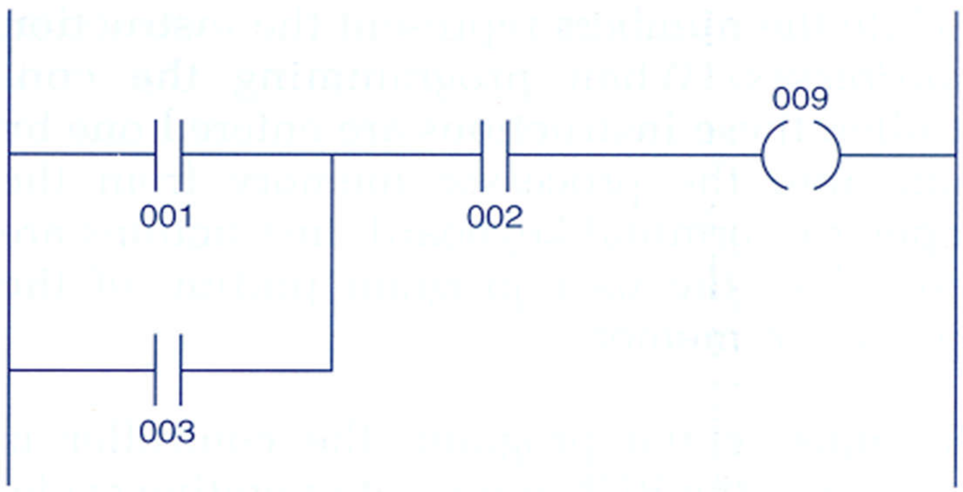
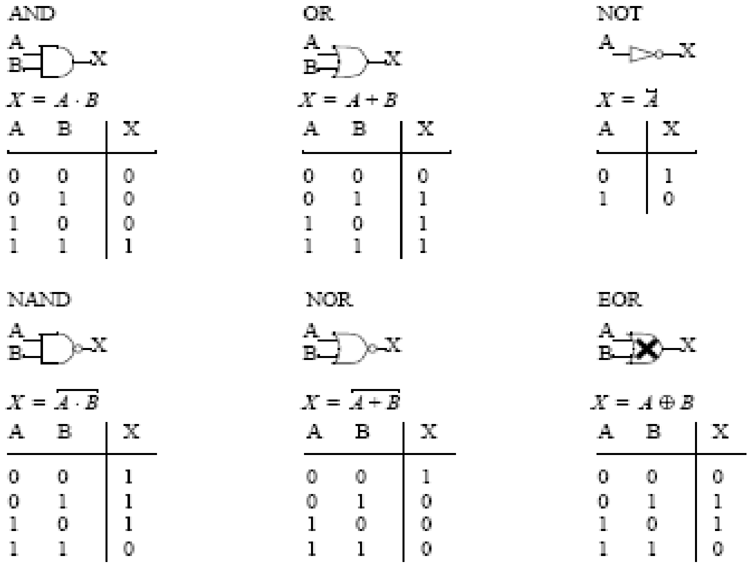


Fig. 1-14
PLC ladder logic diagram for modified process.

Logic Functions



AND: $X = A \cdot B$

A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

OR: $X = A + B$

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

NOT: $X = \overline{A}$

A	X
0	1
1	0

NAND: $X = \overline{A \cdot B}$

A	B	X
0	0	1
0	1	1
1	0	1
1	1	0

NOR: $X = \overline{A + B}$

A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

EOR: $X = A \oplus B$

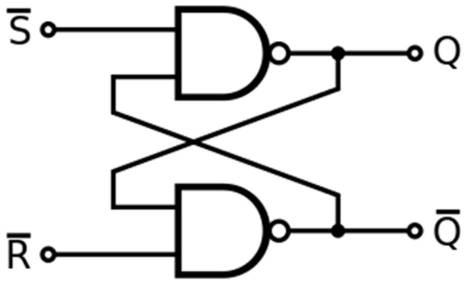
A	B	X
0	0	0
0	1	1
1	0	1
1	1	0

All logic functions

Y= f(A,B,C, …)

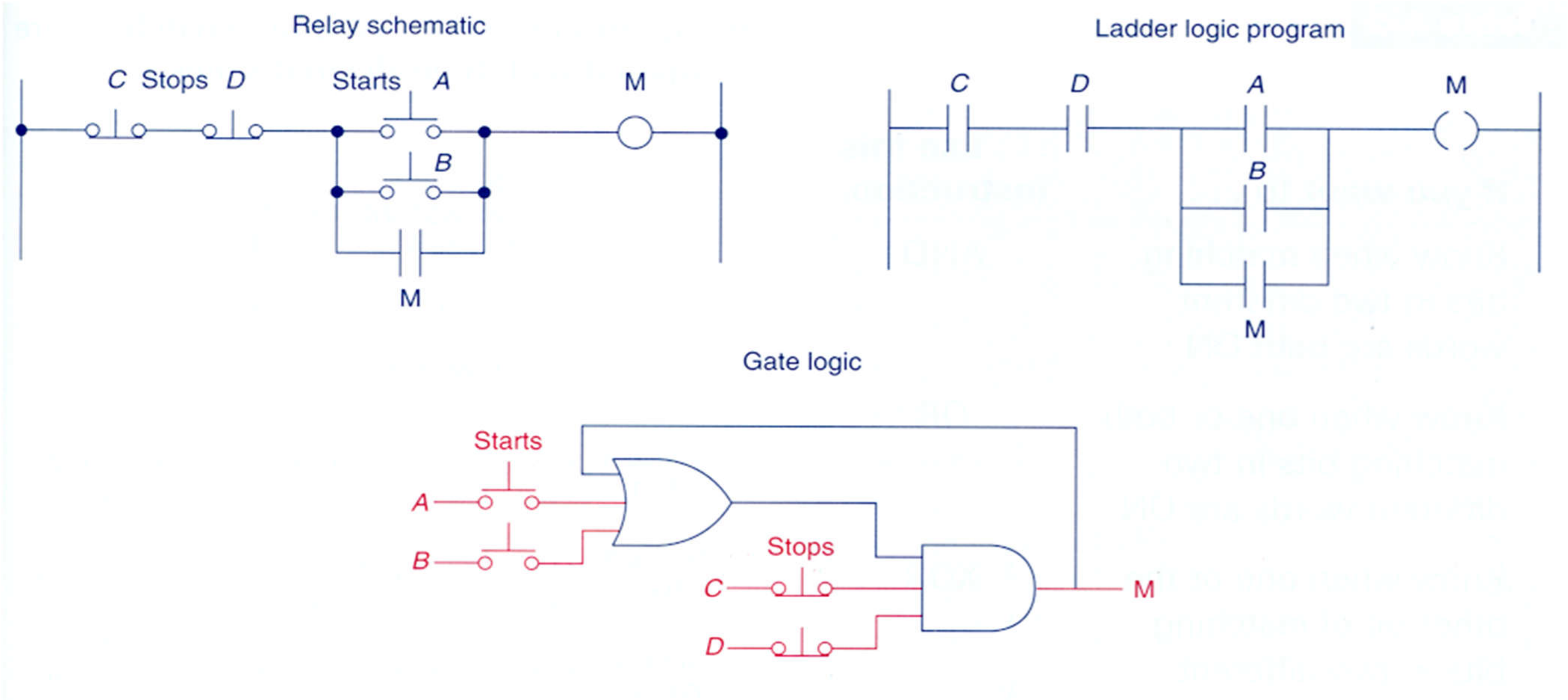
can be written as a ***sum of products***, where *sum* denotes the logic OR and product denotes logic ANDs of the variables or negated variables.

NAND Latch



The latch is a simple dynamic system, in the sense that it has **memory** (note that memory is not present in a logic function).

Example of relay and ladder diagrams, and gate logic:

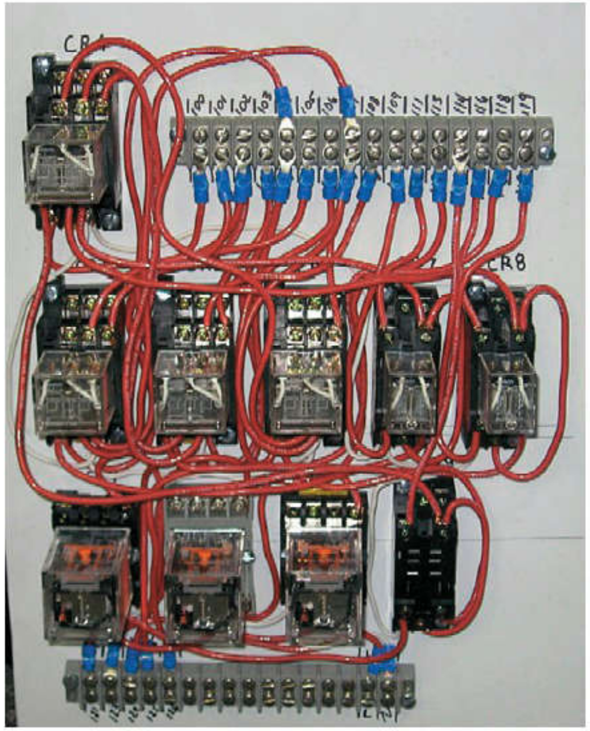


Example 4-9

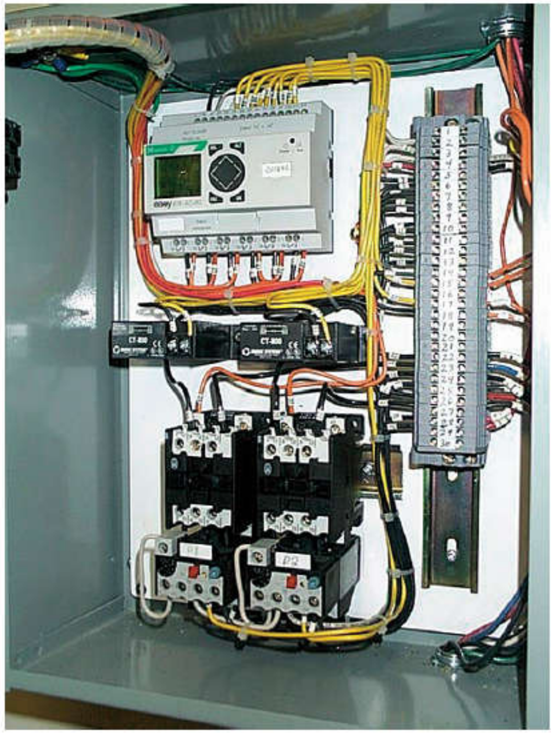
A motor control circuit with two stop buttons. When the start button is depressed, the motor runs. By sealing, it continues to run when the start button is released. The stop buttons stop the motor when they are depressed.

The world is always moving forward: Exploit the advantages of Programmed Logic!

Relay control panel



PLC control panel



Rule of thumb: if using more than 6 relays then a PLC is already lesser expensive