

**RYERSON  
UNIVERSITY**

**Department of Mechanical & Industrial Engineering  
Faculty of Engineering & Architectural Science**

**MEC617  
Manufacturing System  
Control  
Course Workbook – Fall 2016  
Pneumatics Material**

**By:  
Prof F. Stewart  
Office: EPH320  
Email: [fstewart@ryerson.ca](mailto:fstewart@ryerson.ca)**

**With notes from:  
Dr. V. Chan**

## **Introductory Note**

The material contained in this workbook is drawn from many sources and is intended as an inexpensive aid for the manufacturing automation course – MEC617 Introduction to Controls.

The major topics are addressed in the various sections but, by no means, can these notes be considered to provide an exhaustive coverage of each topic. These notes are skeletal and will be used as a starting point within the course lectures. Students are encouraged to take additional notes during lecture periods to provide themselves with a more complete coverage of the various topics.

A design approach is followed in this course with:

- (i) The requirements for a control system are presented as a specification.
- (ii) The circuit is designed and documented in pneumatic/hydraulic schematic diagrams and/or programmable logic controller software.
- (iii) In the course laboratories designed and documented circuits will be constructed and their operation verified.

## Fluid Power System

The function of a basic fluid power system is to provide output motion which can be either **linear** [i.e. a cylinder] or **rotary** [ i.e. a motor]. Depending on what the output device is connected to the circuit will complete a required function. For example, if a cylinder is connected to the bucket of an earth moving vehicle, extension of the cylinder would rotate the bucket to collect debris while retraction of the cylinder would allow the bucket to be emptied.

The fluid to be used in the system can be oil (hydraulic), air (pneumatic) or gaseous. Generally hydraulic oil is used when you require power multiplication capability – as in the case of the earth mover – but it can be messy. If you only need to automate a repetitive action, without high pressure or force requirements, then a pneumatic (air) system will be a cleaner option. Note that air cannot be used in high pressure systems due to its compressibility factor which could create a safety hazard.

A fluid power system requires some basic components to function. These components are illustrated in the simple hydraulic fluid power system, for an earth mover bucket, illustrated on the following page and are described below:

### **Component A: - Output Device**

Double Acting Cylinder for Linear Motion

### **Component B: - Input Device**

A Pump driven by a motor. There are many types of pumps that can be used depending on the system pressure requirements, volumetric delivery flow rates, etc. Pumps such as Vane pumps, Piston pumps (single stage, double stage), Gear pumps and many more. In a pneumatic system this is called a Compressor.

### **Component C: - Hydraulic Reservoir**

This is only needed in a hydraulic system. In an air system the exhaust is simple vented to the atmosphere.

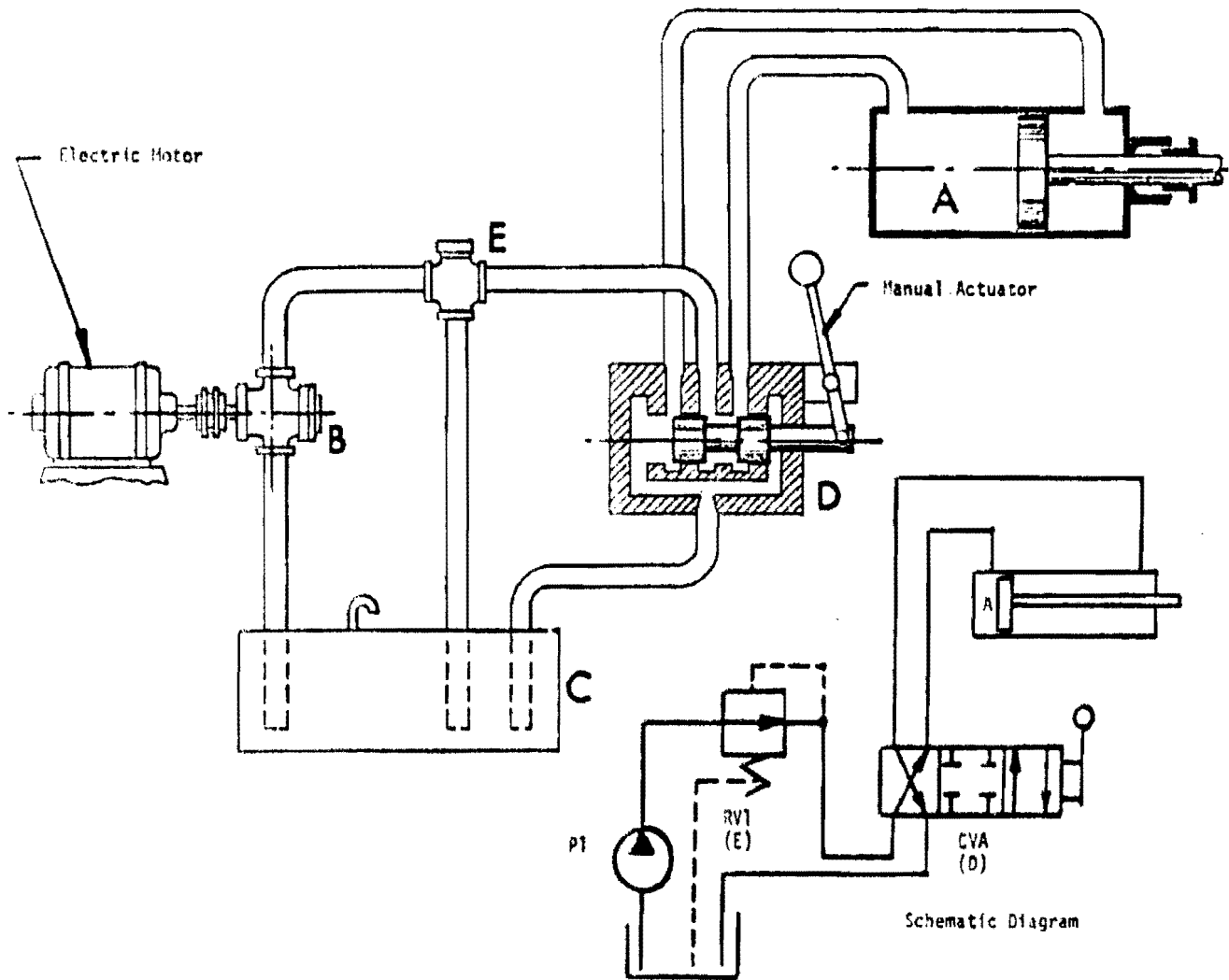
### **Component D: - Control Sub – Circuit**

In this simple system, the control sub-circuit is simply a Directional Control Valve which can exist in any one of three different positions. It has four physical connections to the system piping via a supply port (middle port on top), two outputs to the cylinder (left and right on the top) and one port connection to the reservoir return (bottom). The three different connection arrangements [positions] between the ports are set-up by a manual actuator (a lever within the cab of the earth mover).

### **Component E: - Safety Pressure Relief Valve**

This is a required component in a Hydraulic System but not in an air system. A Pressure Regulator is used in an Air System to maintain a specific pressure level in the holding tank into which the air is delivered by the compressor awaiting use by the system. This kind of system is used in the laboratory in EPH309.

However in a hydraulic system if the pump were left running unchecked the pressure would build-up to a level that could damage valves, piping connections or people. Therefore the function of the pressure relief valve is to normally be inactive, allowing oil to pass through the system at acceptable operating pressures. If a blockage of some kind occurs and system pressure begins to increase then, at a pre-determined required relief pressure, the safety valve will activate and redirect the oil supply back to the reservoir tank thereby not allowing the pressure in the system to increase further to dangerous levels.



**A Simple Hydraulic Fluid Power Circuit**

## Part 1. Design of Control Circuits for Pneumatic Actuators

### Introduction:

Pneumatic actuators are commonly used in automated systems. They can be used for linear movement (Cylinders) and rotational movement (Air Motors). By selecting the correct compressor the pressure and flow of air can be provided to match the power requirements of the application.

In order to function properly and reliably, a pneumatic system must have a supply of clean compressed air at a regulated pressure. In addition, lubricant must be added so that friction and corrosion are controlled. The first components in the compressor output are therefore a shut-off valve and a Filter-Regulator-Lubricator (FRL). If high-pressure air is exhausted to atmosphere it can also create a loud intrusive noise and so mufflers must be used to keep noise exposure levels within workplaces limits.

For this course, we will be designing circuits to achieve a specific function and we will generally assume that the need for clean/quiet operation of the system is being addressed with the incorporation of the required functional components.

### Use of Pneumatic Breadboards in EPH307:

As part of the verification process in our designs we will use pneumatic "breadboards". These are simply blue metal boards with a selection of pneumatic components mounted on them. The components can be inter-connected using small diameter flexible plastic hose and the air is supplied from a distribution manifold connected to a compressed air source under the workbench. Only one pressure source (50psi) is available so the designer must keep track of what is *operating/working air* and what is *control air*. For example, in a "real" application the actuators may require 250 psi *operating/working air* to develop the required force or torque, while the *control air* to move the valve spools may only need to be 25 psi air. When completing circuit diagrams we will identify the distinction between the two types of air by using **solid lines to illustrate/depict operating air and dashed lines to illustrate/depict control air.**

### Steps in the Design Process:

The design of a control circuit requires a series of logical steps to be useful. These can be summarized as follows:

1. Ensure that you have a full understanding of the requirement and the problem that you are solving.
2. Start by making the control circuit as simple as possible adding refinements later to achieve full functionality.
3. Sketch out the circuit using standard ISO1219 symbols.
4. If practical, connect the circuit up on the pneumatic breadboard and verify that it works.

5. Refine your sketch to incorporate any changes you made on the breadboard.
6. Prepare a final working circuit schematic using the correct symbols and layout.

### **Symbols for Pneumatic Circuits – ISO1219:**

Figures 1.1, 1.2 & 1.3 show the ISO [International Standardization Organization] symbols that you will be using in this course. They are very similar to the ANSI [American National Standards Institute] symbols and are widely used throughout the world.

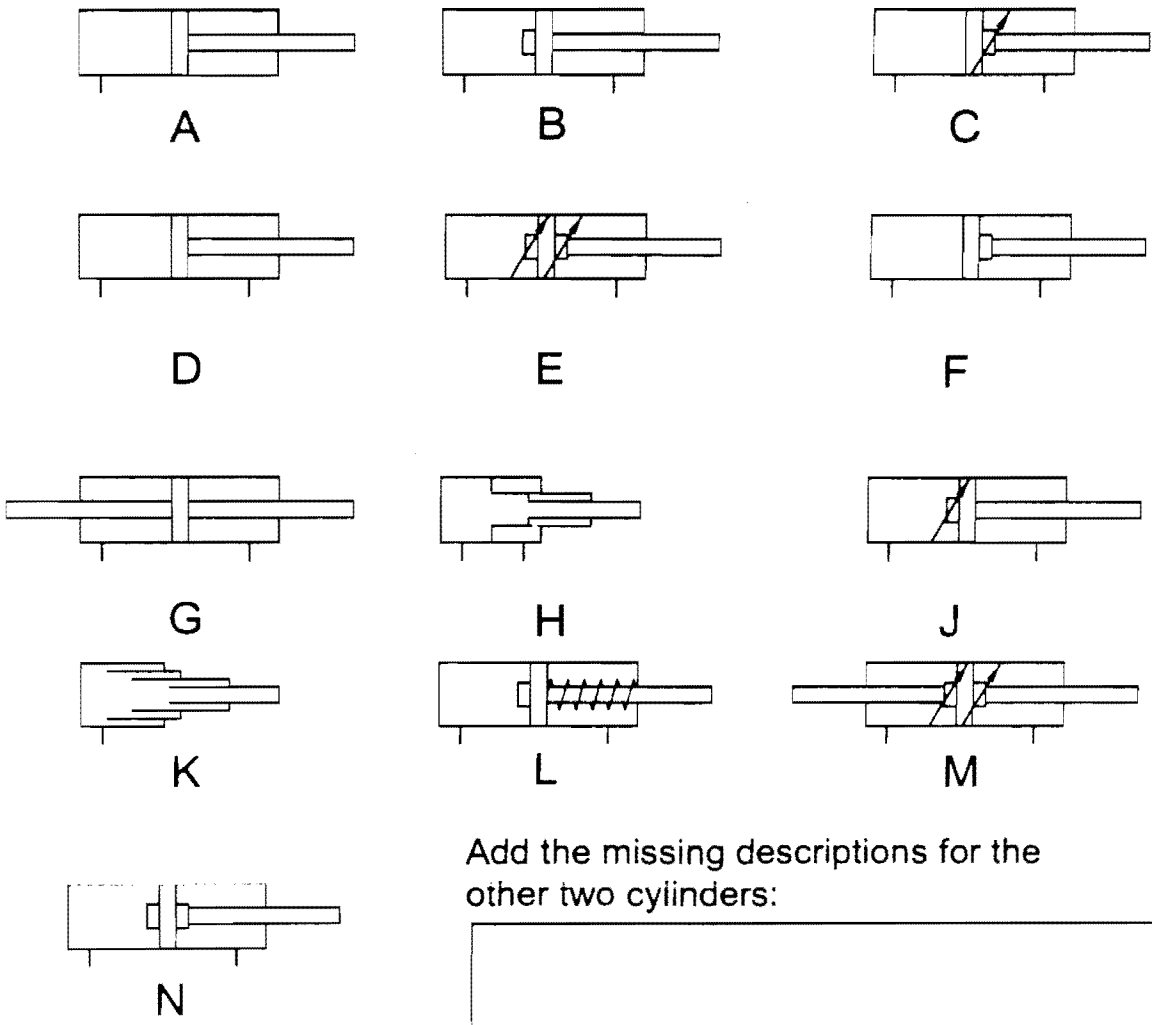
**Cylinders:** These are linear actuators and are widely used in automation. We will be discussing the various components of a pneumatic circuit and you will have an opportunity to examine the physical parts. For example, if you look at figure 1.1 you will see 13 symbols which represent a number of different cylinders. If you are given that, E is a Double-Acting, adjustable cushion both ends, then as an exercise match the remaining descriptions to the lettered cylinders. Note: The cushion is to prevent the piston slamming into the end of the cylinder in high-speed applications. Cushioning is achieved by restricting the flow out of the cylinder at the end of the stroke.

### **Directional Control Valves (CV's).**

These are used to direct the operating or working air to the actuators (cylinder or air-motor) and to direct the exhaust air to atmosphere. The symbols again are very intuitive and a look at figure 1.4 should clarify the function.

Match the descriptions to the symbols

- [ ] Double-Acting, double rod
- [ ] Single-Acting, Telescopic
- [ ] Double-Acting, cushion blank end
- [ ] Single Acting
- [ ] Double-Acting, cushion rod end
- [ ] Double-Acting, cushion and spring
- [ ] Double-Acting, adjustable cushion blank end
- [ ] Double-Acting, cushion both ends
- [ ] Double-Acting, Telescopic
- [ ] Double-Acting, double rod, cushion both ends
- [ ] Double-Acting, adjustable cushion both ends



Add the missing descriptions for the other two cylinders:

Figure 1.1 Standard Cylinder Symbols - ISO1219

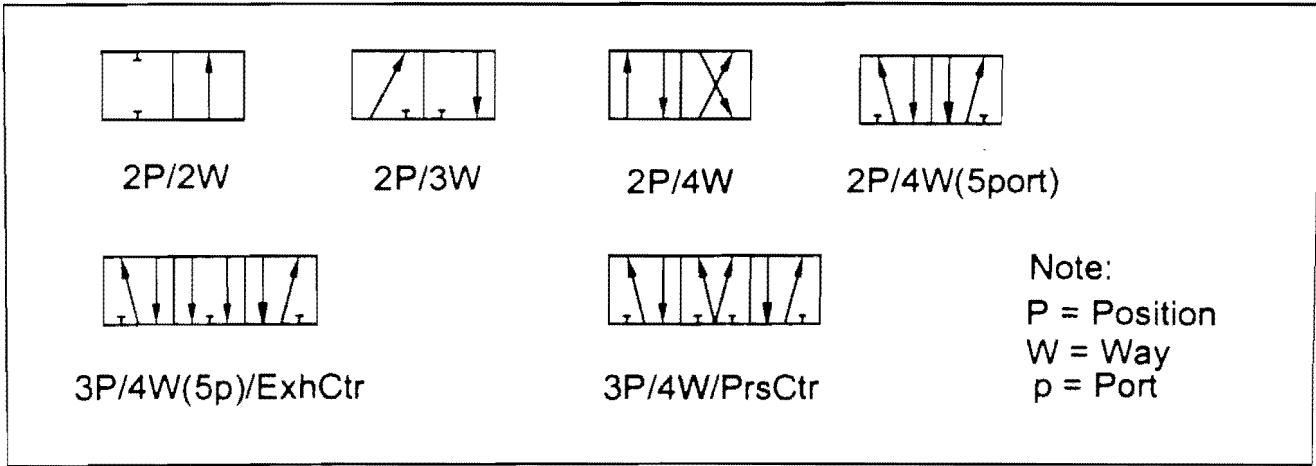
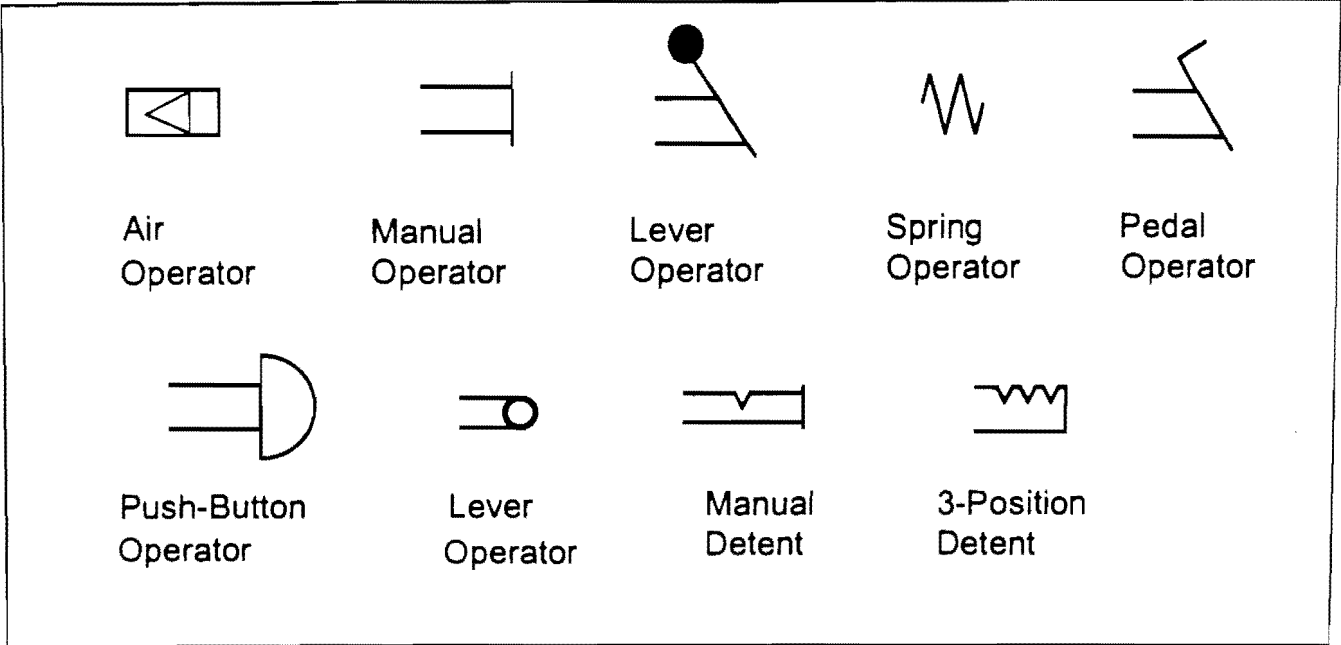


Figure 1.2 Standard Valve Actuators and Function Symbols - ISO 1219

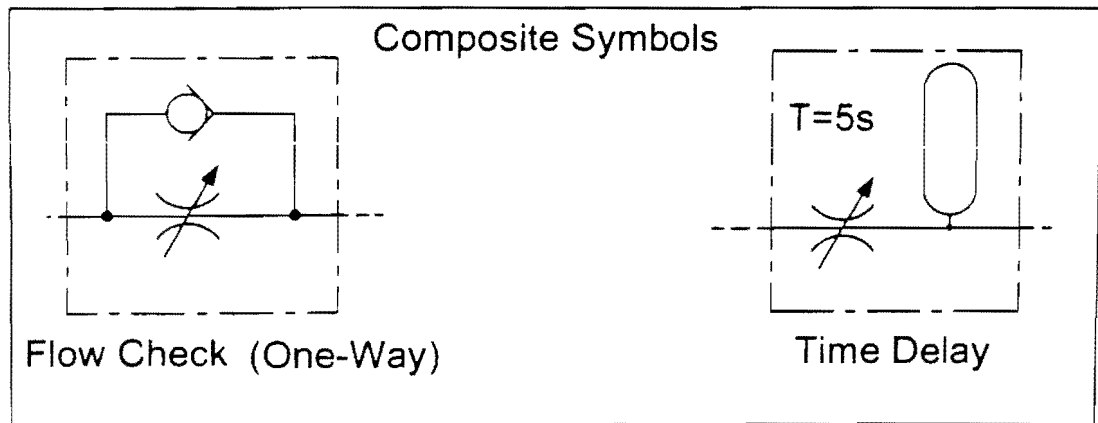
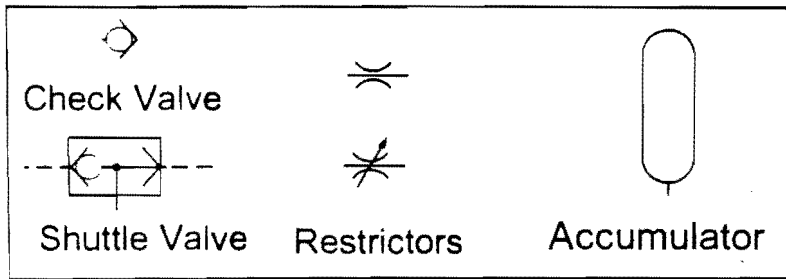
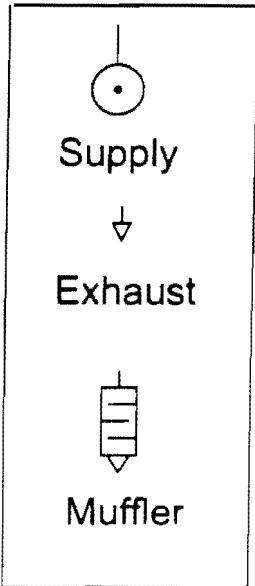
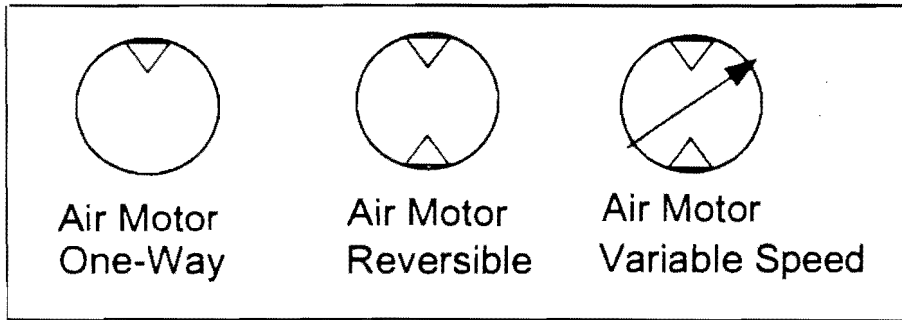
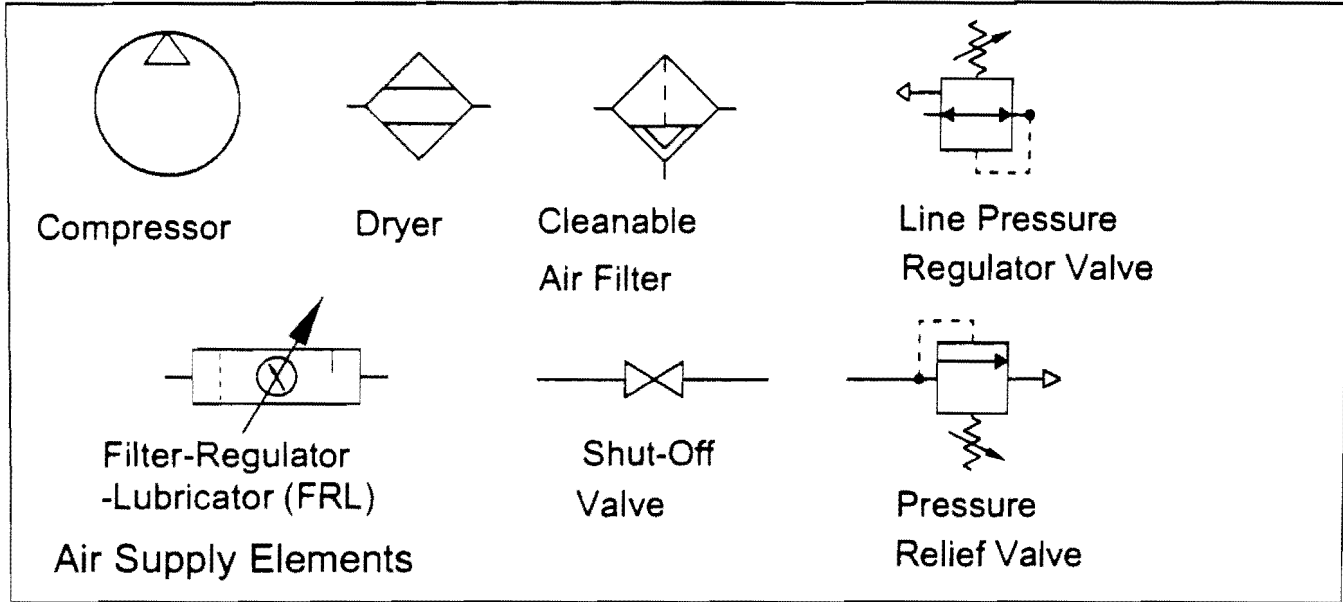


Figure 1.3 Additional Standard Fluidic Symbols - ISO1219

## Building Sub-Circuits.

Figure 1.4 shows how we can use a CV to control the operation of a double-acting cylinder. Note that we differentiate between "operating/working air" [using solid lines] which provides the force that the cylinder exerts and "control air" [using dashed lines] which shifts the spool of the CV's.

**Note:** In the laboratory we have only one air source so you must remember that when you prepare a schematic drawing of the control circuit that the two airs are clearly distinguished by using either a solid or dashed line.

## Multiple Cylinder Control Circuits.

We shall be looking at the problems involved in operating double-acting cylinders to achieve sequential actions in a cyclic operation. For example if we use two cylinders to achieve a Transfer Mechanism we might designate the gripping cylinder as A and the movement cylinder as B, see Figure 1.6 (a) following. Then the required system actions are 1) Grip the Part, 2) Move the Part, 3) Release the Part, and finally 4) Retract back to Original Position to wait for next Part.

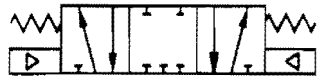
We will describe this sequence in the following terms;

**A+, B+, A-, B-**

(This method of labeling will be used further as we progress through this course to describe all types of variation of cylinder sequences).

Figure 1.6(b) shows the circuit for the sequence described above. In this figure note that we adopt a hierarchical or cascading order for the circuit components. The Actuators and CV's are at the top, the sensors are at the next level and the Start/Stop components are at the lowest level. We also usually ignore the compressor sub-circuits and just show air supplies at the initial valves of the system circuitry (using a circle with a solid filled smaller circle within).

Example:

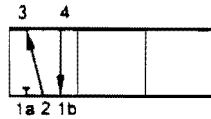


3P/4W(5p)/BlkCtr  
Air Operated  
Spring Centred



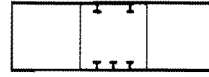
3P

3 valve positions  
called "envelopes"



4W

4 functions to  
connect  
(5 physical port connections  
into the body of the valve)

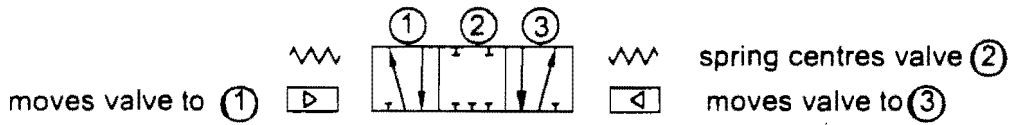
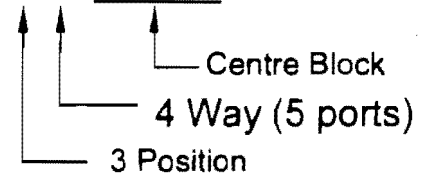


BLK/CTR

blocked centre  
position



3P/4W/BlkCtr



Add Operators adjacent to envelopes they control

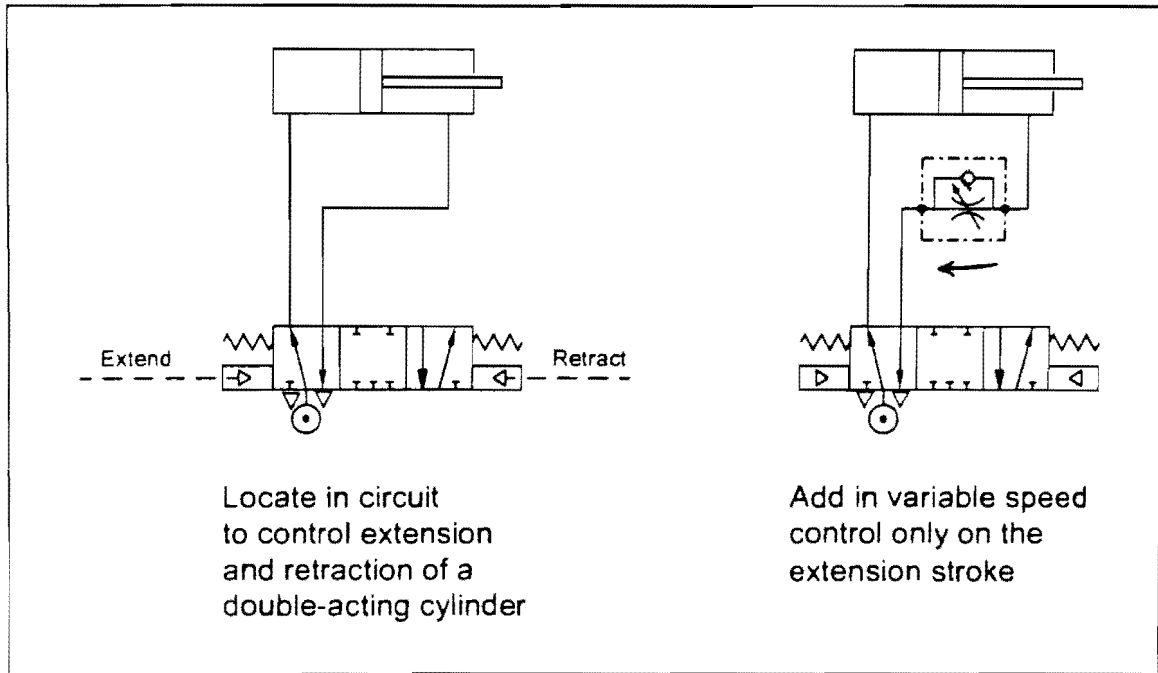


Figure 1.4 Directional Control Valve Symbols - ISO1219

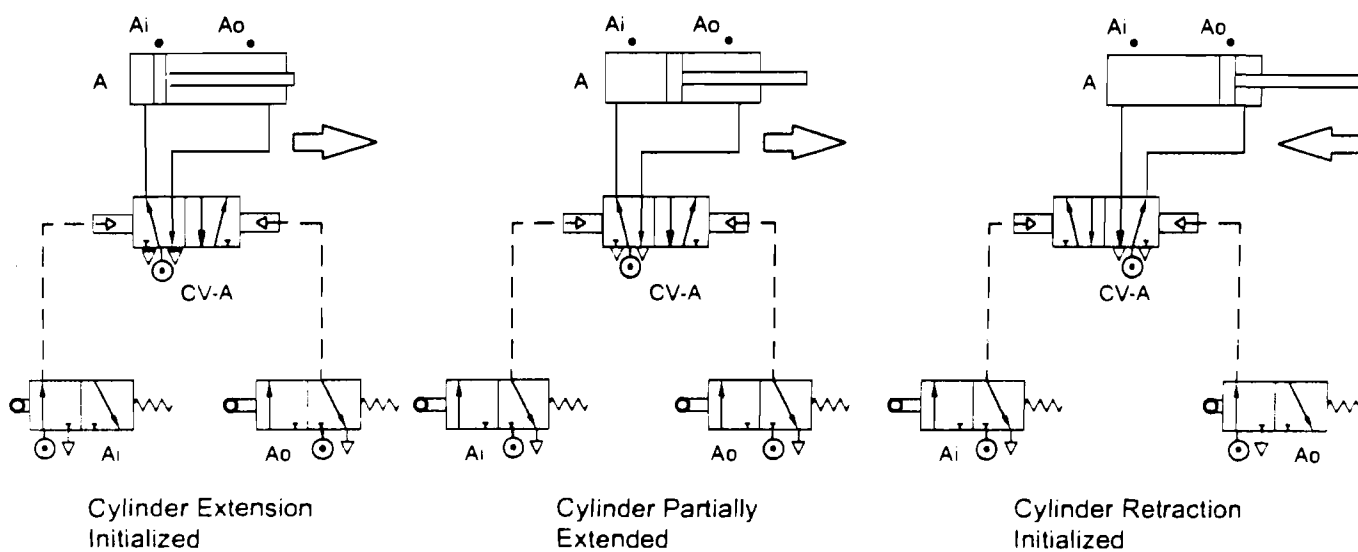
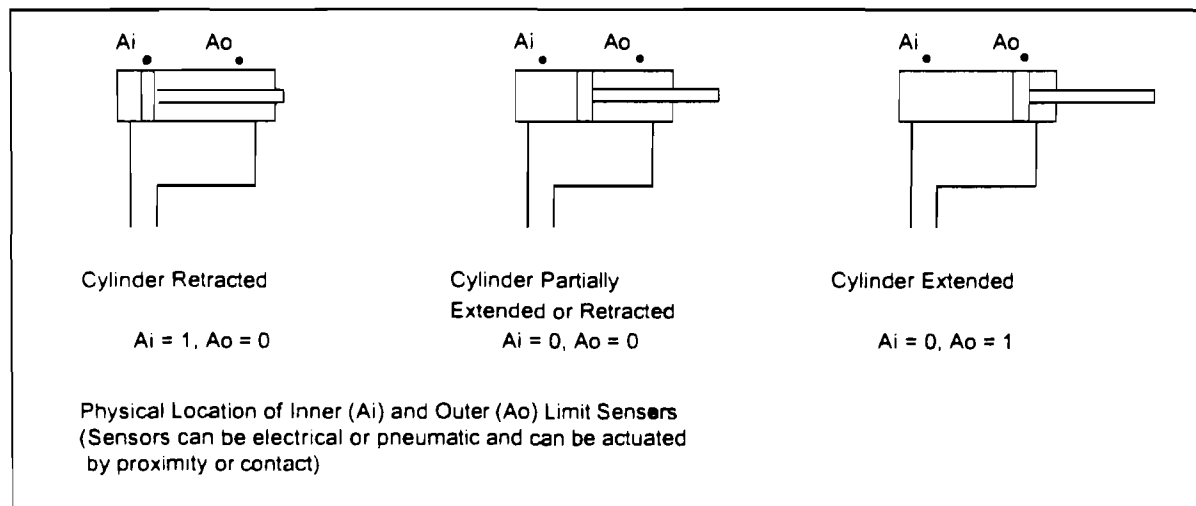
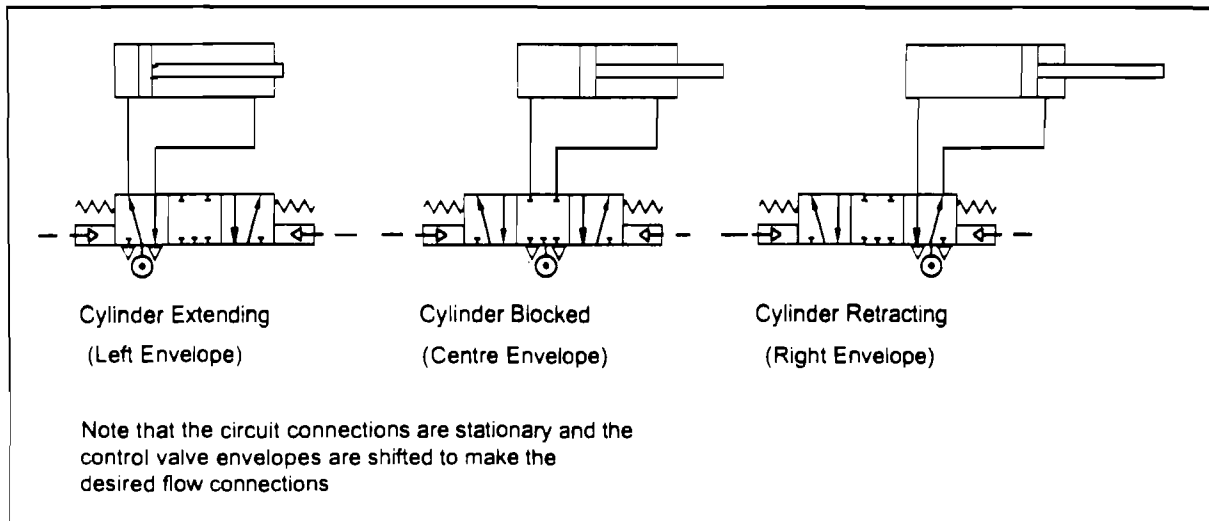


Figure 1.5 Symbols for Cylinder Sub-Circuits ISO1219

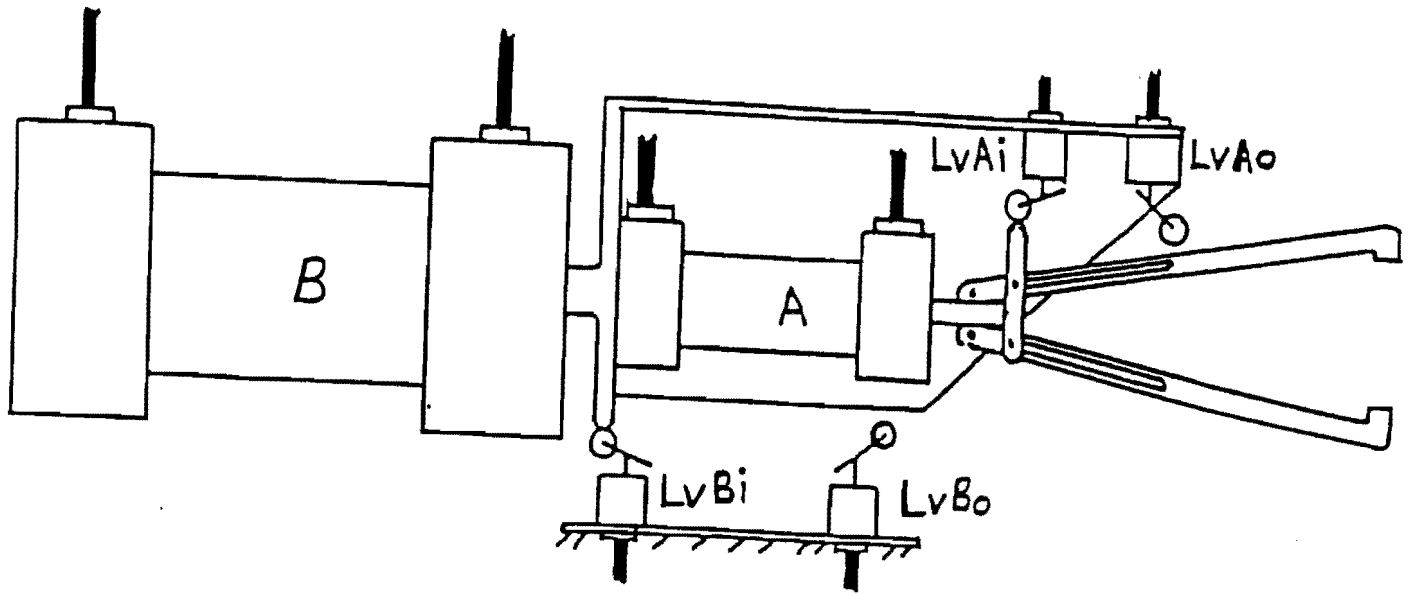


Figure 1.6 (a)

Physical Layout for Transfer Mechanism.

$A+$  ,  $B+$  ,  $A-$  ,  $B-$

where  $A+$  = Extend cylinder A to grip the Part.  
 $B+$  = Extend cylinder B to move the Part.  
 $A-$  = Retract cylinder A to release the Part.  
 $B-$  = Retract cylinder B to return to original position.

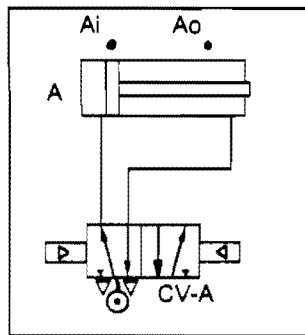
Note: All actions sequential

Actuators

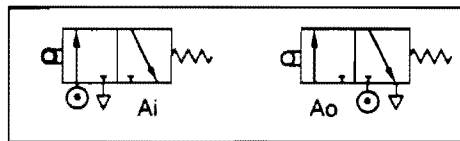
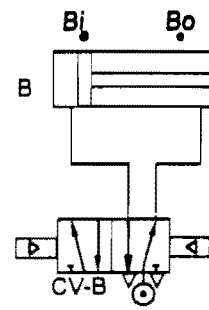
Control Valves

Sensors

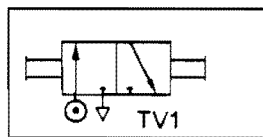
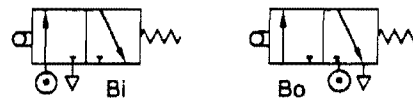
Start/Stop



Working Air Components

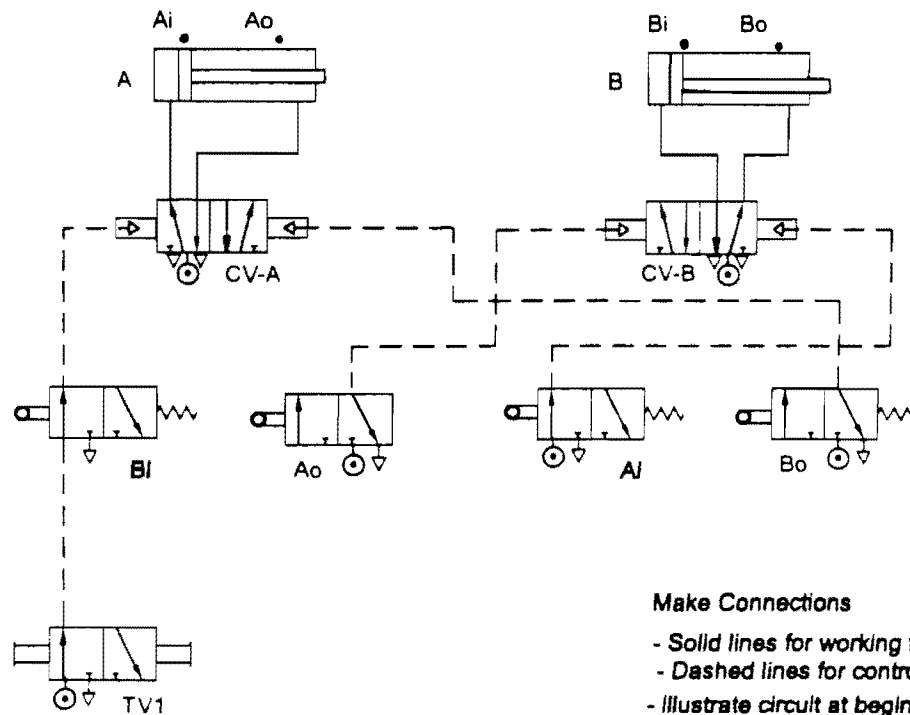


Sensors for CV-A



Toggle Valve

Locate Components



Make Connections

- Solid lines for working fluid
- Dashed lines for control signals
- Illustrate circuit at beginning of cycle actions.

Figure 1.6 Symbols for Multiple Cylinder Circuit - ISO1219

A+, B+, A-, B-

## FLUID POWER – EPH307 Laboratory

### Pneumatic Power Components :

Pneumatic systems operate on air supplied from a compressor. The compressor selected must have sufficient net power to produce the required pressure and flow rate for the applications after losses and inefficiencies have been accounted for. The air supply will be filtered for particulate matter, lubricant will be added to increase the life of seals and valves and the pressure will be regulated. An accumulator will be added to maintain steady pressure and flow rate under expected operating conditions. The necessary components to provide this power supply are housed in the individual work tables in the laboratory.

### Pneumatic Control Components

**Manually Operated Valves:** 2-position, 3-way valves are used to provide signals. The actuators are usually push-buttons or toggle type. The push-button is pressed and released to provide a momentary signal while the toggle is an over-centre device which is set to, and remains in, the ON or OFF state as chosen.

**Limit Valves:** For manual or remote operation of a sequential process 2-position 3-way, spring return directional control valves are often used as limit sensors. There are the same valves as in manual operation with different actuators. The low pressure signals from these valves can be directed to small actuators to shift the spools of much larger control valves working at full system pressure. This is called “pilot” operation and is the basis of remotely controlled systems.

**Note** that when pneumatic operators are used for control valves the line is pressurized to shift the valve spool. After this has been done the line must be vented so that an opposing signal can shift the spool back. For this reason you will find that 3-way valves are used since a 2-way valve can block the air supply but cannot release the pressure in the line.

**Shuttle Valves:** In the case where the outputs from two sensors (A, B) are directed to the same valve operator a shuttle valve must be incorporated. The shuttle valve is shown in figure 2.3. It consists of a small ball which is moved by the air from either A or B and seals off the other signal from the other sensor. This blocking ball is required to ensure that the air in line will not pass back down the opposite supply line and exhaust through the other sensor instead of going to the valve operator, as intended. This is a logical “OR” connection between A and B (noted as A+B or B+A). The ISO symbol shows the ball in a neutral position.

**Line Fittings:** Air may be routed from one source to several destinations by using tees and cross connections. When drawing schematic diagrams, lines may crossover other lines and the convention is that there must be a dot at the intersection if a connection is required (or conversely no dot – no connection).

## Additional Control of Circuit Functions

### Introduction

In most control circuits used in fluid power systems the input power must be conditioned or controlled to perform specific tasks. Since power, by definition is the product of pressure and flow, the control of either or both these functions is basic to all systems.

As systems become more sophisticated control functions increase, timing and sequencing for example are essential in automatic or semi-automatic systems. This section considers control functions in the following categories:

1. Flow (Speed) Control of actuator's working fluid.
2. Time Delay of circuit's control fluid.

### Flow Control

**Actuator Speed Control:** Controlling the flow of working fluid into or out of an actuator termed "metering". Control of fluid inflow is thus "meter-in", while control of fluid outflow from an actuator is "meter-out".

The relationship between velocity and flow is defined as:

$$\text{Velocity} = \frac{\text{Flow}}{\text{Area}}$$

Since the area of an actuator (for example the piston area of a hydraulic cylinder) is fixed, the velocity must be controlled by regulating the flow.

**Flow Control valves:** A variable orifice is used in a simple needle valve to restrict flow such that any rate from zero to full flow is available. It is usual to require control of an actuator speed in only one direction or require different speeds in both directions. For this reason most flow control valves have a built-in bypass which allows for restricted flow in one direction and free flow in the opposite, Figure 1.7 shows such a valve. Fluid entering at the left acts on the spring loaded plunger and lifts it clear while fluid entering from the right is forced to go through the annulus which is varied by the position of the threaded stem.

Shows how this sub-circuit would be installed to obtain "meter-out extension" speed control of a hydraulic cylinder, i.e. metering the hydraulic flow out of the cylinder on the extension stroke. When the four-way directional control valve beneath the cylinder is set to its other position (the right hand envelope) it should be noted that the restriction would be bypassed and the retraction stroke of the cylinder would be accomplished at full speed.

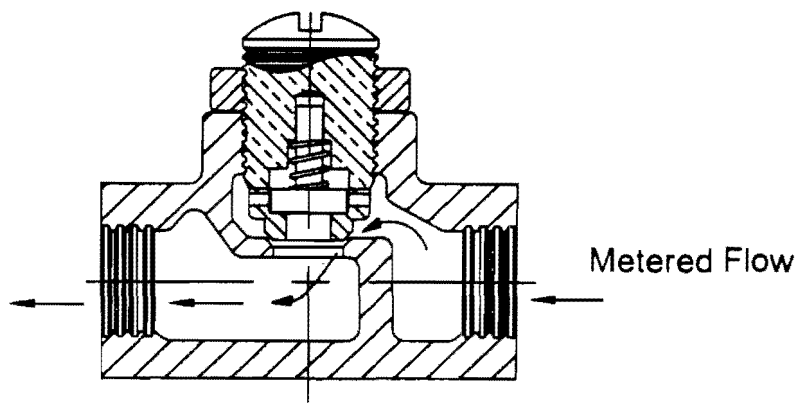
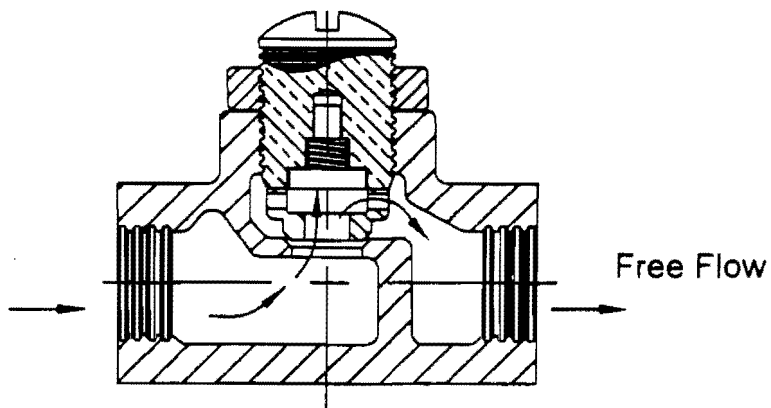
shows how this sub-circuit would be installed (by simply reversing its direction on hook-up) to provide "meter-in retraction" speed control of the same hydraulic cylinder, i.e. metering the hydraulic flow into the cylinder on the retraction stroke. Again if the four-way directional control valve were set to its other position (that left hand envelope) the restriction would be bypassed and the extension stroke of the cylinder would be at full speed.

The decision between “meter-in” and “meter-out” speed control on the cylinder stroke usually includes determination of whether a back-pressure or resistance pressure is required on the speed controlled stroke to provide a positive-positioning capability. For example, if speed control is required as the cylinder extends through a workpiece body and as the workpiece is cleared it is desired not to have a sudden “jerking” or erratic cylinder movement then the presence of a back pressure would be beneficial.

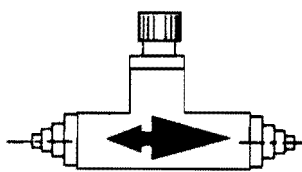
### **Time Delay**

In many system circuits, especially those involving sequential events, a pause or dwell may be required between specific operations. For a fluid power system this time control is achieved with the sub-circuit illustrated in Figure 1.4.

Flow control valves can provide a delay of around 15 seconds at 100 psi with no capacitance. A longer delay of around 40 to 50 seconds would require the additional capacitance of an expansion chamber. However, with leakage and other losses these time delays are not very precise. With the advent of electronic control (programmable controllers) of pneumatic and hydraulic working fluid power systems the time delays are no longer a hardware sub-circuit but rather a software program command. Therefore the time delay is based on the internal computer clock and hence can be programmed to tenths and thousandths of a second resulting in very highly controlled/timed system sequence actions. In addition these electronic time delays can be easily tied in with counters to keep track of the number of times a specific action takes place to provide a data history of the system's operation.

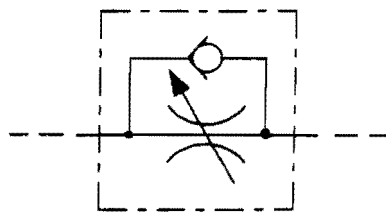


Variable Flow Restrictor



Variable Flow Restrictor

(style used in lab)



ISO1219 Symbol

Figure 1.7 Variable Flow Restrictors

## Example Schematic Circuit Diagram:

See Figure X.1

Toggle valve TV-1 is shown in the "ON" state with the output signal directed to the inner limit valve LVAi of the double acting cylinder A.

**Note: Circuits are always shown at the point of initiation,** in this case with the piston fully retracted and the inner limit valve LVAi actuated. Connections are made to the valve envelopes adjacent to the actuators which are active.

The output signal from LVAi is routed to the left envelope of the 2-position, 5-way, control valve CV-A which directs working air to the cap end of the cylinder to extend the piston. Air trapped in the rod end of the cylinder is allowed to vent through CV-A.

When the piston is fully extended it actuates the limit valve LVAo which sends a signal to the right pilot of CV-A to reverse to connections to cylinder A and retract the piston. Note that LVAo has its own air supply. If it was supplied from TV-1 then the cycle would not complete if TV-1 was actuated to the OFF position during the extension stroke of the piston.

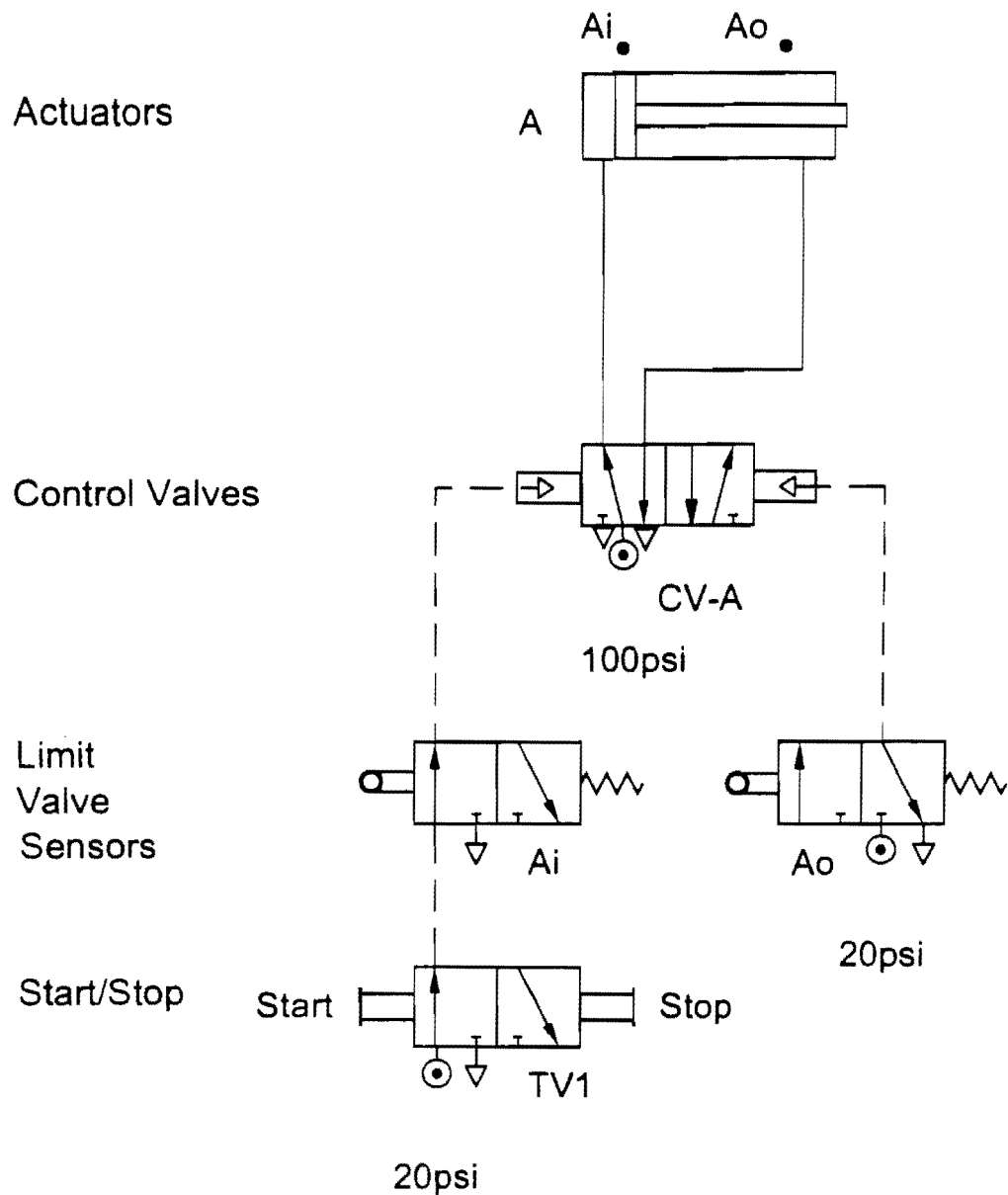
When the piston is fully retracted the cycle will repeat unless the toggle valve has been turned off during the cycle. Note that this is not an emergency stop control and allows the current cycle to complete.

### Sample Problem and Solution

**Statement of Requirement:** Design a circuit which is the same as Figure -X but with a continuous cycling start and stop sub-circuit which uses momentary signals (rather than the sustained signal from the toggle valve).

**Figure Y-1 illustrates the required circuit.**

PB-1 Start is shown actuated and acts on the left pilot of CV-1 to provide the air supply to LVAi. The PB-1 Start need only be momentarily actuated to shift the spool of CV-1 to setup, and maintain, the left hand envelope [i.e. through position] until a signal is received from PB-2 Stop. A signal received from PB-2 Stop at the right pilot which would move CV-1 to the right hand envelope [i.e. blocked position] and cut off the supply to LVAi. Cylinder A would then complete the current extension/retraction cycle and stop, i.e. not extend again.



Note: Show components stacked vertically as shown with all the valve envelopes illustrated horizontally. Make connections starting with the input at the bottom of the diagram and work upward to the control valve pilot actuators.

Figure 4.1

Figure X.1

Schematic Diagram  
For FP-Y

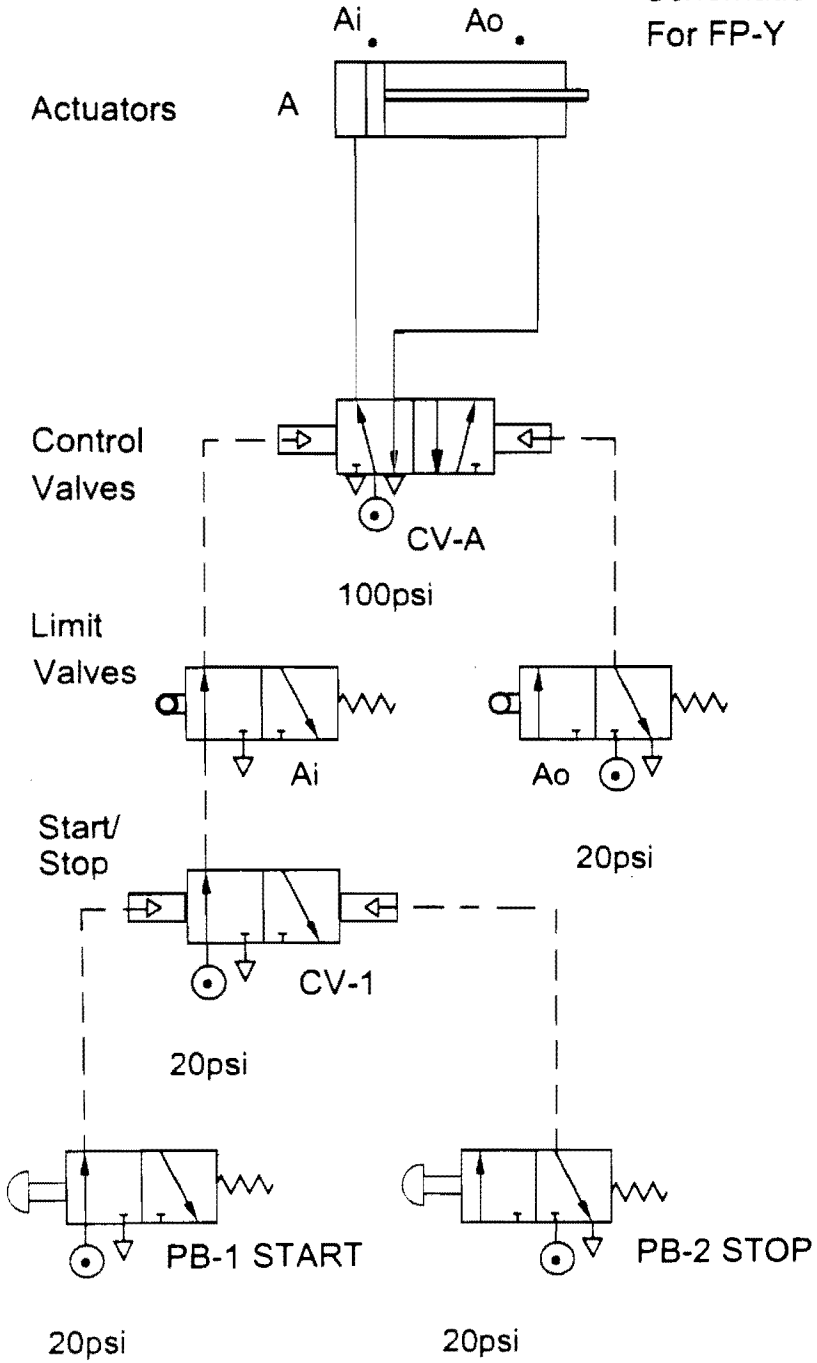


Figure Y.1

# Control Circuit Logic Analysis

## Introduction

In this course we are concentrating our study on the intelligent control of fluid power systems. The logic consists of combinations of 'gates' or valves which possess discrete states (i.e. either a **1 state - actuated**, or a **0 state - unactuated**). These valves are interconnected in such a way that only pre-determined combinations of signals will yield outputs satisfying specific control functions (i.e. permitting cylinder extension and/or retraction).

For fluid power applications it is convenient to sub-divide logic circuits in two main categories:

1. Sequential Logic
2. Combinational Logic

Sequential Logic is employed when addressing the situation of multiple outputs/actuators, i.e. cylinders that have to operate in a specific sequential pattern to successfully complete the required job. We will address this later in the course and identify methodologies that will help us design the required circuits to control the cylinder sequences.

Combinational Logic addresses the required connections needed between sensory valves to satisfy pre-determined conditions before a decision is made to actuate a cylinder. The following sections document it in further detail.

## Combinational Logic – Digital Binary Systems

Circuits which provide a degree of decision making are widely used in fluid power applications. For example, in a hydraulic press, for safety reasons, the operator must have the safety guard down before the foot pedal will actuate the ram extension. This is achieved by having the guard control the actuation of the valve which supplies control pressure fluid to the foot pedal valve which in turn supplies the pilot of the main control valve for the ram. The two valves of this example are said to be functioning in SERIES, or in logic terms as an AND gate.

In order to analyze combination logic circuits it is necessary to understand, and manipulate, algebra associated with digital binary systems. Boolean Algebra provides the mathematical constructs (parameter connections and algebraic expressions) to be used in binary logic circuit analysis.

## Table 1 : Boolean Algebra Constructs

### Basic Operations

$\cdot$  = AND / Series connection       $+$  = OR / Parallel connection

$\overline{\quad}$  (overbar) = NOT / inversion of statement beneath bar

### Basic Combinations

AND followed by NOT = **NAND**

OR followed by NOT = **NOR**

### Postulates

1a.  $A = 1$  if A is not 0

1b.  $A = 0$  if A is not 1

2a.  $0 \cdot 0 = 0$

2b.  $0 + 0 = 0$

3a.  $1 \cdot 1 = 1$

3b.  $1 + 1 = 1$

4a.  $1 \cdot 0 = 0$

4b.  $1 + 0 = 1$

5a.  $\overline{\overline{1}} = 0$

5b.  $\overline{\overline{0}} = 1$

### Theorems

6a.  $A \cdot 0 = 0$

6b.  $A + 0 = A$

7a.  $A \cdot 1 = A$

7b.  $A + 1 = 1$

8a.  $A \cdot A = A$

8b.  $A + A = A$

9a.  $A \cdot \overline{A} = 0$

9b.  $A + \overline{A} = 1$

10a.  $\overline{\overline{A}} = A$

10b.  $A = \overline{\overline{A}}$

### Inversion – DeMorgan's Theorems

$$\overline{A \cdot B} = \overline{A} + \overline{B}$$

$$\overline{A + B} = \overline{A} \cdot \overline{B}$$

### Basic Rules

$$A = A \cdot 1$$

$$\overline{A} = \overline{A} \cdot 1$$

$$AB = A \cdot B$$

$$A \cdot B = B \cdot A \quad A + B = B + A$$

$$A(B \cdot C) = A \cdot B \cdot C \quad A + B + C = A + (B + C)$$

$$A + AB + AC = A \quad (\text{known as the Parent Product Rule})$$

$$A + B + AB + ABC + BCD = A + B \quad (\text{Redundancy Rule})$$

The Boolean algebra constructs in Table 1 above can be used to simplify and verify some combinational expressions. The following 2 examples illustrate this point.

#### Example 1

$$\begin{aligned}
 Y &= \bar{A}B\bar{C} + \bar{A}BC + A\bar{B}\bar{C} + A\bar{B}C \\
 \Rightarrow Y &= \bar{A}B(\bar{C} + C) + A\bar{B}(\bar{C} + C) \\
 \Rightarrow Y &= (\bar{A}B \cdot 1) + (A\bar{B} \cdot 1) && \text{from using Theorem 9b: } A + A = 1 \\
 \Rightarrow Y &= \bar{A}B + A\bar{B} && \text{from using Theorem 9a: } A \cdot 1 = 1
 \end{aligned}$$

The above analysis shows that the status of sensor C does not affect the value of output Y. Either, (i) the circuit does not need sensor C included or (ii) you have not correctly stated the logic requirements for output Y and the output statement needs to be reassessed.

Also the number of AND and OR gates required for the combinational circuit has been significantly reduced.

#### Example 2

$$\begin{aligned}
 Z &= B(A + B)(A + B + C) \\
 &= (ABC + BBC)(A + B + C) && \text{multiply through by } BC \\
 &= (ABC + BC)(A + B + C) && \text{using Thm 8a: } A \cdot A = A
 \end{aligned}$$

$$\begin{aligned}
&= BC(A + 1)(A + B + C) && \text{factoring out } BC \\
&= BC(1)(A + B + C) && \text{using Thm 7b: } A + 1 = 1 \\
&= ABC + BBC + BCC && \text{using Thm 7a: } A \cdot 1 = A \text{ \& multiplying through by } BC \\
&= ABC + BC + BC && \text{using Thm 8a: } A \cdot A = A \\
&= BC(A + 1 + 1) && \text{factoring out } BC \text{ \& using Thm 7b: } A + 1 = 1 \\
&= BC && \text{using Theorem 7b: } A + 1 = 1
\end{aligned}$$

Again, this analysis shows that a much simpler logic circuit is at the root of the output equation and that sensor A has no impact on the evaluation of the circuit output signal, Z.

### **Logic Circuit Preparation**

Visualization of Boolean statements in a logic diagram is very common in circuit development. Indeed it is often used by designers as the method to develop the Boolean statement in the first place. The logic graphic symbols for AND, OR and INVERSION are employed in the circuit documentation.

There is a procedural rule to follow when developing a diagram from a Boolean statement. Evaluate and transcribe the statement in the following Order of Precedence, as illustrated in Example 3 on the following page.

Evaluate:

1. Within brackets and under long overbars.
2. Products (AND)
3. Sums (OR)

### Example 3

Develop circuit for

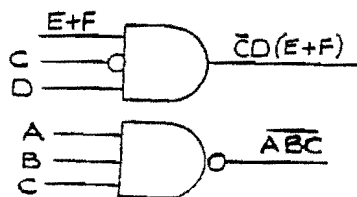
$$\overline{ABC} + \overline{CD}(E+F)$$

(note the periods between the variables have been dropped as they are in normal algebra)

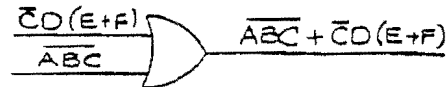
(i) Start within brackets



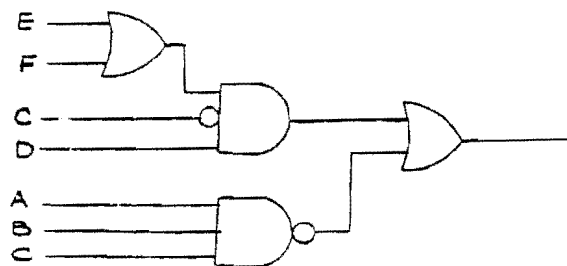
ii) Products



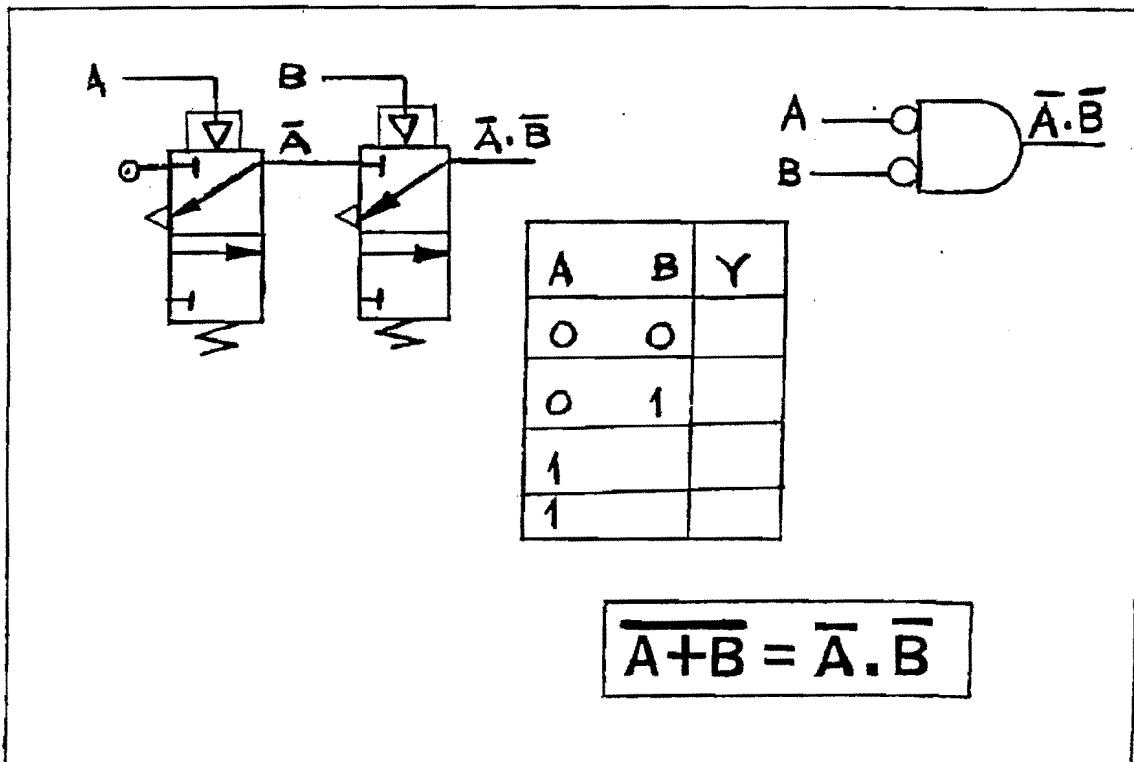
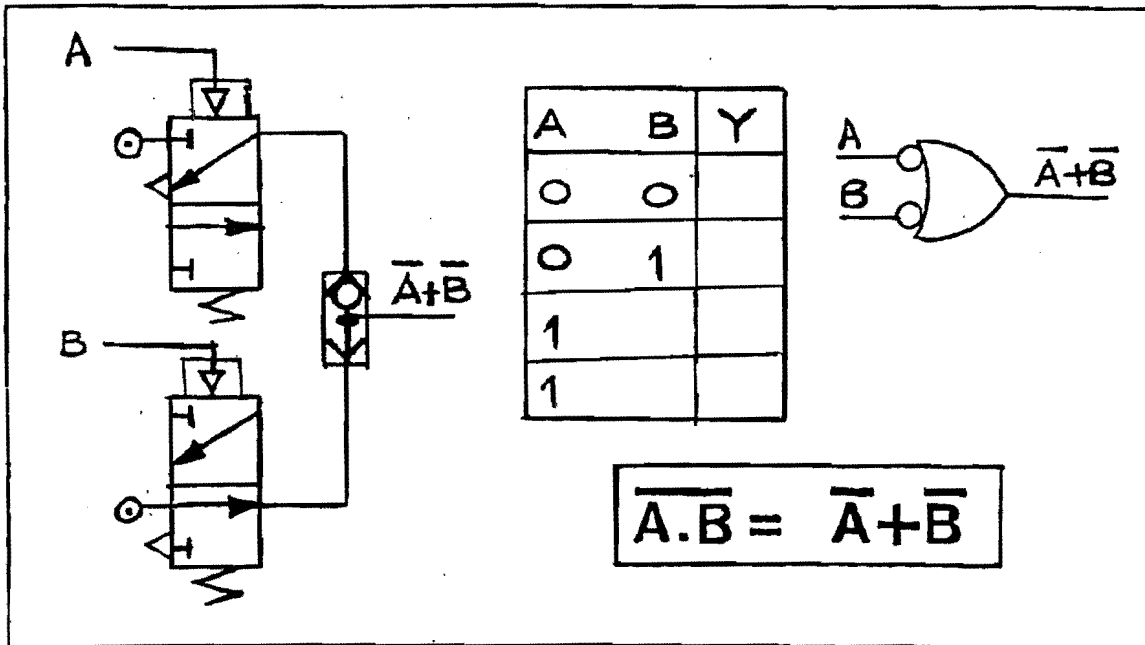
iii) Sums



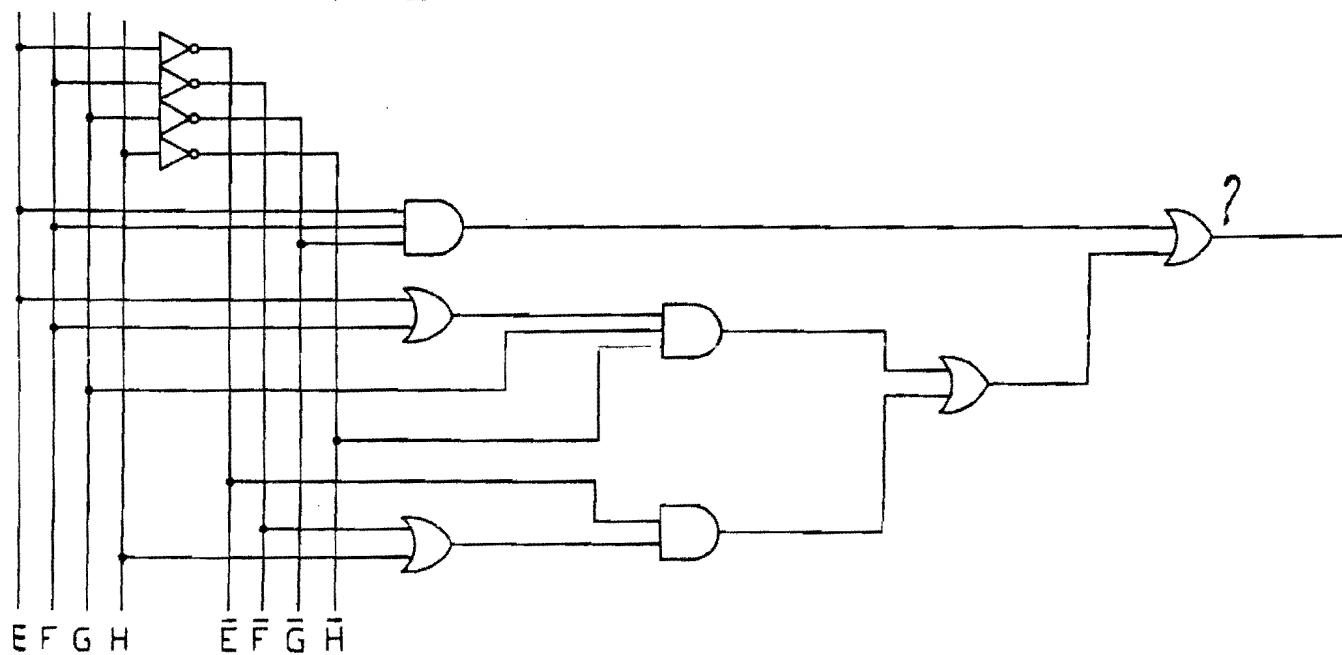
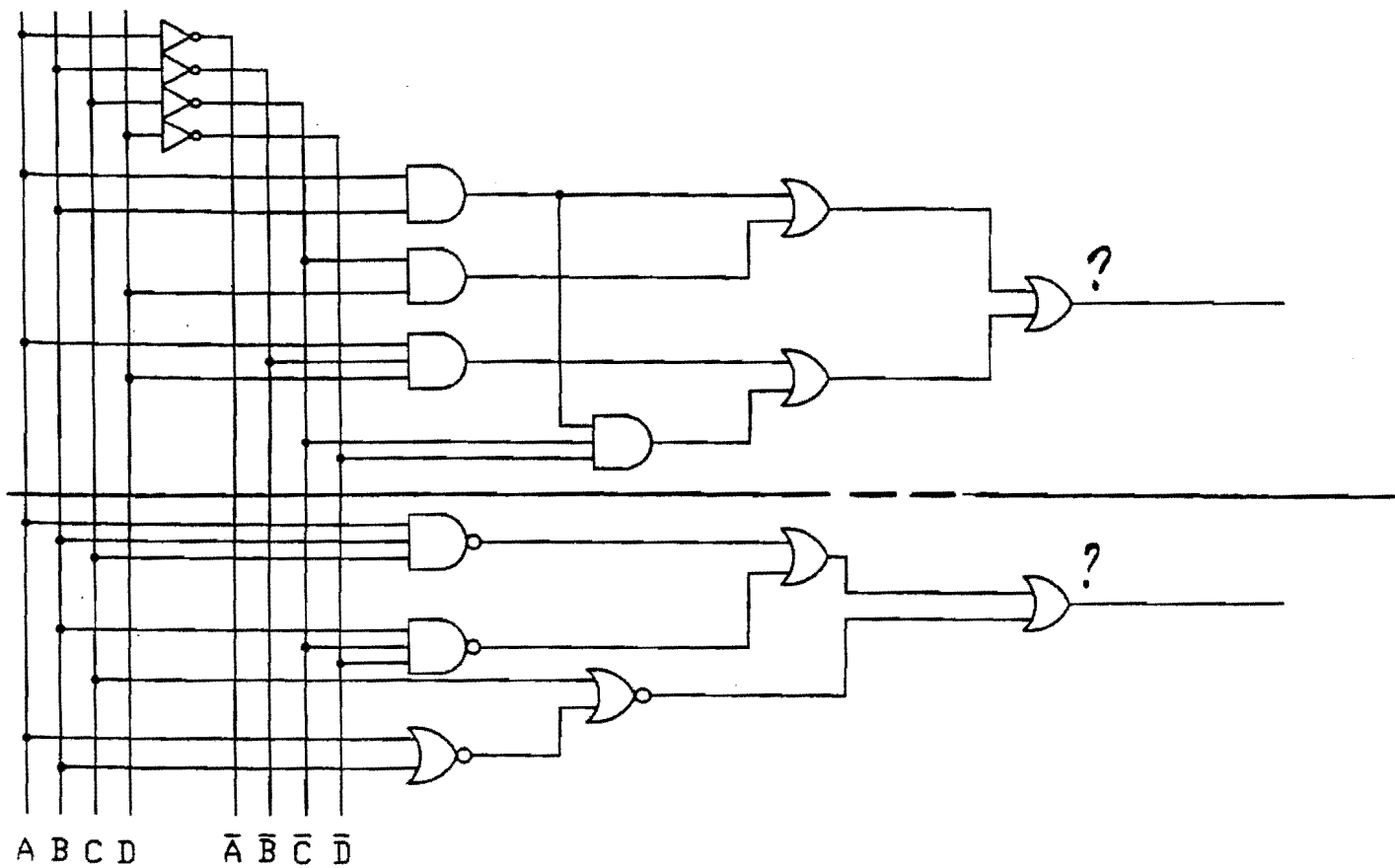
Completed Diagram:



# DeMorgan's Theorems – Proof



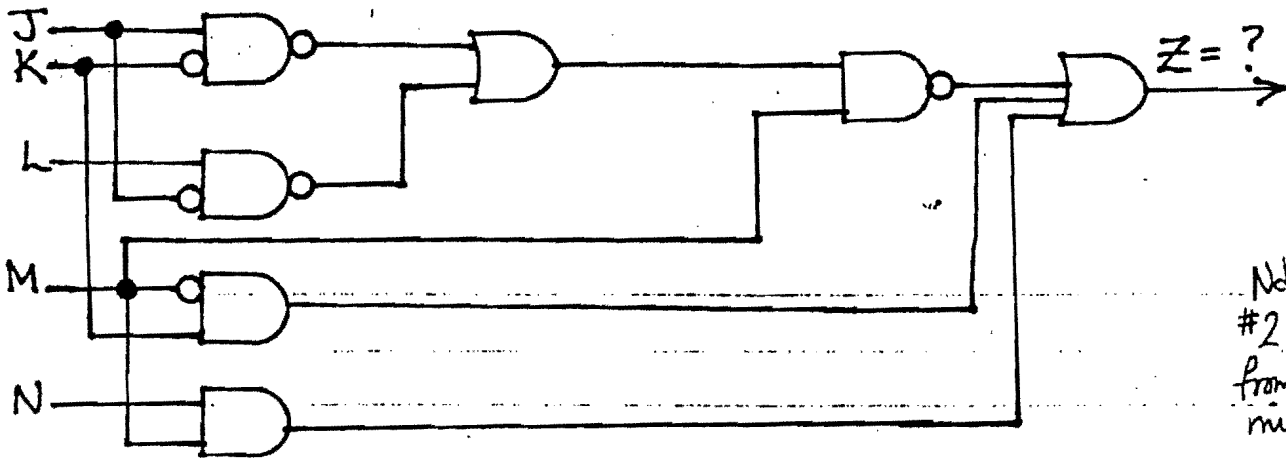
# Obtaining Boolean Expressions from Circuit Diagrams



#1. Develop the logic circuit diagram that would implement the output expression,

$$Y = \overline{ABC} + C + C + D + \overline{A\bar{B}D}$$

#2. Determine the output Boolean expression for the logic circuit diagram shown below. Then simplify Z algebraically.



Note:  
#2 is a question  
from a past  
midterm.

Sample Logic Circuit Questions  
For In-Class Examples

## Sequencing of Workcell Cylinders

In the manufacturing environment there are many automated assembly and machining workcells. Pneumatic cylinders are widely used in these workcells to achieve the required system operation. Often there will be two or more cylinders involved in a workcell and correct operation of a specific task requires that the cylinders cycle (extend and retract) in a specific order to achieve this required system operation.

To ensure that a system's cylinder action occur in a certain order sensory components are required to provide positive indication that a specific cylinder has fully extended or retracted before the next cycle action is initiated. Such indication of cylinder extension and retraction is provided by appropriate placement of 2 Position / 3 Way normally closed cam-actuated pneumatic valves placed at the limits of the extension and retraction stroke of the cylinder. Hence they are referred to as Limit Valves.

As systems become more involved problems occur in the sequencing of cylinder actions and therefore a structured approach to system sequencing is necessary. There are two main organized approaches to cylinder sequence problem identification and manipulation.

Namely:

1. Cascade Logic
2. Shift Register Logic

The first of these methods is more involved requiring a good understanding of system operation and the ability to use Status Tables to track the cylinder sequence. The second method is easier to become familiar with but does not necessarily provide the minimum additional circuitry solution that is possible with the first. Both are discussed in this section.

### Cascade Logic

**Limit Valves:** Commonly a system's correct operation depends on the cylinders sequencing in a specific order usually requiring full extension or retraction of one cylinder before a second cylinder initiates an action. Figure 1 provides an example of a simple cylinder cycle. It illustrates a simple linear transfer mechanism in which cylinder A grasps and releases a workpiece and cylinder B transfers the part from one location to a second location. To ensure correct operation of this system the cylinders must cycle in a specific order. Cylinder A must fully extend to grasp the part, then cylinder B must fully extend to move the grasped part from location one to location two. Then cylinder A fully retracts to release the part at location 2 and finally cylinder B fully retracts to relocate back at location one waiting for the next part which needs to be transferred. Such actions could be time sequence controlled but this would not necessarily ensure correct and safe operation if an obstruction was encountered during cylinder movement. Therefore, as stated previously, sensory components (i.e. limit valves) are required to provide positive indication that a cylinder is either fully extended or fully retracted.

As illustrated in Figure 1, these limit valves are appropriately placed in the transfer mechanism workcell so that:

LvAi

- Is the name given to the inner limit valve associated with cylinder A
- Is actuated only when cylinder A is fully retracted

LvAo

- Is the name given to the outer limit valve associated with cylinder A
- Is actuated only when cylinder A is fully extended

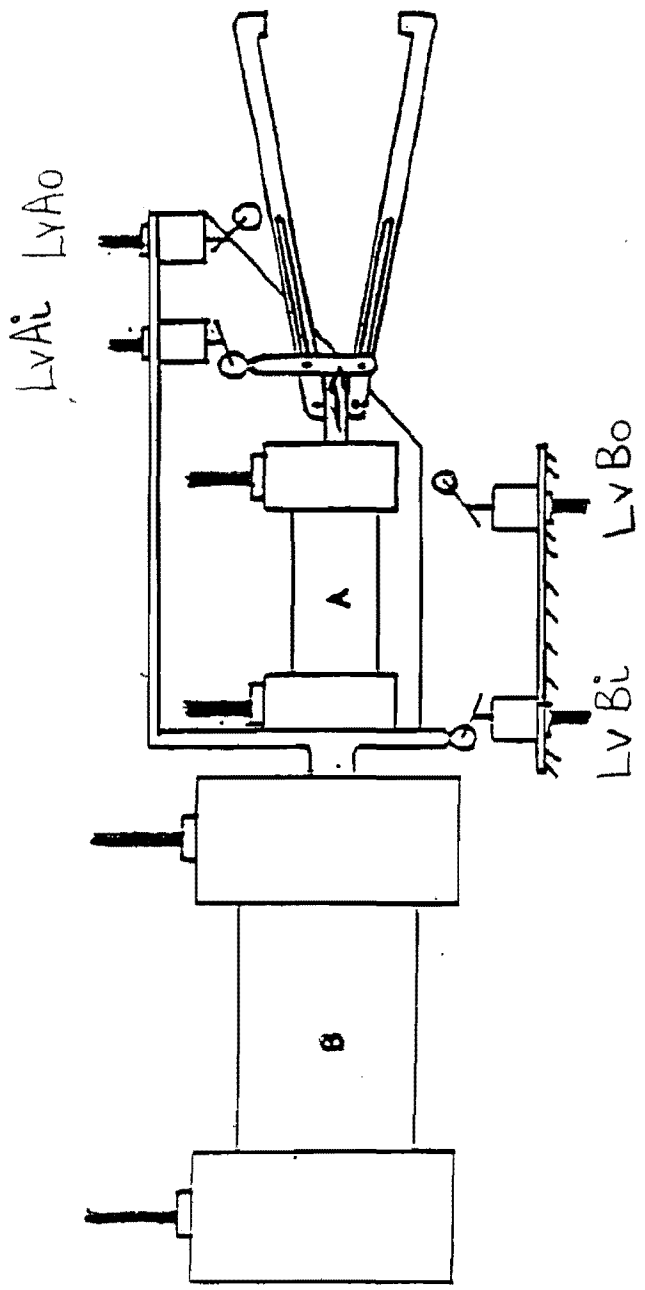


FIGURE 1 : TRANSFER MECHANISM

LvBi

- Is the name given to the inner limit valve associated with cylinder B
- Is actuated only when cylinder B is fully retracted

LvBo

- Is the name given to the outer limit valve associated with cylinder B
- Is actuated only when cylinder B is fully extended

These limit valves are normally closed 2 Position, 3 Way pneumatic valves which when actuated provide an output signal. Therefore if actuation of LvAo provides positive indication of full extension of cylinder A it's output signal could then initiate/trigger the next sequential cylinder action of the extension of cylinder B. In effect the output of LvAo could pilot the directional control valve of cylinder B (CV-B) to route the cylinder's working fluid to begin extension of cylinder B.

**Status Tables:** A Status Table provides a simple method of tracking the status of cylinder limit valves at any stage during a specific cycle no matter how complex. The nomenclature used in truth tables is as follows:

I Cylinders are labeled A, B, C etc.

II Cylinders actions are labeled:  
**A +** = Extension of Cylinder A  
**B -** = Retraction of Cylinder B

III A Cylinder Cycle is written as:

**A+ , B+ , A- , B-**

(cycle for Figure 1 Transfer Mechanism cylinder sequence discussed above)

IV LvXi is the inner limit valve of cylinder X which is actuated when cylinder X is fully retracted.

LvXo is the outer limit valve of cylinder X which is actuated when cylinder X is fully extended.

V A limit valve when actuated has a logic Hi state, i.e. 1  
A limit valve when unactuated has a logic LO state, i.e. 0

To develop a status table, as indicated in Figure 2(A), the specific cycle sequence is written as column headings and the required limit valves are listed as row headings down the left side of the table. The table is then populated with 1's and 0's on a column by column basis to reflect the changing state of the Lv's as the cycle sequence progresses. Since each column is populated looking to the action heading of the previous column as having just taken place then the Lv status is easily identifiable by column and reflects the LV status just before the cylinder action heading of the present column takes place. This helps identification of action triggers as seen in Figure 2 (B) and discussed following.

## Figure 2 Status Table Development

(A)

1. Cylinder Sequence is written as column headings, in required order.
2. Limit Valves (Lv\*i and Lv\*0) of involved cylinders written as row labels.
3. The Table is populated with 0's (for valve unactuated) and 1's (for valve actuated) on a column by column from left to right – on the basis that the action at the heading of the previous column having just been completed.

	A+	B+	A-	B-
<b>LvAi</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>1</b>
<b>LvAo</b>	<b>0</b>	<b>1</b>	<b>1</b>	<b>0</b>
<b>LvBi</b>	<b>1</b>	<b>1</b>	<b>0</b>	<b>0</b>
<b>LvBo</b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>1</b>

(B)

1. Underline limit valves that change from a 0 state to a 1 state in successive columns as the cylinder sequence is completed.
2. To underline a limit valve in the first column assume repeated/continuous cycling and hence the first column follows the last column.

	A+	B+	A-	B-
<b>LvAi</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b><u>1</u></b>
<b>LvAo</b>	<b>0</b>	<b><u>1</u></b>	<b>1</b>	<b>0</b>
<b>LvBi</b>	<b><u>1</u></b>	<b>1</b>	<b>0</b>	<b>0</b>
<b>LvBo</b>	<b>0</b>	<b>0</b>	<b><u>1</u></b>	<b>1</b>

**Trigger Identification:** Referring to Figure 2 (B), from the first column to the second column two Lv's changed state based on the fact that cylinder A just extended, i.e. LvAi went from 1 to 0 and LvAo went from 0 to 1. The cylinder action heading column two is B+ and this action is only triggered/ initiated after full completion of the previous action, i.e. A+. Therefore the only Lv that provides that information is LvAo changing from a 0 (unactuated) state to a 1 (actuated) state. Therefore any Lv that changes from a 0 to a 1 is automatically identified as a trigger for the next cycle action and can be hooked up to pilot the directional control valve of that cylinder to obtain the desired action. The Lv that went from a 0 to a 1 and is then identified as the trigger is underlined in the Status Table, as shown in Figure 2(B).

**Problem Identification:** No matter how complicated the cylinder sequence, the triggers are always identifiable by the method just discussed above. However the system when hooked up may not operate. In the case of Figure 1 and its completed status table, Figure 2(B), the hookup is successful and the system operates as illustrated in Figure 3. However now look at Figure 4 and this system's completed truth table in Figure 5(A) – this system does not operate. Why? – because locked-on/dependent Lv problems occur as cylinder sequences become more complex, as identified in Figure 5(B).

Locked-on problems will occur when the system cycle requires the extension or retraction of a cylinder while the control signal (from the trigger Lv) on the opposite pilot of the cylinder is still actuated. Since that signal was a pre-existing signal there is equal, pilot pressure on both sides of the cylinders control valve spool, providing equal force and the spool will not move to permit the desired cylinder action. The status (0 or 1) of the locked on valve cannot be changed but if its supply fluid is routed away then even though it is actuated it will not present a problem and the opposite pilot signal can take over and move the cylinder's directional control valve spool to permit the required cylinder action to occur and so the cylinder sequence can progress as desired. It requires checking the status of the trigger Lv's for the opposing actions of each cylinder at the time in the cycle when the opposite action must occur. If the extension pilot Lv of a specified cylinder is still a status 1 at the point in the cycle where it is required to retract this cylinder with the retraction pilot Lv, there is a locked-on/dependent valve problem but if the extension pilot Lv is a status 0 then there is no problem. Similarly, if the retraction pilot Lv of a cylinder is a status 1 when it is required to extend that cylinder then there is a locked-on problem. When a Lv is identified as presenting a problem during a cycle it is circled at that stage of the cycle and labeled with L (locked on valve) at the end of the row. If a Lv does not present a problem during the cycle it is labeled with a P (primary limit valve).

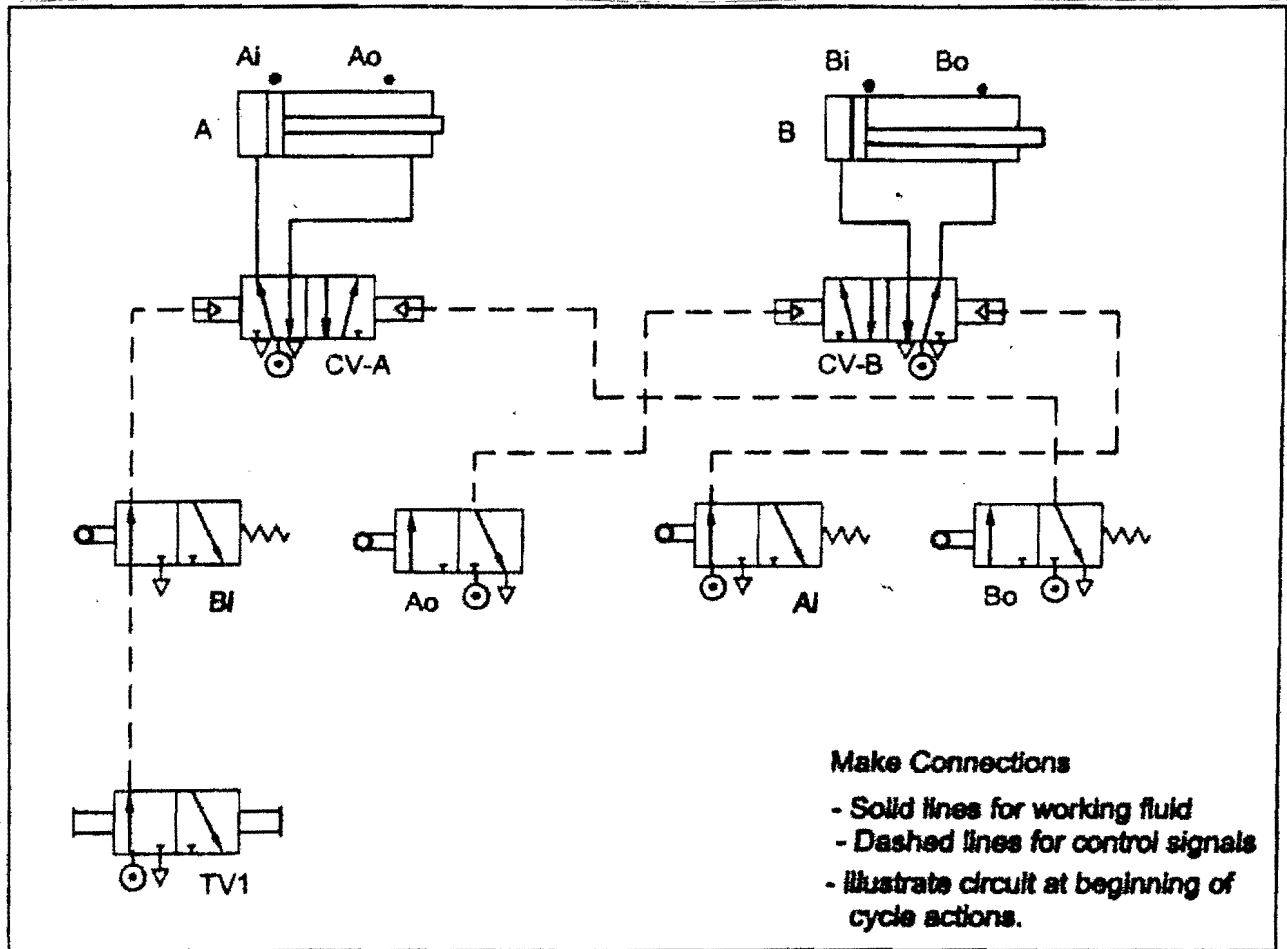
To identify locked-on problems look at the status table of Figure 5(A). Locate the triggers (pilots for B+ and B-) for cylinder B. LvAo tells B to extend and LvBo tells cylinder B to retract. Therefore ask the two questions:-

1. Is the pilot that told B to extend (LvAo) still there (actuated = 1) when it is required that the pilot to tell cylinder B to retract (LvBo) be able to come in the opposite side of CV-B to push the spool over and begin retraction? The answer is found by locating LvAo in the second (B+) column and LvBo in the third (B-) column and intersecting the row and column going forward through the cycle, in effect left to right. The answer is yes and so LvAo is creating a problem and must be identified by circling it in the third column.

2. Is the pilot that told B to retract (LvBo) still there (actuated = 1) when it is required that the pilot to tell cylinder B to extend (LvAo) be able to come in the opposite side of CV-B to begin extension? The answer is found by intersecting the row and column of the same second and third column pilots only this time going right to left assuming continuous cycling and needing to repeat B+ again after B- had been successful in the previous cycle. Therefore a "rectangle" is completed between the rows and columns of the pilots for cylinder B. When intersection is 1 there is a problem (hence circle it) and when intersection is a 0 there is no problem. Repeat this for the pilots of cylinder A: LvAi for A+ and LvBi for A-. There is not a problem going A+ to A- but there is a problem going A- to A+. This is documented in Figure 5(B).

### Figure 3

## Completed System Hook-up for A+ , B+ , A- , B-

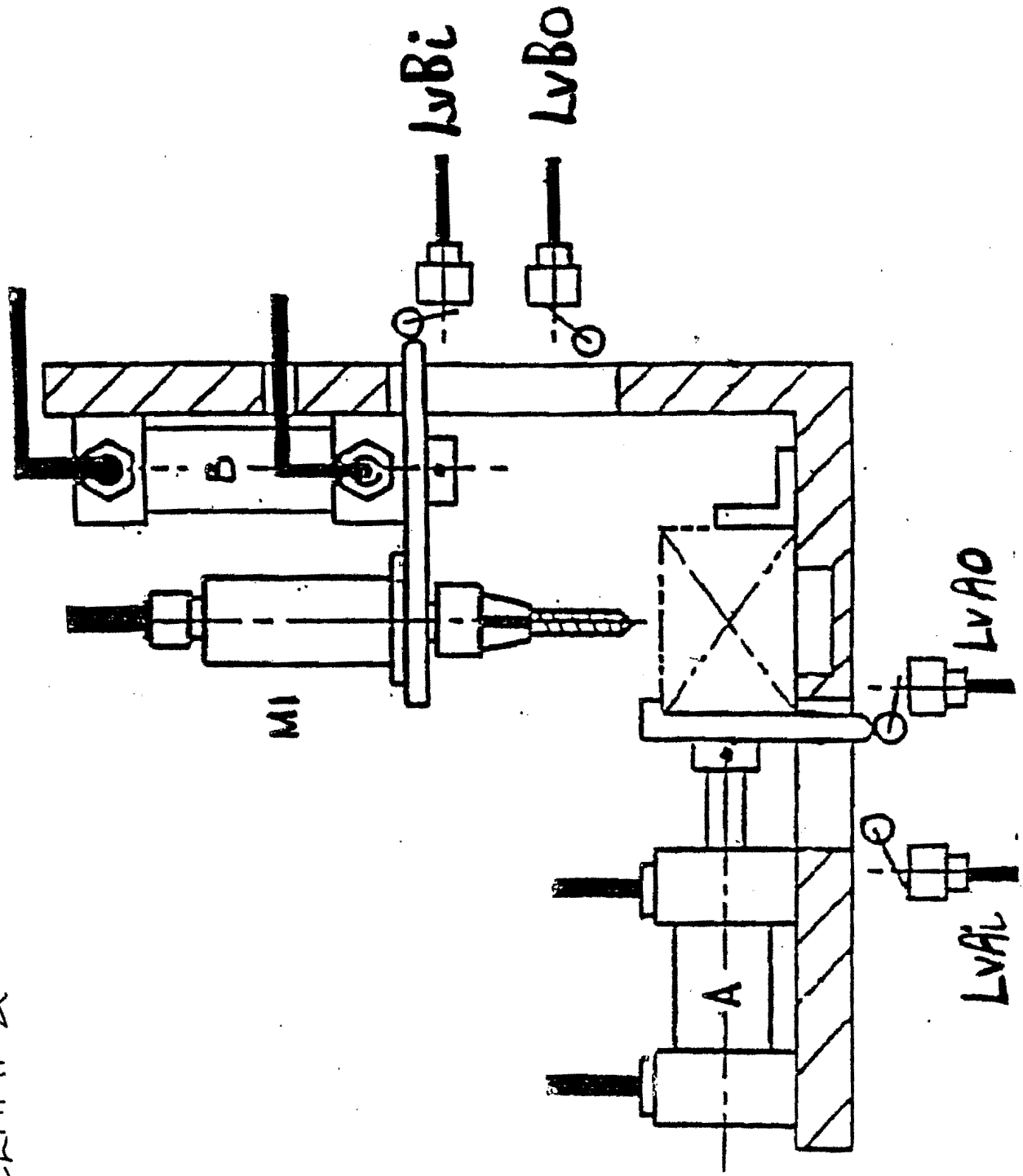


#### Notes:

1. Use the Status Table to identify which limit valves are the triggers for the different cylinder A and B extension and retraction actions.
2. Hook-up the Start/Stop mechanism to the Sequence Initiator, i.e. the limit valve that triggers the first action in the sequence, in this case LvBi which initiates A+.

	A+	B+	A-	B-
<b>LvAi</b>	1	0	0	<u>1</u>
<b>LvAo</b>	0	<u>1</u>	1	0
<b>LvBi</b>	<u>1</u>	1	0	0
<b>LvBo</b>	0	0	<u>1</u>	1

FIGURE 4: CLAMP & DRILL MECHANISM



Lv's that do not present problems. P's (Prime valves), can be supplied from the primary air source manifold whereas the Locked On Lv's. L's, must have their air supply manipulated through another control valve (CV-L). These problem Lv's need to be supplied when they are required to do their trigger actions during the cycle but then that supply must be routed to exhaust when the limit valve is identified (circled in truth table) as presenting a locked on problem during the cycle.

In addition, since the Primary Lv's presented no problems they can be used not only to carry out their own identified (underlined in the truth table) trigger actions but also to manipulate the supply to the Locked-On Lv's. Therefore primary Lv's will also pilot the CV-L's and the locked on Lv's will be supplied through the CV-L. A rule of thumb exists for the number of CV-L's required in a cylinder sequence:

$$\begin{aligned} \# \text{ of CV-L's required} &= [ \# \text{ of Primary Lv's} ] - 1 \\ \text{OR} & [ \# \text{ of Locked-On Lv's} ] - 1 \\ &\text{whichever is least.} \end{aligned}$$

Therefore, since there are 2 Primes and 2 Locked-Ons in this Clamp and Drill example, 1 CV-L is required. As stated above, the Primes will pilot CV-L1. That means LvAi which is actuated right at the beginning of the cycle in column one will come into a CV-L1 pilot at that time (once the Start/Stop mechanism has been actuated). Figure 5(C) illustrates the required CV-L1 set-up. It is arbitrarily set that LvAi goes to the left hand pilot and setups the left hand (LH) envelope. Then the second prime, LvBo, will be actuated in the third column of the status table and will come into the right hand pilot of CV-L1 and set up the right hand (RH) envelope. Therefore the LH envelope of CV-L1 will exist for the first and second time frames and the RH envelope will exist for the third and fourth time frames.

Ask two questions to determine which locked-on limit valve gets connected to which CV-L output:

1. In a certain position (LH or RH) of the CV-L which locked-on limit valve needs to be routed to exhaust because it is causing a problem (circled in the status table)?
2. In the same certain position of the CV-L which locked-on valve needs to be supplied with air because it is underlined and is required to complete a trigger action during that CV-L position?

For this example, the answers are:

1. In the LH position of CV-L (which exists for the first and second time frames in the status table) LvBi is circled in the first column and therefore identified as creating a problem. The supply line for LvBi needs to be routed to exhaust to get rid of this problem, as seen in the graphic of Figure 5(C).
2. In the LH position of CV-L1, LvAo is the other locked on valve which needs to be supplied in the second column/time frame in order to complete it's trigger action and so needs to be connected to supply, as seen in the graphic of Figure 5(C).

The answers are then flipped/reversed when CV-L1 is in the RH envelope which is set-up by the LvBo pilot which comes in at the third time frame/column. In column three, LvAo needs to be routed to exhaust and in column four LvBi needs to be supplied so it can complete it's required trigger action. The switch to the RH envelope of CV-L1 will accomplish this.

Figure 6 illustrates the required valve hook-ups to successfully complete the sequence.

## Figure 5

### Status Table Problem Identification Development

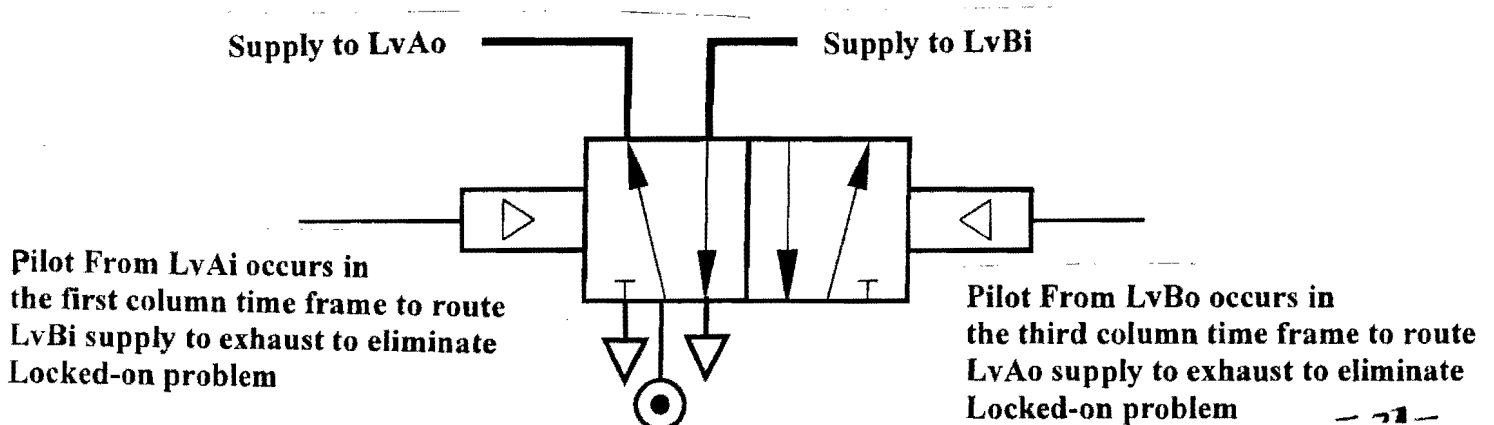
- (A) Status Table for Clamp and Drill Sequence of Figure ; A+, B+, B-, A- Trigger Limit Valves identified with underline.

	A+	B+	B-	A-	
<b>LvAi</b>	<u>1</u>	0	0	0	
<b>LvAo</b>	0	<u>1</u>	1	1	
<b>LvBi</b>	1	1	0	<u>1</u>	
<b>LvBo</b>	0	0	<u>1</u>	0	

- (B) Status Table with Locked-On Problems identified and circled at the time in the cycle when they become a problem.  
 P at end of row indicates a Primary Valve.  
 L at end of row indicates a Locked-On Valve.

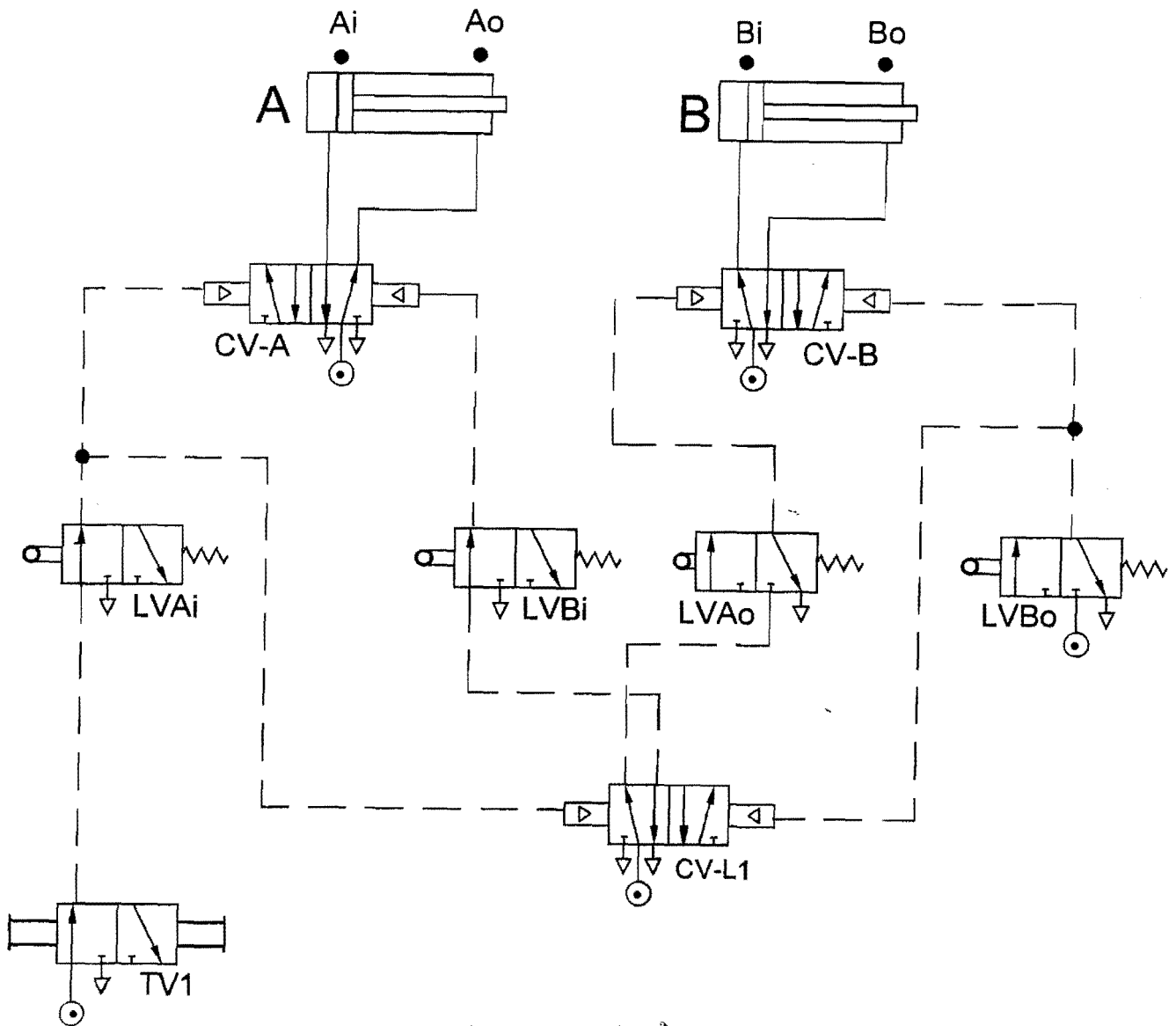
	A+	B+	B-	A-	
<b>LvAi</b>	<u>1</u>	0	0	0	P
<b>LvAo</b>	0	<u>1</u>	①	1	L
<b>LvBi</b>	①	1	0	<u>1</u>	L
<b>LvBo</b>	0	0	<u>1</u>	0	P

- (C) The required CV-L hook-up to control the supply to the locked-on limit valves so that:  
 (i) they will be supplied when they need a supply to allow them to complete a required trigger action (i.e. underlined in the status table) and  
 (ii) they will be routed to exhaust when they are creating a locked-on problem preventing the opposing action of a cylinder from occurring.



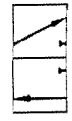
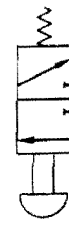
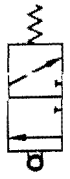
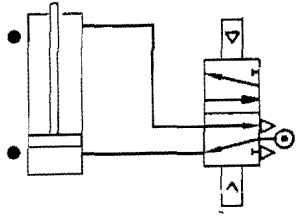
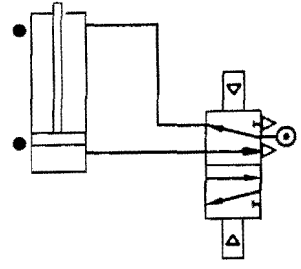
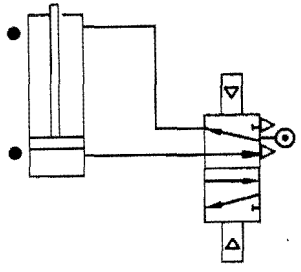
# Figure 6

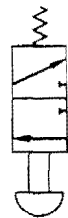
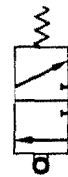
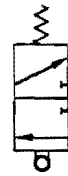
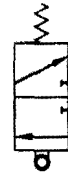
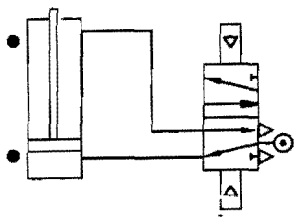
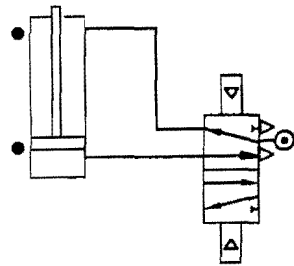
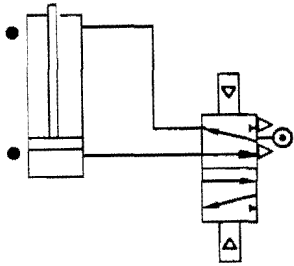
## Complete Hook-up for A+ , B+ , B- , A-



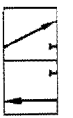
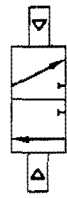
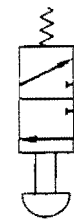
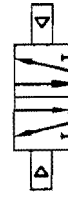
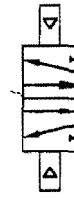
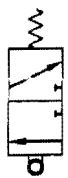
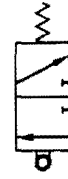
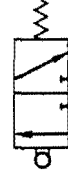
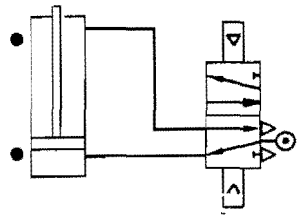
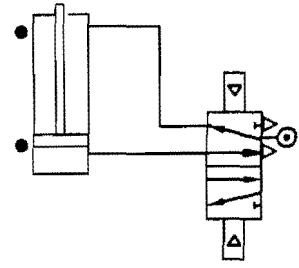
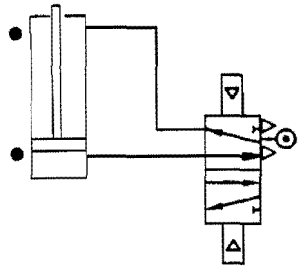
LH of CV-L1 RH of CV-L1

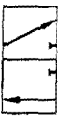
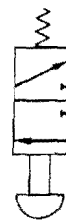
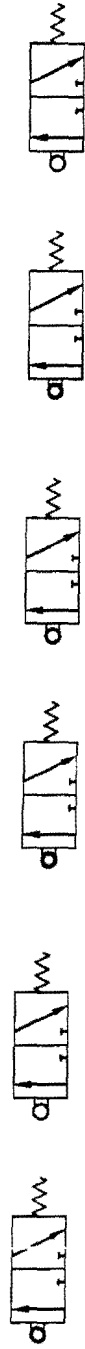
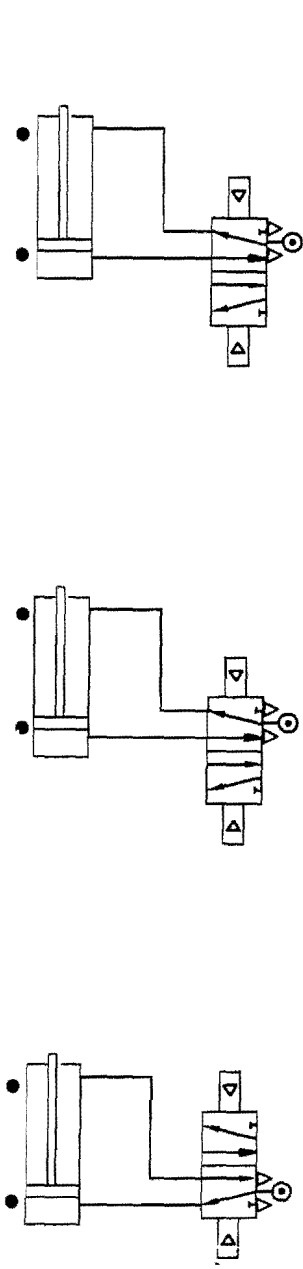
	LH of CV-L1 RH of CV-L1				
	A+	B+	B-	A-	
LvAi	<u>1</u>	0	0	0	P
LvAo	0	<u>1</u>	①	1	L
LvBi	①	1	0	<u>1</u>	L
LvBo	0	0	<u>1</u>	0	P

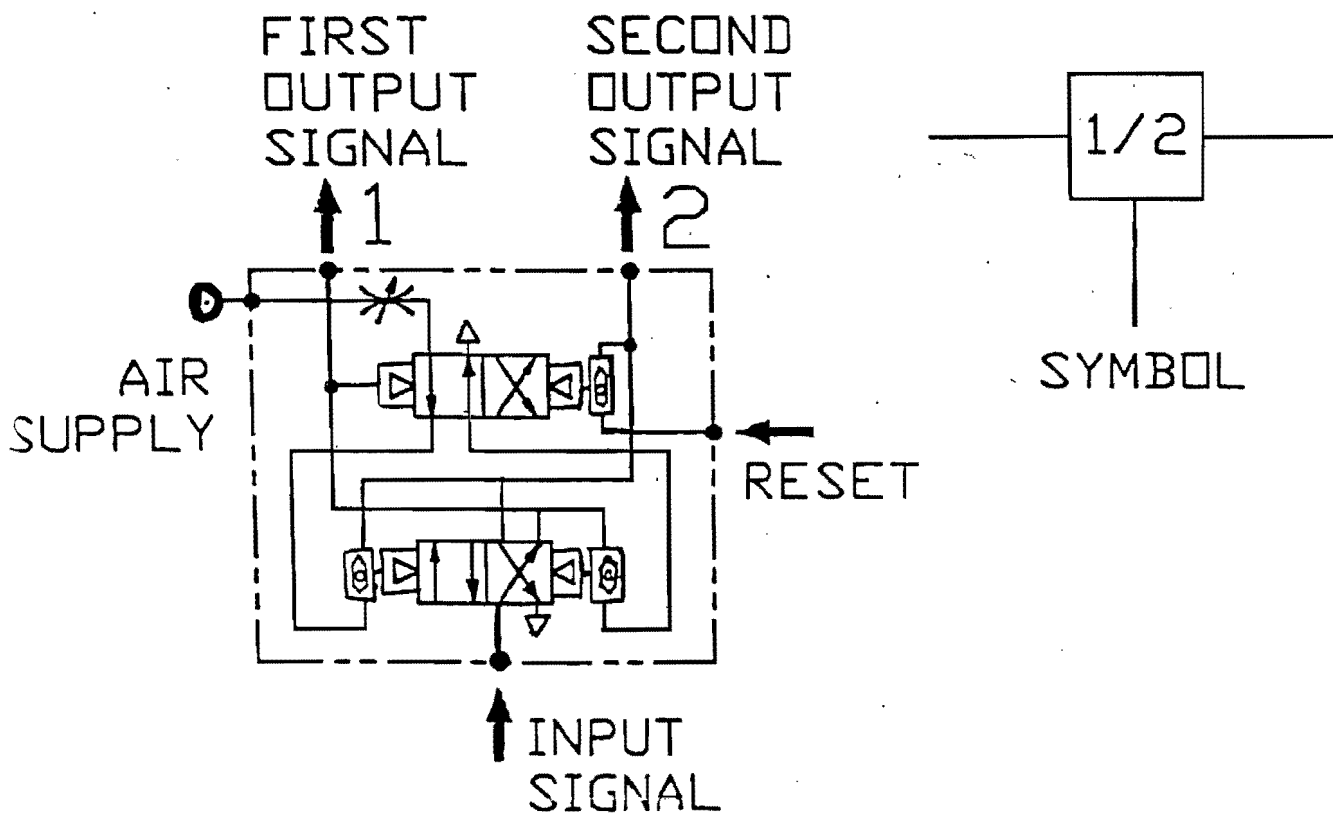
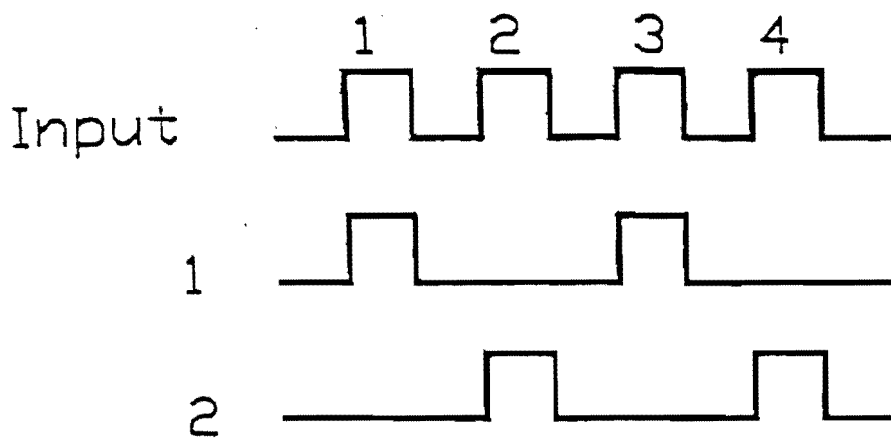




Cascade Logic Worksheet







SELF RE-DIRECT CIRCUIT  
(ONE-TWO COUNT)