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SYSTEM ANALYSIS AND PROTOCOL VERIFICATION BY AN INTERACTIVE PETRI NET PACKAGE

by

XIAOLING QIU

A thesis
presented to the University of Ottawa
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ABSTRACT

In this thesis, I first review the fundamental theory and techniques of basic and extended Petri nets and describe their application in system analysis and verification of communication network protocols. My contribution in this part includes extending and refining the techniques of generating reachability trees from basic Petri nets to token-coloured and predicate/action Petri nets. I also improve techniques for the specification of some protocol components , such as timeout mechanisms and FIFO queues, using Petri net models.

The major work of this thesis is the development of PNPUO, a Petri Net Package developed at the University of Ottawa, as a tool for system analysis and protocol verification. PNPUO is an interactive system with the capability of storing, displaying, modifying, and analysing token-coloured and/or predicate/action Petri nets. It is implemented in PASCAL on an AMDAHL computer under the CMS Operating System . The package automates the analysis process of determining enumerative and structural properties of Petri nets, such as safeness, boundedness, conservation, deadlock freedom, livelock freedom, loops, place invariants, transition invariants, etc.

PNPUO can also be used to verify communication network protocols specified by Petri nets. As illustrations, we have applied it on two well-known protocol systems : the alternating bit protocol and the Connection and Disconnection Phases in Class 1 and Class 2 of the ECMA Transport Protocol. For the first protocol, a predicate/action Petri net is used; and for the second, a basic Petri net and a predicate/action Petri net are used. The analysis results indicate that the design of these two protocols are logically correct. We conclude that PNPUO is a very useful package.

ACKNOWLEDGEMENTS

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Chapter I

INTRODUCTION

Many real-life systems are very complicated to describe, design and implement. Since it is also extremely hard and expensive to correct errors once a system has been implemented, it is important to develop tools for describing and analysing these systems and detecting their errors at an early stage. Automation of these tools will provide invaluable design aids.

There exist many approaches for system modeling and analysis, such as finite state machines, Petri nets, abstract data types, high level languages, temporal logic, etc. [DAIZ82] [DANT80]. As one of the common abstract formal models, Petri nets (PN) are efficient for studying both static and dynamic properties of concurrent systems [MURA77] [RAMA82]. With their simple diagrams for description and powerful techniques for analysis, PN are also used in the modeling of software and hardware systems [NELS83] [PETE77].

In particular, communication network protocols are systems with a high degree of concurrency. Their specification, verification and testing have become important research topics recently. Petri nets have been

applied in these fields lately. Most of these works use basic Petri nets to model simple protocols [BERT82] [TANE81]. A few articles are devoted to the specification of complicated protocols using numerical Petri nets [BILL82] or to their verification using a special type of predicate/action Petri nets [COUR84] [JURG84].

As the size of the Petri nets increases, complexity of the model grows rapidly and analysis by manual processes becomes extremely long and tedious. It is useful to have a software tool for automating the processes. As far as we know, there exists only one such tool, called OGIVE [COUR8]. This system is commercially available only to a limited group of users in the business world. There are very limited publications, especially about its implementational and operational details. It can not handle Petri nets with predicates and actions. In this thesis, we develop another PN package for research purpose. It can handle Petri nets with more general types of predicates and actions, as well as the token-coloured Petri nets, which OGIVE cannot handle.

This thesis begins with a review of the underlying theory and techniques of several types of Petri nets. We then improve the technique of generating reachability trees. Our major work is the design and development of an interactive Petri net package, called PNPUO -- a Petri Net Package developed at the University of Ottawa, to be used as a

computer-aided design tool. This tool provides the users with the facilities of storing, displaying, modifying, and analyzing Petri nets. Using PNPUO, we have specified and analyzed two practical protocols, the alternating bit protocol and the Connection and Disconnection Phases in Classes 1 and 2 of the ECMA Transport Protocol.

Chapter 2 reviews the fundamental techniques and properties of basic Petri nets and many types of more powerful Petri nets extended from the basic one, namely token-coloured Petri nets, predicate/action Petri nets, timed Petri nets, Petri nets with inhibitor arcs, etc. We then extend the transition firing rules and the methodology for generating reachability trees from basic PN to token-coloured and predicate/action PN. This chapter also describes two techniques for analysis, namely reachability analysis and incidence analysis, by which one can derive the enumerative and structural properties of a Petri net.

A vast amount of research work has been done in the application of Petri nets to protocol modeling and verification. Chapter 3 reviews briefly some of these contributions related to our thesis. It also includes our study in the modeling of channels with flow control, FIFO queues for more than one message and the modeling of timeout mechanism with basic Petri nets.

Chapter 4 gives the implementation details, the system environment and user interface of PNPUO. It consists of four main modules: CREATE, DISPLAY, MODIFY and ANALYSIS. System analysis uses our extended method for generating reachability trees. We also present the application of PNPUO to a simple PN for the purpose of explaining the operational steps of this package. At the end of this chapter, we propose some aspects of improvements on PNPUO for further study.

Chapter 5 concentrates on the application of PNPUO to the verification of logical correctness of protocol systems. Two examples are considered: a data link protocol and a transport protocol. We develop a predicate/action PN model for the first protocol so that the 'time-out' function can be realized easily. For the second protocol, we use the same PN model as described in [BERT82] Our analysis results confirm those obtained manually in [BERT82]. Our experience shows that PNPUO is an efficient package and useful for protocol verification. A program listing of PNPUO is attached in the Appendix.

Chapter II

SYSTEM ANALYSIS BY PETRI NETS

Since its inception in 1962 [PETR62] as an abstract formal model, Petri nets (PN) have been applied to many areas of system science. In this chapter, we explain the techniques of analysing a general system specified by means of Petri nets. We first present the basic terminology, properties and fundamental theory of Petri nets in Section 2.1. Different extensions from basic Petri nets are then given in Section 2.2. In particular, based on the theory of basic Petri nets, we develop the rules for firing transitions and the method for generating reachability trees for coloured PN and predicate/action PN. The techniques for system analysis by PN are explained in Section 2.3.

2.1 BASIC PETRI NETS

We first describe the components of and the operations on basic Petri nets. As shown in Figure 2-1, a Petri net is denoted as a directed graph with two types of nodes, circles (called places) and bars (called transitions). These nodes are connected by directed arcs from places to transitions and from transitions to places. A transition represents an event, while its input and output places

indicate the enabling and the resulting conditions of the occurrence of that event, respectively. Tokens, denoted by the existence of dots in the places, imply the fulfillment of the corresponding conditions.

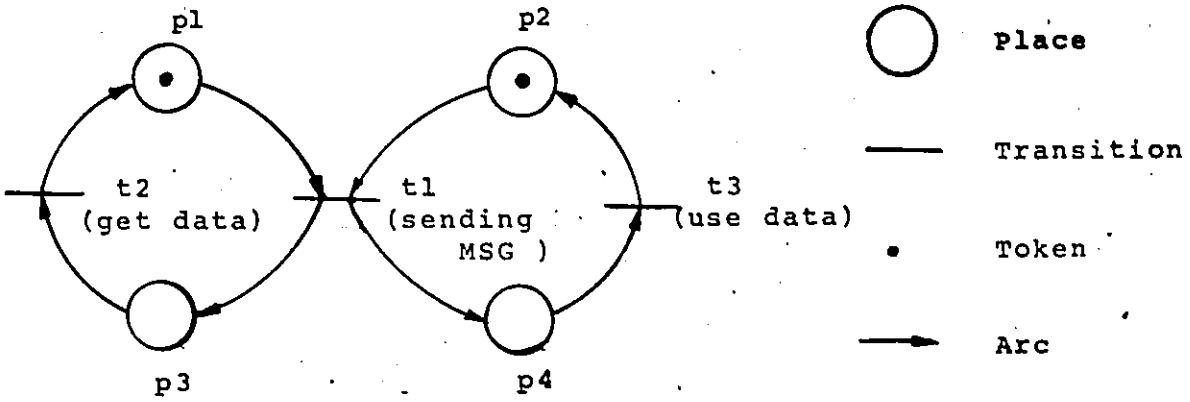


Figure 2-1: A Simple Petri Net

Some formal definitions, concepts and properties about basic Petri nets [BERT82] [HOPC79] [MAGO84] [PETE77] [PETE81] [SYMO8] are given below.

2.1.1 Definitions

Definition 2-1

A Petri net (PN) is a 5-tuple (P,T,PRE,POST,M0) , where

P is a set of places $\{p1,p2,\ldots pm\}$, $m >= 0$,

T is a set of transitions $\{t1,t2,\ldots tn\}$, $n >= 0$,

where $P \cap T = null$,

PRE : $P \times T \rightarrow N$ is the forward incidence function defined on the set of arcs leading from places to transitions ,

where $N = \{0,1,2,\ldots\}$,

POST : $P \times T \rightarrow N$ is the backward incidence function defined on the set of arcs leading from transitions to places,

M0 : $P \rightarrow N$ is the initial marking (see Definition 2-2).

Notes on Definition 2-1

In particular, for basic Petri nets, $N = \{0,1\}$. Thus, we have :

$$PRE(p,t) = \begin{cases} 1 & \text{if there is an arc from place p to transition t} \\ 0 & \text{otherwise .} \end{cases}$$

$$POST(p,t) = \begin{cases} 1 & \text{if there is an arc from transition t to place p} \\ 0 & \text{otherwise .} \end{cases}$$

Example 2-1

In Figure 2-1 ,

$PRE(1,1) = 1$, $PRE(1,2) = 0$,

$POST(1,1) = 0$, $POST(1,2) = 1$.

Definition 2-2

A marking M is an m-vector denoting a distribution of tokens in the places. Notationally, M = (M(p1),M(p2),... M(pm)), where M(pi) is the number of tokens residing in place pi .

An initial marking M0 is the marking of the Petri net at an initial moment.

Examle 2-2

In Figure 2-1 , initial marking M0 = (1,1,0,0) .

Definition 2-3

The set

$$.t = \{ p \mid p \in P \text{ and } PRE(p,t) \neq 0 \}$$

(resp., $t. = \{ p \mid p \in P \text{ and } POST(p,t) \neq 0 \}$)

is called the set of input (resp., output) places of transition t .

The set

$$.p = \{ t \mid t \in T \text{ and } POST(p,t) \neq 0 \}$$

(resp., $p. = \{ t \mid t \in T \text{ and } PRE(p,t) \neq 0 \}$)

is called the set of input (resp. output) transitions of place p.

Exaple 2-3

In Figure 2-1 ,

.t1 = {p1,p2} , t1. = {p3,p4},

.p1 ={t2}, p1. ={t1}.

Definition 2-4

The incidence matrix of a PN is an mxn matrix

$$C = (cij)$$

where cij = POST(pi,tj) - PRE(pi,tj) .

Example 2-4

For Figure 2-1 , the incidence matrix is

$$C = B - A = \begin{bmatrix} -1 & 1 & 0 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix}$$

where $$A = (PRE(pi,tj)) = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and $$B = (POST(pi,tj)) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

Definition 2-5

A transition t is said to be enabled for a marking M, if $M(p) >= PRE(p,t), \quad \forall p \in .t$.

Example 2-5

For Figure 2-1, M0 = (M0(p1),M0(p2),M0(p3),M0(p4)) = (1,1,0,0), PRE(p1,t1) = PRE(p2,t1) = 1. Thus, t1 is enabled for marking M0.

2.1.2 Execution of PN

A Petri net is executed by firing one of its transitions. A transition may be fired if it is enabled. The firing of transition t for a marking M leads to a new marking M´ . The operation can be mathematically expressed as

$$M \ (\ t \ > \ M'$$

where $M'(p) = M(p) - PRE(p,t) + POST(p,t) \ , \ \forall p \in P.$ (1)

Equation (1) is called the firing equation for transition t.

Example 2-6

In Figure 2-1, if M0 = (1,1,0,0), then t1 is enabled. The new marking obtained by firing t1 is M´ = (0,0,1,1) .

There are two simple rules concerning the firing of transitions:

i) Only one transition of the PN may fire at a time, and the whole firing process of a transition is indivisible. This means that the process of firing a transition cannot be interrupted. Therefore, we can assume that the firing of a transition occurs at a single instant.

ii) If, at one moment, more than one transition is enabled, the transition selected for firing is not specified in the PN itself. The selection is usually determined by the application under consideration.

Suppose a sequence σ of firing transitions leads a PN from marking M to M'. The new marking M' is given by the following matrix equation:

$$M' = M + C \cdot \bar{\sigma}$$

where C is the incidence matrix of the PN ,

$\bar{\sigma}$ = ($\bar{\sigma}1$, $\bar{\sigma}2$,... $\bar{\sigma}n$) is the firing vector of the transition sequence σ = (tj1,tj2,... tjk) , with 1 <= ji <= n , 1 <= i <= k , i.e., $\bar{\sigma}i$ is the number of occurrences of ti in sequence σ.

Execution halts when no enabled transitions exist. The reachability set of a marking M , denoted by [M] , is the set of markings each obtained from marking M by firing a transition sequence σ.

$$[M] = \{M' \mid M\ (\sigma > M',\ \sigma \in T^*\}$$

where T^* is the Kleene closure of T .

The reachability set of the initial marking M0 , denoted as [M0] , is called the reachability tree of the PN.

Example 2-7

In Figure 2-1, for M0 = (1,1,0,0), the reachability tree is shown in Figure 2-2 .

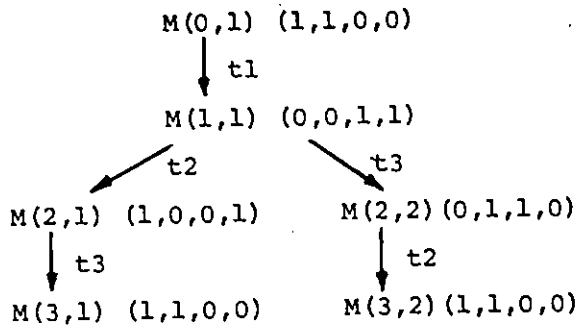


Figure 2-2: The Reachability Tree of the PN in Figure 2-1

2.2 EXTENSIONS OF PETRI NETS

Basic Petri nets are quite limited in their capabilties in modeling for real-life systems. Limitations include the following restrictions :

i) Only one type of token can be used.

ii) It is complicated to express certain constraints on events.

iii) It has no facility for delineating time-related factors of a real-life system .

Several proposals have been put forth for increasing their modeling power, such as PN with constraints, multiple arcs, exclusive-OR transitions, switches, inhibitor arcs, priorities, token colours and times [PETE77] [PETE81]. In the following subsections, we describe some of the better developed models, as illustrations of the diversity of Petri net's extended modeling capabilities. They include :

a. Token-coloured PN ;

b. Predicate/Action PN ;

c. Timed PN ;

and d. PN with Inhibitor Arcs .

More types of models may be obtained by combining some of these types. Numerical PN (NPN), for instance, can be taken as a combination of token-coloured PN and predicate/action PN. NPN and token-coloured predicate/action PN are equivalent [DAIZ82].

2.2.1 Token-coloured PN

In a token-coloured PN, tokens are allowed to have different natures (represented in terms of colours) and values.

Example 2-8 [JENS80]

As an example, we consider the dining philosophers problem (for 5 philosophers). The philosophers alternately think and eat. To eat, a philosopher needs two forks, but unfortunately there are only five forks on a circular table and each philosopher is allowed to use only the two forks one on each of his sides. Obviously two neighbours cannot eat at the same time.

Figure 2-3 shows a predicate/action PN description for this problem. It uses 10 token-colours to distinguish the 5 philosophers and the 5 forks. In this figure, $i \oplus 1$ means (i+1) mod 5. If a philosopher pi is in the place 'THINK' and his two forks fi and fi+1 are in the place 'FREE FORKS', then he can eat, i.e., transition t1 can be fired.

The marking M of a token-coloured PN has become a matrix :

$$M = (M(p,k)) ,$$

where M(p,k) is the number of tokens with the kth colour in place p.

The forward and backward incidence functions have three independent variables :

PRE(p,t,k), POST(p,t,k),

where k denotes the kth colour of the tokens.

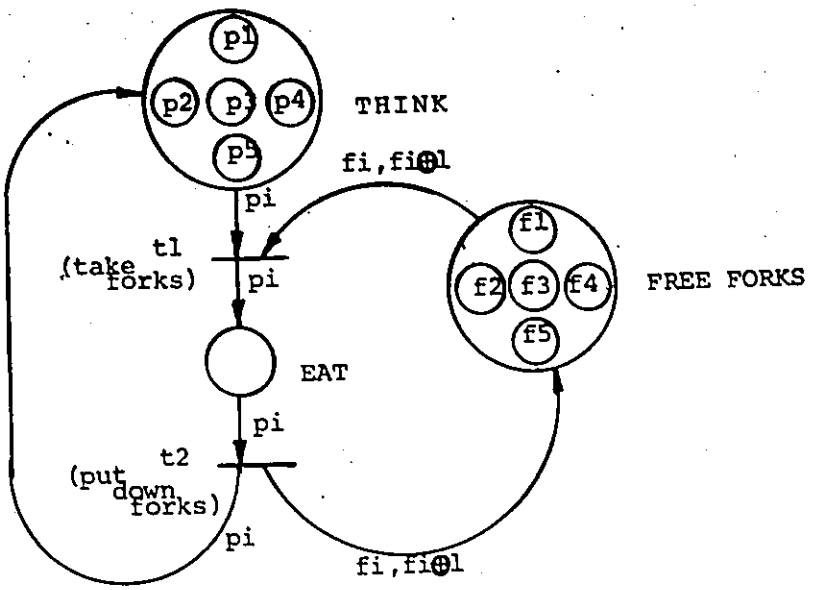


Figure 2-3: A Token-Coloured PN for the Dining Philosophers Problem

A transition t is thus enabled under a more complicated condition :

$$M(p,k) >= PRE(p,t,k) \ , \ \forall p \in P \quad \text{and} \quad \forall k \ .$$

This type of PN is also known as place-coloured PN [DAIZ82]. It has been used for modeling different types of messages in information flow [BILL82].

2.2.2 Predicate/Action PN

In this type of PN [DAIZ82], predicates are associated with transitions and their input places, as additional conditions for the fireability of the transitions; and actions are associated with transitions, as operations to be done after firing the transitions. The predicates and

actions are expressions with numeric and/or logical variables describing the system.

The markings, arcs, and incidence matrices for a predicate/action PN are the same as for a basic PN. However, the fireability conditions and firing operations of a transition are changed from what are in basic PN to the following.

The conditions for firing a transition t include:

i) $M(p) >= PRE(p,t)$, $\forall p \in P$,

and ii) all the predicates associated with t and $\forall p \in .t$ should be true.

On firing transition t, the following operations are executed :

i) $M'(p) = M(p) - PRE(p,t) + POST(p,t)$.

ii) All the actions associated with t are carried out.

Example 2-9

Figure 2-4 is a predicate/action PN taken from [BILL82] , in which t1 is attached with predicate [Z=K] and t2 with action Y := Y + 1. On firing t2 , not only p3 and p4 each get a token, the value of variable Y is also increased by 1. At this moment, the value of variable Z should be equal to constant K in order to fire t1.

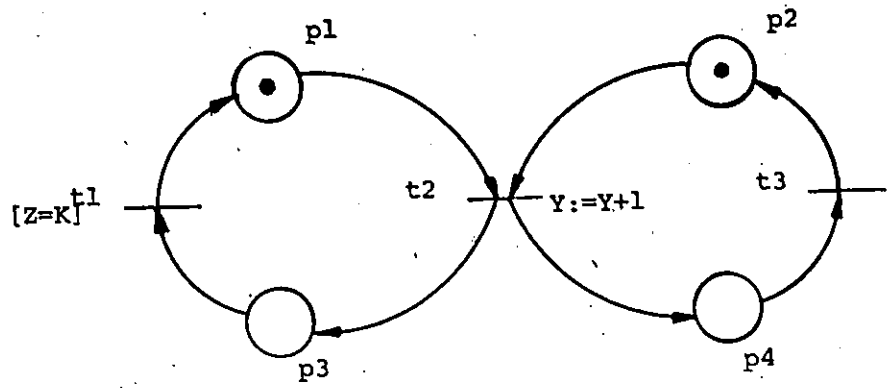


Figure 2-4: An Example of Predicate/Action PN

2.2.3 Timed Petri Nets

There are two different approaches to extending basic PN to this particular type. In the first approach, called Timed PN, a non-negative rational number is attached to each transition in the PN to denote its firing duration. In [MAGO84], it is used for evaluating the cycle time of a PN within which the PN changes its states from the initial marking M0 to M0 again by firing a transition sequence.

In the second approach [DAIZ82] [MERL76a], called Time (out) PN, each transition is associated with a pair of values [t*,t**], where t* is the minimal time that the transition, after being enabled, must wait before it can be fired; t** is the maximal time before which the transition must be fired, if it is still enabled. This approach is useful for modeling recoverable systems [MERL76a]. That is, there are some transitions used for recovering the loss of

tokens (representing lost messages in information flow). We will explain the application of TPN for specifying the timeout mechanism of communication protocol systems in Chapter 3.

2.2.4 Petri Nets with Inhibitor Arcs

A Petri net with inhibitor arcs is another major extension from basic PN [PETE81] [SCHW82]. An inhibitor arc is denoted by an arc with a small circle at its arrowhead [PETE81], such as the arc from p5 to t4 in Figure 2-5. It presents the condition that transition t4 cannot be enabled unless M(p5) = 0 .

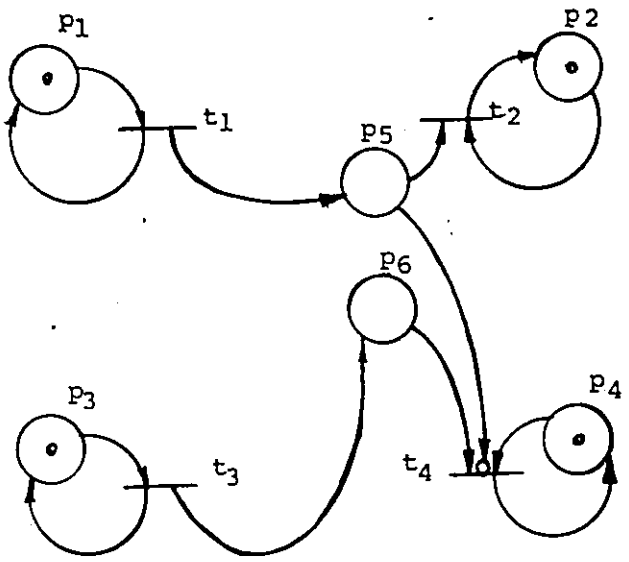


Figure 2-5: A PN with An Inhibitor Arc

Some other extensions of PN, including the introduction of priorities among transitions, time bounds on transition

firings, or constraint sets that prohibit tokens from residing simultaneously in more than one place, are equivalent to PN with inhibitor arcs [PETE77].

A PN with inhibitor arcs can be converted into a basic PN with only general arcs [MOAL78]. Petri nets with inhibitor arcs, therefore, can be analyzed by using the same techniques as for basic PN and applying our package PNPUO (see next section and Chapter 3).

2.3 ANALYSIS BY PETRI NETS

This section discusses how to analyse a general system by applying the techniques of PN. The aim is to determine the presence or absence of desirable or undesirable properties. This provides important insights into the behaviour of a system.

2.3.1 Problems for Analysis

Before presenting the techniques for analysis, we first classify the properties of a PN according to three aspects: token-related properties, execution-related properties, and structural properties.

(1) Token-related properties include safeness, boundedness, and token conservation [PETE81]. They are defined below.

Definition 2-6

A PN is safe if the number of tokens in each place never exceeds 1. That is,

$$M(p) <= 1 \ , \ \forall p \in P \ , \ \forall M \in [M0] \ .$$

Definition 2-7

A PN is bounded if there exists an integer K >= 0 which the number of tokens in each place never exceeds. That is,

$$M(p) <= K \ , \ \forall p \in P \ , \ \forall M \in [M0] \ .$$

Definition 2-8

A PN is conservative if the total number of tokens in the net remains constant, that is

$$\sum_{p \in P} M(p) = \sum_{p \in P} M0(p) \quad , \quad \forall M \in [M0] \ .$$

(2) Execution-related properties include liveness and reachability. A PN is live if for any marking $M' \in [M0]$ and any transition $t \in T$, there always exists at least one sequence of transitions including t can be fired from M. The liveness of a PN concerns the following status of its markings :

Deadlock - In this status, no transition can be fired.

Livelock - In this status, marking M is included in an execution loop without any transition leaving the loop.

Live-looping - In this status, marking M is included in an execution loop which has at least one possible transition leaving the loop.

Home-state - In this status, Marking M is the same as the initial marking, i.e., M = M0, but is not the root of the reachability tree.

Another important concern in analysis is the reachability problem [PETE77] : Given a PN and a marking M, is M reachable from M0? An algorithm and an excellent review for the general Petri net reachability problem appears recently in [MAYR84].

(3) Structural Properties

The structure of a PN is conveyed through place invariants and transition invariants of the net. A place invariant states that, during execution of a PN, the total number of tokens within a specific subset of places remains constant. A transition invariant represents a sequence of firing transitions which have no effects on a marking M [BERT82], i.e., M (σ > M .

2.3.2 Techniques for Analysis

There are two major techniques for analyzing systems described by Petri nets : enumerative analysis and structural analysis [JURG84]. The first technique is based on executing the PN and generating its reachability tree. The second is related to the structure of the net and the existence of place and transition invariants. More explanation is given below.

Enumerative Analysis

The reachability tree of a PN has its root at the initial marking M0. Its nodes represent the reachable markings and its arcs are labelled with the transitions fired.

The reachability set of a PN may be finite or infinite. To reduce an infinite reachable set to a finite representation, the symbol ω is used to map many markings into one node of the reachability tree. That is, if the number of tokens in a place becomes arbitrarily large during execution of the PN, then we use ω to represent the number of tokens in that place [PETE77] [PETE81]. Section 4.4 includes an example of a PN whose reachability set uses the symbol ω.

The procedure of enumerative analysis begins with generating the reachabilty tree. The generated markings (i.e., nodes of the tree) are checked. If a marking is in

the status of deadlock, or livelock, or live looping, or home-state, it is set as a terminal node, a leaf of the tree. Other nodes are called internal nodes.

The reachability tree provides an overview of the Petri net states (markings). From its nodes, all the token-related properties (safeness, boundedness, conservation) are easily detected. Liveness of the net is also observable from its leaves (possibly a deadlock, livelock, etc.).

Structural Analysis

In structural analysis, we get two sets of invariants (if they exist) - place invariants and transition invariants. Interpretation of these invariants is problem-dependent. Examples for protocol verification are given in Chapter 5.

(1) Place invariants are the solutions of the matrix equation

$$\Phi \cdot C = 0 \ ,$$

where o is an m-vector (m is the total number of places of the PN) and C is the incidence matrix of the PN. Suppose R is a solution of this equation, and for any new marking M' obtained by firing a sequence of transitions σ from a marking M, we have $M'=M+C\cdot\sigma$. Then by left multiplying both sides by R, we get

$$R \cdot M' = R \cdot M + R \cdot C \cdot \bar{\sigma} = R \cdot M.$$

This equation implies that, if the values of the components of R are 1 or 0, the total number of tokens in the places associated with the non-zero conponents of R remains constant. Thus, we can say that a place invariant corresponds to a set of places where the total number of tokens is constant.

(2) Transition invariants are the solutions of the equation $C \cdot \Omega = 0$. A transition invariant is related to a transition sequence which has no effects on the marking. Let S be an n-vector solution to this equation, Suppose σ' is the sequence of transitions corresponding to S, then $\vec{\sigma}' = S$. For the new marking M' obtained by firing σ' from a marking M, we have $M' = M + C \cdot \vec{\sigma}'$. Since $C \cdot \vec{\sigma}' = C \cdot S$, we get $M' = M$. Therefore, firing the transition sequence σ' has no effects on anv marking. This means that S is a transition invariant of the PN.

Thus, structural analysis involves essentially solving two linear algebraic equations $\Phi \cdot C = 0$ and $C \cdot \Omega = 0$.

Chapter III

PROTOCOL SPECIFICATION AND VERIFICATION BY PETRI NETS

Communication network protocols are extremely complicated distributed systems. They are prone to a lot of design errors, such as deadlocks, unspecified receptions, etc. It is very useful to have some formal methods for their modeling and verification so that they can be clearly specified and their design errors can be detected before implementation.

Because of their powerfulness for mathematical manipulation and for describing concurrency of systems, Petri nets, including their extensions, have been found as suitable tools for modeling and analysing the behaviours of both the control aspect (connection and disconnection) and the data transfer aspect of communication protocols.

This chapter reviews briefly the methods of applying PN to the specification of protocols and verification of their logical correctness. Though one of the main themes of this thesis is protocol verification, we consider also models for specification, as methods for verification are besed on these models. The review provides the background knowledge for our applying PNPUO, an interactive Petri net package we

developed at the University of Ottawa, to the verification of protocols. Section 3.1 addresses the basic concepts of protocol specification and verification. Section 3.2 explains how to use various PN models in the specification of protocol entities, virtual media and error recovery mechanisms. Section 3.3 discusses the PN models for service specification. In Section 3.4, enumerative and structural analysis techniques for protocol verification are explained.

3.1 SPECIFICATION AND VERIFICATION OF PROTOCOLS

This section presents the concepts of protocol specification and verification.

According to the OSI Reference Model, each communicating system is organized as a hierarchy of up to seven layers. A protocol is a set of rules for governing the orderly exchange of control and data messages among a number of peer entities residing in these communicating systems [ISO81a] [TANE81].

In fact, messages are not directly transferred between entities of the same layer (except at the lowest layer). Instead, a message at layer N+1 is passed on to the lower layer by using the service primitives provided by layer N (i.e., operations at the interface between layer N+1 and layer N). The set of primitives provided by layer N to its user at layer N+1 and their way of operations forms the layer N service. Figure 3-1 illustrates this concept.

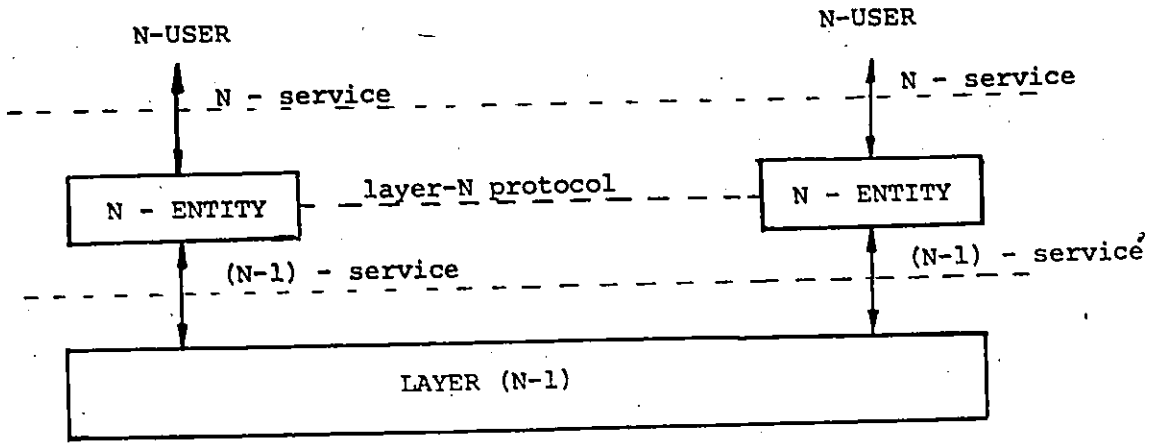


Figure 3-1: Service at Layer N

A service specification defines these service primitives provided by layer N. It describes only those operations executable by the user at layer N+1.

A protocol specification describes the interactions between peer layer N entities via the layer (N-1) service. According to Courier [COUR84], it should include the following three aspects:

a. Specification of the Communicating Protocol Entities
   This describes the specific interactions between the entities at the same layer [COUR84] [DAIZ82] [SIDH82].

b. Specification of the Communicating Virtual Medium
   This is required because entity interactions more or less depend on the behaviour of virtual medium.

c. Specification of the Recovery Mechanizm

Protocol systems use recovery mechanisms such as time-out to recover from failures.

There exist many modeling tools for specifying protocols, such as finite state machines, Petri nets, abstract data types, high level languages, temporal logic, etc. [DAIZ82] [DANT80]. In Section 3.2, we shall describe some well-known Petri net models for this purpose.

The objective of verifying a protocol is mainly to demonstrate its logical correctness and its conformance with the service specification. Logical correctness of a protocol includes the following aspects [PETR] [SIDH82]:

Freedom from Deadlocks - The entities never get into a state in which no more message transmissions or receptions are possible.

Livelock Freeness - The entities never get into any non-progressive loop of states.

Correct Termination - If started from the initial state of the protocol, the entities always reach the initial state again.

Freedom from Channel Overflow - The total number of messages in each channel does not exceed a fixed number (channel capacity).

If a protocol conforms with the service specification, it should provide the services to the upper layer entities in the specified manner.

3.2 PROTOCOL SPECIFICATION USING PN MODELS

This section describes several existing PN models for the specification of protocol components: protocol entities, virtual media, error recovery mechanizms, etc.

3.2.1 Specification of Protocol Entities by PN

Depending on its functions, a protocol entity may be considered as a Sender or as a Receiver. Three major types of PN models have been used for their specification: basic PN models, predicate/action PN models, and Timed PN models.

(1) Basic PN Models (BPN)

Figure 2-1 can also be viewed as a basic PN model for a pair of Sender and Receiver. The left part (p1, p3, t1, and t2) describes the Sender, the right part the Receiver. Here, t1 indicates 'sending a message'; t2 represents 'get the data'; and t3 is for 'consume the data'.

Basic Petri net (BPN) models have been used for specifying several protocol systems recently. Tanebnaum [TANE81] presented a BPN model for the alternating bit protocol at the data link layer. Berthelot and Terrat [BERT82] introduced a BPN model for the transport layer entities (Connection and Disconnnection Phases). These two models will be used for analysing protocols in Chapter 4. They will be described in details later.

It is intuitive and convenient to verify protocols, specified by BPN models, using the general analysis methods of Section 2.3. However, if a protocol is complicated, its BPN model will be considerably large and tedious to handle. The situation will be improved if we employ some predicates and actions in the model to represent constraints and events.

(2) Predicate/Action PN Models

Predicate/action PN models can be used for modeling local protocol entities. As a special form of predicates and actions, specific notation is used by Ayache [AYAC82] and Courtiat [COUR84] for exchanging messages:

p?m means reception of message m sent by entity p;

p!m means transmission of message m to entity p .

p!m is associated to the transitions of the entity 'Sender' as an action 'sending a message', p?m to the transitions of the 'Receiver' as a predicate 'receiving a message'. Their CAD protocol verification system OGIVE works on these types of predicates and actions only.

By using predicates and actions, an extended PN becomes a better model for complicated protocols. Methods for analysis, however, are not so simple, as they cannot be extended directly from the methodology of basic PN. More elements have to be taken into account during the process of

reachability analysis : all the predicates and actions, the values of all the variables which are involved in the expressions of the predicates or actions (see Section 2.2).

(3) Timed PN Models

Both the basic PN model and predicate/action PN model do not describe the time-related properties of protocols, such as time-out, time delay, and cycle time.

Obviously Timed PN models have advantages in this respect, since they have included the firing time period of every transition in the Petri net. It is easy to calculate the time delay and to realize the function of timeout mechanizm. Many research papers are devoted to the application of timed PN to protocol specification and analysis [MAGO84] [MENA83] [MERL76a]. A typical TPN model for an alternating bit protocol is introduced by Menasche [MENA83]. In this model, as shown in Figure 3-2, places p1, p2, p3, p4 and transitions t1, t2, t3, t4, t5, t6 on the left form the Sender, those on the right form the Receiver, and the central part is the channel. Each transition is associated with a time duration. For example, the time duration [5,6] is associated with the timeout transition t2, meaning that retransmission of a message must take place in a time interval between 5 and 6 units after the last copy of the message has been sent.

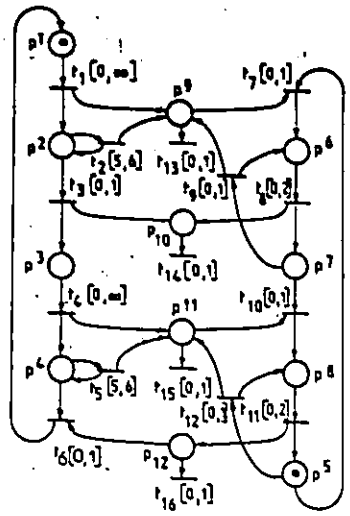


Figure 3-2: A TPN Model for the Alternating Bit Protocol

3.2.2 Specification of Virtual Media by PN

In a specification of media, we may make different assumptions on the virtual medium: perfect medium, 'messages may be lost', 'messages may be duplicated', FIFO, bounded capacity of the channels, etc. There exist several methods for specifying the medium, such as direct coupling, virtual channel and distantly initiated action. In the following, we describe these methods in terms of Petri net models.

(1) Direct Coupling

Direct coupling is a technique in which a pair of labels !m and ?m are attached with two transitions, one in the Sender and the other in the Receiver, as an indication of the transfer of message m. We say that these two transitions are coupled, meaning that no explicit component in the model

is used to describe the virtual medium. The event 'message loss' can be specified by labelling a transition with !m in Sender without coupling with any transition in the Receiver [AYAC82] [COUR84].

(2) Virtual Channels

This approach is based on explicit modeling of any message in transit. The behaviours of the communication medium mentioned at the beginning of this subsection are specified as follows.

a. Perfect Medium and Medium Allowing Loss of Messages

If a medium is assumed to be perfect, there are no transmission errors. This is specified by using a set of places shared by two peer entities. As shown in Figure 3-3a, for each transfer direction, each place is related to a certain type of messages. A token inside a place indicates the existence of the corresponding message.

If loss of messages is possible, it is required to add and connect a transition without output places, called 'loss' in Figure 3-3b, to each of the shared places.

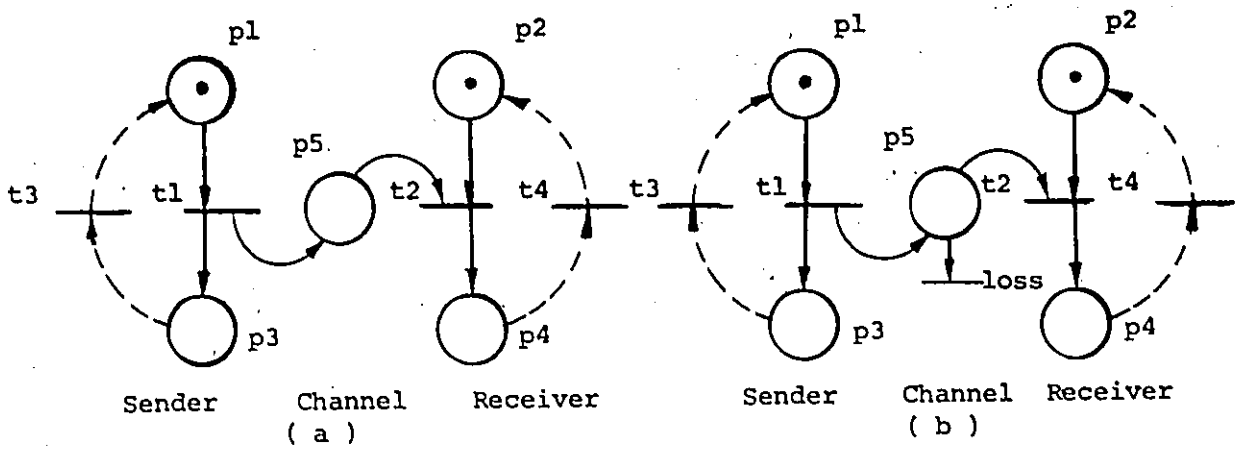


Figure 3-3: (a) A Perfect Channel (b) A Channel Allowing Message Loss

b. Bounded Capacity

Courtiat [COUR84] introduced a model for describing the message flow control aspect of a channel with limited capacity. As shown in Figure 3-4a , the portion with dotted arcs indicates the flow control mechanism. The number of tokens in place UE represents the maximum number of one type of messages allowed in the medium.

A model for several (say 2) types of messages is illustrated in Figure 3-4b.

c. FIFO virtual Channels

Courtiat [COUR84] also presented a model for the virtual channel with FIFO ordering of messages. As shown in Figure 3-5a, each slot of the queue has the same structure: place ES , place E , transition SE and transition 'Loss'. A token

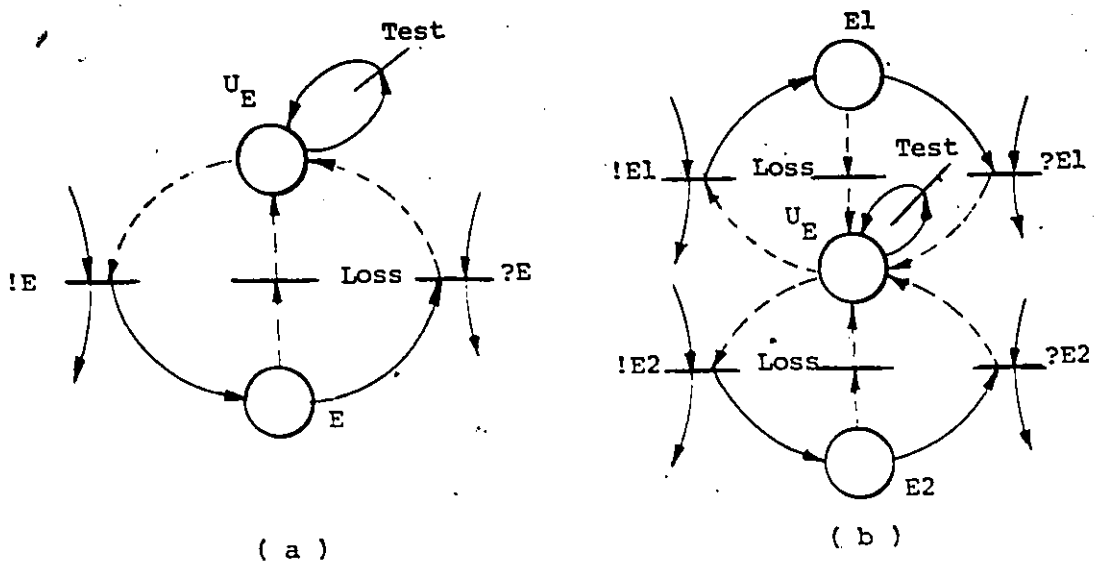


Figure 3-4: A Flow Control Model (a) For One MSG Type (b) For Two MSG Types

inside place ES indicates that the jth slot of the queue is empty; a token inside E indicates that the jth slot of the queue contains a message of type E; transition SE denotes the shift of a message from slot j to slot j+1; transition 'Loss' denotes the possible loss of messages in the queue.

A model for several, say 2, types of messages is illustrated in Figure 3-5b. This model shows that two different types of messages can be transmitted through the same queue.

Another FIFO queue model using a predicate/action PN was introduced by Michel Daiz [DAIZ82]. In this model, a file F is used to carry the messages being transmitted. The 'sending MSG' transition in Sender is associated with an action 'DO APPEND(i,F)', which means that the message is to

be appended to F. The receiving transition in Receiver is associated with another action 'DO j=TAKEFIRST(F)', which indicates that the first message from F is removed to guarantee the FIFO feature.

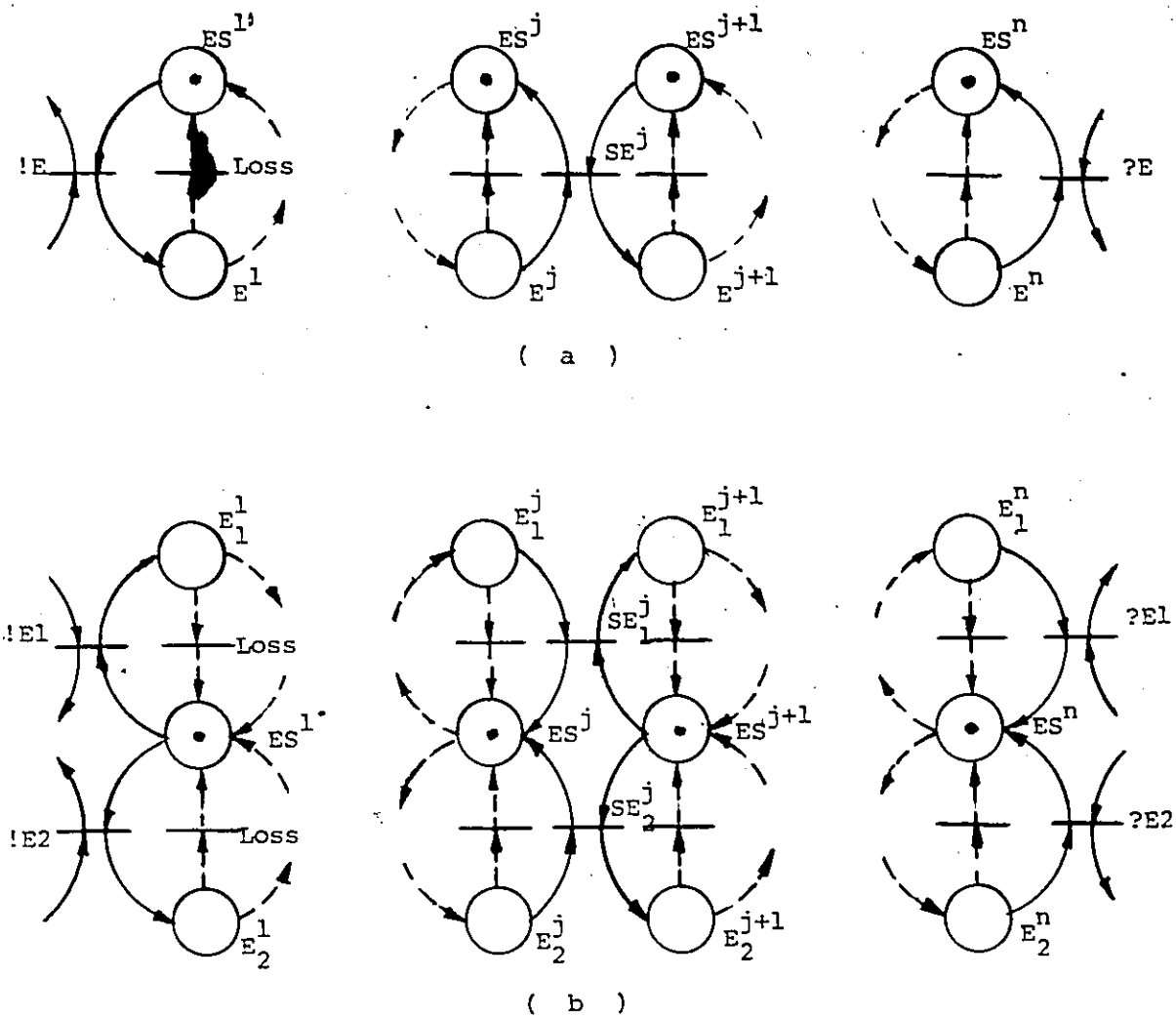


Figure 3-5: A FIFO Channel Model (a) For One MSG Type
(b) For Two MSG Types

(3) Distantly Initiated Actions

Another technique for modeling the virtual medium was proposed by Bochmann [BOCH77] . In his model each communicating entity has certain distantly initiated actions which will be executed after a finite period of time following their initiation by the distant entity. These actions assign new values to local variables.

As an example, consider the alternating bit protocol., Sender is associated with a distantly initiated action TRANSA(p:(0,1)) to indicate the transmission of Acknowledgement, where parameter p is the MSG sequence number (0 or 1). Receiver has TRANSD(p1:(0,1); p2:...) to imply the transmission of data, where p1 is the MSG sequence number, p2 is the data. In Sender, an action INITIATE(TRANSD,seq,data) is associated with the transition 'Emit'. In Receiver, an action INITIATE(TRANSA,seq) is associated with transition 'Assume Data', as shown below.

	Action attached with a transition	Distantely Initiated Action
Sender	INITIATE(TRANSD,seq,data)	TRANSA(p:(0,1))
Receiver	INITIATE(TRANSA,seq)	TRANSD(p1:(0,1);P2)

Once the 'Emit' transition of Sender is fired, the related action INITIATE(TRANSD,seq, data) is executed, i.e. the distantly initiated action TRANSD in Receiver is initiated. After a certain period of time, TRANSD will be executed automatically and will assign new values to the local variables of Receiver: seqnb:=p1, data:=p2. This indicates the Receiver has received the message with the sequencwe number of p1 which is the parameter 'seq' of the action with transition 'Emit' in the Sender.

Similar process occurs to TRANSA. When Receiver processes a message (by firing transition 'Assume Data'), its action INITIATE(TRANSA,seq) is executed. Thus, the distantly initiated action TRANSA is initiated. Some time after TRANSA has been executed , the Sender 'receives' ACK and a communication cycle is fulfilled.

3.2.3 Specification of Recovery Mechanizms

Protocol systems ought to be recoverable from two cases of transmission anomalies:

Case 1. In this case, there are message errors (MSG misordered, duplicated, or distorted).

Case 2. In this case, messages are lost.

In both cases, retransmisson of the message is required.

Message errors can be detected by checking sequence numbers and recovered by adding some transitions with logical predicates in the Sender and Receiver (see Figure 5 in [PETR] for details). Recovery from message loss is usually done by a time-out mechanism in the Sender. Time-out mechanisms can be implemented in BPN models, NPN models, predicate/action PN models or timed PN models. In most of the available PN models [MENA83] [MERL76a] [TANE81], a time-out mechanizm is simply denoted as a transition called 'timeout', as t5 shown in Figure 3-6a.

In the literature of these proposed models, except TPN, there is not much explanation on how to carry out the function 'time is out'. In the following, we describe our suggestions for how to get this tome-out mechanism to work in each type of PN models.

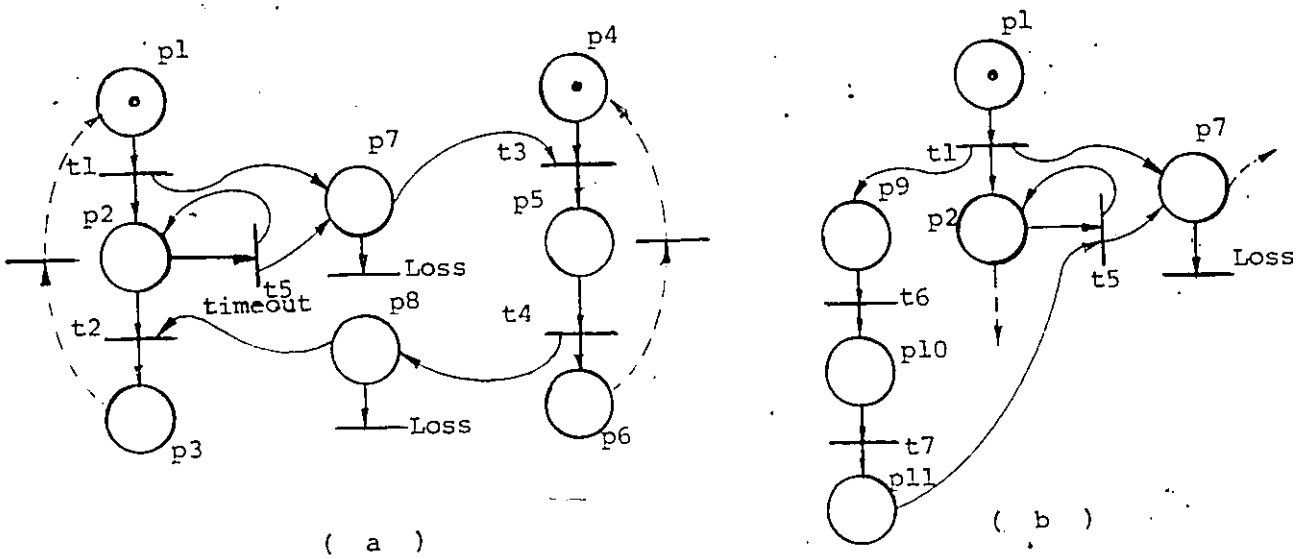


Figure 3-6: Time-out Mechanism (a) General Model (b) BPN Model

In a NPN or predicate/action model, t5 can be associated with a predicate, which has variables common with the action associated with transition 'loss'. For instance, an action A:=1 may be attached with 'loss' and a predicate [A=1] attached to t5. If a message (token) is lost, i.e., 'loss' is fired, the action A:=1 sets A to 1. Then, the predicate associated with t5 is satisfied (A=1) and t5 may be fired (depending on whether p2 has a token or not). This approach is used in the PN model for the first protocol investigated in Chapter 5.

In a TPN model, the function 'timeout' is carried out as follows: Associate a time interval [t5*, t5**] with transition t5 (in Figure 3-6a) such that t5* > t3** + t4** , t5** is finite. Here, [t3*, t3**] and [t4*, t4**] are associated with transitions t3 and t4, respectively. Suppose a message or an acknowledgement of a message is lost. Having waited longer than a period t5**, transition t5 will be fired and send the message again (putting another token in place p7).

Merlin [MERL76a] explained the development of TPN for protocol recovery mechanism in [MERL76b]. Menasche [MENA83] presented an explicit example of TPN for the alternating bit protocol (see Figure 3-2).

For BPN models, time-out can be handled by a set of places and transitions forming a timer mechanism. For

example, as shown in Figure 3-6b, p9, p10, p11 and t6, t7 (called timer transitions) are added between t1 and t5. The following special firing rule is assumed: if an original transition (t1-5,'loss's) and a timer transition (t6,t7) are enabled at the same time, the original transition should be fired first and then the firing of the timer transition follows. This rule guarantees that after waiting for a certain 'period' of time without firing any original transitions, t5 will be fired. For instance, if the first 'loss' transition is fired (a message is lost), then the only enabled transitions are t6, then t7. Finally t5 is fired - time out, the MSG is retransmitted.

3.3 SERVICE SPECIFICATION BY PN MODELS

An N-service specification describes the functions performed at layer N in response to service requests from the upper layer N+1. Petri nets are widely used for modeling these functions. Among these works, Billington's contribution [BILL82] is worth special attention. In his specification of Transport Service using predicate/action Petri nets, two variables, A and B, are used to represent the states of the interfaces between the protocol entities in layer N and their users in layer N+1, respectively. The four possible states of each interface are : Idle, Outgoing (Incoming) Connction Pending, Data Transfer Transfer Ready, and Disconnection Pending. Based on these two variables,

some predicates and actions are attached with the transitions. For example, in the Connection Phase (see FIG.4 in [BILL82]), predicate [A=0] and action A:=1 are associated with transition ST1. It indicates that, once user A issues a Connect Request while being in the Idle state (A=0), the interface will enter the Connection Pending state (A=1).

In order to distinguish the service primitives, different coloured tokens may be used. Billington has defined 16 coloured tokens to represent the primitives of Connect Request, Connect Indication, Connect Response, Connect Confirmation, etc.

Courtiat, Ayache, Algayres and Daiz also made significant contributions in protocol service specifications [COUR84] [DAIZ82]. Their models are based on the special forms of predicates and actions : ?m and !m.

3.4 PROTOCOL VERIFICATION USING PETRI NETS

Two steps are involved in the verification of protocol by Petri nets:

Step 1. Specify the protocol using a PN model.

Step 2. Use PN analysis techniques of Section 2.3 to verify the PN model.

In Section 3.2 we have already discussed the PN models for specification of protocol components. There are two objectives in Step 2: To verify the logical correctness of a protocol and its conformance with the service specification. In this thesis, we concentrate on just the verification of logical correctness. Conformance of a protocol with its service specification will only be briefly mentioned in Section 3.4.2.

3.4.1 Logical Correctness

As mentioned in Section 3.1, the logical correctness of a protocol includes deadlock freeness, livelock freeness, correct termination and freedom from channel overflow. They correspond to the following properties of a PN:

freedom from deadlocks

livelock freeness

M0 is a home-state

boundedness

Enumerative analysis as described in Section 2.3.2 can be used to verify these logical properties. The transition invariants produced in structural analysis are also useful for determining the termination property (home-state), while the place invariants are useful for investigating the flow control property (boundeness).

We have developed a CAD software package called PNPUO to be used for the verification of protocols specified with token-coloured and predicate/action PN models. It is possible to specify, modify, store the PN models, to analysis their logical properties by enumerating of the reachable markings and to obtain the place and transition invariants.(For operational details of PNPUO, see Chapter 4).

In the timed PN model, the size of the reachability tree may be smaller than that in the corresponding BPN model. The reason of this is that pairs of time values are considered so that some enabled transitions are ignored from firing [MERL76b]. The rest of the analysis process is the same as in BPN models. Menasche and Bochmann [MENA83] proposed a new analysis method based on their new concept ' TPN state classes'.

3.4.2 Conformance of Protocol with Service Specification

The next step in protocol verification is to prove its conformance with the service specification. It is to check whether the protocol uses the service from a lower layer and performs the service for the upper layer as specified in the service specifications. Currently, this is becoming a inportant research issue of protocol testing. An automated

testing system and some references are given by Ural and Probert [URAL84].

The conformance of protocol with the service specification is a very profound subject itself and is out of the scope of our thesis.

Chapter IV

PNPUO - AN INTERACITIVE PETRI NET PACKAGE AT UNIVERSITY OF OTTWA

This chapter describes in details both the user interface and the system aspect of an interactive Petri net package implemented at the University of Ottawa (hereafter abbreviated as PNPUO). A brief overview of PNPUO is given in the first section. User interface with the system is described in Section 4.2. Section 4.3 explains the organization and functions of its various components. By means of an example, typical sessions of conversation between the user and the system are illustrated in Section 4.4. At the end of the chapter , we propose some possible improvements on the system and directions for further research.

4.1 OBJECTIVES AND CAPABILITIES OF PNPUO

PNPUO provides the user with interactive facilities for analysing properties of systems which use basic, or token-coloured, or predicate/action Petri nets as design models. This is done mainly in two phases :

Phase I Creation and Storage of Data

A user can interactively input, display, modify, store and get hard copies of the following input data::

a. The numbers of places, transitions, and token colours of the Petri net.

b. Labels (numbers and colours) of arcs from places to transitions and from transitions to places.

c. User variables (integer, real, Boolean) used in the predicates and actions of the Petri nets).

d. Predicates and actions at places and transitions.

e. Initial marking and initial values of variables.

Phase II System Analysis

After data have been correctly input, the system enters the analysis phase, during which the user can investigate properties of the system by the following two processses (see Section 2.3 for theoretical background):

(i). In the process of enumerative analysis, it checks:

a. Token-related properties: safeness, boundedness and conservation of tokens.

b. Execution-related properties : deadlocks, livelocks, live-loops and home-state.

c. Reachability of states.

(ii). In the process of structural analysis, it determines:

a. Place invariants .

b. Transition invariants .

4.2 USER'S INTERFACE WITH SYSTEM

PNPUO is a menu-driven system. At each step it provides the user with a set of options and instructions. It then passes control to an internal process determined by the user's selection.

A conversational session starts with PNPUO displaying the following information :

```
**************************************************
*   DO YOU WANT TO ENTER :                       *
*      1.  PROCESS MODULE SPECIFICATION          *
*      2.  MODULE DISPLAY                        *
*      3.  MODULE MODIFY                         *
*      4.  MODULE ANALYSIS                       *
**************************************************
   *   ENTER YOUR SELECTION   *
 *  HIT ANY DIGITS OTHER THAN 1, 2, 3, 4 TO GET OUT OF THIS PROCESS  *
```

Selection of an option will start the control hierarchy of the user interface, as shown in Figure 4-1. The different parts of this hierarchy are explained in details in Subsections 4.2.2 to 4.2.5 . Subsection 4.2.1 summarizes the limitation in the application of PNPUO

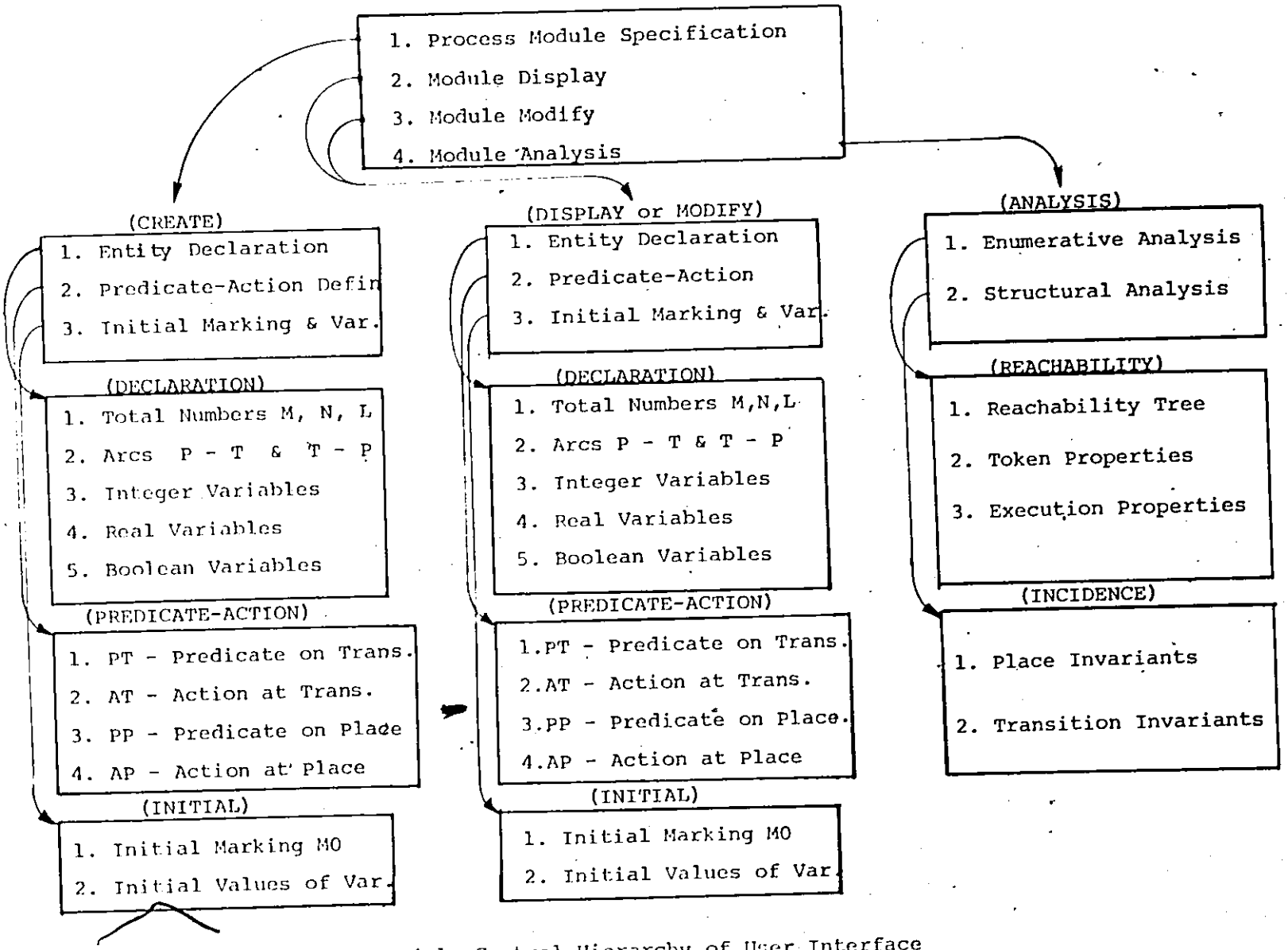


Figure 4-1. Control Hierarchy of User Interface

4.2.1 Scope and Limitation of Application

Though the framework of PNPUO is designed in such a way that many types of Petri nets can be analysed, the current version has only the software for token-coloured and predicate/action PN, including basic PN as a special case. Other types of Petri nets, such as timed PN and PN with inhibitor arcs, are not included. (See Section 4.5 for discussion on extending the scope of applications.)

The following limitations on the selection of maximum values of the PN parameters and on the formats of predicates and actions are mainly due to implementational convenience and restrictions. Most of them can be removed easily, possibly at the expense of larger storage space or computational efficiency.

Limitations

a. The maximum numbers of places, transitions, and token colours are limited to 40, 40, and 9, respectively ;

b. The maximum number of each type of user variables, namely integer, real and Boolean, is limited to 8 ;

c. Use of Symbols for integer, real and Boolean variables is restricted to A B,... H; A1, B1,... H1; and A2, B2, ... H2, respectively. (It will be shown later that, in the Display Phase, three tables are used to list the user variables and the corresponding program variables of each type.)

d. A predicate must be one of the following two logical

expressions:

i) X = R

ii) X = R and Y = S

where X, Y are program variables of any type (integer, real, or Boolean), and R S are constants of the same type as X and Y, respectively ;

e. An action must be one of the following two logical expressions :

i) X := X' + R

ii) X := X' + R and Y := Y' + S

where X, Y, R, S are the same as above and X' (Y') is either X (Y) or null.

f. The maximum number of levels of the reachability tree is 15 .

Note that user variables are the variables used in the predicates or actions of the PN. Program variables are those used in the program modules.

4.2.2 Creating Modules for Analysis

Once the system enters the module CREATE, the following information will be displayed:

```
        * * *   MODULE SPECIFICATION   * * *
                      < ON CREATE >
*************************************************
*  DO YOU WANT TO ENTER :                       *
*     1.  ENTITY DECLARATION PHASE              *
*     2.  PREDICATE-ACTION DEFINITION PHASE     *
*     3.  INITIAL MARKING & VARIABLES PHASE     *
*************************************************
        *   ENTER YOUR SELECTION   *
        *  HIT ANY DIGITS OTHER THAN 1, 2, 3
       TO GET OUT OF MODULE SPECIFICATION SESSION  *
```

These three phases (i.e., options) are as follows :

(1) Entity Declaration Phase

In this phase, a user enters the data about a protocol entity, following the instructions displayed by the system:

```
      * * *   ENTITY DECLARATION PHASE   * * *
                      < ON CREATE >
*****************************************
*  DO YOU WANT TO DECLARE :                *
*     1.  NUMBERS OF PLACES, TRANSITIONS,  *
*           AND COLOUR TYPES               *
*     2.  ARCS P-->T  &  T-->P             *
*     3.  INTEGER VARIABLES                *
*     4.  REAL VARIABLES                   *
*     5.  BOOLEAN VARIABLES                *
*****************************************
        *   ENTER YOUR SELECTION   *
*   HIT ANY DIGITS OTHER THEN 1, 2, 3, 4, 5
       GET OUT OF ENTITY DECLARATION PHASE  *
```

Each option triggers the display of one of the following sets of instructions.

Option 1. To enter number of places, transitions and colour types.

Displayed Information	Range of data
Enter Total No. of Places	0 <= M <= 40
Enter Total No. of Transitions	0 <= N <= 40
Enter Total No. of Token-colours	0 <= L <= 9

Option 2. To define arcs p --> t & t --> p.

Displayed Information	Range of Data
pi tj	any digits
ti pj	any digits

Here, the user should input the number of arcs from place pi to transition tj behind 'pi tj', and input the number of arcs from transition ti to place pj behind 'ti pj'.

Option 3. To define integer variables A, B, ...H.

Displayed Information	Range of Data
Enter Total No. of Integer Var.	0 <= k <= 8
Enter name of ith Integer Var.	character string (length <= 80)

Option 4. To define real variables A1, B1, ...H1 (similar to Option 3).

Option 5. To define Boolean variables A2, B2, ...H2 (similar to Option 3).

(2) Predicate-Action Definition Phase

In this phase, the user inputs all the predicates and actions of the PN. The process starts with the following information displayed by the system :

```
   * * *   CONSTRANTS DEFINITION PHASE   * * *
                    < ON CREATE >
 ************************************************
 *   DO YOU WANT TO DEFINE :                    *
 *     1. PT --- PREDICATES ON TRANSITIONS      *
 *     2. AT --- ACTIONS AT TRANSITIONS         *
 *     3. PP --- PREDICATES ON PLACES           *
 *     4. AP --- ACTIONS AT PLACES              *
 ************************************************
     *    ENTER YOUR SELECTION    *
 *  PRESS ANY DIGITS OTHER THAN 1, 2, 3, 4
     TO GET OUT OF CONSTRAINTS DEFINITION PHASE  *
```

These options are explained below:

Option 1. To enter PT --- Predicates on Transitions.

Displayed Information	Format of Data
T1 :	Character string as X = R or X = R and Y = S

Option 2. To enter AT --- Actions at Transitions.

Displayed Information	Format of data
Ti :	Character string as X := X'+ R or X:=X'+R and Y:=Y'+S

Option 3. To enter PP --- Predicates on Places (Similar to Option 1).

Option 4. To enter AP --- Actions at Places (Similar to Option 2).

(3) Marking and Variable Initialization Phase

In this phase, the user enters the initial marking and the initial values of each type of variables. The interactive process is shown in the following table.

Displayed Information	Range of Data
Pi	any integer (value of M0(pi))
A (or B,... H)	any integer (value for A or B,... H)
A1 (or B1,... H1)	any real number (value for A1 or B1,... H1)
A2 (or B2,... H2)	'true' or 'false' (value for A2 or B2,... H2)

4.2.3 Displaying of Data

By means of the DISPLAY module, the system allows two ways of displaying information by asking the user the following question:

```
WHICH WAY OF DISPLAY DO YOU WANT TO CHOOSE :
    A.  DISPLAY ALL THE INFORMATION AT ONCE
    B.  DISPLAY INFORMATION INTERACTIVELY
```

If Option A is chosen, the system displays all of the input data together, i.e., including:

a) Total numbers of places, transitions, and token colours.

b) Arcs from places to transitions and arcs from transitions to places.

c) The list of user variables and their correspon-

ponding program variables.

d) Predicates and actions at places and transitions.

e) Initial marking and initial values of variables.

If Option B is chosen, the system displays these input data part by part. At each step, it displays only that part of data the user requests.

4.2.4 Modifying Modules

The process of modifying a module is similar to the process of module displaying as described in Subsection 4.2.3, except that, in the modification phase, each line of displayed data is followed by a question :

* Do you want to change ? --- Y or N *

If the user presses 'Y' , the system displays :

* Enter the new line *

The user then inputs the new data.

4.2.5 Analysing Modules

In the analysis phase, the system will enter the process of reachability analysis or incidence analysis according to the user's request. At first, the system displays the following information :

```
          < MODULE  ANALYSIS >
*********************************************
*   DO YOU WANT TO DO :                     *
*        1.  REACHABILITY ANALYSIS          *
*        2.  INCIDENCE ANALYSIS             *
*********************************************
   *  ENTER YOUR SELECTION  *
   *  HIT ANY DIGIT OTHER THEN 1 AND 2 TO END  ANALYSIS  *
```

The interactive process for each kind of analysis is described below:

(I) Enumerative Analysis

Displayed Information	User's choice
(if the PN has predicate/action:) Do you want give variable values from terminal during analysing ?	'Y' or 'N'
(if 'Y', after getting each node of the reachability tree:) Enter new values (if any) to the variable(s) (e.g. A=1). If no entry press N	'N'or character string as A=1..

The outputs of this process consist of :

i) the reachability tree with terminal labels on the leaves,

ii) token-related properties (safeness, boundedness, and conservation), and

iii) execution-related properties (deadlocks, live-
(deadlocks, livelocks and live loops).

(II) Structural Analysis

No interactions are needed in this process. Results about transition invariants and place invariants are automatically output.

4.3 IMPLEMENTATIONAL DETAILS

PNPUO was coded in PASCAL 8000 and implemented in the main frame computer AMDAHL at the University of Ottawa. It operates under the Operating System CMS (Conversational Monitor System). Its main program controls the operations of two major components: one used for the construction of PN and the other for the analysis of PN.

Module CONSTRUCTION consists of three componenets :

Module CREATE

Module DISPLAY

and Module MODIFY.

Module ANALYSIS includes two parts :

Enumerative Analysis

and Structural Analysis.

A brief overview of the program organization is shown in Figure 4-2. Details of the various parts are described in the following subsections.

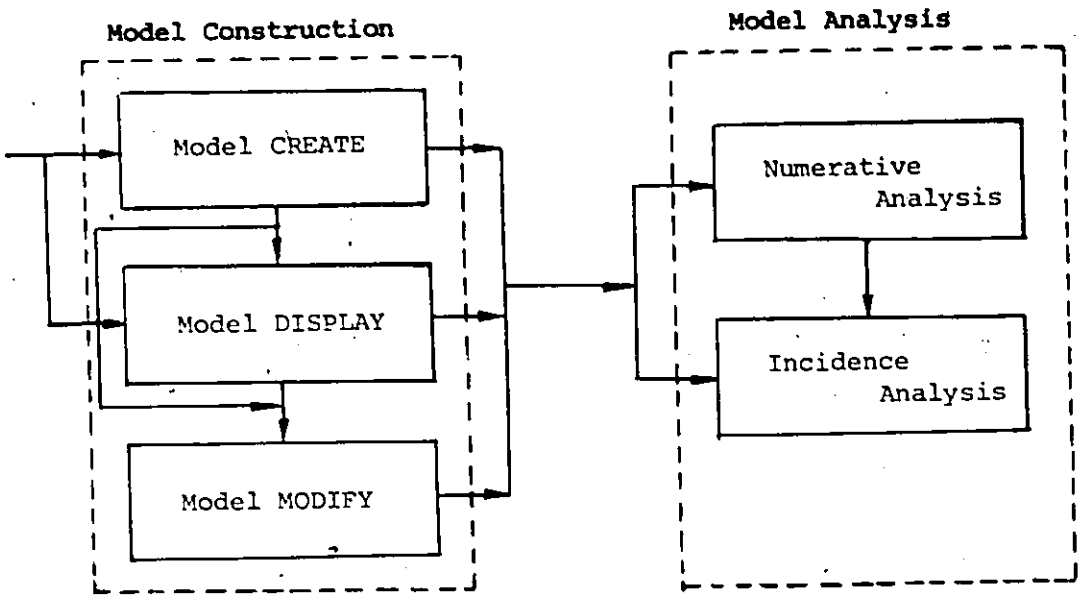


Figure 4-2: Program Organization of PNPUO

4.3.1 Main Program

The main program serves three functions :

a. At the beginning, it opens all I/O files and initializes all program flags .

b. Next, it invokes the procedure NEW to display the first page of information :

```
************************************************
*   DO YOU WANT TO ENTER :                     *
*      1.  PROCESS MODULE SPECIFICATION        *
*      2.  MODULE DISPLAY                      *
*      3.  MODULE MODIFY                       *
*      4.  MODULE ANALYSIS                     *
************************************************
   *   ENTER YOUR SELECTION   *
 *  HIT ANY DIGITS OTHER THAN 1, 2, 3, 4 TO GET OUT OF THIS PROCESS  *
```

c. Subsequently, it interacts with the user by invoking procedures in response to user's selection of options .

4.3.2 Module CREATE

The module CREATE stores the input data into arrays and assigns values to variables. This is realized in three phases: Entity Declaration, Input of Constraints, and Variable Initialization.

The procedures of Module CREATE and their parameters are summarised in TABLE 4-1.

Having received all the information, Module CREATE invokes the external procedure CWRITE to store the numerical data and character data into the files OUTIN DATA and OUT DATA , respectively. Before logoff, copies of these two files, DATAIN DATA and DIN DATA are produced and stored automatically for subsequent usage.

TABLE 4-1

Procedures and Data Types of Module CREATE

Phase	Procedure	Input data	Data Types
CDECLARATION (entity declatration)	CNUMBER	# of places, transitions & colours	Var M,N,L
	CARC	Arcs P-]T & T-]P	Array PARC,TARC
	CINTEGER	Integer variables	Var A,B,...H
	CREAL	Real variables	Var A1,B1,..H1
	CLOGIC	Boolean variables	Var A2,B2,..H2
CPERDACT (input of constraints)	CPREDTR	Predicates on transitions	Array PT
	CACTTR	Actions at transitions	Array AT
	CPREDPL	Predicates on places	Array PP
	CACTPL	Actions on places	Array AP
CINITIAL (initialization)	CINIMARK	Initial marking M0	Array P
	CINIVAR	Initial variable values	Var A,..H A1,.. .H1, A2,..H2

4.3.3 Module DISPLAY

This module invokes three internal procedures:

Procedure DDECLARATION

Procedure DPREDACT

and Procedure DINITIAL.

Each procedure has a similar set of subprocedures as Module CREATE. The difference is : Module CREATE prepares data whereas Module DISPLAY displays them.

To implement the two display Options A and B as mentioned in Subsection 4.2.3, a program flag, DFLAG, is set to the

value 0 or 1 according to the user's selection. Different parts of this procedure will then be executed for Option A or Option B.

TABLE 4-2 lists all the procedures and subprocedures of Module DISPLAY.

TABLE 4-2

Procedures of Module DISPLAY

Procedure	Sub-pro.	Function	Data Resource
DDECLARATION	DNUMBER	display # of places, transitions & colors	Var M, N L
	DARC	display Arcs P-->T & T--> P	Array PARC , TARC
	DINTEGER	display integer Vars	Var A,B,..H
	DREAL	display real Vars	Var A1,B1,..H1
	DLOGIC	display Boolean Vars	Var A1,B2,..H2
DPREDCACT	DPREDTR	display predicates on transitions	Array PT
	DACTTR	display actions at transitions	Array AT
	DPREDPL	display pred. on pl.	Array PP
	DACTPL	display act. at pl.	Array AP
DINITIAL	DINIMARK	display initial marking M0	Array P
	DINIVAR	display initial values of Vars	Var A,..H, A1, ..H1, A2,..H2
DREAD	/	read numerical,character data	Files DATAIN DATA, DIN DATA

4.3.4 Module MODIFY

Before entering Module MODIFY, the main program sets the program flag MFLAG to 1 and then invokes procedure DISPLAY. In procedure DISPLAY, some specific program statements can only be executed when MFLAG = 1. These specific statements and the subprocedures MODI, DMOD, PMOD constitute the Module MODIFY.

At the end of this process, procedure CWRITE is invoked to store the modified data into the output files OUTIN DATA and OUT DATA.

4.3.5 Module ANALYSIS

This module contains two processes for enumerative analysis and structural analysis. They are implemented as procedures REACHABILITY and INCIDENCE, respectively.

I. Enumerative Analysis

This process delineates the reachability tree , token-related properties , and execution-related properties. (See Section 2.3)

During the generation of a reachability tree, the system determines whether a transition Tj0 is fireable or not by checking the following two conditions :

(1) Whether the transition Tj0 is enabled, i.e., whether

$$M(i,k) >= PARC(i,j0,k)$$

$$\forall i \in \{i | P \in .Tj0\} \text{ and } \forall k \in \{k | 1 <= k <= l\},$$

(2) Whether all the predicates related to Tj0 are satisfied, i.e., whether

PT(jo,j) (1 <= j <= 81) is ture, and

PP(i,j) (1 <= j <= 81) is ture

$$\forall i \in \{i | Pi \in .Tj0\} \cup \{i | Pi \in Tj0.\}.$$

For each marking, the system fires the firable transitions in the ascending order of their subscripts.

To denote different markings at the same level of the reachability tree, a two-dimentional array M(i,j) is used to label each node (marking), where i is the level number of the reachability tree and j is the serial number of the marking at this level.

For each marking, the system checks whether it has the same token numbers in m-1 places with an available node generated previously and the number of token in the other place is larger than that in the previous node. If so, it sets the symbol ω to the element of this making corresponding to this place. Furthermore, for each node, the system checks whether or not it is a terminal node (leaf) of the reachability tree. If so, it determines its status of termination : home-state, livelock, deadlock, live looping,

or the tree level has excessed 15 (maximum number of levels of the reachability tree allowed by the system.)

During execution of the Petri net, the system outputs the nodes of the reachability tree (with type-labels on its leaves). Then, the system summarizes the token-related properties, execution-related properties and liveness properties of the PN

There are seven subprocedures in the process ANALYSIS :

1) PREP : It initializes all variables and arrays, and asks if the user wants to change variable values during the execution. If so, it sets flag GG=1.

2) RECEIVE : At each level, if GG=1, it receives values for the variables (like A=1) from the console.

3) CHECK : It checks token-related properties .

4) FIND : It finds fireable transitions. If Tj is fireable, it sets TTj=1.(Otherwise, TTj=0)

5) FIRING (J) : It fires Tj, gets next marking Mk1+1 and executes the action associated with Tj and with the output places of Tj .

6) LEAF (J UU) : It tests whether Mk1+1 is a leaf or not. If so, it determines its type.

7) LOCK (J,VV) : It detects deadlocks and livelocks.

The flowchart of Procedure REACHABILITY is shown in Figure 4-3.

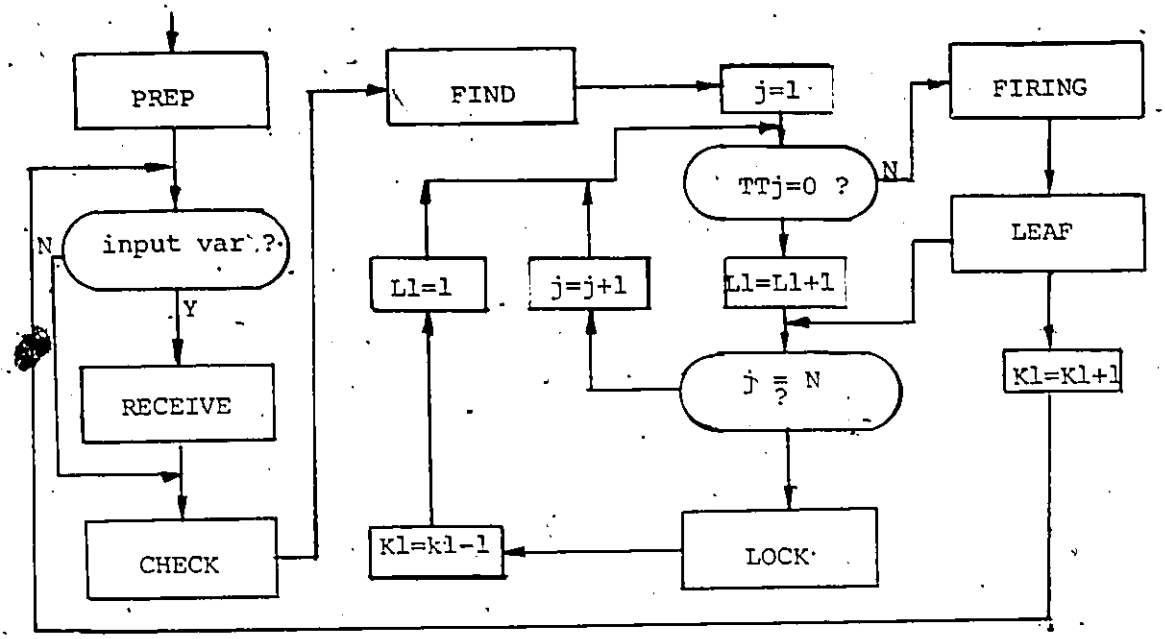


Figure 4-3: Flowchart of Procedure REACHABILITY

II. Structural Analysis

In structural analysis, place invariants and transition invariants are determined by solving two linear equations :

$$\Phi \cdot C = 0 \quad \text{and} \quad C \cdot \Omega = 0 \ .$$

Procedure INCIDENCE consists of Subprocedures SOLUTION, FAI and OMAGA. It obtains the incidence matrix C from arrays PARC and TARC. In fact C = TARC - PARC . It then invokes Procedure OMAGA which, in turns calls Procedure SOLUTOIN to perform the elementary operations on matrix C. OMAGA then solves the equation $C \cdot \Omega = 0$ with only 0/1 solutions. It outputs sequences of transition invariants in the form

Tj1, Tj2, ... Tjk

M ----------> M

The above indicates that the sequence of transitions Tj1 .... Tjk leads a marking M to M itself again. However, the process of INCIDENCE analysis does not point out which specific marking M is. It may or may not be the initial marking M0. To determine this, the user has to refer to the results of reachability analysis.

At this stage, INCIDENCE invokes Subprocedure FAI, which transposes the incidence matrix C , D = C' . Then it passes D on to Subprocedure SOLUTION to perform the elementary operations. At the next step, FAI solves $\Phi \cdot C=0$ (also with only 0/1 solutions) and outputs the place invariant equations:

$$\Phi \cdot M = \Phi \cdot M0 \quad .$$

i.e., if v is the total number of solutions of $\Phi \cdot C=0$, then for each h : $1<=h<=V$, the printout will be

$$M(pi1) + M(pi2) + \ldots + M(pij)$$

$$= M0(pi1) + M0(pi2) + \ldots + M0(pij)$$

where $\Phi h(ik) = 0$ k : $1 <= k <= j$.

In total, there are V outputs similar to the above expression.

4.4 AN EXAMPLE SHOWING HOW PNPUO OPERATES

In this section, we illustrate the various typical user-system interactions through an example. The simple basic Petri net used in this example is shown in Figure 4-4.

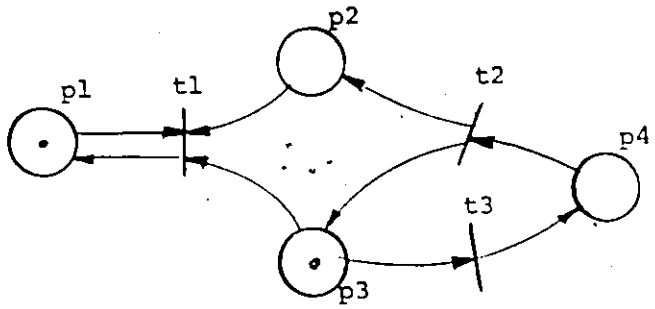


Figure 4-4: Petri Net for the Example

The user starts PNPUO by typing the command 'RUN'. The following instructions will appear on the screen:

```
*************************************************
*   DO YOU WANT TO ENTER :                      *
*      1.  PROCESS MODULE SPECIFICATION         *
*      2.  MODULE DISPLAY                       *
*      3.  MODULE MODIFY                        *
*      4.  MODULE ANALYSIS                      *
*************************************************
   *   ENTER YOUR SELECTION   *
 *  HIT ANY DIGITS OTHER THAN 1, 2, 3, 4 TO GET OUT OF THIS PROCESS  *
```

The user should select Option 1, so as to input the data of the Petri net. Then the system displays a set of instructions :

```
        * * *   MODULE SPECIFICATION   * * *
                    < ON CREATE >
*************************************************
*    DO YOU WANT TO ENTER :                     *
*      1.  ENTITY DECLARATION PHASE             *
*      2.  PREDICATE-ACTION DEFINITION PHASE    *
*      3.  INITIAL MARKING & VARIABLES PHASE    *
*************************************************
    *   ENTER YOUR SELECTION   *
*   HIT ANY DIGITS OTHER THAN 1, 2, 3
     TO GET OUT OF MODULE SPECIFICATION SESSION  *
```

The user inputs all the data after these instructions:

Numbers of places, transitions and colours

(4, 3 and 1),

Arcs from places to transitions and from transitions to places :

PARC(1,1) = 1, PARC(1,2) = 0, PARC(1,3) = 0,

TARC(1,1) = 1, TARC(1,2) = 0, TARC(1,3) = 0,

etc.

Initial marking M0 : (1,0,1,0) .

Next, if the user chooses Option A , Module DISPLAY will display all the input data as follows.

```
TOTAL # OF PLACES          M= 4
TOTAL # OF TRANSITIONS     N= 3
TOTAL # OF TOKEN TYPES     L= 1

* *   ARCS  P --> T  &  T --> P   * *

PLACE   TO  TRANS.     COL1
-------------------------------
 P01        T01         1
 P02        T01         1
 P03        T01         1
 P03        T03         1
 P04        T02         1
```

```
TRANS.   TO PLACE   COL.1
-------------------------
T01         P01       1
T02         P02       1
T02         P03       1
T03         P04       1

* *   INTEGER VARIABLES   * *
PROGRAM"S              USER"S
-------------------------------
          < NIL >

* *   REAL VARIABLES   * *
PROGRAM"S              USER"S
-------------------------------
          < NIL >
```

```
* *    LOGIC VARIABLES    * *

PROGRAM"S          USER"S
--------------------------
         <  NIL  >

* *   PREDICATES ON TRANSITIONS
  TRANS.          PREDICATE.
  -------------------------
   T01
   T02
   T03

* *   ACTIONS AT TRANSITIONS   *
  TRANS.           ACTION
  ----------------------
   T01
   T02
   T03
```

```
* *   PREDICATES ON PLACES    * *
  PLACE           PREDICATE
  ------------------------
   P01
   P02
   P03
   P04

* *   ACTIONS AT PLACES   * *
  PLACE            ACTION
  ----------------------
   P01
   P02
   P03
   P04

  * * *   INITIAL MARKING  M0    * *
                < DISPLAY >
PLACE   COL.1
---------------
  P01     1
  P02     0
  P03     1
  P04     0
```

If errors are found in this list, they should be corrected by calling the process MODIFY.

Finally, the user enters the process ANALYSIS and obtains the following information :

Reachability Tree (see Figure 4-5) :

Token-related Properties (output by the system) :

```
THE RESULTS OF REACHABILITY ANALYSIS :
<1>  THE NET IS NOT SAFE .

<2>  THE MAX NUMBER OF TOKENS IN EACH PLACE >=
                              ( FOR COLOUR1 )      1
<3>  THE NET IS NOT CONSERVED .
```

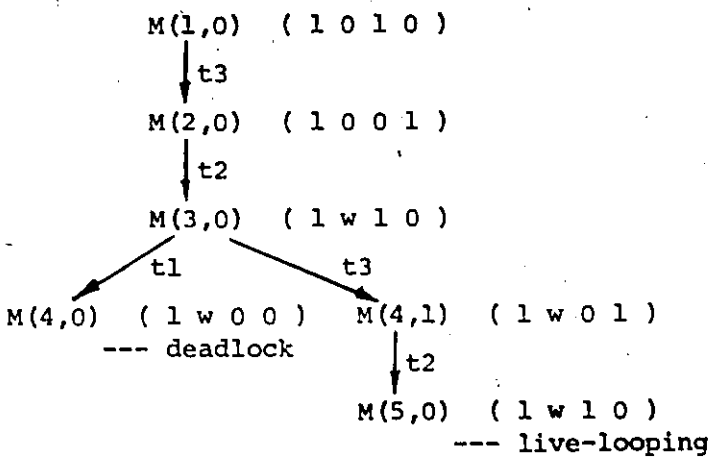


Figure 4-5: Reachability Tree of the PN in Figure 4-4

Execution-related Properties (output by the system) :

```
<4>  EXECUTION-RELATED PROPERTIES :
   THE NET HAS DEADLOCK<S> .
               NO LIVE-LOCKS .
   THE NET HAS LIVE-LOOPING<S>.
               M0 IS NOT A HOME-STATE .
```

Place Invariants (output by the system) :

```
PLACE INVARIANT  1 :
                        M (1 )  =  1
```

Transition Invariants (output by the system) :

```
*  THERE IS NOT ANY TRANSITION INVARIANT FOR THIS NET  *
```

It can be checked manually that the Petri net does have all the above properties. The fact that Place 1 always keeps one token is shown by the above place invariant.

Chapter V

PROTOCOL VERIFICATION BY PNPUO

This chapter describes the application of PNPUO (described in Chapter 4) in the field of communication network protocol verification. The theory and techniques behind these applications are developed in Chapters 2 and 3. For illustration purpose, we consider in details two protocol systems. Section 5.1 considers the alternating bit protocol, a well known protocol in the data link layer. The Connection and Disconnection Phases of Class 1 and Class 2 of the Transport Protocol are verified in Section 5.2, using both BPN and predicate/action PN. This protocol is of current research interest.

As mentioned in Chapter 3, only correctness of the logical properties of the protocols will be dealt with.

5.1 ANALYSIS OF THE ALTERNATING BIT PROTOCOL BY PNPUO

We assume a noisy channel (i.e., messages may be damaged or lost in the channel) for the alternating bit protocol. In this protocol, every message has a one-bit sequence number as an identifier . During transmission, the sequence number alternates between the values 0 and 1. A protocol

entity does not send the next message until the one sent previously has been positively acknowledged. Recovery from transmission anomalies (errors or loss) is achieved by a time-out mechanism and retransmission of messages.

A basic PN model with a recovery mechanism for this protocol, including a pseudo-code program, is described in [TANE81]. It does not explain how the time-out mechanism works. Based on this model, we develop a predicate/action PN model, in which the predicates and actions take care of the time-out mechanism.

5.1.1 A Predicate/Action PN Model

As shown in Figure 5-1, our predicate/action PN model for the alternating bit protocol uses two variables, A and B, to specify the functions 'message loss' and 'time-out'. It attaches predicate [A=1] and actions 'A:=0 and B:=1' to the transitions 'loss' (t5, t6 and t7) and predicate [B=1] and action 'B:=0' to the transitions 'timeout' (t3 and t4).

In the initial state M0 (only places p1, p3, and p7 each has a token), Sender is waiting for ACK0 (acknowledgemnet for the message with sequence number 0), while Receiver has sent ACK1 and is expecting for message 0. Suppose Receiver receives message 0 (by firing t10) and sends ACK0 (also by firing t10). The state of the PN changes to marking M1 (only places p1, p4 and p6 each has a token). On receiving ACK0,

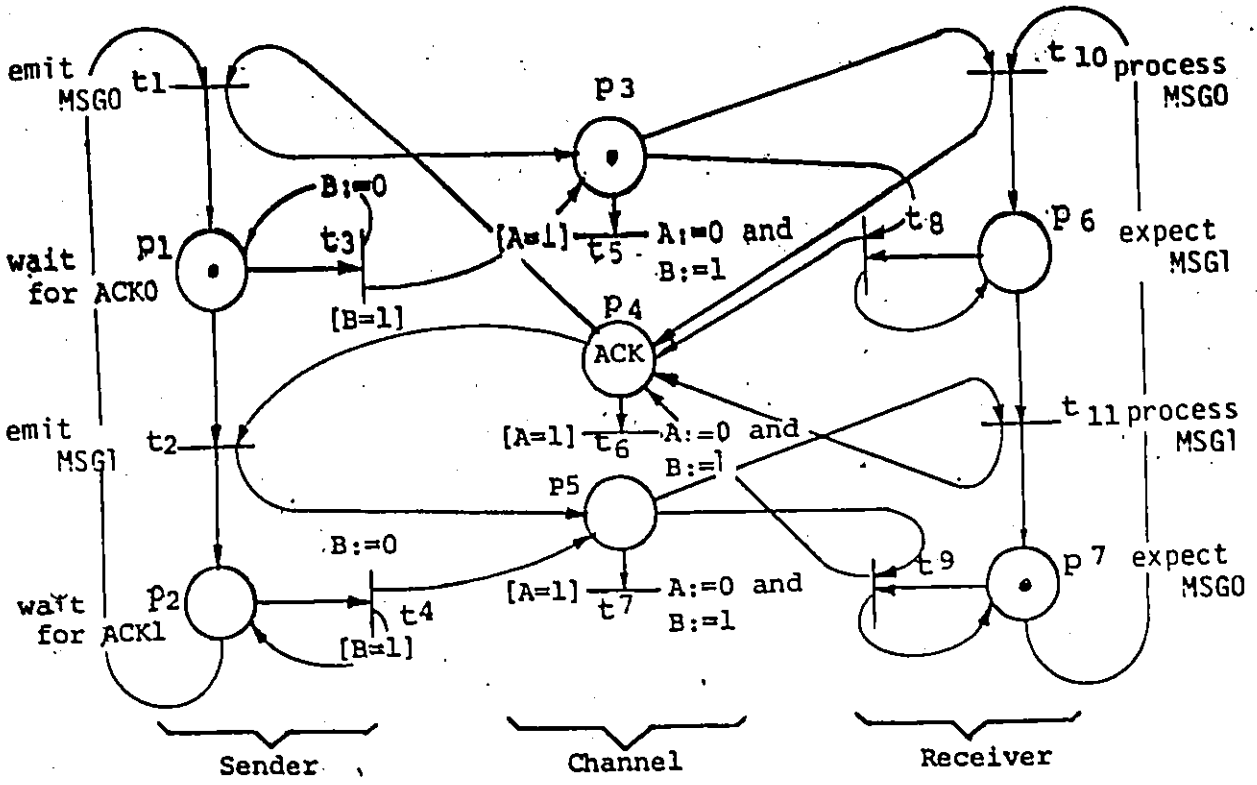


Figure 5-1: A Predicate/Action PN Model for the Alternating Bit Protocol

Sender sends (by firing t2) message 1 and then waits for ACK1. Once Receiver gets (t11) message 1, it sends ACK1 (p4 gets a token). If Sender receives ACK1 (by firing t1), it transmits the next message 0. The system returns to the initial state of the next cycle.

When a message is lost, i.e., when Predicate [A=1] is true and one of transitions t5, t6 and t7 is fired, B is set to 1 (i.e., Action 'A:=0 and B:=1' is executed). Since transitions t3 and t4 ('time-out') are associated with Predicate [B=1], one of them will be fired, i.e., time is out, Sender retransmits the message.

5.1.2 Results of Analysis

The results of applying PNPUO to this protocol model are recorded below.

(1) Enumerative Analysis

Reachability Trees (shown in Figures 5-2, 5-3, 5-4 and 5-5):

Figure 5-2 shows the reachability tree for the case of a channel without message loss, i.e., A=B=0 during the execution of the PN. It shows that, starting from M0, it has only one path reaching the home-state, also M0. If a message is lost in the channel (i.e., variable A is set to 1), the reachability tree will be different from the one in Figure 5-2. It depends on the state (marking) in which the message is lost. Figures 5-3, 5-4 and 5-5 show the reachability trees for the cases where a message is lost in the first, second and third state, respectively. The reachability set of the PN is the combination of these trees.

Token-related properties (output of PNPUO):

```
THE RESULTS OF REACHABILITY ANALYSIS :
<1>  THE  NET  IS  SAFE .

<2>  THE MAX NUMBER OF TOKENS IN EACH PLACE IS :
                              ( FOR COLOUR1 )      1

<3>  THE NET IS NOT CONSERVED
```

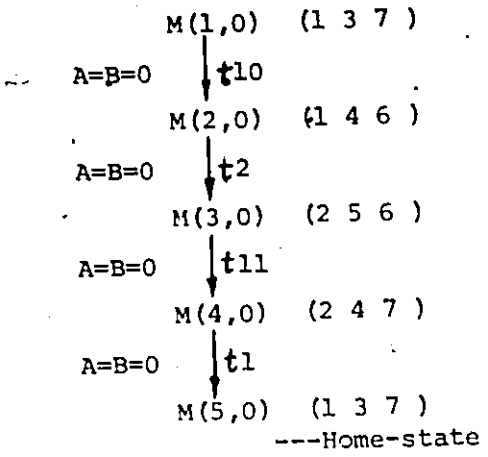


Figure 5-2: Reachability Tree for A Perfect Channel

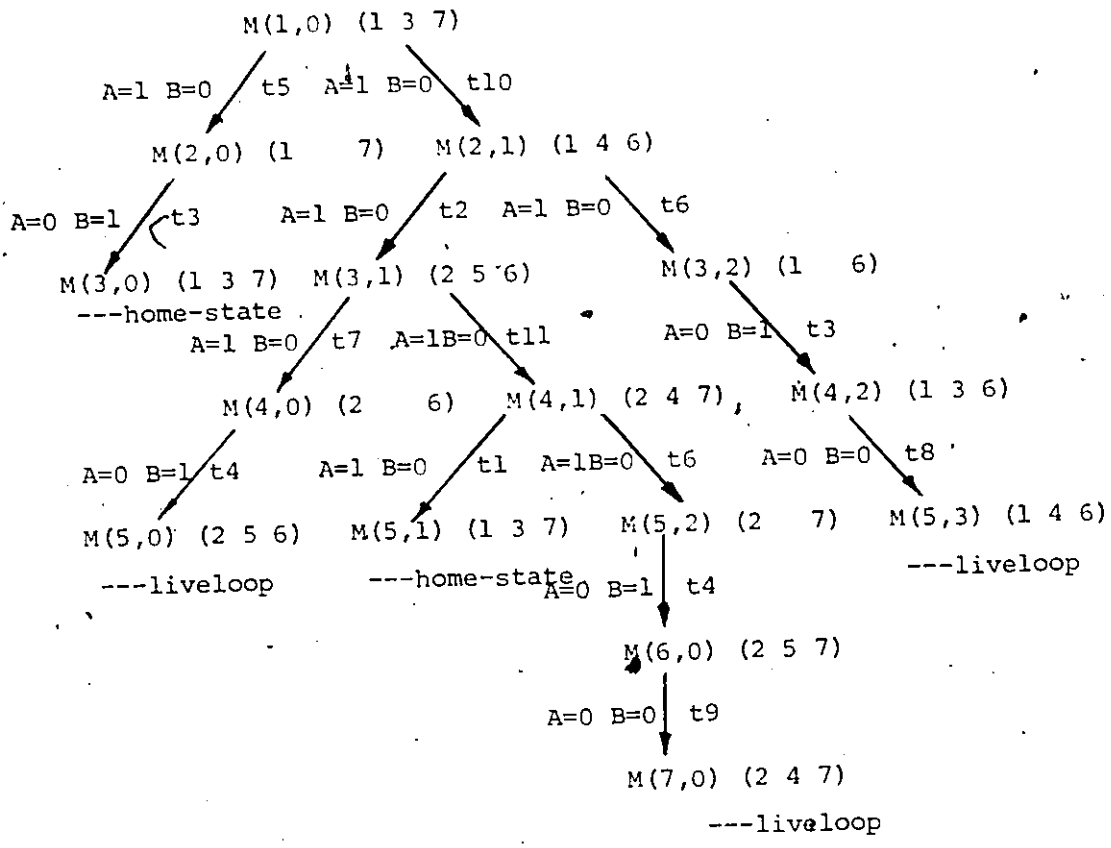


Figure 5-3: The Reachability Tree When a MSG is Lost in the 1st state of Execution

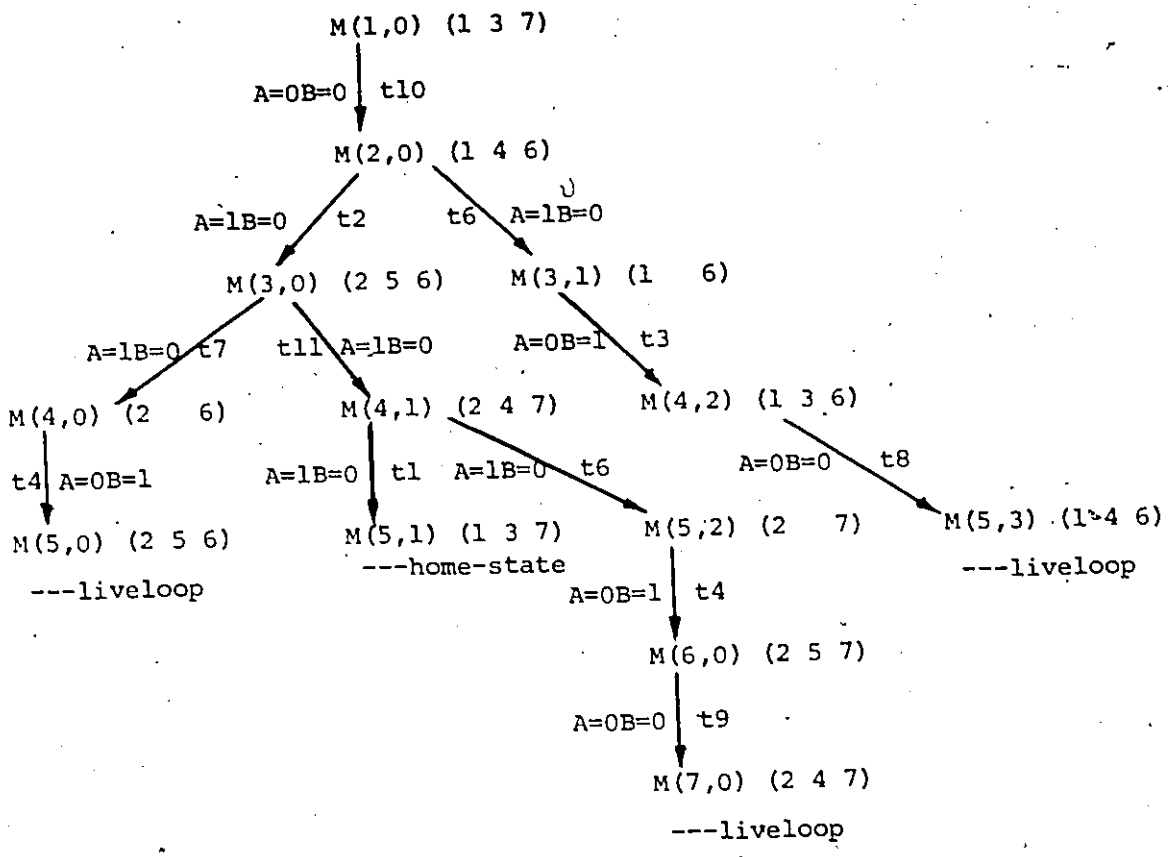


Figure 5-4: The Reachability Tree When a MSG is Lost in the 2nd state of Execution

Execution-related Properties (output of PNPUO):

```
<4>  EXECUTION-RELATED PROPERTIES :
          NO DEADLOCKS .
          NO LIVE-LOCKS
          NO LIVE-LOOPING .
          M0 IS A HOME-STATE .
```

The logical correctness of the protocol can be verified by using the above output information. For example, the absence of deadlocks and livelocks in the trees shows that the protocol is free from these anomalies. Since M0 is both

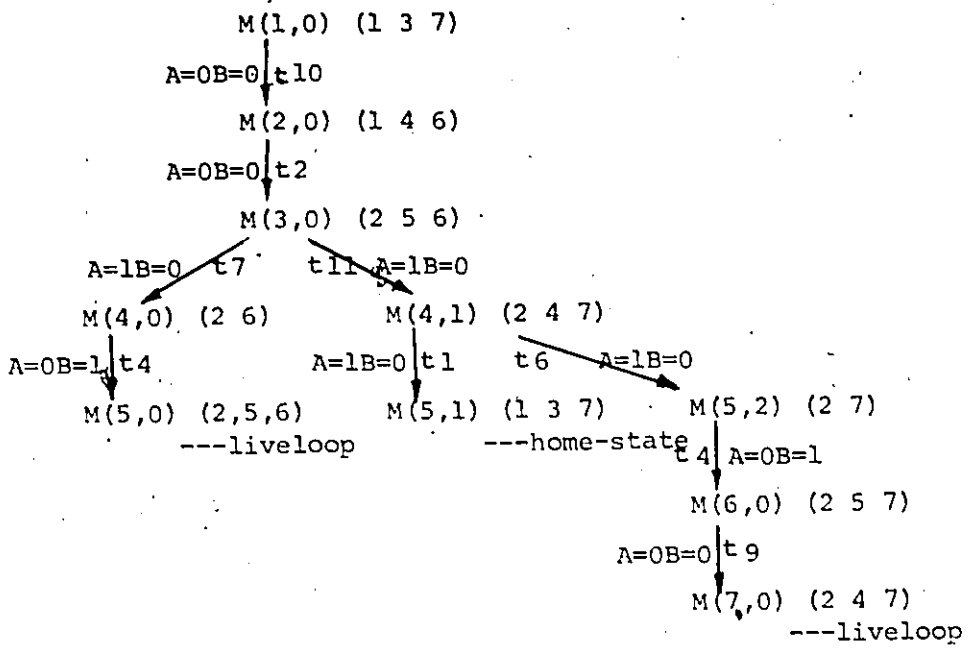


Figure 5-5: The Reachability Tree When a MSG is Lost in the 3rd State of Execution

the initial state and a home-state, the protocol terminates correctly. There is no message overflow, as the PN (including the channel as a subset) is bounded.

(2) Structural Analysis

Place Invariants (output of PNPUO):

PLACE INVARIANT 1 : M (1) + M (2) = 1

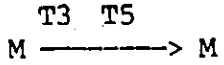
PLACE INVARIANT 2 : M (6) + M (7) = 1

PLACE INVARIANT 3 : M (1) + M (2) + M (6) + M (7) = 2

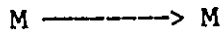
These place invariants show, for example, that, during the execution of this PN, there is always a token in either p1 or p2, but not in both. The same situation is also true for p6 and p7. This means that in the alternating bit protocol, both entities (Sender and Receiver) have to stay in a single state, i.e., there is no state ambiguity of the protocol entity.

Transition Invariants (output of PNPUO):

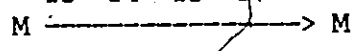
TRANSITION INVARIANT 1 :



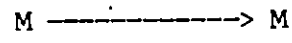
TRANSITION INVARIANT 2 :



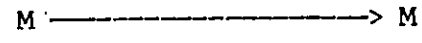
TRANSITION INVARIANT 3 :



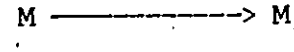
TRANSITION INVARIANT 4 :



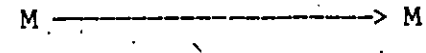
TRANSITION INVARIANT 5 :



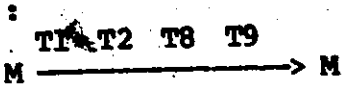
TRANSITION INVARIANT 6 :



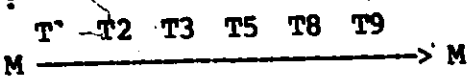
TRANSITION INVARIANT 7 :



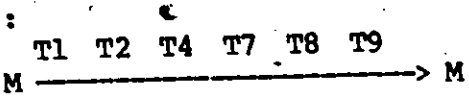
TRANSITION INVARIANT 8 :



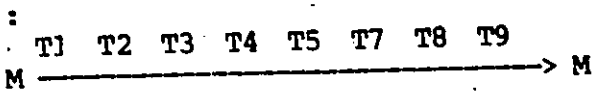
TRANSITION INVARIANT 9 :



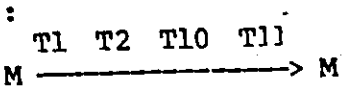
TRANSITION INVARIANT 10 :



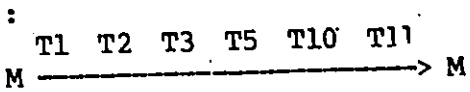
TRANSITION INVARIANT 11 :



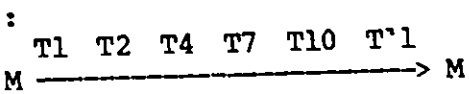
TRANSITION INVARIANT 12 :



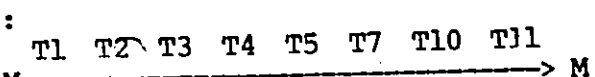
TRANSITION INVARIANT 13 :



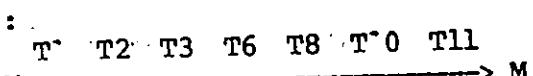
TRANSITION INVARIANT 14 :



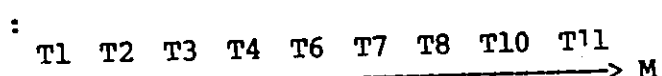
TRANSITION INVARIANT 15 :



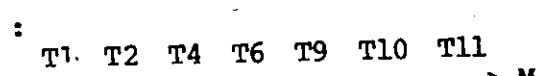
TRANSITION INVARIANT 16 :



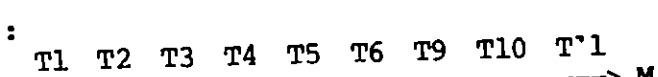
TRANSITION INVARIANT 17 :



TRANSITION INVARIANT 18 :



TRANSITION INVARIANT 19 :



These transition invariants indicate that there are 19 loops during the execution of this PN. They may be life-cycles (correct termination) or live loops, or even livelocks. The structural analysis process cannot distinguish them. It is necessary to check them in the reachability tree.

Transition invariant 1 implies that firing the transition sequence (t3, t5) leads a marking (here it is the initial marking M0) to itself again. This is obviously true for this PN. Correctness of the other invariants can also be checked in a similar way.

5.2 ANALYSING THE CONNECTION AND DISCONNECTION PHASES OF CLASS 1 AND CLASS 2 OF TRANSPORT PROTOCOL

This section describes our application of PNPUO to a portion of the Transport Protocol. We first use a basic PN model proposed by Berthelot [BERT82] and compare his manually obtained results with ours. We then apply PNPUO again, using a predicate/action PN.

The Transport Protocol (TP), as proposed by both ISO (International Organization for Standardization) and ECMA (European Computer Manufacturers Association), has five different classes which handle errors of increasing severity [ECMA81] [ISO 8?]. Each class provides services in three phases :

(1) Connection Establishment Phase

(2) Data Transfer Phase

(3) Disconnection Phase

The function of the Connection Establishment Phase is to provide the TP primitives: connect request, connect indication, connect response and connect confirmation for the establishment of an end-to-end transport connection between two transport entities. The Data Transfer Phase serves the exchange of data messages via TP primitives: data request, data indication, expedited-data request and expedited-data indication. The Disconnection Phase uses the TP primitives disconnect request, disconnect indication, disconnect response and disconnect confirmation to terminate a transport connection.

In the Class 1 protocol, not only are the functions of these three phases provided, the ability of error detection and reporting and of recovery from failures is also included. Class 2 provides also flow control for merging multiple Transport connections on a single Network connection.

Subsection 5.2.1 describes a basic PN model for the Connection and Disconnection Phases in Class 1 and Class 2 of the ECMA Transport Protocol. Subsection 5.2.2 gives the analysis results of applying PNPUO and compares them with those obtained manually by Berthelot [BERT82]. We also

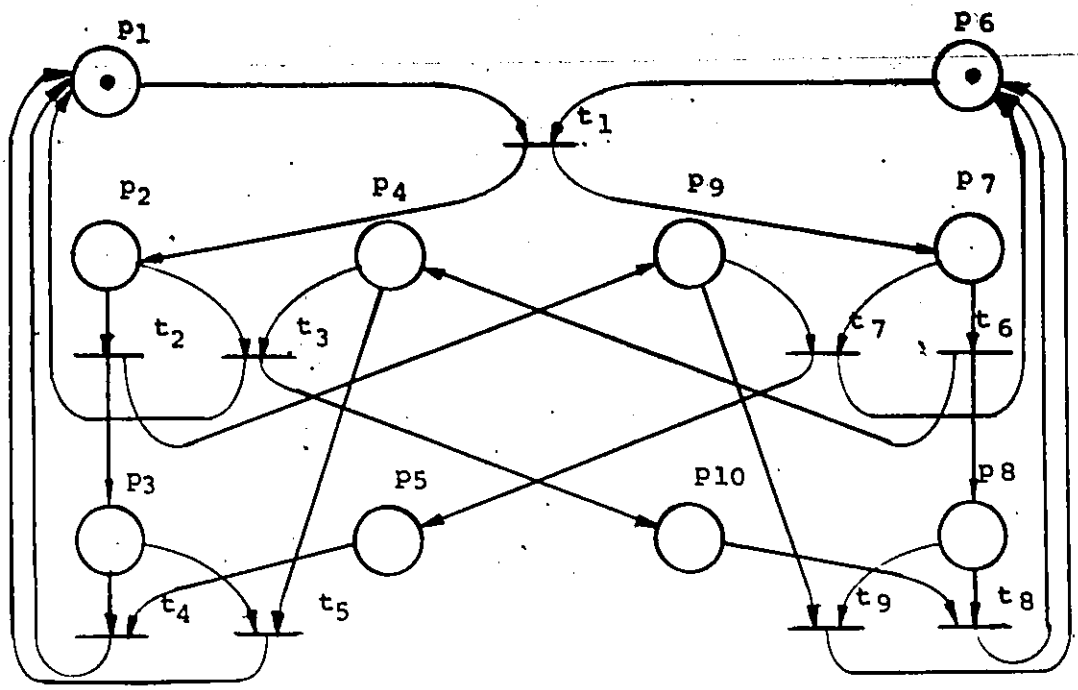
apply PNPUO to analyse a predicate/action PN model for this protocol in Subsection 5.2.3.

5.2.1 The BPN Model for Transport Protocol

In Berthelot's model (Figure 5-6), transition t1 is shared by the two transport protocol entities and is used to indicate the reception of a connection request either from its Session Layer or from its peer Transport Protocol entity.

When t1 is fired, each entity enters the Data Transfer State (p2 and p7 each get a token). Suppose, having transmitted data, one of the two entities sends (firing t2 or t6) a Disconnect Request (p9 or p4 gets a token). It then waits (p3 or p8) for Disconnection Confirm (waiting until p5 or p10 has got a token). If the other entity is still in a Data Transfer State (p7 or p2 has a token), it accepts (firing t7 or t2) the Disconnect Request and returns to its initial state , p6 or p1 . Meanwhile, it sends Disconnection Confirm (p5 or p10 gets a token) to the requesting entity. The latter then returns (firing t4 or t8) to its initial state p1 or p6. Thus, a life-cycle is completed.

Another possible case occurs when one of the entities sends (firing t2 or t6) a Disconnect Request (p9 or p4 gets a token). The other entity, while waiting for (p8 or p3 has a token) a Disconnect Confirm, accepts (firing t9 or t5) the



PLACES

State of Entities
p1,p6 : idle
p2,p7 : data transfer
p3,p8 : waiting p5, p10

Control Frames
p4,p9 : disconnection request
p5,p10: disconnection confirm

TRANSITIONS

Event of Entities
t1 : connection accepted
t2,t6 : request for disconnection
t3,t7 : disconnection accepted
t4,t8 : end of disconnection
t5,t9 : disconnection accepted

Figure 5-6: A BPN Model for the Connection and Disconnection Phases of Transport Protocol

request and returns to the initial state (p6 or p1). The former receives (firing t5 or t9) the request (p4 or p9 has a token) and returns to the initial state p1 or p6.

5.2.2. Results of Analysis Based on a BPN Model

Following is the analysis results of applying PNPUO to the model discussed above.

(1) Enumerative Analysis

Reachability Tree (Figure 5-7):

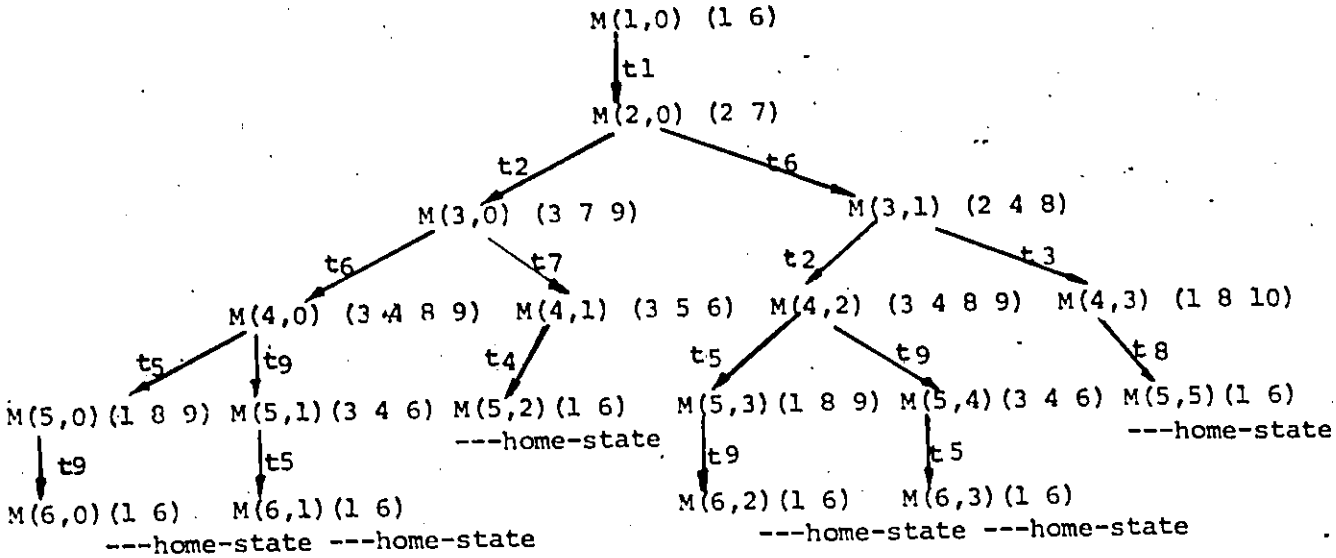


Figure 5-7: Reachability Tree of the PN in Figure 5-6

Token-related properties (output of PNPUO):

```
THE RESULTS OF REACHABILITY ANALYSIS :
<1> THE NET IS SAFE .

<2> THE MAX NUMBER OF TOKENS IN EACH PLACE IS :
                                ( FOR COLOUR1 )      1
<3> THE NET IS NOT CONSERVED
```

Execution-related Properties (output of PNPUO):

<4> EXECUTION-RELATED PROPERTIES :

NO DEADLOCKS .
NO LIVE-LOCKS .
NO LIVE-LOOPING .
M0 IS A HOME-STATE .

(2) Structural Analysis

Place Invariants (output of PNPUO):

PLACE INVARIANT 1 :

M (1) + M (2) + M (3) = 1

PLACE INVARIANT 2 :

M (1) + M (4) + M (5) + M (7) = 1

PLACE INVARIANT 3 :

M (6) + M (7) + M (8) = 1

PLACE INVARIANT 4 :

M (1) + M (2) + M (3) + M (6) + M (7) + M (8) = 2

PLACE INVARIANT 5 :

M (2) + M (6) + M (9) + M (10) = 1

PLACE INVARIANT 6 :

M (1) + M (2) + M (4) + M (5) + M (6) + M (7) + M (9) + M (10) = 2

Transition Invariants (output of PNPUO):

TRANSITION INVARIANT 1 :

$$M \xrightarrow{T1\ T2\ T4\ T7} M$$

TRANSITION INVARIANT 2 :

$$M \xrightarrow{T1\ T3\ T6\ T8} M$$

TRANSITION INVARIANT 3 :

$$M \xrightarrow{T1\ T2\ T5\ T6\ T9} M$$

From these results, it can be concluded that the protocol is free from deadlocks and livelocks and that it terminates correctly at the initial state. As the PN is safe and bounded, there is no channel overflow.

The place invariants (1), (3), (2), (5) we obtain are the same as those of [BERT82]. The other two, (4) and (6), are also correct, but do not appear in [BERT82]. Here, (1) and (3) show that each entity stays in one of the three phases at any moment. (2) and (5) indicate that, if one entity is in the Disconnection Phase (p1 or p6), the other cannot be in the Data Transfer Phase (p7 or p2) and cannot issue a Disconnect Request (p4 or p9) or Disconnect Confirm (p10 or p5) primitive. Place invariant (4) is implied by (1) and (3), and place invarint (6) by (2) and (5).

All our transition invariants are the same as those obtained by Berthelot [BERT82] manually. The first one indicates that firing the sequence of transitions t1, t2, t4, t7 leads a marking M (here M0) to itself (M0). The same situations occur for the sequence t1, t3, t6, t8 and sequence t1,t2, t5, t6, t9. These invariants are reflected

in the reachability tree (Figure 5-7) as those paths starting from the root M0 and terminating at the leaves which are home-states. Note that occasionally different paths in the tree may correspond to the same sequence of firing transitions. For example, the third transition invariant corresponds to the two leftmost paths in the tree :

(i) M(1,0) ->M(2,0) ->M(3,0) ->M(4,0) ->M(5,0) ->M(6,0)

(ii) M(1,0) ->M(2,0) ->M(3,0) ->M(4,0) ->M(5,1) ->M(6,1) .

5.2.3 Results of Analysis Based on A Predicate/action PN

For more efficient analysis, we have also applied PNPUO to verify the Transport Protocol using a predicate/action PN. We associate a predicate, say [A=1], with transition t1, to indicate that the demanded quality of the connection is met. The initial value of A is 0. Two predicates, [B=1] and [C=1], are attached to t2 and t6, to represent the end of the Data Transfer Phase in each entity. The corresponding actions, A:=0, B:=0 and C:=0, are related to transitions t1, t2 and t6, respectively. This model is shown in Figure 5-8.

We got the following analysis results for this model. If we assign the value 1 to the variables A, B, and C at the beginning of the reachability analysis, we get the same reachability tree as Figure 5-7. This means that if the protocol entities requires connection and data transfer, the protocol works and terminates properly.

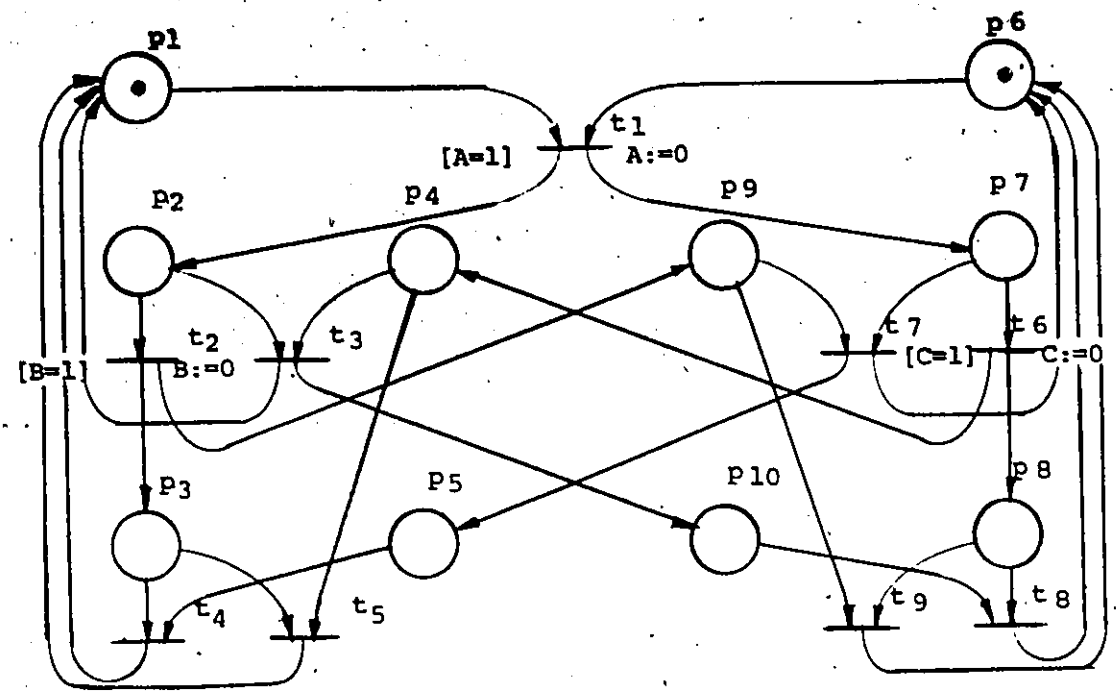


Figure 5-8: A Predicate/Action PN Model for the Transport Protocol

If we do not give new values to these variables (the system keeps A=B=C=0) during the generation of the reachability tree, we get the outputs as shown in Figure 5-9. This result indicates that if the Session layer or the peer entity does not issue any Connection Request, the Transport Protocol will not enter the Connection Phase.

Figure 5-10 shows the reachability tree in the case of assigning A=1 at the beginning of executing the PN and keeping B=C=0 during the execution. This is the situation when both entities stay in the Data Trasfer Phase for ever.

If we set A=1 and B=1 but keep C=0 during the execution, we get the reachability tree as shown in Figure 5-11. This figure shows that one of the entities is forced back to the Disconnection Phase before it has finished transferring its data.

For structural analysis, we get the same results as for the BPN model (Subsection 5.2.2).

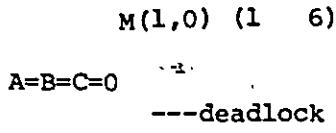


Figure 5-9: The Reachability Tree for the improved Model with A=B=C=0

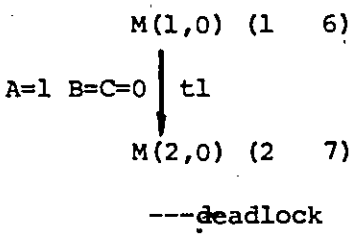


Figure 5-10: The Reachability Tree for the Improved Model with A=1 and B=C=0

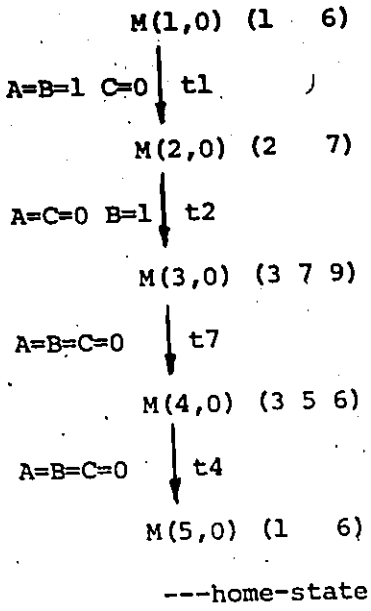


Figure 5-11: The Reachability Tree for the Improved Model with A=B=1 and C=0

Chapter VI -

CONCLUSION AND SUGGESTIONS FOR FURTHER RESEARCH AND DEVELOPMENT

In this thesis, we have introduced the basic concepts and properties of Petri nets. A brief review of the application of Petri net theory on the modeling and verification of communication protocols were summarized. Indepedent of OGIVE, we have developed a software package, PNPUO, for specifying and analysing logical properties of systems modeled in terms of Petri nets. It is implemented in PASCAL 8000 under CMS operating system on the AMDAHL computer. Its program requires about 10 kwords of memory space. For a Petri net with 40 places and 40 transitions, it is necessary to have another 10 kwords space to contain the data. Its objectives, user's interface, and implementational details were precented. Usefulness of the package for protocol verification was shown in the analysis results of two well-known protocols: the alternating bit protocol and a Transport Protocol.

In an efficient way, PNPUO provides a lot of convenience to the user as an automated aid for analysing many properties, such as reachability trees, deadlocks, livelocks, home-states, safeness, boundedness and

invariants. The user does not have to know the transition firing rules, the techniques for generating reachability trees, or the algebra of solving incidence equations.

Though the current version of PNPUO is for token-coloured and coloured predicate/action PN only, other types of PN can be handled quite easily. For timed PN, the time interval [t*,t**] can be represented by a predicate like [t>=t* and t<=t**]. This kind of predicates and the corresponding actions like t:=t+t** should be related to each transition of the net, where t is a time variable whose initial value is 0. In order to perform 'timeout' function in a timed PN, we can give larger value of t** with transition 'timeout' than that with other transitions, but less than the sum of any two of them. In this case, the format of predicates in PNPUO has to extend to including '>' (larger) and '<' (less) expressions.

Petri nets with inhibitor arcs can be converted into basic PN by adding pairs of places and transitions as described in [MOAL78]. The resulting PN can be analysed by PNPUO.

To enhance PNPUO, it can be extended in several aspects:

(1) The maximum numbers of places, transitions, colours, and variables of the Petri nets allowed in the current version of PNPUO can be changed arbitarily by setting the corresponding program parameters(m, n, l etc.).

(2) Other types of PN can be handled, possibly without conversion first, by adding into the current version of PNPUO procedures similar to the existing ones for handling input data and recognizing predicates and actions.

(3) Graphics capability may be added to PNPUO. The current PNPUO has no facilities for drawing the input Petri net diagrams or the subsquent reachability trees on the screen or on to hard copies. Graphics features will greatly enhance its visible capability.

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Appendix A

PROGRAM LISTINGS OF PNPUO

```
(*****************************************************************)
(* NAME :            PACKAGE                                     *)
(* FUNCTION :        This is  a software package for storing,    *)
(*                   displying, analysing coloured pridecats     *)
(*                   action Petri nets .                         *)
(* INPUT FILES :     DATAIN DATA    --   numerical data           *)
(*                   DIN DATA       --   character data           *)
(* OUTPUT FILES :    OUTIN DATA     --   numerical data           *)
(*                   OUT DATA       --   character data           *)
(*                   DATAOUT DATA   --   the record of the       *)
(*                          complete interactive process         *)
(* PROCEDURES CALLED :       NINTO                               *)
(*                           CWRITE                              *)
(*                           CREATE                              *)
(*                           DISPLAY                             *)
(*                           ANALYSIS                            *)
(*****************************************************************)
 PROGRAM PACKAGE(INPUT/, OUTPUT, DATAIN,DATAOUT,OUTIN,DIN,OUT) ;
   TYPE LIST = PACKED ARRAY (.1..40 , 1..9.) OF INTEGER;
        CB   = PACKED ARRAY (.1..40 , 1..40 , 1..9.) OF INTEGER;
        CC   = PACKED ARRAY (.1..8, 1..81.) OF CHAR ;
        CD   = PACKED ARRAY (.1..40,1..81.) OF CHAR ;
   VAR  PARC, TARC : CB ;
        P : LIST ;
        COM, COM1, COM2 : CC ;
        PP, PT, AP, AT : CD ;
        N,M,L,N1,N2,N3 : INTEGER ;
        A B,C,D,E F,G,H : INTEGER ;
        A',B1,C1,D1,E1,F1,G1,H1 : REAL ;
        A?,B2,C2,D2,E2,F2,G2,H2 : BOOLEAN ;
        T : CHAR ;
        R  FLAG,DFLAG,MFLAG : INTEGER ;
        DATAIN. DATAOUT, OUTIN  : TEXT ;
        DIN OUT : TEXT ;
   PROCEDURE ANALYSIS (VAR P:LIST; VAR PARC,TARC: CB;
                       VAR PP,PT AP,AT:CD;VAR M,N,L:INTEGER ) ;
   EXTERN ;                  (*  procedure analysis is  external *)
(*****************************************************************)
(* NAME :            CWRITE                                      *)
(* FUNCTION :        Write numerical and character data          *)
(*                   from variables and arrays into two          *)
(*                   output files 'OUTIN DATA' and 'OUT          *)
(*                   DATA', respectively,  for   subse-          *)
(*                   quent use.                                  *)
(* DATA RESOURCE :   program variables and arrays                *)
(*****************************************************************)
   PROCEDURE CWRITE ;
    VAR I J,K : INTEGER ;
     BEGIN
      REWRITE'OUTIN) ;              (* Open file 'OUTIN DATA' *)
      REWRITE (OUT) ;               (* Open file 'OUT DATA'   *)
      WRITELN (OUTIN,M:2,' ',N:2,' ',L:1) ;
      (*                                                       *)
      (*  write arcs P->T  --  PARC  -- MxNxL matrix           *)
```

```
(*              into  OUTIN DATA                              *)
(*                                                            *)
FOR I:=1 TO M DO
  FOR J:=1 TO N DO
    BEGIN
      FOR K:=1 TO L DO
        WRITE (OUTIN,PARC(.I J K.):2,' ') ;
      WRITELN (OUTIN)
    END ;
(*                                                            *)
(*  Write arcs T->P  -- TARC  -- MxNxL matrix                 *)
(*              into  OUTIN DATA                              *)
(*                                                            *)
FOR J:=1 TO N DO
  FOR I:=1 TO M DO
    BEGIN
      FOR K:=1 TO L DO
        WRITE (OUTIN,TARC(.I,J,K.):2,' ') ;
      WRITELN (OUTIN)
    END ;
(*                                                            *)
(*  Write names of user's integer variables -- COM            *)
(*           -- character strings into OUT DATA .             *)
(*                                                            *)
FOR I:=1 TO 8 DO
  BEGIN
    J := 1 ;
    WHILE COM(.I,J.)<>'$' DO
      BEGIN
        WRITE (OUT,COM(.I,J.)) ;
        J := J+1
      END ;
    WRITELN (OUT,'$')
  END ;
(*                                                            *)
(*  Write names of user's real variables -- COM1              *)
(*            -- character strings  into OUT DATA             *)
(*                                                            *)
FOR I:=1 TO 8 DO
  BEGIN
    J := 1 ;
    WHILE COM1(.I,J ) <> '$'  DO
      BEGIN
        WRITE (OUT,COM1(.I J )) ;
        J := J+1
      END ;
    WRITELN (OUT,'$')
  END ;
(*                                                            *)
(*  Write names of user's Boolean variables -- COM2           *)
(*           -- character strings  into OUT DATA              *)
(*                                                            *)
FOR I:=1 TO 8 DO
  BEGIN
```

```
    J := 1 ;
    WHILE COM2(.I J.) <> '$'  DO
      BEGIN
        WRITE (OUT,COM2(.I,J.)) ;
        J := J+1
      END ;
    WRITELN (OUT,'$')
  END ;
(*                                                    *)
(*    Write the predicates on transitions -- PT       *)
(*          -- character strings  into OUT DATA       *)
(*                                                    *)
FOR I:=1 TO N DO
  BEGIN
    J := 1 ;
    WHILE PT'.I,J ) <> '$' DO
      BEGIN
        WRITE (OUT,PT'.I J.)) ;
        J := J+1
      END ;
    WRITELN (OUT,'$')
  END ;
(*                                                    *)
(*  Write the actions at transitions  --  AT          *)
(*        -- character strings  into OUT DATA         *)
(*                                                    *)
FOR I:=1 TO N DO
  BEGIN
    J := 1 ;
    WHILE AT(.I,J ) <> '$'  DO
      BEGIN
        WRITE (OUT,AT(.I J.)) ;
        J := J+1
      END ;
    WRITELN (OUT,'$')
  END;
(*                                                    *)
(*  Write the predicates on places  --  PP            *)
(*        --  character strings  into OUT DATA        *)
(*                                                    *)
FOR I:=1 TO M DO
  BEGIN
    J := 1 ;
    WHILE PP(.I,J.) <> '$'  DO
      BEGIN
        WRITE (OUT,PP(.I,J.)) ;
        J := J+1
      END;
    WRITELN (OUT,'$')
  END ;
(*                                                    *)
(*  Write the actions on places  --  AP               *)
(*            -- character srings  into OUT DATA      *)
(*                                                    *)
```

```
    FOR I:=1 TO M DO
      BEGIN
        J := 1 ;
        WHILE AP(.I,J.) <>'$'  DO
          BEGIN
            WRITE (OUT,AP(.I,J.)) ;
            J := J+1
          END ;
        WRITELN (OUT,'$')
      END ;
    (*                                                    *)
    (*  Write initial marking M0  -- P                    *)
    (*               -- mxl matrix   into OUTIN DATA      *)
    (*                                                    *)
    FOR I:=1 TO M DO
      BEGIN
        FOR J:=1 TO L DO
          WRITE (OUTIN,P(.I,J ):2,'  ') ;
        WRITELN (OUTIN)
      END ;
    (*                                                    *)
    (*  Write the numbers of user's integer, real, and    *)
    (*             Boolean varioables  into OUTIN DATA    *)

    WRITELN (OUTIN,'  ',N1:1,'  ',N2:1,'  ',N3:1) ;
    (*                                                    *)
    (*  Write the value of each integer variable          *)
    (*            into OUTIN DATA,  if there are some     *)
    (*                                                    *)
    IF N' <> 0  THEN
      FOR I:=1 TO N1 DO
        CASE I-1 OF
          0 :  WRITELN(OUTIN A:2) ;   ' :  WRITELN(OUTIN,B:2) ;
          ^ :  WRITELN(OUTIN,C:2) ;   3 :  WRITELN(OUTIN,D:2) ;
          4 :  WRITELN(OUTIN,E:2) ;   5 :  WRITELN(OUTIN,F:2) ;
          6 :  WRITELN(OUTIN,G:2) ;   7 :  WRITELN(OUTIN,H:2)
        END ;
      FLAG := 1 (* Remember PN data has alreay stored in files*)
    END ;
(*************************************************************)
(*  NAME :              CREATE                               *)
(*  FUNCTION :          To accept user's data of a PN and    *)
(*                      store them into the follwing Vars    *)
(*                      and arrays .                         *)
(*  PROCEDURES CALLED :    INTRO                             *)
(*                         CDECLARATION                      *)
(*                         CPREDACT                          *)
(*                         CINITIAL                          *)
(*                         CWRITE                            *)
(*  PROGRAM VARIABLES :                                      *)
(*       M -- the total number of places in the PN <integer> *)
(*       N -- the total number of transition in PN <integer> *)
(*       L -- the total number of token colours    <integer> *)
(*  PROGRAM ARRAYS :                                         *)
```

```
(*       PARC -- number of arcs P->T, MxNxL integer matrix    *)
(*       TARC -- number of arcs T->P, MxNxL integer matrix    *)
(*       P    -- initial marking  M0, MxL   integer matrix    *)
(*       COM  -- user's integer varibbles, 8x80 cha. matrix   *)
(*       COM1 -- user's real variables,    8x80 cha. matrix   *)
(*       COM2 -- user's Boolean variables, 8x80 cha. matrix   *)
(*       PT   -- predicates on transitions, Nx80 cha. matrix  *)
(*       AT   -- actions at transitions ,   Nx80 cha. matrix  *)
(*       PP   -- predicates on places ,     Nx80 cha. matrix  *)
(*       AP   -- actions at places ,        Nx80 cha. matrix  *)
(* DATA RESOURCE :   from the terminal                         *)
(***************************************************************)
   PROCEDURE CREATE ;
     VAR  I, J. K, R : INTEGER ;
          T, CH : CHAR ;
(***************************************************************)
(* NAME :           CDECLARATION                               *)
(* FUNCTION :       Declare the PN entity in terms of          *)
(*                      total numbers of places, transitions,  *)
(*                                    and coloures ,           *)
(*                      arcs P->T & T-> P                      *)
(*                      names of variables (integer, real, and *)
(*                                    Boolean) .               *)
(* PROCEDURES CALLED : INTO                                    *)
(*                      CNUMBER                                *)
(*                      CARC                                   *)
(*                      CINTEGER                               *)
(*                      CREAL                                  *)
(*                      CLOGIC                                 *)
(***************************************************************)
     PROCEDURE CDECLARATION ;
(***************************************************************)
(*    NAME :           CNUMBER                                 *)
(*    FUNCTION :       Accept the total numbers of places,     *)
(*                                transitions, and colours.    *)
(*                     store them in Vars M, N, and L .        *)
(***************************************************************)
    PROCEDURE CNUMBER ;
      VAR I : INTEGER ;
      BEGIN
       WRITE (' * ENTER TOTAL NO. M OF PLACES  ');
       WRITELN ('  <NO BIGGER THAN 40>  OF YOUR NET *') ;
       READLN ;
       READ(M) ;           (* input the total number of places *)
       WRITELN (DATAOUT,'   TOTAL NO. N OF PLACES     M=',M:2) ;
       WRITE   (' * ENTER TOTAL NO. OF TRANSITIONS ');
       WRITELN ('   < NO BIGGER THAN 40 >  OF YOUR NET *') ;
       READLN ;
       READ(N) ;          (* input total number of transitions *)
       WRITELN (DATAOUT,'  TOTAL NO. OF TRANSITIONS   N=',N:2) ;
       WRITE (' * ENTER TOTAL NO. L OF COLOUR-TYPES OF TOKENS');
       WRITELN ('< NO BIGGER THAN 10 > OF YOUR NET *') ;
       READLN ;
       READ(L) ;       (* input total number of token colours *)
```

```
      WRITELN (DATAOUT,'   TOTAL NO OF TOKEN TYPES  \L=',L:2) ;
      WRITELN ;
      WRITELN(DATAOUT) ;
      *                                                          *)
     (* If did not store any data of this PN into the two       *)
     (*        output files 'OUTIN' and 'OUT',                  *)
     (* then initialize the numbers of each type of variables*)
     (*        <n1,n2 n3 for integer, real, Boolean resp.>      *)
     (*        and all the arrays.                              *)
     (*                                                         *)
      IF FLAG=0 THEN
      BEGIN
      N':=0 ; N2:=0; N3:=0 ;
      FOR I:=1 TO 8 DO
        BEGIN
          COM(.I,1.) :=  '$'  ;
          COM1(.I,1.) := '$'  ;
          COM2(.I,1.) := '$'
        END ;
      FOR I:=1 TO N DO
        BEGIN
          PT'.I,1.) := '$'  ;
          AT(.I,1.) := '$'
        END ;
      FOR I:=1 TO M DO
        BEGIN
          PP(.I,1.) := '$'  ;
          AP(.I 1.) := '$'
        END
      END
    END ;
(*****************************************************************)
(* NAME :            CARC                                        *)
(* FUNCTION :        Input all the numbers of arcs from          *)
(*                         places to transitions P->T,  and'     *)
(*                         from transitions to places T->P .     *)
(*****************************************************************)
   PROCEDURE CARC ;
     VAR I J,K,K1 : INTEGER ;
     BEGIN
       (*                                                       *)
       (*     Write the titel in each output file              *)
       (*        and the terminal                              *)
       (*                                                       *)
      WRITELN (DATAOUT,'  **  ARCS  P ---> T  &  T ---> P  **');
      WRITELN (DATAOUT) ;
      WRITELN('* SPECIFY TOKEN NUMBER FOR ERACH COLOUR TYPE *');
       WRITE ('  PLACE  TO  TRANS.') ;
       WRITE (DATAOUT,'  PLACE  TO  TRANS.') ;
       FOR K:=1 TO L DO
        BEGIN
         WRITE (' COL',K:1);
         WRITE (DATAOUT,'  COL',K:1)
        END ;
```

```
WRITELN ;
WRITELN (DATAOUT) ;
 WRITE (' ------------------') ;
 WRITE (DATAOUT,' --------------------') ;
 FOR K:=1 TO L DO
  BEGIN
   WRITE ('------') ;
   WRITE (DATAOUT,'------') ;
  END ;
 WRITELN ;
 WRITELN ;
 WRITELN (DATAOUT) ;
 (*                                      *)
 (*          inpute arcs P->T            *)
 (*                                      *)
 FOR I:=1 TO M DO
  FOR J:=1 TO N DO
   BEGIN
     IF I<= 9 THEN BEGIN            (*     write Pi     *)
                    WRITE(' P0',I:1) ;
                    WRITE(DATAOUT,' P0',I:1)
                   END
              ELSE BEGIN
                    WRITE('  P',I:2) ;
                    WRITE(DATAOUT,'  P',I:2)
                   END ;
          IF J<=9 THEN BEGIN        (*     write Tj     *)
                        WRITELN('          T0',J:1) ;
                        WRITE(DATAOUT,'          T0',J:1)
                       END
                  ELSE BEGIN
                        WRITELN('          T',J:2) ;
                        WRITE(DATAOUT,'          T',J:2)
                       END ;
          READLN ;
          (*                                *)
          (*         input Pi -> Tj         *)
          (*                                *)
          FOR K:=1 TO L DO
            BEGIN
              READ(R) ;       (* input Pi->Tj in colour k *)
              PARC(.I,J K.) := R
            END ;
          WRITE ('                    ') ;
          (*                                *)
          (*      display Pi -> Tj          *)
          (*                                *)
          FOR K:=1 TO L DO
            BEGIN          (*   on teminal and in file   *)
             WRITE('    ',PARC(.I J K.):2) ;
             WRITE(DATAOUT,'    ',PARC(.I,J,K.):2)
            END ;
          WRITELN ;
          WRITELN ;
```

```
      WRITELN (DATAOUT) ;
      WRITELN (DATAOUT)
END ;
(*                                                    *)
(*  write titel in each file and on the terminal      *)
(*                                                    *)
   WRITELN ;
   WRITELN ;
   WRITELN (DATAOUT) ;
   WRITELN (DATAOUT) ;
   WRITE('  TRANS.  TO  PLACE') ;
   WRITE(DATAOUT,'  TRANS.  TO  PLACE') ;
   FOR K:=1 TO L DO
    BEGIN
     WRITE('   COL',K:1) ;
     WRITE(DATAOUT,'    COL',K:1)
    END ;
   WRITELN(DATAOUT) ;
   WRITELN ;
    WRITE('  ----------------') ;
    WRITE(DATAOUT,'  ----------------') ;
   FOR K:=1 TO L DO
    BEGIN
     WRITE('--------') ;
     WRITE(DATAOUT,'--------')
    END ;
   WRITELN(DATAOUT) ;
   WRITELN(DATAOUT) ;
   WRITELN ;
   WRITELN ;
   (*                                    *)
   (*          input arcs T->P           *)
   (*                                    *)
   FOR J:=1 TO N DO
    FOR I:=1 TO M DO
     BEGIN
       IF J<=9 THEN BEGIN      (*    write Tj    *)
                      WRITE('  T0',J:1) ;
                      WRITE(DATAOUT,'   T0',J:1)
                    END
               ELSE BEGIN
                      WRITE('   T',J:2) ;
                      WRITE(DATAOUT,'    T',J:2)
                    END ;
          IF I<=9 THEN BEGIN      (*    write Pi    *)
                      WRITELN('          P0',I:1) ;
                      WRITE(DATAOUT,'          P0',I:1)
                    END
               ELSE BEGIN
                      WRITELN('           P',I:2) ;
                      WRITE(DATAOUT,'           P',I:2)
                    END ;
              READLN ;
              (*                                *)
```

```
                    (*       input Tj -> Pi        *)
                    (*                             *)
                    FOR K:=1 TO L DO
                      BEGIN
                        READ(R) ; '* input Tj->Pi in colour k*)
                        TARC(.I,J,K.)  := R
                      END ;
                    WRITE (´                    ´) ;
                    (*                                  *)
                    (*       display  Tj -> Pi          *)
                    (*                                  *)
                    FOR K:=1 TO L DO
                     BEGIN     (*   on terminal and in file   *)
                      WRITE(´  .    ´,TARC(.I J,K.):2) ;
                      WRITE(DATAOUT,´       ´,TARC(.I,J,K.):2)
                     END ;
                    WRITELN(DATAOUT) ;
                    WRITELN(DATAOUT) ;
                    WRITELN ;
                    WRITELN
          END
      END ;
'*****************************************************************)
(* NAME :            CINTEGER                                     *)
(* FUNCTION :        Accept names of user´s integer variables,    *)
(*                   store them in array ´COM´.                   *)
(*****************************************************************)
    PROCEDURE CINTEGER ;
     VAR I J : INTEGER ;
     BEGIN
       WRITELN (´ * * DEFINE PROGRAM INTEGER VARIABLES * *´) ;
       WRITELN (DATAOUT,´    * *   INTEGER VARIABLES   * *´) ;
       WRITELN (´  *  ENTER THE TOTAL NUMBER OF INTEGER   ´) ;
       WRITELN (´    VARIABLES       < NOT BIGGER THAN 8 > :´);
       READLN  ;
       READ(N1);(*input the total number of integer variables*)
       WRITELN'DATAOUT) ;
       (*                                                   *)
       (*  input all the names of user´s integer variables  *)
       (*                                                   *)
       FOR I:=1 TO N' DO
         BEGIN
           CH := CHR (I+ORD(´A´)-1) ;
           WRITE   (´  *  ENTER YOUR NO.´,I:1,);
           WRITELN (´ INTEGER VARIABLE NAME:´);
           READLN ;
           (*                                       *)
           (*    input the ith variable name        *)
           (*                                       *)
           J := 1 ;
           WHILE NOT EOLN DO
             BEGIN
               READ(T) ;   (* input jth char. in ith name *)
               COM (.I,J.) := T ;
```

```
            J := J+ 1
          END ;
          (*  add the suffix '$' in ith name  *)
          COM(.I,J.) := '$' ;
          (*                                   *)
          (*  display ith name of integer name  *)
          (*                                   *)
          J := 1 ;
          WRITE ('     ') ;
            WRITE (DATAOUT,'      ',CH:2.' :    ') ;
            WHILE COM(.I,J.)<>'$' DO
              BEGIN
                WRITE (COM(.I,J.)) ;          (* on terminal *)
                WRITE (DATAOUT,COM(.I,J.)) ; (* on file   *)
                J := J+1
              END ;
            WRITELN ;
            WRITELN (DATAOUT)
        END
    END ;
(*****************************************************************)
(* NAME :           CREAL                                        *)
(* FUNCTION :       Accept all the names of user's real vari- *)
(*                    ables and store them into array 'COM1'. *)
(*****************************************************************)
  PROCEDURE CREAL ;
    VAR I J : INTEGER ;
        T : CHAR ;
    BEGIN
        WRITELN ('  **  DEFINE PROGRAM REAL VARIABLES  * ') ;
        WRITELN ;
        WRITELN (DATAOUT) ;
        WRITELN(DATAOUT,'    * *    REAL VARIABLES   * *') ;
        WRITELN(DATAOUT) ;
        WRITELN ('  *  ERNTER THE TOTAL NUMBER OF REAL  ') ;
        WRITELN ('     VARIABLES  < NO BIGGER THAN 8 > :') ;
        READLN ;
        READ (N2) ;(* input the total num. f real variables *)
        FOR I:=1 TO N2 DO
          BEGIN
            CH := CHR ( I+ORD('A')-1) ;
            WRITELN ('* ENTER NO.',I:1,'REAL VARIABLE NAME:');
            READLN ;
            (*                                  *)
            (*   input ith real variable name   *)
            (*                                  *)
            J := 1;
            WHILE NOT EOLN DO
              BEGIN
                 READ (T) ;'*input jth character in ith name*)
                 COM1(.I J ) := T ;
                 J := J+1
              END;
            WRITE ('      ') ;
```

```
                COM1(.I,J ) := '$' ;  (* add suffix in ith name *)
                (*                                                *)
                (*     display ith real variable name             *)
                (*                                                *)
                J := 1 ;
                WRITE ('    ') ;
                WRITE (DATAOUT,'      ',CH:2,'1  :  ') ;
                WHILE COM1(.I,J.)<>'$' DO
                  BEGIN
                    WRITE (COM1(.I,J.)) ;       (*  on terminal  *)
                    WRITE (DATAOUT,COM1(.I,J.)) ; (*  on file    *)
                    J := J+1
                  END ;
                WRITELN ;
                WRITELN(DATAOUT)
              END
          END ;
(*****************************************************************)
(* NAME :           CLOGIC                                       *)
(* FUNCTION :       Accept all names of user's Boolean           *)
(*                    variables store them into array 'COM2'.*)
(*****************************************************************)
    PROCEDURE CLOGIC ;
      VAR I J : INTEGER ;
          T : CHAR ;
      BEGIN
        WRITELN (' * *  DEFINE PROGRAM BOOLEAN VARIABLES  * *');
        WRITELN ;
        WRITELN (DATAOUT) ;
        WRITELN(DATAOUT,'    * *   BOOLEAN VARIABLES   * *') ;
        WRITELN (DATAOUT) ;
        WRITELN ('  *  ENTER THE TOTAL NUMBER OF BOOLEAN ') ;
        WRITELN ('      VARIABLES     < NO BIGGER THAN 8 > :') ;
        READLN ;
        READ (N3); (*input the total num. of Boolean variables*)
        FOR I:=1 TO N3 DO
          BEGIN
            CH := CHR(I+ORD('A')-1) ;
            WRITE (' * ENTER YOUR NO.',I:1,' BOOLEAN VARIABLE');
            WRITELN ('NAME :') ;
            READLN  ;
            (*                                                *)
            (*    input ith Boolean variable name             *)
            (*                                                *)
            J :=1 ;
            WHILE NOT EOLN DO
              BEGIN
                READ (T) ; (* input jth character in ith name *)
                COM2(.I,J.) := T ;
                J := J+1
                  END ;
              WRITE('    ') ;
              (*   add sufix '$' for each name  *)
              COM2(.I,J ) := '$' ;
```

```
                (*                                                    *)
                (*    display ith Boolean variable name               *)
                (*                                                    *)
                J := 1 ;
                WRITE (´    ´) ;
                WRITE (DATAOUT,´      ´,CH:?,´2  :   ´) ;
                WHILE COM2(.I J )<>´$´ DO
                  BEGIN
                    WRITE (COM2(.I J )) ;      (*  on terminal  *)
                    WRITE (DATAOUT,COM2(.I,J.)) ; (*  on file  *)
                    J := J+1
                  END ;
                WRITELN ;
                WRITELN(DATAOUT)
                END
          END ;
(*****************************************************************)
(* NAME :            FIRST                                       *)
(* FUNCTION :        contain the options of entity declaration *)
(*****************************************************************)
    PROCEDURE FIRST ;
      BEGIN
       WRITELN (´   * * *   ENTITY DECLARATION PHASE   * * *´);
       WRITELN (´                    < ON CREATE >´)  ;
       WRITELN (´ ***********************************************´);
       WRITELN (´ *  DO YOU WANT TO DECLARE :                    *´);
       WRITELN (´ *     1.  NUMBERS OF PLACES, TRANSITIONS,      *´);
       WRITELN (´ *           AND COLOUR TYPES                   *´);
       WRITELN (´ *     2.  ARCS P-->T  &  T-->P                 *´);
       WRITELN (´ *     3.  INTEGER VARIABLES                    *´);
       WRITELN (´ *     4.  REAL VARIABLES                       *´);
       WRITELN (´ *     5.  BOOLEAN VARIABLES                    *´);
       WRITELN (´ ***********************************************´);
       WRITELN (´     *   ENTER YOUR SELECTION   *´) ;
       WRITELN (´ *  HIT ANY DIGITS OTHER THEN 1, 2, 3, 4, 5  ´);
       WRITELN (´      GET OUT OF ENTITY DECLARATION PHASE  *´)
      END ;
(*****************************************************************)
(* NAME :            INTO                                        *)
(* FUNCTION :        dispay the options of entity declaration  *)
(*                      on the terminal                          *)
(* PROCEDURES CALLED :   FIRST                                   *)
(*****************************************************************)
     PROCEDURE INTO ;
       BEGIN
         T:=´N´ ;
         WHILE T <> ´Y´ DO
           BEGIN
             FIRST ;          (* invoke procedure FIRST  *)
             READLN ;
             READ (R) ;       (*  input user´s selection  *)
             WRITELN (´ <´, R:1,´>    OK ?  --- Y OR N´) ;
             READLN ;
             READ (T)     (*  input user´s Y/N decision  *)
```

```
        END
    END ;
    (*                                                          *)
    (*   The main program of procedure CDECLARATION             *)
    (*                                                          *)
    BEGIN
      WRITELN(DATAOUT,'    * *   ENTITY DECLARATION    * *') ;
      WRITELN (DATAOUT) ;
      INTO  ;              (*   invike procedure INTO    *)
      WHILE (R>0) AND (R<6) DO
        BEGIN
          IF R=1
             THEN CNUMBER     (*  call procedure CNUMBER  *)
             ELSE IF R=2
                     THEN CARC      (*  call procedure CARC  *)
                     ELSE IF R=3
                             THEN CINTEGER (* call CINTEGER *)
                             ELSE IF R=4
                                     THEN CREAL  (*  call  *)
                                     ELSE CLOGIC ; (* call *)
          INTO         (*    call procedure INTO    *)
        END
    END ;
(*************************************************************)
(* NAME :           CPREDACT                                 *)
(* FUNCTION :       Accept all the predicates and actions and *)
(*                  store them into arrays PT  AT, PP,AP.    *)
(* PROCEDURE CALLED :    RECOM                               *)
(*                       CPREDTR                             *)
(*                       CACTTR                              *)
(*                       CPREDPL                             *)
(*                       CACTPL                              *)
(*************************************************************)
    PROCEDURE CPREDACT ;
     VAR  R I : INTEGER ;
(*************************************************************)
(* NAME :           CACTPL                                   *)
(* FUNCTION :       Accept all actions at all the places and *)
(*                  store them into array 'AP' .             *)
(*************************************************************)
     PROCEDURE CACTPL ;
        VAR I,J : INTEGER ;
            T : CHAR ;
       BEGIN
      WRITELN (' * *   ENTER ACTION AT EACH PLACE  * *') ;
      WRITELN ('      *  IN THE FORMAT AS  A:=A+1  *') ;
      WRITELN (DATAOUT) ;
      WRITELN (DATAOUT,'    * *   ACTIONS AT PLACES   * *') ;
      WRITELN (DATAOUT) ;
      WRITELN ;
      FOR I:=1 TO M DO
        BEGIN
          (*    write 'Pi  :' on terminal and record file   *)
          IF I<=9 THEN BEGIN
```

```
                    WRITELN ('     P',I:1,'   : ') ;
                    WRITE (DATAOUT,'      P',I:1,'   : ')
                  END
              ELSE BEGIN
                    WRITELN('     P',I:2,'   : ') ;
                    WRITE (DATAOUT,'      P',I:2,'   : ')
                  END ;
          READLN ;
          (*                                          *)
          (*    input the action at ith place         *)
          (*                                          *)
          J := 1 ;
          WHILE NOT EOLN DO
            BEGIN
              (*  input jth char. of action at ith place  *)
              READ (T) ;
              AP(.I,J ) := T ;
              J := J+1
            END ;
          (*   add suffix '$' in the action at ith palce   *)
          AP(.I J.) := '$' ;
          (*                                              *)
          (*     display the action at ith place          *)
          (*                                              *)
          J := 1 ;
          WRITE ('                ') ;
          WRITE (DATAOUT,'    ') ;
          WHILE AP(.I J )<>'$' DO
            BEGIN
              WRITE(AP(.I J )) ;      '*  display on terminal  *)
              WRITE(DATAOUT,AP(.I,J.)) ; (*   write on file   *)
              J := J+1
            END ;
          WRITELN ;
          WRITELN (DATAOUT)
        END
    END ;
(*****************************************************************)
(* NAME :            CACTTR                                      *)
(* FUNCTION :        Accept all the action at all the tran-      *)
(*                   sitions and store them into array 'AT' .    *)
(*****************************************************************)
    PROCEDURE CACTTR ;
      VAR I,J : INTEGER ;
          T : CHAR ;
      BEGIN
      WRITELN (' * *  ENTER ACTION AT EACH TRANSITION   * *') ;
      WRITELN ('      *  IN THE FORMAT AS A:= A+1  *') ;
      WRITELN (DATAOUT) ;
      WRITELN (DATAOUT,'   * *   ACTIONS AT TRANSITIONS   * *');
      WRITELN(DATAOUT) ;
      WRITELN ;
      FOR I:=1 TO N DO
        BEGIN
```

```
          (*    write 'Ti  :' on terminal and record file   *)
          IF I<=9 THEN BEGIN
                         WRITELN ('   T0',I:1,'   : ') ;
                         WRITE (DATAOUT,'    T0',I:1,'   : ')
                       END
                  ELSE BEGIN
                         WRITELN ('    T',I:2,'   : ') ;
                         WRITE(DATAOUT,'    T',I:^,'   : ')
                       END ;
          READLN ;
          (*                                                  *)
          (*    input the action at ith transition            *)
          (*                                                  *)
          J := 1 ;
          WHILE NOT EOLN DO
            BEGIN
              (* input jth char. of the action at ith trans. *)
              READ (T) ;
              AT(.I,J.) := T ;
              J := J+1
            END ;
           (*  ass suffix '$' in the action at ith transition *)
           AT(.I,J.) := '$' ;
           (*   display the action at ith transition    *)
           J := 1 ;
           WRITE ('              ') ;
           WRITE (DATAOUT,'    ') ;
           WHILE AT(.I J )<>'$' DO
             BEGIN
              WRITE(AT(.I,J.)) ;      (*  display on terminal  *)
              WRITE(DATAOUT,AT(.I,J.));(*write into record file*)
              J := J+1
             END ;
           WRITELN ;
           WRITELN (DATAOUT)
        END
    END ;
(*****************************************************************)
(* NAME :            CPREDPL                                     *)
(* FUNCTION :        Accept all the predicates on all the        *)
(*                   places and store them into array 'PP' .     *)
(*****************************************************************)
    PROCEDURE CPREDPL ;
      VAR I J : INTEGER ;
          T : CHAR ;
      BEGIN
      WRITELN (' * *  ENTER PREDICATES ON EACH PLACE  *'*') ;
      WRITELN ('        *  IN THE FORMAT AS A=0  *') ;
      WRITELN (DATAOUT) ;
      WRITELN (DATAOUT,'    * *   PREDICATES ON PLACES   * *') ;
      WRITELN (DATAOUT) ;
      WRITELN ;
      FOR I:=1 TO M DO
        BEGIN
```

```
          (*    write 'Pi  :'  on terminal and record file   *)
          IF I<=9 THEN BEGIN
                         WRITELN ('    P0',I:1,'   : ') ;
                         WRITE(DATAOUT,'    P0',I:1,'   : ')
                       END
                  ELSE BEGIN
                         WRITELN ('     P',I:2,'    : ') ;
                         WRITE(DATAOUT,'     P',I:2,'   : ')
                       END ;
          READLN ;
          (*                                                *)
          (*     input the predicate on place Pi            *)
          (*                                                *)
          J := 1 ;
          WHILE NOT EOLN DO
            BEGIN
              (* input jth char. of the predicate on ith place*)
              READ (T) ;
              PP(.I J ) := T ;
              J := J+1
            END ;
          PP(.I J.) := '$' ;(* add suffix to the ith predicate*)
          (*   display the predicate on ith place   *)
          J := 1 ;
          WRITE ('              ') ;
          WRITE (DATAOUT,'    ') ;
          WHILE PP(.I,J )<>'$' DO
            BEGIN
              WRITE(PP(.I,J.)) ;      (*  display on terminal  *)
              WRITE(DATAOUT,PP(.I,J.)) ; (* display on record *)
              J := J+1
            END ;
          WRITELN ;
          WRITELN (DATAOUT)
        END
      END ;
(*****************************************************************)
(* NAME :          CPREDTR                                       *)
(* FUNCTION :      To accept all the predicates on all the       *)
(*                 transitions and store them into array 'PT'.*)
(*****************************************************************)
    PROCEDURE CPREDTR ;
      VAR I,J : INTEGER ;
          T : CHAR ;
      BEGIN
      WRITELN (' *  ENTER PREDICATES ON EACH TRANSITION  *') ;
      WRITELN ('         *  IN THE FORMAT AS A=0  *') ;
      WRITELN (DATAOUT) ;
      WRITELN (DATAOUT,'  * *  PREDICATES ON TRANSITIONS  * *');
      WRITELN (DATAOUT) ;
      WRITELN ;
      FOR I:=1 TO N DO
        BEGIN
          (*   write 'Ti  :'  on terminal and record file   *)
```

```
        IF I<=9 THEN BEGIN
                       WRITELN (' T0',I:1,'  : ') ;
                       WRITE (DATAOUT,' T0',I:1,'  : ')
                     END
                ELSE BEGIN
                       WRITELN (' T',I:2,'  : ') ;
                       WRITE (DATAOUT,' T',I:2,'  : ')
                     END ;
        READLN ;
        (*                                                    *)
        (*    input the predicate on ith transition           *)
        (*                                                    *)
        J := 1 ;
        WHILE NOT EOLN DO
          BEGIN
            (*  input jth char. of predicate on ith thans.  *)
            READ (T) ;
            PT'.I,J.) := T ;
            J := J+1
          END ;
        PT'.I,J ) := '$' ;    (*  add suffix to ith tran.  *)
        (*      display the predicate on ith trnsition      *)
        J := 1 ;
        WRITE ('                ') ;
        WRITE (DATAOUT,'  ') ;
        WHILE PT'.I,J )<>'$' DO
          BEGIN
            WRITE(PT'.I J.)) ;      (*  display on terminal  *)
            WRITE(DATAOUT,PT(.I,J.));(*  display on record  *)
            J := J+1
          END ;
        WRITELN ;
        WRITELN (DATAOUT)
      END
    END ;
(*************************************************************)
(* NAME :          SECOND                                    *)
(* FUNCTION :      To contain the options of constraints     *)
(*                 definition phase                          *)
(*************************************************************)
  PROCEDURE SECOND ;
    BEGIN
      WRITELN ('     ***  CONSTRANTS DEFINITION PHASE  *** ');
      WRITELN ('                    < ON CREATE >') ;
      WRITELN ('  ****************************************');
      WRITELN ('  * DO YOU WANT TO DEFINE :              *');
      WRITELN ('  *    1. PT --- PREDICATES ON TRANSITIONS *');
      WRITELN ('  *    2. AT --- ACTIONS AT TRANSITIONS    *');
      WRITELN ('  *    3. PP --- PREDICATES ON PLACES      *');
      WRITELN ('  *    4. AP --- ACTIONS AT PLACES         *');
      WRITELN ('  ****************************************');
      WRITELN ('       *    ENTER YOUR SELECTION    *') ;
      WRITELN ('  *  PRESS ANY DIGITS OTHER THAN 1, 2, 3, 4');
      WRITELN (' TO GET OUT OF CONSTRAINTS DEFINITION PHASE*')
```

```
    END ;
(*****************************************************************)
(* NAME :            RECOM                                       *)
(* FUNCTION :        To display the optoins of constraints       *)
(*                   definition phase on the terminal            *)
(* PROCEDURE CALLED :    SECOND                                  *)
(*****************************************************************)
  PROCEDURE RECOM ;
    BEGIN
      T := 'N' ;
      WHILE T<>'Y' DO
        BEGIN
          SECOND ;              (*  call procedure SECOND  *)
          READLN ;
          READ(R) ;             (*  accept user's selection  *)
          WRITELN ('             <',R:1,'>  OK ?  --- Y OR N') ;
          READLN ;
          READ(T'                (*  accept user's decision  *)
        END
  END ;
    (*                                                         *)
    (*    the main program of procedure CPREDACT               *)
    (*                                                         *)
    BEGIN
      WRITELN (DATAOUT) ;
      WRITELN(DATAOUT '<** PREDICATE-ACTION DEFINITIONS **>');
      RECOM ;                       (*  call procedure RECOM  *)
     WHILE (R>0) AND (R<5) DO
       BEGIN
         IF R=1 THEN CPREDTR      (* call procedure CPREDTR *)
                ELSE IF R=2 THEN CACTTR    (*  call CACTTR  *)
                           ELSE IF R=3 THEN CPREDPL (* call*)
                                       ELSE CACTPL ;(* call*)
         RECOM                      (*  call procedure RECOM  *)
       END
    END ;
(*****************************************************************)
(* NAME :            CINITIAL                                    *)
(* FUNCTION :        To accept the initial marking M0  ,         *)
(*                   the initial values of program variables ,   *)
(*                   and store M0 into array P, assign           *)
(*                   variables to initial values.                *)
(* PROCEDURES CALLED :   COMM                                    *)
(*                       CINIMARK                                *)
(*                       CINIVAR                                 *)
(*****************************************************************)
  PROCEDURE CINITIAL ;
(*****************************************************************)
(* NAME :            CINIMARK                                    *)
(* FUNCTION :        To accept the initial marking M0   and      *)
(*                   store it into array P                       *)
(*****************************************************************)
    PROCEDURE CINIMARK ;
     VAR I J : INTEGER ;
```

```
BEGIN
  WRITELN (´     * *   ENTER  INITIAL  MARKING  M0   * *´);
  WRITELN (´              < CREATE OR MODIFY >´) ;
  WRITELN ;
  WRITELN (DATAOUT) ;
  WRITELN (DATAOUT,´  * * *   INITIAL MARKING  M0  * * *´);
  WRITELN (DATAOUT) ;
  (*   write the titel on terminal and record file   *)
  WRITE (´      P    ´) ;
  WRITE (DATAOUT,´      P    ´) ;
  FOR J:=1 TO L DO
   BEGIN
    WRITE (´ COL.´,J:1,´    ´) ;
    WRITE (DATAOUT,´ COL´,J:1,´    ´)
   END ;
  WRITELN ;
  WRITELN (DATAOUT) ;
  WRITE (DATAOUT,´     ---´) ;
  WRITE (´     ---´);
  FOR J:=1 TO L DO
   BEGIN
    WRITE (´---------´) ;
    WRITE (DATAOUT,´---------´) ;
   END ;
  WRITELN ;
  WRITELN (DATAOUT) ;
  (*   to accept M0   *)
  FOR I:=1 TO M DO
    BEGIN
      (*     write ´Pi ´ on teminal and record file    *)
      IF I<=9 THEN BEGIN
                     WRITELN (´     P0´,I:1) ;
                     WRITE (DATAOUT,´     P0´,I:1)
                   END
              ELSE BEGIN
                     WRITELN (´      P´,I:2) ;
                     WRITE (DATAOUT,´      P´,I:2)
                   END ;
      READLN ;
      (*                                                    *)
      (* to accept the initial token number in ith place *)
      (*                                                    *)
      FOR J:=1 TO L DO
       BEGIN
         (* input token no. in ith place with jth colour *)
         READ (R);
         P(.I J.) := R
       END ;
      WRITE (´              ´) ;
      WRITE (DATAOUT,´      ´) ;
      (* display the initial marking on terminal and file*)
      FO J:=1 TO L DO        marking
        IF P(.I,J )<=9 THEN BEGIN
                              WRITE (P(.I,J.):1,´       ´);
```

```
                                        WRITE (DATAOUT,P(.I,J.):1,' ')
                                      END
                                ELSE BEGIN
                                       WRITE(P(.I J ):2,'       ');
                              WRITE (DATAOUT,P(.I J ):2,'       ') ;
                                      END ;
            WRITELN (DATAOUT) ;
            WRITELN
          END
      END ;
(*****************************************************************)
(* NAME :            CINIVAR                                     *)
(* FUNCTION :        To accept initial values of all variables *)
(*                   and assign them to the variables A,B,...H *)
(*                   A1,B1,...H1,  A2,B2,...H2 .                 *)
(*****************************************************************)
  PROCEDURE CINIVAR ;
   VAR I J : INTEGER ;
   BEGIN
      WRITELN('   * *  ENTER INITIAL VALUES OF VARIABLES  * *');
      WRITELN ;
   IF N1 <> 0  THEN
     BEGIN
      WRITELN('     <ENTER INTEGER VARIABLE VALUES>') ;
      WRITELN('       PROGRAM"S   USER"S    VALUE') ;
      WRITELN('       ---------------------------') ;
      WRITE ('          ') ;
      (*      accept initial values of integer variables     *)
      FOR I:=1 TO N1 DO
        BEGIN
          CH := CHR  I + ORD('A') - 1) ;
          (*   display ith program variable name   *)
          WRITE(CH,'       ')  ;
          (*   display user's ith variable name on terminal   *)
          J := 1 ;
          WHILE COM(.I,J.)<>'$' DO
            BEGIN
              (* display jth char. of ith user's variable name*)
              WRITE (COM(.I,J.)) ;
              J := J + 1
            END ;
          WRITELN ('       ') ;
          (*  input initial values of ith variable  *
          READLN ;  READ (R) ;
          WRITELN('                          ',R) (* disply value *)
       END
      END ;
   IF N^<>0 THEN
    BEGIN
      WRITELN('     < ENTER REAL VARIABLE VALUES >') ;
      WRITELN('       PROGRAM"S   USER"S   VALUE') ;
      WRITELN('       ---------------------------') ;
      WRITE  ('          ') ;
      (*    accept all value of real variables    *)
```

```
    FOR I:=1 TO N2 DO
      BEGIN
        CH := CHR(I + ORD('A') -1) ;
        (*  display ith programe variable name  *)
        WRITE(CH '          ') ;
        (*  display user's ith real variabale name   *)
        J := 1 ;
        WHILE COM1(.I J )<>'$' DO
          BEGIN
            (*  write jth char. of ith user variable  *)
            WRITE(COM1(.I,J )) ;
            J := J + 1
          END ;
        WRITELN('       ') ;
        READLN ;   READ (R) ;  (*  input ith variable value  *)
        WRITELN('                          ',R) (* display value *)
      END
    END ;
  IF N3<>0 THEN
    BEGIN
     WRITELN('     < ENTER LOGIC VARIABLE VALUES >') ;
     WRITELN('      PROGRAM"S    USER"S    VALUE') ;
     WRITELN('      ----------------------------') ;
     WRITE  ('        ') ;
     (*    accept all initial values of Boolean variables    *)
     FOR I := 1 TO N3 DO
      BEGIN
        CH := CHR (I + ORD('A') -1) ;
        WRITE(CH,'       '); (* write ith program variable name*)
        (*   write user's ith Boolean variable name    *)
        J := 1 ;
        WHILE COM2(.I,J.)<>'$' DO
          BEGIN
            (*  write jth charactor of ith user variable  *)
            WRITE(COM2(.I J.)) ;
            J := J + 1
          END ;
        WRITELN ('     ') ;
        (*   inputr initial value of ith variable   *)
        READLN ;   READ (R) ;
        WRITELN('                          ',R) (* display value *)
      END
      END
    END ;
(*************************************************************)
(* NAME :           THIRD                                    *)
(* FUNCTION :       TO contain the options of initialization  *)
(*                  markings and variables phase             *)
(*************************************************************)
  PROCEDURE THIRD ;
    BEGIN
      WRITELN ('       * * *   INITIALIZATION   * * *  ') ;
      WRITELN ('                < ON CREATE  >') ;
      WRITELN (' ******************************************') ;
```

```
      WRITELN (' *    DO YOU WANT TO INPUT :                    *') ;
      WRITELN (' *         1. INITIAL MARKING  M0               *') ;
      WRITELN (' *         2. INITIAL VALUES OF VARIABLES       *') ;
      WRITELN (' ***************************************************') ;
      WRITELN ('    *  ENTER YOUR SELECTION  *') ;
      WRITE   ('    *  HIT ANY DIGIT OTHER THAN 1 AND 2 TO END');
      WRITELN (' INIALIZATION  *') ;
    END ;
(*************************************************************)
(* NAME :            COMM                                    *)
(* FUNCTION :        To display the options of initialization *)
(*                   markings and variables on termonal       *)
(* PROCEDURE CALLED :   THIRD                                 *)
(*************************************************************)
  PROCEDURE COMM ;
    BEGIN
      T := 'N' ;
      WHILE  T <> 'Y' DO
        BEGIN
          THIRD ;              (*  call procedure THIRD   *)
          READLN ;
          READ (R) ;           (*  accept user's selection  *)
          WRITELN ('           <',R:1,'>    OK  ?   --- Y OR N') ;
          READLN ;
          READ (T)             (*  accept user's decision  *)
        END
    END ;
  (*                                                  *)
  (*    the main program of procedure CINITIAL        *)
  (*                                                  *)
  BEGIN
    COMM ;                          (*  call procedure COMM  *)
    WHILE (R>0) AND (R<3) DO
      BEGIN
        IF R = 1 THEN CINIMARK      (*  call procedure CINIMARK  *)
                 ELSE CINIVAR ;     (*  call procedure CINIVAR   *)
        COMM                        (*  call procedure COMM  *)
      END
  END ;
(*************************************************************)
(* NAME :            ZERO                                    *)
(* FUNCTION :        To contain the options of procedure CREATE*)
(*                   -- module specification                  *)
(*************************************************************)
   PROCEDURE ZERO ;
    BEGIN
      WRITELN ;
      WRITELN ;
      WRITELN ('       * * *   MODULE SPECIFICATION   * * *') ;
      WRITELN ('                   < ON CREATE >   ') ;
      WRITELN('***************************************************');
      WRITELN('*  DO YOU WANT TO ENTER :                         *');
      WRITELN('*    1.  ENTITY DECLARATION PHASE                 *');
      WRITELN'*    2.  PREDICATE-ACTION DEFINITION PHASE        *');
```

```
      WRITELN('*     3.  INITIAL MARKING & VARIABLES PHASE    *');
      WRITELN('*********************************************');
      WRITELN ('      *    ENTER YOUR SELECTION    *') ;
      WRITELN ('  *  HIT ANY DIGITS OTHER THAN 1, 2, 3 ') ;
      WRITELN (' TO GET OUT OF MODULE SPECIFICATION SESSION  *')
    END ;
(*****************************************************************)
(* NAME :              INTRO                                     *)
(* FUNCTION :          To display the option of module           *)
(*                        specification process on terminal      *)
(* PROCEDURE CALLED :  ZERO                                      *)
(*****************************************************************)
    PROCEDURE INTRO ;
     BEGIN
       T := 'N' ;
       WHILE T <> 'Y' DO
         BEGIN
           ZERO ;                  (*  call procedure ZERO  *)
           READLN ;
           READ (R) ;              (*  accept user's selection  *)
           WRITELN ('              <',R:1,'> OK ?  --- Y OR N') ;
           READLN ;
           READ (T)                (*  accept user's decision  *)
         END
     END ;
(*                                                             *)
(*      then main program of procedure CREATE                  *)
(*                                                             *)
   BEGIN
      WRITELN (DATAOUT) ;
      WRITELN (DATAOUT,' *** PROCESS MODULE SPECIFICATION ***');
      WRITELN (DATAOUT) ;
      INTRO;                          (*  call procedure INTRO  *)
      WHILE (R>0) AND (R<4) DO
        BEGIN
          IF R=1   THEN CDECLARATION                (*   call   *)
                   ELSE IF R=2   THEN CPREDACT      (*   call   *)
                                 ELSE CINITIAL ;    (*   call   *)
          INTRO                      (*  call procedure INTRO  *)
        END ;
        CWRITE                       (*  call procedure CWRITE  *)
     END ;
(*****************************************************************)
(* NAME :              DISPLAY                                   *)
(* FUNCTION :          To display all the data of PN on terminal *)
(*                     and modify these data                     *)
(* PROCEDURES CALLED :     DREAD                                 *)
(*                         CWRITE                                *)
(*                         DINTRO                                *)
(*                         DDECLARATION                          *)
(*                         DPREDACT                              *)
(*                         DINITIAL                              *)
(* PROGRAM IDENTIFIERS :                                         *)
(*                    MFLAG  --  identify the function of        *)
```

```
(*                                  this procedure :                  *)
(*                                  MFLAG=0 -- to display data        *)
(*                                  MFLAG=1 -- to modify data         *)
(*                      DFLAG   --  identify the way of display:      *)
(*                                  DFLAG=0 -- <B> potion by potion   *)
(*                                  DFLAG=1 -- <A> all together       *)
(*                      FLAG    -- indentify whether has already      *)
(*                                  called CWRITE so that stored data*)
(*                                  in the output files or not:       *)
(*                                    FLAG=0  --  not                 *)
(*                                    FLAG=1  --  yes                 *)
(*     DATA RESOURCES :                                               *)
(*             <i>  program variables, arrays <when FLAG=1>           *)
(*             <ii>  input files 'DATAIN DATA', DIN DATA'             *)
(*                                              <when FLAG=0>         *)
(*****************************************************************)
    PROCEDURE DISPLAY ;
     VAR I J,K,R : INTEGER ;
         T, CH   : CHAR ;
(*****************************************************************)
(* NAME :              DDECLARATION                                  *)
(* FUNCTION :          To display/modify the PN interms of        *)
(*                        total numbers of places, transitions,  *)
(*                                  and token colours            *)
(*                        arcs P->T and T->P                     *)
(*                        names of variables (integer, real, and *)
(*                                        Boolean) .             *)
(* PROCEDURES CALLED :         DINTO                             *)
(*                             DNUMBER                           *)
(*                             DARC                              *)
(*                             DINTEGER                          *)
(*                             DREAL                             *)
(*                             DLOGIC                            *)
(*****************************************************************)
     PROCEDURE DDECLARATION ;
       VAR L1 : INTEGER  ;
(*****************************************************************)
(* NAME :              DNUMBER                                   *)
(* FUNCTION :          To display/modify the total numbers of    *)
(*                     places, transitions, and colours of PN    *)
(*                     on the terminal : M, N  L .               *)
(* PROCEDURE CALLED :     MODI                                   *)
(*****************************************************************)
     PROCEDURE DNUMBER ;
       VAR V :CC ;
(*****************************************************************)
(* NAME :              MODI                                      *)
(* FUNCTION :          To display and accept user's decision in  *)
(*                     the modify process :                      *)
(*                     whether user wants to change current line.*)
(*****************************************************************)
       PROCEDURE MODI ;
         BEGIN
           WRITELN(' *   DO YOU WANT TO CHANGE ?  --- Y  OR  N');
```

```
        READLN ;
        READ (T) ;          (*  input user's decision   *)
        IF T='Y' THEN
          WRITELN('*YOU SHOULD GO BACK TO "MODULE CREATE"*');
      END ;                                                  *)
    (*                                                       *)
    (*    the main program of procedure DNUMBER              *)
    (*                                                       *)
    BEGIN
     WRITELN (' TOTAL # OF PLACES    M=',M:2) ; (* display M*)
     IF MFLAG=1 THEN MODI ;          (*  call procedure MODI  *)
     WRITELN ('    TOTAL # OF TRANSITIONS   N=',N:2) ;
     IF MFLAG=1 THEN MODI ;          (*  call procedure MODI  *)
     WRITELN ('    TOTAL # OF TOKEN TYPES   L=',L:2) ;
     IF MFLAG=1 THEN MODI ;          (*  call procedure MODI  *)
     WRITELN
    END ;
(*************************************************************)
(* NAME :              DARC                                  *)
(* FUNCTION :          To dispay/modify all the numbers of arcs  *)
(*                        P  -->  T  and  T  -->  P          *)
(* PROCEDURE CALLED :      MMODI                             *)
(*************************************************************)
    PROCEDURE DARC ;
     VAR I J K,LAG : INTEGER ;
(*************************************************************)
(* NAME :              MMODI                                 *)
(* FUNCTION :          To change numbers of arcs P->T and T->P   *)
(*                     in the modify process                 *)
(*************************************************************)
      PROCEDURE MMODI ;
        VAR I, J, K, PT. R1: INTEGER ;
            T1: CHAR ;
        BEGIN
          WRITELN ('  *  DO YOU WANT TO CHANGE ?   --- Y OR N');
          READLN ;   READ (T) ;   (*  accept user's decision  *)
          PT := 0 ;
          WHILE (T = 'Y') AND (PT < 3) DO
            BEGIN
             WRITELN('*ENTER THE NEW LINE formed like above :');
             (*                                                *)
             (* read input line like 'P07 T10 0' from terminal*)
             (*                                                *)
             READLN ;  READ (T1) ;    (*  read the first cha.  *)
             WHILE T1 = ' '  DO   READ (T1); '*  read blanks  *)
             IF T1 = 'P'  THEN   PT := 1 (*first letter is 'P'*)
                         ELSE IF T1 = 'T' THEN  PT := 2
                                  THEN PT := 2   (* it is 'T' *)
                                  ELSE  BEGIN
                  (*  first non-blank cha. neither 'P' nor 'T' *)
                  PT := 3 ;
                  WRITELN(' * INPUT ERROW  ENTER AGAIN *')
                                        END ;
              (* find and read the second non-blank character  *)
```

```
        READ(T1) ;
        WHILE T1 = ' '  DO    READ (T1)  ;(*  found it  *)
       (*   change charactor to digit    *)
        I := ORD(T1) - ORD('0')  ;
        READ (T1) ;              (*   read the third cha.  *)
        I := I * 10 + ORD(T1) - ORD('0');(*  get  digit *)
        (*                                                *)
        (* find and read the second non-blank cha. group*)
        (*                                                *)
        READ (T1) ; WHILE T1 = ' ' DO   READ (T1) ;
        READ (T1) ; WHILE T1 = ' ' DO   READ (T1) ;
        J := ORD(T1) - ORD('0') ;  (*  change to digit  *)
        READ (T1) ;              (*  read the third cha.  *)
        J := J * 10 + ORD(T1) - ORD('0');(* get integer *)
        (*                                                *)
        (* find and read the rest non-blank cha. groups *)
        (*                                                *)
        READ (T1) ; WHILE T1 = ' ' DO   READ (T1) ;
        K := 1 ;
        WHILE K <= L DO
          BEGIN
            R := ORD(T1) - ORD('0') ; READ(T1) ;
            WHILE T1 <> ' ' DO  BEGIN
                          R := R * 10 + ORD(T1) - ORD('0');
                          READ (T1)
                                END ;
            (*  assign new values to array PARC or TARC *)
            IF PT = 1 THEN PARC(.I,J,K.) := R  ;
            IF PT = 2 THEN BEGIN
                             R1 := I;   I := J;  J := R1 ;
                             TARC(.I J K.) := R
                           END ;
            K := K + 1
          END ;
        READLN ;
        WRITELN('*DO YOU WANT TO CHANGE ONE MORE LINE ?');
        WRITELN('            ---  Y OR N') ;
        READLN ;  READ (T)
      END
 END ;
(*                                              *)
(*  the main program of procedure DARC          *)
(*                                              *)
BEGIN
 WRITELN ;
 WRITELN ('    * *   ARCS  P --> T  &  T --> P   * *') ;
 WRITELN ;
 (*    write the heading for PARC      *)
 WRITE ('   PLACE  TO  TRANS.     ') ;
 FOR K:= 1 TO L DO
   WRITE ('COL',K:1,'     ') ;
 WRITELN ;
 WRITE ('   -------------------') ;
 FOR K:=1 TO L DO
```

```
  WRITE ('-------') ;
WRITELN ;
(*                                        *)
(*      display/modify  PARC              *)
(*                                        *)
FOR I:=1 TO M DO
  FOR J:=1 TO N DO
    BEGIN
      LAG := 0; (* LAG -- to mark non-zero arcs <LAG=1>*)
      FOR K:=1 TO L DO
        IF PARC(.I,J,K.) <> 0 THEN  LAG := 1  ;
       (*    only display non-zero arcs          *)
       IF LAG=1 THEN
         BEGIN
           IF I<=9 THEN WRITE ('     P0',I:1)
                   ELSE WRITE ('     P',I:2) ;
           IF J<=9 THEN WRITE ('       T0',J:1)
                   ELSE WRITE ('       T',J:2) ;
           WRITE('       ') ;
           FOR K:=1 TO L DO
               WRITE (PARC(.I,J,K.):2,'       ') ;
           WRITELN
         END
    END ;
  (*  for modifying, call procrdure MMODI  *)
  IF MFLAG=1 THEN MMODI;
  WRITELN ;
  (*    write heading for TARC     *)
  WRITE ('    TRANS.  TO PLACE   ') ;
  (*    write the heading      *)
  FOR K:=1 TO L DO
    WRITE('COL.',K:1,'    ') ;
  WRITELN ;
  WRITE ('    ------------------') ;
  FOR K:=1 TO L DO
    WRITE('-------') ;
  WRITELN ;
  (*                                        *)
  (*      modify/modify TARC                *)
  (*                                        *)
  FOR J:=1 TO N DO
    FOR I:=1 TO M DO
      BEGIN
        LAG := 0; (* LAG -- LAG=1 to mark non-zero arcs *)
        FOR K:=1 TO L DO
          IF TARC(.I J K.) <> 0  THEN   LAG := 1 ;
         (*   only disply non-zero arcs on terminal   *)
         IF LAG=1 THEN
           BEGIN
             IF J<=9 THEN WRITE ('    T0',J:1)
                     ELSE WRITE ('    T',J:2) ;
             IF I<=9 THEN WRITE ('         P0',I:1)
                     ELSE WRITE ('         P',I:2) ;
             WRITE('       ') ;
```

```
                FOR K:=1 TO L DO
                    WRITE (TARC(.I J K.):2,'      ') ;
                WRITELN
              END
          END ;
        IF MFLAG=1 THEN MMODI   '*  for modifing, call MMODI    *)
      END ;
(*****************************************************************)
(* NAME :            DMOD                                        *)
(* FUNCTION :        To change the name of variables             *)
(* INPUT PARAMETER :   V -- 8x81 array of char. to represent     *)
(*                          COM, or COM1, or COM2 .              *)
(*****************************************************************)
  PROCEDURE DMOD(VAR V :CC) ;
    VAR J : INTEGER ;
    BEGIN
      WRITELN''* DO YOU WANT TO CHANGE THIS NAME? --- Y OR N');
      READLN ;
      READ (T) ;                  (*   input user's decision    *)
      IF T = 'Y' THEN
        BEGIN
          WRITELN ('   *  ENTER NEW NAME OF THIS VARIABLE :') ;
          READLN ;
          WRITE ('                    ') ;
          (*    input a new name     *)
          J := 1 ;
          WHILE NOT EOLN DO
            BEGIN
              READ (T) ;      (*  input jth char. of name 11  *)
              V(.L1,J.) := T ;
           WRITE (V(.L',J.));(* display new name on terminal *)
              J := J + 1
            END ;
          V(.L1,J.) := '$' ; (*  add suffix to the new name  *)
          WRITELN
        END
      END ;
(*****************************************************************)
(* NAME :            DNUM                                        *)
(* FUNCTION :        To change the total number of any type of   *)
(*                   variables                                   *)
(* INPUT PARAMETER : G -- integer,to represent the total         *)
(*                        number of a type of variables          *)
(*****************************************************************)
     PROCEDURE DNUM(VAR G : INTEGER) ;
       BEGIN
      WRITELN('* TOTAL NUMBER OF VARIABLE IN THIS TYPE IS',G:3);
      WRITE (' * ENTER NEW VALUE OF TOTAL NUMBER OF VARIABLES');
      WRITELN (' IN THIS TYPE') ;
      WRITELN('       < IF NO CHANGE HIT 0 >    :') ;
      READLN ;
      READ (R) ;                (*  input new number  *)
      IF R <> 0 THEN G := R
       END ;
```

```
(*****************************************************************)
(* NAME :            DINTEGER                                    *)
(* FONCTION :        To display or modify the names of user's    *)
(*                   integer variables (COM) .                   *)
(* PEOCEDURES CALLED :   DNUM                                    *)
(*                   DMOD                                        *)
(*****************************************************************)
    PROCEDURE DINTEGER ;
      VAR I,J : INTEGER ;
      BEGIN
        WRITELN ;
        WRITELN ('    * *   INTEGER VARIABLES   * *') ;
        IF MFLAG=1 THEN DNUM (N1) ;   (* call procedure DNUM *)
        (*   display integer variable names    *)
        WRITELN ('   PROGRAM"S          USER"S ') ;
        WRITELN ('    -------------------------') ;
      IF N1 = 0  THEN
        WRITELN ('           < NIL >')
                ELSE
        FOR I:=1 TO N1 DO
          BEGIN
            CH := CHR(I+ORD('A')-1) ;
            WRITE ('        ',CH:1,'                ') ;
            J := 1 ;
            WHILE COM(.I J.)<>'$' DO
              BEGIN
                WRITE(COM(.I,J )) ;
                J := J+1
              END ;
            WRITELN ;
            (* for modifying, call DMOD to change ith name  *)
            IF MFLAG=1 THEN BEGIN
                              L1 := I ;
                              DMOD (COM)      (*  call DMOD  *)
                            END
          END
      END ;
(*****************************************************************)
(* NAME :            DREAL                                       *)
(* FUNCTION :        To display or modify names of user's real   *)
(*                   variables                                   *)
(* PROCEDURES CALLED   :    DNUM                                 *)
(*                   DMOD                                        *)
(*****************************************************************)
    PROCEDURE DREAL ;
      VAR I J : INTEGER ;
      BEGIN
        WRITELN ;
        WRITELN ('    * *   REAL VARIABLES   * *') ;
        IF MFLAG=1 THEN DNUM(N2) ;              (*  call DNUM  *)
        WRITELN ('   PROGRAM"S          USER"S ') ;
        WRITELN ('    -------------------------') ;
      IF N2 = 0 THEN
        WRITELN ('           <  NIL  >')
```

```
          ELSE
        (*    display real variable names on terminal     *)
        FOR I:=1 TO N2 DO
          BEGIN
            CH := CHR(I+ORD('A')-1) ;
            WRITE ('       ',CH:',1              ') ;
            J := 1 ;
            WHILE COM1(.I,J.)<>'$' DO
              BEGIN
                (* display jth charactor og ith variable name *)
                WRITE(COM1(.I,J.)) ;
                J := J+1
              END ;
            WRITELN ;
            (* for modifying, call DMOD to change ith name *)
            IF MFLAG=1 THEN BEGIN
                              L1 := I ;
                              DMOD (COM1)
                            END
          END
        END ;
(*****************************************************************)
(* NAME :            DLOGIC                                      *)
(* FUNCTION :        To display or modify names of user's        *)
(*                   Boolean variables                           *)
(* PROCEDURES CALLED :     DNUM                                  *)
(*                         DMOD                                  *)
(*****************************************************************)
    PROCEDURE DLOGIC ;
      VAR I J : INTEGER ;
      BEGIN
        WRITELN ;
        WRITELN ('    * *    LOGIC VARIABLES    * *') ;
        WRITELN ;
        IF MFLAG=1 THEN DNUM(N3) ;          (*  call DNUM  *)
        WRITELN ('   PROGRAM"S          USER"S ') ;
        WRITELN ('    -------------------------') ;
      IF N3 = 0 THEN
        WRITELN ('             <  NIL  >')
              ELSE
        (*   display names of Boolean variables on terminal   *)
        FOR I:=1 TO N3 DO
          BEGIN
            CH := CHR (I + ORD('A')-1) ;
            WRITE ('       ',CH:1,'2             ') ;
            J := 1 ;
            WHILE COM2(.I,J.)<>'$' DO
              BEGIN
                (* display jth charactor of ith variable name *)
                WRITE (COM2(.I,J )) ;
                J := J + 1
              END ;
            WRITELN ;
            (*    for modify, call DMOD to change ith name    *)
```

```
          IF MFLAG=1 THEN BEGIN
                            L1 := I ;
                            DMOD (COM2)
                          END
        END
      END ;
(*****************************************************************)
(* NAME :           DFIRST                                       *)
(* FUNCTION :       To contain the options of entity             *)
(*                  declaration phase on DISPLAY or MODIFY       *)
(*****************************************************************)
    PROCEDURE DFIRST ;
      BEGIN
        WRITELN ;
        WRITELN ('         * * *   ENTITY DECLARATION   * * *');
        IF MFLAG=0 THEN
        WRITELN ('                   < ON DISPLAY >') ;
        IF MFLAG=1 THEN
        WRITELN ('                   < ON MODIFY >') ;
        WRITELN('*********************************************');
        WRITELN('* DO YOU WANT TO DISPLAY :                  *');
        WRITELN('*    1.   NUMBERS OF PLACES, TRANSITIONS,   *');
        WRITELN('*           AND COLOUR TYPES                *');
        WRITELN('*    2.   ARCS   P --> T  &  T --> P        *');
        WRITELN('*    3.   INTEGER VARIABLES                 *');
        WRITELN('*    4.   REAL VARIABLES                    *');
        WRITELN('*    5.   BOOLEAN VARIABLES                 *');
        WRITELN('*********************************************');
        WRITELN ('     *   ENTER YOUR SELECTION   *') ;
        WRITELN (' *HIT ANY DIGITS OTHER THAN 1, 2, 3, 4, 5 ');
        WRITELN (' TO GET OUT OF ENTITY DECLARATION SESSION *')
      END ;
(*****************************************************************)
(* NAME :          DINTO                                         *)
(* FUNCTION :      To display the options of entity declaration  *)
(*                 on the terminal and accept user's selection   *)
(* PROCEDURE CALLED :    DFIRST                                  *)
(*****************************************************************)
    PROCEDURE DINTO ;
      BEGIN
        T := 'N' ;
        WHILE T<> 'Y' DO
          BEGIN
            DFIRST ;       (*  call DFIRST to display options  *)
            READLN ;
            READ (R) ;         (*    input user's selection     *)
            WRITELN ('          <',R:1,'>    OK ?  ---  Y OR N');
            READLN ;
            READ (T)           (*    accept user's decision     *)
          END
      END ;
    (*                                                           *)
    (*    main program of procedure DDECLARATION                 *)
    (*                                                           *)
```

```
      BEGIN
        (*     in option A, call subprocedures one by one *)
        IF DFLAG=1 THEN
          BEGIN
            DNUMBER ;
            DARC ;
            DINTEGER ;
            DREAL ;
            DLOGIC
          END
                  ELSE
          (*  in option B, call subprocedures interactively   *)
          BEGIN
        DINTO ;              (*  call DINTO to get user's selection  *)
        WHILE (R>0) AND (R<6) DO
          BEGIN
            IF R=1 THEN DNUMBER
                   ELSE IF R=2
                           THEN DARC
                           ELSE IF R=3
                                   THEN DINTEGER
                                   ELSE IF R=4
                                           THEN DREAL
                                           ELSE DLOGIC ;
            DINTO (*  call DINTO to get user's next selection *)
          END
         END
       END ;
(*****************************************************************)
(* NAME :            DPREDACT                                    *)
(* FUNCTION :        to display or modify all the predicates     *)
(*                   and actions of PN                           *)
(* PROCEDURES CALLED :      DRECOM                               *)
(*                          DPREDTR                              *)
(*                          DACTTR                               *)
(*                          DPREDPL                              *)
(*                          DACTPL                               *)
(*****************************************************************)
    PROCEDURE DPREDACT ;
      VAR L2,R : INTEGER ;
          T    : CHAR ;
(*****************************************************************)
(* NAME :            PMOD                                        *)
(* FUNCTION :        To modify a predicate or an action          *)
(* INPUT PARAMETER :       U  -- 40x81 array of char.            *)
(*****************************************************************)
      PROCEDURE PMOD (VAR U : CD ) ;
        VAR J : INTEGER ;
        BEGIN
          WRITELN (' *  DO YOU WANT TO CHANGE ?  --- Y  OR  N');
          READLN ;
          READ (T) ;              (*  accept user's decision  *)
          IF T='Y' THEN
            BEGIN
```

```
            WRITELN ('  * ENTER THE NEW CONSTRAINT :') ;
            READLN ;
            (*    accept the new constraint     *)
            J := 1 ;
            WRITE ('                    ') ;
            WHILE NOT EOLN DO
              BEGIN
                (* accept jth charactoer of L2 th constraint*)
                READ (T) ;
                U(.L^,J.) := T ;
                WRITE (U(.L2,J )); (* display 12th constraint*)
                J := J + 1
              END ;
            WRITELN ;
            U(.L2,J.) := '$'  (*  add suffix to 12th cons.  *)
        END
      END ;
(*************************************************************)
(* NAME :            DPREDTR                                 *)
(* FUNCTION :        To display or modify all the predicates *)
(*                   on all the transitions                  *)
(* PROCEDURE CALLED :     PMOD                               *)
(*************************************************************)
    PROCEDURE DPREDTR ;
    VAR I,J : INTEGER ;
    BEGIN
      WRITELN ;
      WRITELN ('     * *   PREDICATES ON TRANSITIONS   * *') ;
      WRITELN ('       TRANS          PREDICATE') ;
      WRITELN ('       ------------------------') ;
      FOR I:=1 TO N DO
        BEGIN
          IF I<=9 THEN WRITE ('       T0',I:1,'              ')
                  ELSE WRITE ('       T',I:2,'               ') ;
            (*   display the predicate on ith transition    *)
            J := 1 ;
            WHILE PT'.I J )<>'$' DO
              BEGIN
                WRITE(PT'.I,J )) ;
                J := J+1
              END ;
            WRITELN ;
            (*  for modify, call PMOD to change ith pred.  *)
            IF MFLAG=1 THEN BEGIN
                              L? := I ;
                              PMOD (PT)       (*   call PMOD   *)
                            END
        END
      END ;
(*************************************************************)
(* NAME :            DACTTR                                  *)
(* FUNCTION :        To disply or modify all the actiond at all*)
(*                      the transitions                      *)
(* PROCEDURE CALLED :     PMOD                               *)
```

```
(*****************************************************************)
    PROCEDURE DACTTR ;
      VAR I,J : INTEGER ;
      BEGIN
        WRITELN ;
        WRITELN ('   * *   ACTIONS AT TRANSITIONS   * *') ;
        WRITELN ('      TRANS.          ACTION') ;
        WRITELN ('      ----------------------') ;
        FOR I:=1 TO N DO
          BEGIN
            IF I<=9 THEN WRITE('       T0',I:1,'           ')
                    ELSE WRITE('       T',I:2,'           ') ;
            (*    display the action at ith transition     *)
            J := 1 ;
            WHILE AT(.I J )<> '$'  DO
              BEGIN
                WRITE (AT(.I,J )) ;
                J := J + 1
              END ;
            WRITELN ;
            (*  for modify, call PMOD to change ith action   *)
            IF MFLAG=1 THEN BEGIN
                              L2 := I ;
                              PMOD(AT)     (*    call PMOD   *)
                            END
          END
      END ;
(*****************************************************************)
(* NAME :            DPREDPL                                     *)
(* FUNCTION :        To display or modify all the predicates     *)
(*                      on all the places                        *)
(* PROCEDURE CALLED :   PMOD                                     *)
(*****************************************************************)
    PROCEDURE DPREDPL ;
      VAR I J : INTEGER ;
      BEGIN
        WRITELN ;
        WRITELN ('    * *   PREDICATES ON PLACES   * * ') ;
        WRITELN ('      PLACE          PREDICATE') ;
        WRITELN ('      ------------------------') ;
        FOR I:=1 TO M DO
          BEGIN
            IF I<=9 THEN WRITE('       P0',I:1,'           ')
                    ELSE WRITE('       P',I:2,'           ') ;
            (*      display the predicate on ith place       *)
            J := 1 ;
            WHILE PP(.I J )<>'$' DO
              BEGIN
                WRITE (PP(.I J )) ;
                J := J+1
              END ;
            WRITELN ;
            (*  for modify, call PMOD to change ith pred.  *)
            IF MFLAG=1 THEN BEGIN
```

```
                                L2 := I ;
                                PMOD(PP)
                              END
          END
      END ;
(*****************************************************************)
(* NUME :              DACTPL                                    *)
(* FUNCTION :          To display or modify all the actions at   *)
(*                        all the places                         *)
(* PROCEDURES CALLED :    PMOD                                   *)
(*****************************************************************)
    PROCEDURE DACTPL ;
      VAR I J : INTEGER ;
      BEGIN
        WRITELN ;
        WRITELN ('    * *    ACTIONS AT PLACES  * *') ;
        WRITELN ('       PLACE              ACTION') ;
        WRITELN ('       ----------------------') ;
        FOR I:=1 TO M DO
          BEGIN
            IF I<=9 THEN WRITE ('        P0',I:1,'              ')
                    ELSE WRITE ('        P',I:2,'               ') ;
            (*   display ten action at ith place   *)
            J := 1 ;
            WHILE AP(.I,J ) <> '$'  DO
              BEGIN
                WRITE (AP(.I J )) ;
                J := J+1
              END ;
            WRITELN ;
            (* for modify, call PMOD to change ith action *)
            IF MFLAG=1 THEN BEGIN
                              L2 := I ;
                              PMOD(AP)       (*  call PMOD   *)
                            END
          END ;
        WRITELN
    END ;
(*****************************************************************)
(* NAME :              DSECOND                                   *)
(* FUNCTION :          To contain the options of predicate-      *)
(*                     action definition phase on DISPLAY or     *)
(*                     MODIFY                                    *)
(*****************************************************************)
    PROCEDURE DSECOND ;
      BEGIN
        WRITELN ;
        WRITELN('* * *  PREDICATE-ACTION DEFINITOINS  * * *  ');
        IF MFLAG=0 THEN
        WRITELN''                       < ON DISPLAY >') ;
        IF MFLAG=1 THEN
        WRITELN('                       < ON MODIFY >') ;
        WRITELN('*********************************************');
        WRITELN('* DO YOU WANT TO DISPLAY :                   *');
```

```
      WRITELN('*  1.  PT  --  PREDICATES ON TRANSITIONS   *');
      WRITELN('*  2.  AT  --  ACTIONS AT TRANSITIONS      *');
      WRITELN('*  3.  PP  --  PREDICATES ON PLACES        *');
      WRITELN('*  4.  AP  --  ACTIOS AT PLACES            *');
      WRITELN('*********************************************');
      WRITELN('    *  ENTER YOUR SELECTION   *') ;
      WRITELN(' *  HIT ANY DIGITS OTHER THAN 1, 2, 3, 4') ;
      WRITELN('TO GET OUT OF CONSTRAINTS DEFINITION SESSION*')
    END ;
(*************************************************************)
(* NAME :            DRECOM                                  *)
(* FUNCTION :        To display the options on terminal and  *)
(*                      accept user's selections             *)
(* PROCEDURE CALLED :  DSECOND                               *)
(*************************************************************)
  PROCEDURE DRECOM ;
    BEGIN
      T := 'N' ;
      WHILE T <> 'Y'  DO
        BEGIN
          DSECOND ;  (*   call DSECOND to display options   *)
          READLN ;
          READ (R) ; (*     accept user's selection         *)
          WRITELN ('       <',R:1,'>   OK ?  --  Y OR N') ;
          READLN ;
          READ (T)   (*      accept user's decision         *)
        END
    END ;
    (*                                                       *)
    (*     Main program of procedure DPREDACT                *)
    (*                                                       *)
    BEGIN
     (*   in option A, call subprocedures one by one    *)
     IF DFLAG=1 THEN
       BEGIN
         DPREDTR ;
         DACTTR ;
         DPREDPL ;
         DACTPL
       END
              ELSE
       (*  In option B, call subprocedures interactively    *)
       BEGIN
      DRECOM ;   (*   call DRECOM to get user's selection   *)
      WHILE (R>0) AND (R<5) DO
        BEGIN
          IF R=1 THEN DPREDTR
                 ELSE IF R=2 THEN DACTTR
                             ELSE IF R=3 THEN DPREDPL
                                         ELSE DACTPL ;
          DRECOM   (*  call DRECOM to get next selection   *)
        END
      END
    END ;
```

```
(*****************************************************************)
(* NAME :          DINITIAL                                      *)
(* FUNCTION :      To display or modify initial marking M0       *)
(*            and the initial values of all the variables        *)
(*****************************************************************)
    PROCEDURE DINITIAL ;
      VAR I J : INTEGER ;
      BEGIN
        (*   write the heading of initial marking M0     *)
        WRITELN ;
        WRITELN (' * * *   INITIAL MARKING  M0   * * *') ;
        IF MFLAG=0 THEN
        WRITELN ('                    < DISPLAY >') ;
        IF MFLAG=1 THEN
        WRITELN ('                    < MODIFY >') ;
        WRITE ('    PLACE   ') ;
        FOR I:=1 TO L DO
          WRITE ('COL ',I:',    ') ;
        WRITELN ;
        WRITE ('    ---------') ;
        FOR I:=1 TO L DO
          WRITE ('---------') ;
        WRITELN ;
        (*   display initial marking M0     *)
        FOR I:=1 TO M DO
          BEGIN
            IF I<=9 THEN WRITE ('      P0',I:',    ')
                    ELSE WRITE ('      P',I:',    ') ;
            FOR J:=1 TO L DO
              WRITE (P(.I,J.):2,'       ') ;
            WRITELN  ;
            (*    for modify, change M0      *)
            IF MFLAG=1 THEN
              BEGIN
                WRITE (' *  DO YOU WANT TO CHANGE THIS LINE ?');
                WRITELN ('  ---  Y  OR N') ;
                READLN ;
                READ (T) ;        (*  accept user's decition  *)
             (* accept token num. in ith place for each colour *)
                IF T='Y' THEN
                  BEGIN
                    WRITELN('* ENTER NEW VALUE OF THIS LINE :');
                    READLN ;
                    WRITE ('            ') ;
                    FOR J:=1 TO L DO
                      BEGIN
                        READ (R) ;
                        P(.I,J.) := R ;
                        WRITE (P(.I J ):?,'       ')
                      END ;
                    WRITELN ;
                  END
              END
          END ;
```

```
IF N1 <> 0 THEN
  BEGIN
   (* write heading for initial values of integer variables*)
   WRITELN('      * *  INTEGER VARIABLE VALUES  * * ') ;
   IF MFLAG=0 THEN
   WRITELN('                    < DISPLAY >') ;
   IF MFLAG=1 THEN
   WRITELN('                    <  MODIFY  >') ;
   WRITELN('      PROGRAM'S    USER'S    VALUES') ;
   WRITELN('      ------------------------------') ;
   FOR I:=1 TO N1 DO
     BEGIN
       (*  display program name of ith integer variables *)
       WRITE ('         ') ;
       CH := CHR ( I + ORD('A') - 1 )  ;
       WRITE (CH,'          ') ;
       (*  display user's name of ith interger variable  *)
       J := 1  ;
       WHILE COM(.I J.)<>'$' DO
         BEGIN
           WRITE(COM(.I,J )) ;
           J := J + 1
         END ;
       (*  display initial value of ith integer variables  *)
       CASE I-1 OF
         0 :   WRITELN(A)  ;        1 :   WRITELN(B)  ;
         2 :   WRITELN(C)  ;        3 :   WRITELN(D)  ;
         4 :   WRITELN(E)  ;        5 :   WRITELN(F)  ;
         6 :   WRITELN(G)  ;        7 :   WRITELN(H)
       END
     END
  END ;
  IF N2 <> 0  THEN
    BEGIN
      (*  write heading for initial values of real var.  *)
      WRITELN('      * *  REAL VARIABLE VALUES  * *') ;
      IF MFLAG=0 THEN
      WRITELN('                    < DISPLAY >') ;
      IF MFLAG=1 THEN
      WRITELN('                    <  MODIFY  >') ;
      WRITELN('       PROGRAM'S    USER'S    VALUE') ;
      WRITELN('       ------------------------------') ;
      WRITE  ('          ') ;
      FOR I:=1 TO N2 DO
        BEGIN
          (*  display program name of ith real variable  *)
          CH := CHR (I + ORD('A') - 1)  ;
          WRITE(CH,'          ')  ;
          (*  display user's name of ith real variable   *)
          J := 1  ;
          WHILE COM1(.I J.)<>'$'  DO.
            BEGIN
              WRITE(COM1(.I,J )) ;
              J := J + 1
```

```
          END ;
          (*  display initial value of ith real variable   *)
          CASE I-1 OF

            0 :  WRITELN(A1)  ;     1 :  WRITELN(B1) ;
            2 :  WRITELN'C1)  ;     3 :  WRITELN(D') ;
            4 :  WRITELN(E1)  ;     5 :  WRITELN(F') ;
            6 :  WRITELN(G1)  ;     7 :  WRITELN(H')
        END
       END
     END ;
   IF N3 <> 0  THEN
     BEGIN
       (*  write heading for initial Boolean variables   *)
       WRITELN('     * *  LOGIC VARIABLE VALUES  * *') ;
       IF MFLAG=0 THEN
       WRITELN('                < DISPLAY >') ;
       IF MFLAG=1 THEN
       WRITELN('                < MODIFY  >') ;
       WRITELN('      PROGRAM"S    USER"S    VALUE') ;
       WRITELN('      ----------------------------') ;
       WRITE  ('          ') ;
       FOR I:=1 TO N3 DO
         BEGIN
           (*   display program name of ith Boolean var.   *)
           CH := CHR (I + ORD('A') - 1 ) ;
           WRITE(CH,'       ') ;
           (*   display user's name of ith Boolean var.    *)
           J := 1 ;
           WHILE COM2(.I,J.)<>'$' DO
             BEGIN
               WRITE(COM2(.I J )) ;
               J := J + 1
             END ;
           (*  display initial value of ith Boolean var.  *)
           WRITE('       ') ;
           CASE I-1 OF
             0 :   WRITELN(A2)  ;     1 :   WRITELN(B2)  ;
             2 :   WRITELN(C2)  ;     3 :   WRITELN(D2)  ;
             4 :   WRITELN(E2)  ;     5 :   WRITELN(F^)  ;
             6 :   WRITELN(G2)  ;     7 :   WRITELN(H2)
           END
         END
     END
   END ;
(*****************************************************************)
(* NAME :            DZERO                                       *)
(* FUNCTION :        to contain to options Module DISPLAY"       *)
(*                   and Module MODIFY                           *)
(*****************************************************************)
  PROCEDURE DZERO ;
    BEGIN
      WRITELN ;
      IF MFLAG=0 THEN
```

```
        WRITELN (´     * * *   MODULE DISPLAY SESSION   * * *´);
        IF MFLAG=1 THEN
        WRITELN (´     * * *   MODULE MODIFY SESSION   * * *´);
        WRITELN(´*************************************************´);
        WRITELN(´* DO YOU WANT TO INPUT :                        *´);
        WRITELN(´*   1.   ENTITY DECLARATION                     *´);
        WRITELN(´*   2.   PREDICATE-ACTION DEFINITIONS           *´);
        WRITELN(´*   3.   INITIAL MARKING  M0                    *´);
        WRITELN(´*************************************************´);
        WRITELN (´    *   ENTER YOUR SELECTION   *´) ;
        WRITE   (´   *  HIT ANY DIGITS OTHER THAN 1, 2, 3´) ;
        WRITELN (´ TO GET OUT OF DISPLAY SESSION  *´)
      END ;
(*****************************************************************)
(* NAME :          DINTRO                                        *)
(* FUNCTION :      To display the options on terminal and        *)
(*                    accept user´s selection                    *)
(* PROCEDURE CALLED :    DZERO                                   *)
(*****************************************************************)
    PROCEDURE DINTRO ;
      BEGIN
        T := ´N´ ;
        WHILE T<>´Y´ DO
          BEGIN
            DZERO ;       (*   call DZERO to display options   *)
            READLN ;
            READ (R) ;      (*     accept user´s selection      *)
            WRITELN (´        <´,R:1,´>   OK  ?  ---  Y OR N´) ;
            READLN ;
            READ (T)        (*     accept user´s decision       *)
          END
      END ;
(*****************************************************************)
(*  NAME :        DREAD                                          *)
(*  FUNCTION :    To read data from input files: DATAIN DATA     *)
(*                                          and    DIN DATA      *)
(*****************************************************************)
  PROCEDURE DREAD ;
    VAR I J K : INTEGER ;
    BEGIN
      (*  read total num. of places, transitions, and colours *)
      READ (DATAIN,M) ;
      READ (DATAIN,N) ;
      READLN (DATAIN,L) ;
      (*    read arcs from places to transitions     *)
      FOR I:=1 TO M DO
        FOR J:=1 TO N DO
          BEGIN
            FOR K:=1 TO L DO
              READ (DATAIN PARC(.I,J K.)) ;
            READLN (DATAIN)
          END ;
      (*    read arcs from transitions to places     *)
      FOR J:=1 TO N DO
```

```
  FOR I:=1 TO M DO
    BEGIN
      FOR K:=1 TO L DO
        READ (DATAIN TARC(.I,J,K.)) ;
      READLN (DATAIN)
    END ;
(*      read initial marking M0          *)
FOR I:=1 TO M DO
  BEGIN
    FOR K:=1 TO L DO
        READ (DATAIN,P(.I,K.)) ;
    READLN(DATAIN)
  END ;
(*  read total num. of integer,real,Boolean variables    *)
READLN (DATAIN,N1,N2,N3) ;
(*     read initial values of integer variables     *)
IF N1 <> 0 THEN
  FOR I := 1 TO N1 DO
    CASE I-1 OF
      0 :  READLN(DATAIN,A) ;     ' :  READLN(DATAIN,B)  ;
      2 :  READLN(DATAIN C) ;    3 :  READLN'DATAIN,D)  ;
      4 :  READLN(DATAIN,E) ;    5 :  READLN(DATAIN,F)  ;
      6 :  READLN(DATAIN,G) ;    7 :  READLN(DATAIN,H)
    END ;
(*    read initial values of real variables      *)
IF N2 <> 0 THEN
  FOR I := 1 TO N2 DO
    CASE I-1 OF
      0 :  READLN(DATAIN A1) ;    1 :  READLN(DATAIN,B1)  ;
      2 :  READLN(DATAIN,C1) ;    3 :  READLN(DATAIN,D1)  ;
      4 :  READLN(DATAIN E') ;    5 :  READLN(DATAIN,F1)  ;
      6 :  READLN(DATAIN,G1) ;    7 :  READLN(DATAIN,H1)
    END ;
(*     read user's names of integer variables      *)
WHILE NOT EOF(DIN) DO
   BEGIN
FOR I:=1 TO 8 DO
  BEGIN
    J := 1 ;  READ (DIN,T)  ;
    WHILE T <>'$'  DO
      BEGIN
        COM(.I J ) := T ;
        J := J+1 ; READ (DIN,T)
      END ;
    READLN (DIN) ;
    COM(.I J.) := '$'
  END ;
(*     read user's names of real variables     *)
FOR I:= 1 TO 8 DO
  BEGIN
    J := 1 ;  READ(DIN,T) ;
    WHILE T <> '$'  DO
      BEGIN
        COM1(.I,J ) := T ;
```

```
        J := J+1 ;  READ (DIN,T)
      END ;
    READLN (DIN) ;
    COM1(.I J.) := '$'
  END ;
(*    read user's name of Boolean variables    *)
FOR I:=1 TO 8 DO
 BEGIN
  J := 1 ; READ (DIN,T) ;
  WHILE T <> '$'  DO
    BEGIN
      COM2(.I,J.) := T ;
      J := J+1 ; READ (DIN,T)
    END ;
  READLN (DIN) ;
  COM2(.I,J.) := '$'
 END ;
(*    read all predicates on transitions     *)
FOR I:=1 TO N DO
  BEGIN
    J := 1 ; READ (DIN,T)  ;
    WHILE T <> '$' DO
      BEGIN
        PT(.I,J.) := T ;
        J := J+1 ;  READ (DIN,T)
      END ;
    READLN (DIN) ;
    PT(.I J.) := '$'
  END ;
(*    read all actions at transitions    *)
FOR I:=1 TO N DO
  BEGIN
    J := 1 ;  READ (DIN,T' ;
    WHILE T <> '$'  DO
      BEGIN
        AT(.I,J.) := T ;
        J := J+1  ;  READ (DIN,T)
      END ;
    READLN (DIN) ;
    AT(.I,J.) := '$'
  END ;
(*    read all predicates on places     *)
FOR I:=1 TO M DO
  BEGIN
    J := 1 ;  READ(DIN,T) ;
    WHILE T <> '$'  DO
      BEGIN
        PP(.I J.) := T ;
        J := J+1 ; READ(DIN,T)
      END ;
    READLN (DIN) ;
    PP(.I,J ) := '$'
  END ;
(*    read all action at places    *)
```

```
    FOR I:=1 TO M DO
      BEGIN
        J := 1 ;  READ (DIN T) ;
        WHILE T <> '$'  DO
          BEGIN
            AP(.I,J ) := T ;
            J := J + 1 ;  READ (DIN,T)
          END ;
        READLN (DIN) ;
        AP(.I,J.) := '$'
      END
     END
    END ;
    (*                                                    *)
    (*     the main program of procedure DISPLY           *)
    (*                                                    *)
    BEGIN
      IF FLAG = 0 THEN BEGIN
                         DREAD ;
                         CWRITE
                       END ;
      WRITELN('  WHICH DISPLAY FORM DO YOU WANT TO CHOOSE : ');
      WRITELN('       A   DISPLAY ALL THE INFORMATION AT ONCE');
      WRITELN('        B.  DISPLAY INFORMATION INTERACTIVELY') ;
      READLN ;
      READ(T) ;
      IF T = 'A' THEN
       (*   in option A  call subprocedures one by one      *)
       BEGIN
         DFLAG := 1 ;       (*  set DFLAG=1 to mark option A   *)
         DDECLARATION ;
         DPREDACT ;
         DINITIAL ;
         DFLAG := 0                          (*  initial DFLAG    *)
       END
       (*    in option B, call subprocedures interactively    *)
             ELSE IF T='B' THEN
       BEGIN
       DINTRO ;        (*  call DINTRO to ger user's selection  *)
       WHILE (R>0) AND (R<4) DO
         BEGIN
           IF R=1 THEN DDECLARATION
                  ELSE IF R=2 THEN DPREDACT
                              ELSE DINITIAL ;
           DINTRO
         END
       END
    END ;
(*****************************************************************)
(*  NAME :        NEW                                            *)
(*  FUNCTION :    To contain the options of the package          *)
(*****************************************************************)
  PROCEDURE NEW ;
    BEGIN
```

```
      WRITELN ;
      WRITELN (' ************************************************');
      WRITELN (' *  DO YOU WANT TO ENTER :                      *');
      WRITELN (' *     1.  PROCESS MODULE SPECIFICATION         *');
      WRITELN (' *     2.  MODULE DISPLAY                       *');
      WRITELN (' *     3.  MODULE MODIFY                        *');
      WRITELN (' *     4.  MODULE ANALYSIS                      *');
      WRITELN (' ************************************************');
      WRITELN ('     *   ENTER YOUR SELECTION   *') ;
      WRITE   ('   *  HIT ANY DIGITS OTHER THAN 1, 2, 3, 4') ;
      WRITELN (' TO GET OUT OF THIS PROCESS  *')
    END ;
(*****************************************************************)
(*  NAME :          NINTO                                        *)
(*  FUNCTION :      To display options on terminal and           *)
(*                     accept user's selection                   *)
(*  PROCEDURE CALLED :    NEW                                    *)
(*****************************************************************)
  PROCEDURE NINTO ;
    BEGIN
      T := 'N' ;
      WHILE T <> 'Y' DO
        BEGIN
          NEW ;
          READLN ;
          READ (R) ;
          WRITELN ('         <',R:1,'>   OK  ?  ---  Y OR N') ;
          READLN ;
          READ (T)
        END
    END  ;
  (*                                                  *)
  (*      the main program of this package            *)
  (*                                                  *)
  BEGIN
    (*       open the disk files        *)
    RESET (DATAIN) ;
    RESET (DIN) ;
    REWRITE (DATAOUT) ;
    REWRITE (OUTIN) ;
    REWRITE (OUT) ;
    (*      initialize the program identifiers        *)
    FLAG := 0 ;
    DFLAG := 0 ;
    MFLAG := 0 ;
    (*      start process , call procedures        *)
    NINTO ;
    WHILE (R>0) AND (R<5) DO
      BEGIN
        IF R=1 THEN CREATE
               ELSE IF R=2 THEN DISPLAY
                          ELSE IF R=3 THEN BEGIN
                                             MFLAG := 1 ;
                                             DISPLAY ;
```

```
                    CWRITE ;
                    MFLAG := 0
                END
            ELSE ANALYSIS (P,PARC,TARC,PP,
                PT AP,AT,M,N,L)  ;

        NINTO
    END
END
```

```
(*$E+*)
PROGRAM PACK   (INPUT/, OUTPUT, DATAIN,DATAOUT,OUTIN,DIN,OUT) ;
  TYPE LIST = PACKED ARRAY (.1..40 , 1..9.) OF INTEGER;
       CA   = PACKED ARRAY (.1..40 , 1..40.) OF INTEGER ;
       CB   = PACKED ARRAY (.1..40 , 1..40 , 1..9.) OF INTEGER;
       CC   = PACKED ARRAY (.1..8, 1..81.) OF CHAR ;
       CD   = PACKED ARRAY (.1..40,1..81.) OF CHAR ;
       CF   = PACKED ARRAY (.1..40.) OF INTEGER ;
  VAR  PARC, TARC : CB ;
       P : LIST ;
       COM, COM1, COM2 : CC ;
       PP, PT, AP, AT : CD ;
       N,M,L,N1,N2,N3 : INTEGER ;
       A B,C,D,E F G,H : INTEGER ;
       A1,B1,C1,D1,E1,F1,G1,H1 : REAL ;
       A2,B2,C2,D2,E2,F2,G2,H2 : BOOLEAN ;
       T : CHAR ;
       R  FLAG,DFLAG,MFLAG : INTEGER ;
       DATAIN  DATAOUT, OUTIN  : TEXT ;
       DIN.OUT : TEXT ;
(*****************************************************************)
(*  NAME :          ANALYSIS                                     *)
(*  FUNCTION :      To analyze the numerative and incidence      *)
(*                     properties of the PN                      *)
(*  INPUT PARAMETERS :                                           *)
(*                  P  --  MxL array, initial marking M0         *)
(*                  PARC  --MxNxL array, arcs  P->T              *)
(*                  TARC  --MxNxL array, arcs  T->P              *)
(*                  PP --  Mx80 array, predicates on places      *)
(*                  PT --  Nx80 array, pred. on transitions      *)
(*                  AP --  Mx80 array, actions at places         *)
(*                  AT --  Nx80 array, actions at trans.         *)
(*                  M  --  integer, total number of places       *)
(*                  N  --  integer, total number of trans.       *)
(*                  L  --  integer, total number of colours      *)
(*  PROCEDURES CALLED :   AINTO                                  *)
(*                        REACHABILITY                           *)
(*                        INCIDENCE                              *)
(*****************************************************************)
  PROCEDURE ANALYSIS (VAR P:LIST; VAR PARC,TARC :CB;
                      VAR PP,PT AP,AT:CD; VAR M,N,L : INTEGER );
(*****************************************************************)
(*  NAME :      REACHABILITY                                     *)
(*  FUNCTION :  To analyze the numerative properties of PN       *)
(*  PROGRAM CONSTANTS :                                          *)
(*    E0 -- integer,the max. levels allowed of the tree E0=15    *)
(*    E4 -- integer, E4 = E0 + 1 = 16                            *)
(*  PROGRAM VARIABLES :                                          *)
(*    K1 -- integer, the current level # of the tree             *)
(*    K0 -- nteger, the new marking  Mk1+1 = Mk0                 *)
(*    K2 -- integer, rotation var. for finding Mk0               *)
(*    K3 -- integer, if Mk1+1 = Mk0, let K3 = K1+1               *)
(*    K4 -- integer, if Mk1+1 >=Mk2 ,let K4 = K1+1 (w-symbol)    *)
(*    L1 -- integer, sum of unfirable Tj in level K1             *)
```

```
(*    L2 -- integer, sum of such levels which has only one      *)
(*                  one branch ( livelock)                      *)
(*  PROGRAM IDENTIGIERS :                                       *)
(*       SAF    --  0/1, the PN is safe / not                  *)
(*       CFLAG  -- 0/1, the PN is conservative / not           *)
(*       DDLK   -- 1/0, the PN has deadlock / not              *)
(*       LFLK   -- 1/0, the PN has livelock / not              *)
(*       LVLP   -- 1/0, the PN has live-loop / not             *)
(*       HMST   -- 1/0, M0 is home-state / not                 *)
(*       KFOUND -- 1/0, found K0 so that Mkl+1 = Mk0  / not    *)
(*       WFLAG  -- 1/0, the PN has predicates or actions/not   *)
(*       E3     -- 1/0, the current level > E0   / not         *)
(*       GG     -- 1/0, during the analysis the user wants to  *)
(*                      give variable value(s)  / not          *)
(*  PROGRAM ARRAYS :                                           *)
(*    MR'kl,i,k) -- E0xMxL, integer, marking of level kl (Mkl) *)
(*    TT(kl,j)   -- E0xN. 1/0, at level kl, Tj is firable/not  *)
(*    BD(k)  -- 1<=K<=L  max.Mkl(i,k)   for  all 1<=i<=M       *)
(*    CS(k)  -- 1<=k<=L, sum of M0(i,k)  for all 1<=i<=M       *)
(*    CSK(k) -- 1<=k<=L, sum of Mkl(i,k)  for all 1<=i<=M      *)
(*    Q(kl)  -- 1<=kl<=E0, # of transition fired in level kl   *)
(*    Ql(kl) -- 1<=kl<=E0, the # of marking in level kl        *)
(*    QI'kl,i) -- E4x8, integer, the values of A,B,...H        *)
(*    QR'kl,i) -- E4x8, real, the values of A1,B1,...H1        *)
(*    QL'kl,i) -- E4x8, Boolean, the values of A2,B2,...H2     *)
(*  PROCEDURES CALLED :    PREP                                *)
(*                         RECEIVE                             *)
(*                         CHECK                               *)
(*                         FIND                                *)
(*                         FIRING                              *)
(*                         LEAF                                *)
(*                         LOCK                                *)
(*                         VARIABLES                           *)
(*************************************************************)
    PROCEDURE REACHABILITY ;
      LABEL  100, 200, 300  ;
      CONST  E0 = 15 ; E4=16 ;
      VAR    L1  L2, K0, K1, K2, K3, K4, R, R',E3 : INTEGER ;
             GG, SAF, FLAG, CFLAG, FOUND,KFOUND,WFLAG : INTEGER;
             DDLK, LVLK, LVLP, HMST : INTEGER ;
             Q, Q1 : ARRAY(.1..E4.) OF INTEGER ;
             QI : ARRAY(.1..E4,1..8.) OF INTEGER ;
             QR : ARRAY(.1..E4,1..8.) OF REAL ;
             QL : ARRAY(.1..E4,1..8.) OF BOOLEAN ;
             BD : ARRAY(.1..9.) OF INTEGER ;
             QK : ARRAY(.1..40,1..9.) OF INTEGER ;
             CS. CSK : ARRAY(.1..9.) OF INTEGER ;
             TT : ARRAY(.1..E4,1..40.) OF INTEGER ;
             MR : ARRAY(.1..E4,1..40,1..40.) OF INTEGER ;
             I, J, K, XX, YY : INTEGER ;
             BL : BOOLEAN ;
             R0 : REAL ;
```

```
(*****************************************************************)
(*  NAME :       PREP                                            *)
(*  FUNCTION :   To initialize all the variables and arrays      *)
(*                  and ask whether the user want to input       *)
(*                  new values of PN variables during            *)
(*                  reachability analysis or not                 *)
(*****************************************************************)
    PROCEDURE PREP ;
      VAR I,K : INTEGER ;
    BEGIN
      WRITELN (´     PREP´) ;
      (*    initialize marking     *)
      FOR K:=1 TO L DO
        FOR I:=1 TO M DO
          MR(.1,I,K.) := P(.I,K.) ;
      (*    initialize program variables    *)
      SAF := 0 ;  FLAG := 0 ;  CFLAG := 0 ;  FOUND := 0 ;
      KFOUND := 0 ;    HMST := 0 ;
      E3 := 0 ;  GG := 0 ; DDLK:= 0 ; LVLK:= 0; LVLP:= 0 ;
      WFLAG := 0 ; K4 := 0 ;
      (*    initial some arrays   *)
      FOR K:=1 TO L DO
        BEGIN
          BD(.K.) := 0 ;
          CS(.K.) := 0 ;
          CSK(.K.) := 0
        END ;
      FOR K:=1 TO L DO
        FOR I:=1 TO M DO
          QK(.I K.) := 0 ;
      (*  set WFLAG to 1  when there are some PN variables  *)
      I := 1 ;
      WHILE (I<=M) AND (WFLAG=0) DO
          IF (PP(.I,1.)<>´$´) OR (AP(.I,1.)<>´$´)
            THEN WFLAG := 1
            ELSE I := I + 1  ;
      I := 1 ;
      WHILE (I<=N) AND (WFLAG=0) DO
          IF (PT(.I,1.)<>´$´) OR (AT(.I 1.)<>´$´)
            THEN WFLAG := 1
            ELSE I := I + 1  ;
      (*   get CS  for determining conservation    *)
      FOR K:=1 TO L DO
       FOR I:=1 TO M DO
        CS(.K.) := CS´.K.) + P(.I,K.)  ;
     (*   if there are PN variables,                              *)
     (*   ask does the user wants input new values or not         *)
     IF WFLAG = 1 THEN
       BEGIN
WRITELN(´ *  DO YOU WANT GIVE VARIABLE VALUES FROM TERMINAL´);
       WRITELN (´      DURING ANALYSISNG ?   ---  Y OR N  *´);
       READLN ;
       READ (T) ;                (*  accept user´s decision   *)
       IF T = ´Y´ THEN GG := 1;(*  set GG=1 to indicate ´Y´ *)
```

```
        END ;
        (*      display M0  --  MR(.1,i,k)      *)
        WRITE (´            M< 1, 0>  :   <      ´) ;
        FOR K:= 1 TO E4 DO
                  Q1(.K.) := 0  ;
        FOR K:=1 TO L DO
          BEGIN
            FOR I:=1 TO M DO
              WRITE (MR(.1,I,K.) : ^,´ ´) ;
            WRITELN(´>´)
          END
        END ;
(*****************************************************************)
(*  NAME :          RECEIVE                                      *)
(*  FUNCTION :      To receive PN variable values from terminal  *)
(*  PROGRAM ARRAYS :                                             *)
(*                  SS(i) -- 1<=i<=81, char. store input string  *)
(*                  RR(i) -- 1<=i<=81, integer, store input      *)
(*                                     values                    *)
(*  DATA RESOURCE   :  from terminal                             *)
(*****************************************************************)
     PROCEDURE RECEIVE ;
       VAR I J,J1 : INTEGER ;
           SS   : ARRAY(.1..81.) OF CHAR ;
           RR   : ARRAY(.1..81.) OF INTEGER ;
           T0   : CHAR ;
       BEGIN
        WRITELN (´    RECEIVE´) ;
     REPEAT
       (*   give the user input instruction      *)
       WRITELN´´ ENTER NEW VALUES (IF ANY)TO THE VARIABLE(S):´);
       WRITELN (´  A, B... < E G. A=1 >. IF NO ENTRY PRESS  N´);
       READLN ; READ (T0) ;              (*  accept a new value  *)
       (*                                                        *)
       (*  asign the new value to the corresponding PN var.     *)
       (*                                                        *)
       IF T0 <> ´N´  THEN
         BEGIN
           SS(.1.) := T0 ;
           I := 2 ;
           WHILE NOT EOLN DO
             BEGIN
               READ (T) ;
               SS(.I.) := T ;
               I := I + 1
             END ;
           IF SS(.2.) = ´=´
              THEN BEGIN
                     (*   for integer variable   *)
                     R := ORD(SS´.3.)) - ORD(´0´) ;(*the value*)
                     R1:= ORD(SS´.1.)) - ORD(´A´) ;(*# of var.*)
                     CASE R1 OF
                       0 :   A := R ;     1 :   B := R ;
                       2 :   C := R ;     3 :   D := R ;
```

```
                4 :   E := R ;      5 :   F := R ;
                6 :   G := R ;      7 :   H := R
              END   ;
            END
        ELSE IF SS(.2.) = '1'
             THEN BEGIN
                    (*    for real variable    *)
                   FOR J :=4 TO I-1 DO
                     IF SS(.J ) = '.'
                       THEN J := J
                   ELSE RR'.J.) := ORD(SS(.I )) - ORD('0');;
                   R0 := 0.0 ;
                   FOR J :=  4 TO J1 - 1 DO
                     R0 := R0 *10 + RR(.J ) ;
                   FOR J := J + 1 TO I-1 DO
             R0 := R0 + RR(.J.) * EXP((J-J1) * LN(0.1)) ;
                   R1:= ORD(SS(.1.)) - ORD('A') ;
                   CASE R1 OF
                     0 :  A1 := R0 ;     1 :   B1 := R0 ;
                     2 :  C1 := R0 ;     3 :   D1 := R0 ;
                     4 :  E1 := R0 ;     5 :   F1 := R0 ;
                     6 :  G1 := R0 ;     7 :   H1 := R0
                   END
                 END
             ELSE IF SS(.2.) = '2'
                    THEN BEGIN
                           (*    for Boolean variable      *)
                          IF SS(.4.) = 'T' THEN BL := TRUE
                                           ELSE BL := FALSE;
                           R1 := ORD(SS(.1.)) - ORD('A') ;
                           CASE R1 OF
                             0 : A2 := BL ;  1 : B2 := BL;
                             2 : C2 := BL ;  3 : D2 := BL;
                             4 : E2 := BL ;  5 : F2 := BL;
                             6 : G2 := BL ;  7 : H2 := BL
                           END
                         END
                    ELSE BEGIN
(*    for error of input form     *)
WRITELN (' *  SORRY WHAT YOU ENTERED IS NOT CORRECT FORMED');
WRITELN ('    ---  ENTER IT AGAIN  *')
                         END
          END
      UNTIL T0 = 'N'
END ;
```

```
(*****************************************************************)
(*  NAME :       CHECK                                           *)
(*  FUNCTION :  To check token properties : safeness,            *)
(*                boundedness, and conservation of the PN .      *)
(*****************************************************************)
    PROCEDURE CHECK ;
      VAR I,J,K : INTEGER ;
      BEGIN
        WRITELN ('    CHECK') ;
        (*    check safeness    *)
        I := 1 ;
        WHILE (I<=M) AND (SAF=0) DO
          BEGIN
            K := 1 ;
            WHILE (K<=L) AND (SAF=0) DO
                IF MR(.K1,I,K.) > 1 THEN SAF := 1 (* not safe *)
                                    ELSE K := K + 1 ;
            I := I + 1
          END ;
        (*   get max. value of BD  for cheking boundedness    *)
        FOR K:=1 TO L DO
          FOR I:=1 TO M DO
         IF MR(.K1,I,K.) > BD(.K.) THEN BD(.K.) := MR(.K1,I,K.);
        (*    check conservation    *)
        FOR K:=1 TO L DO  CSK(.K.) := 0 ;
        K := 1 ;
        WHILE (K<=L) AND (CFLAG=0) DO
          BEGIN
            FOR I:=1 TO M DO
              CSK(.K.) := MR(.K1,I,K.) + CSK(.K.)  ;
            IF CSK(.K.) <> CS .K.) THEN CFLAG := 1
                                    ELSE K := K + 1
          END ;
        END ;
(*****************************************************************)
(*  NAME :       FIND                                            *)
(*  FUNCTION :   To find firable transitions,                    *)
(*                  set TT(k1,j)=1, when Tj is firable .         *)
(*****************************************************************)
      PROCEDURE FIND ;
        VAR I,J,K,I1,J1 : INTEGER ;
        BEGIN
        WRITELN ('   FIND') ;
        FOR J:=1 TO N DO
          BEGIN
            (*                                                  *)
            (*    check Tj is enabled or not                    *)
            (*                                                  *)
            FLAG := 0  ;
            K := 1  ;
            WHILE (K<=L) AND (FLAG=0) DO
              BEGIN
                I := 1 ;
                WHILE (I<=M) AND (FLAG=0) DO
```

```
        IF MR(.K1,I,K.) < PARC(.I,J K.) THEN FLAG := 1
                                        ELSE I := I + 1 ;
      K := K + 1
    END ;
(*                                                        *)
(*       check the predicate associated with Tj .         *)
(*       is true or not                                   *)
IF PT(.J,1.) <> '$' THEN
  IF  FLAG = 0  THEN
    IF PT(.J,2.) = '='
      THEN BEGIN
        (*  for the predicate with integer PN var.  *)
            R1 := ORD(PT'.J,1.)) - ORD('A')  ;
            R := 0 ;  I1 := 3 ;
            WHILE PT(.J I1.) = ' ' DO   I1 := I1 + 1;
            WHILE (PT(.J,I1.) <> 'A') AND
                  (PT(.J,I1.) <> '$')    DO
              BEGIN
            R := R * 10 + ORD(PT(.J,I1.)) - ORD('0');
                I1 := I1 + 1
              END ;
            CASE R1 OF
              0 :  IF A<>R THEN FLAG := 1 ;
              1 :  IF B<>R THEN FLAG := 1 ;
              2 :  IF C<>R THEN FLAG := 1 ;
              3 :  IF D<>R THEN FLAG := 1 ;
              4 :  IF E<>R THEN FLAG := 1 ;
              5 :  IF F<>R THEN FLAG := 1 ;
              6 :  IF G<>R THEN FLAG := 1 ;
              7 :  IF H<>R THEN FLAG := 1
            END ;
           IF PT(.J,I1.) = 'A' THEN
             BEGIN
         (* for the predicate with form 'A=1 and B=0'*)
              I1 := I1 + 3 ;
              WHILE PT'.J,I1.)=' ' DO I1 := I1 + 1;
              R1 := ORD(PT'.J I1.)) - ORD('A') ;
              I1 := I1 + 2 ;
              WHILE PT'.J,I1.) <> '$'  DO
                BEGIN
             R := R * 10 + ORD(PT(.J,I1.)) - ORD('0');
                  I1 := I1 + 1
                END ;
              CASE R1 OF
                0 :   IF A <> R  THEN FLAG := 1 ;
                1 :   IF B <> R  THEN FLAG := 1 ;
                2 :   IF C <> R  THEN FLAG := 1 ;
                3 :   IF D <> R  THEN FLAG := 1 ;
                4 :   IF E <> R  THEN FLAG := 1 ;
                5 :   IF F <> R  THEN FLAG := 1 ;
                6 :   IF G <> R  THEN FLAG := 1 ;
                7 :   IF H <> R  THEN FLAG := 1
              END
          END
```

```
    END
  ELSE IF PT(.J 2.)='1'
        THEN BEGIN
               (*for predicate with real PN var.*)
               I' := 4 ;
               R0 := 0.0 ;
               WHILE PT'.J,I1.) <> '.' DO
                 BEGIN
                  R := ORD(PT(.J I1.)) - ORD('0');
                  R0 := R0 * 10 + R  ;
                  I1 := I1 + 1
                 END ;
               J1 := I1  ;
               I1 := J1 + 1 ;
               WHILE PT(.J.I1.) <> '$' DO
                 BEGIN
                  R := ORD(PT'.J,I'.)) - ORD('1');
                  R0:= R0 + EXP((I1-J1) * LN(0.1));
                   I' := I1 + 1
                 END ;
               R' := ORD(PT(.J,1.)) - ORD('A')  ;
               CASE R' OF
                 0 :  IF A1<>R0 THEN FLAG := 1 ;
                 1 :  IF B1<>R0 THEN FLAG := 1 ;
                 2 :  IF C1<>R0 THEN FLAG := 1 ;
                 3 :  IF D1<>R0 THEN FLAG := 1 ;
                 4 :  IF E1<>R0 THEN FLAG := 1 ;
                 5 :  IF F1<>R0 THEN FLAG := 1 ;
                 6 :  IF G1<>R0 THEN FLAG := 1 ;
                 7 :  IF H1<>R0 THEN FLAG := 1
               END
             END
        ELSE BEGIN
               (*for predicate with Boolean PN var.*)
               IF PT'.J,4.)='T' THEN BL := TRUE
                                ELSE BL := FALSE ;
               R' := ORD(PT'.J,1.)) - ORD('A')  ;
               CASE R' OF
                 0 :  IF A2<>BL THEN FLAG := 1 ;
                 1 :  IF B2<>BL THEN FLAG := 1 ;
                 2 :  IF C2<>BL THEN FLAG := 1 ;
                 3 :  IF D2<>BL THEN FLAG := 1 ;
                 4 :  IF E2<>BL THEN FLAG := 1 ;
                 5 :  IF F2<>BL THEN FLAG := 1 ;
                 6 :  IF G2<>BL THEN FLAG := 1 ;
                 7 :  IF H2<>BL THEN FLAG := 1
               END
             END ;
I := 1 ;
(*                                                    *)
(*    check the predicate at Tj input places          *)
(*                                                    *)
WHILE (FLAG=0) AND (I<=M) DO
      BEGIN
```

```
 FOUND := 0 ;
 K := 1 ;
 WHILE (K<=L) AND (FOUND=0) DO
IF (PARC(.I,J,K.) <>0) OR (TARC(.I,J,K.) <>0)
     THEN FOUND := 1
     ELSE K := K+1 ;
IF PP(.I,1.) <> '$' THEN
 IF FOUND = 1 THEN
        IF PP(.I,2.) = '='
          THEN BEGIN
        (* for predicate with integer var.*)
             R := ORD(PP(.I,3.)) - ORD('0');
             R1 := ORD(PP(.I 1.)) - ORD('A');
              CASE R1 OF
                 0 :  IF A<>R THEN FLAG := 1;
                 1 :  IF B<>R THEN FLAG := 1;
                 2 :  IF C<>R THEN FLAG := 1;
                 3 :  IF D<>R THEN FLAG := 1;
                 4 :  IF E<>R THEN FLAG := 1;
                 5 :  IF F<>R THEN FLAG := 1;
                 6 :  IF G<>R THEN FLAG := 1;
                 7 :  IF H<>R THEN FLAG := 1
               END ;
              END
          ELSE IF PP(.I 2.) = '1'
             THEN BEGIN
               (*  pred. with real var.  *)
              R := ORD(PP(.I,4.)) - ORD('0');
              r1:= ORD(PP(.I,1.)) - ORD('A');
              CASE R1 OF
                   0 : IF A1<>R THEN FLAG:=1;
                   1 : IF B1<>R THEN FLAG:=1;
                   2 : IF C1<>R THEN FLAG:=1;
                   3 : IF D1<>R THEN FLAG:=1;
                   4 : IF E1<>R THEN FLAG:=1;
                   5 : IF F1<>R THEN FLAG:=1;
                   6 : IF G1<>R THEN FLAG:=1;
                   7 : IF H1<>R THEN FLAG:=1
                    END
                   END
             ELSE BEGIN
            (* predicate with Boolean var.*)
                    IF PP(.I 4.)='T'
                       THEN  BL := TRUE
                       ELSE  BL := FALSE ;
             R1:= ORD(PP(.I,1.)) - ORD('A');
             CASE R1 OF
                 0 : IF A2<>BL THEN FLAG:=1;
                 1 : IF B2<>BL THEN FLAG:=1;
                 2 : IF C2<>BL THEN FLAG:=1;
                 3 : IF D2<>BL THEN FLAG:=1;
                 4 : IF E2<>BL THEN FLAG:=1;
                 5 : IF F2<>BL THEN FLAG:=1;
                 6 : IF G2<>BL THEN FLAG:=1;
```

```
                                    7 : IF H2<>BL THEN FLAG:=1
                                      END
                                     END ;
                    I := I + 1
                  END ;
          (*   if all the above conditions are satisfied,    *)
          (*        Tj is firable                            *)
          IF FLAG=0 THEN TT(.K1,J.) := 1
                    ELSE TT(.K1,J.) := 0
      END ;                                                  *)
          (*                                                 *)
          (*     record the values of erach PN variable      *)
          (*              in level k1                        *)
          IF N1 > 0 THEN
            (*   for integer PN variables    *)
            FOR I := 1 TO N1 DO
              CASE I-1 OF
                0 :  QI(.K1,1.) := A ;  1 :  QI(.K1,2.) := B ;
                2 :  QI(.K1,3.) := C ;  3 :  QI(.K1,4.) := D ;
                4 :  QI(.K1,5.) := E ;  5 :  QI(.K1,6.) := F ;
                6 :  QI(.K1,7.) := G ;  7 :  QI(.K1,8.) := H
              END ;
          IF N2 >0 THEN
            (*    for real  PN variables     *)
            FOR I:=1 TO N2 DO
              CASE I-1 OF
                0 :  QR(.K1,1.) := A1;  1 :  QR(.K1,2.) := B1;
                2 :  QR(.K1,3.) := C1;  3 :  QR(.K1,4.) := D1;
                4 :  QR(.K1,5.) := E1;  5 :  QR(.K1,6.) := F1;
                6 :  QR(.K1,7.) := G1;  7 :  QR(.K1,8.) := H1
              END ;
          IF N3 > 0 THEN
            (*    for Boolean PN variables    *)
            FOR I:=1 TO N3 DO
              CASE I-1 OF
                0 :  QL(.K1,1.) := A2;  1 :  QL(.K1,2.) := B2;
                2 :  QL(.K1,3.) := C2;  3 :  QL(.K1,4.) := D2;
                4 :  QL(.K1,5.) := E2;  5 :  QL(.K1,6.) := F2;
                6 :  QL(.K1,7.) := G2;  7 :  QL(.K1,8.) := H2
              END
    END ;
(*************************************************************)
(*  NAME :            FIRING                                 *)
(*  FUNCTION :        To fire Tj and get new marking Mk1+1   *)
(*  INPUT PARAMETER :    J  -- the subscript of transition Tj *)
(*************************************************************)
  PROCEDURE FIRING (VAR J: INTEGER) ;
  VAR I K,I1,J1 : INTEGER ;
      BEGIN
        WRITELN ('    FIRING') ;
        IF K0 <> 0  THEN
          BEGIN                                              *)
            (*                                               *)
            (*   check Mk1 is in live-loop or not            *)
```

```
      (*                                                    *)
      R := Q1(.K3.)-1 ;
      WRITE (´          M<´,K3:2,´,´,R:2,´>  =  ´)  ;
      WRITE (´ M<´,K0:2,´,´,Q1(.K0.)-1:2,´>  :  ´)  ;
      FOR I:=K0 TO K3-1  DO
        WRITE(´ M<´,I:2,´,´,Q1(.I.)-1 :2,´>  --> ´) ;
      WRITELN(´ M<´,K0:2,´,´,Q1(.K0.)-1 :2,´>´) ;
      WRITE (´                          ´) ;
      WRITELN (´ --- LIVE-LOOPING  <TERMINAL NODE>´) ;
      K0 := 0 ; LVLP := 1 ;  K3 := 0
    END ;
Q(.K1.) := J ;
 IF N1 > 0 THEN
  BEGIN
   (*                                                    *)
   (* write the values of PB variables in level k1 *)
   (*                                                    *)
   WRITE(´                  ´) ;
   FOR I := 1 TO N1 DO
     CASE I-1 OF
       0 : WRITE(´ A =´,A:4);  1 : WRITE(´ B =´,B:4);
       2 : WRITE(´ C =´,C:4);  3 : WRITE(´ D =´,D:4);
       4 : WRITE(´ E =´,E:4);  5 : WRITE(´ F =´,F:4);
       6 : WRITE(´ G =´,G:4);  7 : WRITE(´ H =´,H:4)
     END ;
   WRITELN
  END ;
  IF N2 >0 THEN
   BEGIN
    WRITE(´                  ´) ;
    FOR I:=1 TO N2 DO
      CASE I-1 OF
       0 : WRITE(´ A1 = ´,A1);  1 : WRITE(´ B1 = ´,B1);
       2 : WRITE(´ C1 = ´,C1);  3 : WRITE(´ D1 = ´,D1);
       4 : WRITE(´ E1 = ´,E1);  5 : WRITE(´ F1 = ´,F1);
       6 : WRITE(´ G1 = ´,G1);  7 : WRITE(´ H1 = ´,H1)
      END ;
    WRITELN
   END ;
  IF N3 > 0 THEN
   BEGIN
    WRITE(´                  ´) ;
    FOR I:=1 TO N3 DO
      CASE I-1 OF
       0 : WRITE(´ A2 = ´,A2);  1 : WRITE(´ B2 = ´,B2);
       2 : WRITE(´ C2 = ´,C2);  3 : WRITE(´ D2 = ´,D2);
       4 : WRITE(´ E2 = ´,E2);  5 : WRITE(´ F2 = ´,F2);
       6 : WRITE(´ G2 = ´,G2);  7 : WRITE(´ H2 = ´,H2)
      END ;
    WRITELN
   END ;
  (*                                                    *)
  (*  write the symbol showing to go to next marking    *)
  (*                                                    *)
```

```
WRITELN ('                |') ;
WRITELN ('                | T',J:2)  ;
WRITELN ('                V') ;
WRITE ('          M<',Kl+1 :2,',',Q1(.Kl+1.):2,'>  :');
(*   increase the level    *)
Q1(.Kl+1.) := Q1(.Kl+1.) + 1 ;
(*                                  *)
(*   .   get new marking Mkl+1      *)
(*                                  *)
FOR K:=1 TO L DO
  FOR I:=1 TO M DO
    MR(.Kl+1,I,K.) := MR(.Kl,I,K.) - PARC(.I,J,K.)
                                   + TARC(.I,J,K.) ;
                                                  *)
(*                                                 *)
(*     execute the action at transition Tj         *)
(*                                                 *)
IF AT(.J,1.) <> '$' THEN
 IF AT(.J,2.) = ':' THEN
   BEGIN
     (**    for the action with integer PN var.     **)
     R1:= ORD(AT(.J,1.)) - ORD('A')  ;
     IF AT(.J,4.) = AT(.J,1.)
       THEN BEGIN
              (* for the action with form 'X:=X+R'  *)
              R := 0 ;  I1 := 6 ;
              WHILE (AT(.J I1.) <> ' ')  DO
                BEGIN
                R := R * 10 + ORD(AT(.J,I1.)) - ORD('0');
                  I1 := I1 + 1
                END ;
              CASE R1 OF
                0 :  A := A + R  ;     1 :  B := B + R;
                2 :  C := C + R  ;     3 :  D := D + R;
                4 :  E := E + R  ;     5 :  F := F + R;
                6 :  G := G + R  ;     7 :  H := H + R
              END
            END
       ELSE BEGIN
              (*  for the action with form 'X:=R'   *)
              R := 0 ;  I1 := 4 ;
              WHILE (AT(.J I1.) <> ' ')  AND
                    (AT(.J,I1.) <> '$')  DO
                BEGIN
                  R := R * 10 + ORD(AT(.J,I1.)) - ORD('0');
                  I1 := I1 + 1
                END ;
              CASE R1 OF
                0 :   A := R ;      1 :   B := R ;
                2 :   C := R ;      3 :   D := R ;
                4 :   E := R ;      5 :   F := R ;
                6 :   G := R ;      7 :   H := R
              END
            END ;
     WHILE (AT(.J,I1.) = ' ')  DO   I1 := I1 + 1 ;
```

```
IF AT(.J,I1.) = 'A' THEN
  BEGIN
    I1 := I1 + 3 ;
    (* for the second part of 'X:=X+R and Y:=Y+S' *)
    WHILE (AT(.J,I1.) = ' ') DO  I1 := I1 + 1 ;
    R1 := ORD(AT(.J I1.)) - ORD('A') ;
    IF AT(.J,I1+3.) = AT(.J,I1.)
      THEN BEGIN
             R := 0  ;  I1 := I1 + 5  ;
             WHILE (AT(.J I1.) <> ' ') DO
               BEGIN
          R := R * 10 + ORD(AT(.J I1.)) - ORD('0');
                 I1 := I1 + 1
               END ;
             CASE R1 OF
               0 :  A := A + R  ;  1 :  B := B + R;
               2 :  C := C + R  ;  3 :  D := D + R;
               4 :  E := E + R  ;  5 :  F := F + R;
               6 :  G := G + R  ;  7 :  H := H + R
             END
           END
      ELSE BEGIN
             R := 0 ;  I1 := I1 + 3  ;
             WHILE (AT(.J I1.) <> '$')  DO
               BEGIN
           R := R * 10 + ORD(AT(.J I1.)) - ORD('0');
                 I1 := I1 + 1
               END ;
             CASE R1 OF
               0 :  A := A + R ;  1 :  B := B + R ;
               2 :  C := C + R ;  3 :  D := D + R ;
               4 :  E := E + R ;  5 :  F := F + R ;
               6 :  G := G + R ;  7 :  H := H + R
             END
           END
  END
END
                  ELSE
IF AT(.J,2.) = '1'
  THEN BEGIN
         (**  for the action with real PN var. **)
         I1 := 8 ;
         R0 := 0 ;
         WHILE AT(.J I1.) <> '.'  DO
           BEGIN
             R := ORD(AT(.J,I1.)) - ORD('0') ;
             R0:= R0 * 10 + R ;
             I1 := I1 + 1
           END ;
         J1 := I1 ;
         I1 := J1 + 1 ;
         WHILE AT(.J I1.) <> '$'  DO
           BEGIN
             R := ORD(AT(.J,I1.)) - ORD('0') ;
```

```
                R0:= R0 + EXP((I1-J1) * LN(0.1)) ;
                I1 := I1 + 1
              END ;
            R:= ORD(AT(.J 1.)) - ORD('A')  ;
            CASE R1 OF
              0 :  A1 := A1 + R  ;
              1 :  B1 := B1 + R  ;
              2 :  C1 := C1 + R  ;
              3 :  D1 := D1 + R  ;
              4 :  E1 := E1 + R  ;
              5 :  F1 := F1 + R  ;
              6 :  G1 := G1 + R  ;
              7 :  H1 := H1 + R
            END
          END
      ELSE BEGIN
             IF AT(.J,9.)='T' THEN  BL := TRUE
                              ELSE  BL := FALSE  ;
             R1:= ORD(AT(.J 1.)) - ORD('A')  ;
             CASE R1 OF
               0 :  A2 := A2 OR BL  ;
               1 :  B2 := B2 OR BL  ;
               2 :  C2 := C2 OR BL  ;
               3 :  D2 := D2 OR BL  ;
               4 :  E2 := E2 OR BL  ;
               5 :  F2 := F2 OR BL  ;
               6 :  G2 := G2 OR BL  ;
               7 :  H2 := H2 OR BL
             END
           END ;
FOR I:=1 TO M DO
  BEGIN
    FOUND := 0  ;
    K := 1  ;
    WHILE (K<=L' AND (FOUND=0) DO
      IF (PARC(.I,J,K.)<>0) OR (TARC(.I,J,K.)<>0)
        THEN FOUND := 1
        ELSE K := K + 1  ;
   IF AP(.I,1.) <> '$' THEN
    IF FOUND = 1  THEN
      IF AP(.I,2.) = ':'
        THEN BEGIN
               (** for action with Boolean PN var. **)
               R := ORD(AP(.I 6.)) - ORD('0')  ;
               R1:= ORD(AP(.I 1.)) - ORD('A')  ;
               CASE R1 OF
                 0 :  A := A + R  ;
                 1 :  B := B + R  ;
                 2 :  C := C + R  ;
                 3 :  D := D + R  ;
                 4 :  E := E + R  ;
                 5 :  F := F + R  ;
                 6 :  G := G + R  ;
                 7 :  H := H + R
```

```
                    END
                  END
            ELSE IF AP(.I 2.) = '1'
                   THEN BEGIN
                          R := ORD(AP(.I,8.)) - ORD('0');
                          R':= ORD(AP(.I,1.)) - ORD('A');
                          CASE R1 OF
                            0 :  A1 := A1 + R  ;
                            1 :  B1 := B1 + R  ;
                            2 :  C1 := C1 + R  ;
                            3 :  D1 := D1 + R  ;
                            4 :  E1 := E1 + R  ;
                            5 :  F1 := F1 + R  ;
                            6 :  G1 := G1 + R  ;
                            7 :  H1 := H1 + R
                          END
                        END
                 ELSE BEGIN
                          IF AP(.I,9.)='T' THEN  BL:=TRUE
                                           ELSE  BL:=FALSE;
                          R1:= ORD(AP(.I,1.)) - ORD('A')  ;
                          CASE R1 OF
                             0 :  A2 := A2 OR BL  ;
                             1 :  B2 := B2 OR BL  ;
                             2 :  C2 := C2 OR BL  ;
                             3 :  D2 := D2 OR BL  ;
                             4 :  E2 := E2 OR BL  ;
                             5 :  F2 := F2 OR BL  ;
                             6 :  G2 := G2 OR BL  ;
                             7 :  H2 := H2 OR BL
                          END
                        END
            END
        END ;
(*****************************************************************)
(*  NAME :          LEAF                                         *)
(*  FUNCTION :      To determine the new marking Mk1+1 is a      *)
(*                     leaf (terminal node) or not,              *)
(*                  if so, determine its type : home-state or    *)
(*                         live-looping , or # level > E0.       *)
(*                                                               *)
(*  INPUT PARAMETER :                                            *)
(*           J  -- subscript of the fired transition Tj          *)
(*  OUTPUT PARAMETER :                                           *)
(*          UU  -- 1/0, Mk1+1 is an internal node/leaf           *)
(*  PROGRAM IDENTIFIER :  FOUND  --  exist k2 and k, so that     *)
(*                                     Mk1+1(k) < Mk2(k)         *)
(*                        FOUND1 --  exist k2 and k, so that     *)
(*                                     Mk1+1(k) > Mk2(k)         *)
(*                        KFOUND --  exist k2, so that           *)
(*                                     Mk1+1 = Mk2               *)
(*                        KFOUND1 -- exist k2, so that           *)
(*                                   Mk1+1 > Mk2   (w-symble)    *)
(*****************************************************************)
  PROCEDURE LEAF (VAR J,UU : INTEGER) ;
```

```
VAR I,K,FOUND',KFOUND' : INTEGER ;
    QK1 : ARRAY(.1..40,1..9.) OF INTEGER ;
BEGIN
      KFOUND := 0  ;  KFOUND1 := 0 ;
      IF WFLAG=1 THEN  K2 := 1
                 ELSE  K2 := K4 - 1 ;
      (*                                                              *)
      (*  find whether exist k2 <= k1, that Mk1+1=Mk2                 *)
      (*  and whether exist K4 <= k1, that Mk1+1 > Mk4                *)
      (*                                                              *)
      WHILE (K2<=K1) AND (KFOUND=0) AND (KFOUND1=0) DO
        BEGIN
          FOUND := 0  ;  FOUND' := 0 ;
          FOR K:=1 TO L DO
            FOR I:=1 TO M DO
              QK1(.I,K.) := 0 ;
          I := 1 ;
          WHILE (I<=M) AND (FOUND=0) DO
            BEGIN
              K := 1  ;
              WHILE (K<=L) AND (FOUND=0) DO
                IF QK(.I,K.) = 0
                  THEN IF MR(.K1+1,I,K.) < MR(.K2,I,K.)
                         THEN FOUND := 1
                       ELSE IF MR'.K1+1,I,K.) > MR(.K2,I,K.)
                              THEN BEGIN
                                     FOUND1 := 1 ;
                                     QK1(.I,K.) := 1 ;
                                     K := K + 1
                                   END
                            ELSE K := K + 1
                  ELSE K := K + 1  ;
              I := I + 1
            END ;
          IF FOUND = 0
            THEN IF FOUND1 = 0
                   THEN BEGIN
                          KFOUND := 1 ;    (*  found k2  *)
                          K0 := K2
                        END
                   ELSE BEGIN
                          KFOUND1 := 1 ;   (*  found k4  *)
                          K4 := K1
                        END
                 ELSE K2 := K2 + 1
        END ;
      IF KFOUND1 = 0
        THEN FOR K:=1 TO L DO
               FOR I:=1 TO M DO
                 QK1(.I,K.) := 0 ;
      FOR K:=1 TO L DO
        FOR I:=1 TO M DO
          QK(.I,K.) := QK(.I K.) + QK1(.I,K.) ;
      '*                                                              *)
```

```
(*       write the new marking Mk1+1                    *)
(*                  as a node of the tree               *)
FOR K:=1 TO L DO
    BEGIN
      WRITE('  <    ') ;
      FOR I:=1 TO M DO
        IF WFLAG = 1
        THEN WRITE (MR(.K1+1,I K.):2,'    ')
          ELSE IF QK(.I,K.) = 0
                THEN WRITE(MR(.K1+1,I,K.):2,'    ')
                ELSE WRITE(' W','    '); (* w-symbol *)
      WRITELN('>')
    END ;
  IF KFOUND = 0
    THEN BEGIN
           (* no such k2 or k4 exist, check current  *)
           (*     #  of level exceeds E0 or not      *)
           K1 := K1 + 1 ;
           IF K1 <= E0
             THEN UU :=1          (*   not exceeds   *)
             ELSE BEGIN
               WRITE ('   M<',K1:2,',',Q1(.K1.):2,'>');
               WRITE ('   --- LEVELS  >= ALLOWED ') ;
               WRITELN ('   < TERMINAL NODE >') ;
               WRITELN ;
               E3 := 1 ;
               K1 := K1 -1 ;
               UU := 0   (* Mk1+1 is a leaf *)
                  END
         END
        ELSE IF K0 = 1
               THEN BEGIN
                      (*    Mk1+1 is home-state    *)
          WRITE ('      M<',K1+1:2,',',Q1(.K1+1.)-1:2,'>');
          WRITELN (' ---  HOME-STATE  < DUPLICATE NODE >');
          K0 := 0 ;  K3 := 0 ; HMST := 1 ; UU := 0
                      END
               ELSE IF J = LJ + 1
                      THEN BEGIN
                             K3 := K1 + 1 ;  UU := 0
                           END
                      ELSE BEGIN
                      (*    Mk1+1 is in a live-loop    *)
    WRITE ('         M<',K1+1:2,',',Q1(.K1+1.)-1:2,'>');
    WRITE (' = M<',K0:2,',',Q1(.K0.)-1 :2,'>  :    ') ;
    FOR I:=K0 TO K3-1  DO
    WRITE(' M<',I:2,',',Q(.I.)-1:2,'> -->') ;
    WRITELN(' M<',K0:2,',',Q(.K0.)-1,'>') ;
    WRITE('                              ') ;
    WRITE (' --- LIVE-LOOPING  <  DUPLICATE NODE  >') ;
    K0 := 0 ; LVLP:=1 ; UU := 0
                           END
  END ;
(*************************************************************)
```

```
(*  NAME :          LOCK                                              *)
(*  FUNCTION :      To detect deadlocks and livelocks                 *)
(*  INPUT PARAMETER :                                                 *)
(*            J -- the subscript of Tj which just fired               *)
(*  OUTPUT PARAMETER :                                                *)
(*            VV -- 0/1, when go back from a leaf may                 *)
(*                       find another branch / not                    *)
(*******************************************************************)
  PROCEDURE LOCK (VAR J, VV : INTEGER) ;
    VAR I K : INTEGER ;
    BEGIN
      WRITELN ('    LOCK') ;
                IF L1 = N
                  THEN BEGIN
                    (*   Mk1+1 is a deadlock     *)
                    WRITE '    M<',K1:2,',',Q1(.K1.)-1:2,'>');
                    WRITE (' --- DEADLOCK < TERMINAL NODE >');
                    DDLK := 1
                       END
                 ELSE IF K0 <> 0
                        THEN IF L1 = N - 1
                               THEN BEGIN
                                      L2 := L2 + 1 ;
                                      IF K1 = K0
                                        THEN IF L2 <> K3 - K0
                                               THEN L2 := 0
                                               ELSE
                                 BEGIN
                                 (*   Mk1+1 is a livelock    *)
                    WRITE ('     M<',K3:2,',',Q1(.K3.)-1:2,'> = M<');
                    WRITELN (K0:2,',',Q1(.K0.)-1:2,'>')  ;
                    FOR I:=K0 TO K3-1 DO
                      WRITE (' M<',I:2,',',Q1(.I )-1:2,'> -- ') ;
                    WRITELN (' M<',K0:2,',',Q1(.K0.)-1:2,'>') ;
                    WRITE ('                    ') ;
                    WRITELN (' --- LIVE-LOCK  < TERMINAL NODE >') ;
                              WRITELN ;   LVLK := 1
                                 END
                                      END;
          IF K1 > 1 THEN VV := 0
                    ELSE VV := 1
      END ;
(*******************************************************************)
(*  NAME :          VARIABLES                                        *)
(*  FUNCTION :      To assign the old velues in lower level          *)
(*                     to the PN variables when tracing back         *)
(*                     from a leaf to find another branch            *)
(*******************************************************************)
  PROCEDURE VARIABLES ;
    VAR I : INTEGER ;
    BEGIN
            (*      for integer PN variables       *)
            IF N1 > 0 THEN
              FOR I:= 1 TO N1 DO
```

```
            CASE I-1 OF
              0 : A := QI(.K1,1.) ;   1 : B := QI(.K1,2.) ;
              2 : C := QI(.K1,3.) ;   3 : D := QI(.K1,4.) ;
              4 : E := QI(.K1,5.) ;   5 : F := QI(.K1,6.) ;
              6 : G := QI(.K1,7.) ;   7 : H := QI(.K1,8.)
            END ;
          (*       for real PN variables          *)
          IF N2 > 0 THEN
            FOR I:=1 TO N2 DO
              CASE I-1 OF
                0 : A1 := QR(.K1,1.) ;   1 : B1 := QR(.K1,2.) ;
                2 : C1 := QR(.K1,3.) ;   3 : D1 := QR(.K1,4.) ;
                4 : E1 := QR(.K1,5.) ;   5 : F1 := QR(.K1,6.) ;
                6 : G1 := QR(.K1,7.) ;   7 : H1 := QR(.K1,8.)
              END ;
          (*      for Boolean PN variables        *)
          IF N3 > 0  THEN
            FOR I:=1 TO N3 DO
              CASE I-1 OF
                0 : A2 := QL(.K1,1.) ;   1 : B2 := QL(.K1,2.) ;
                2 : C2 := QL(.K1,3.) ;   3 : D2 := QL(.K1,4.) ;
                4 : E2 := QL(.K1,5.) ;   5 : F2 := QL(.K1,6.) ;
                6 : G2 := QL(.K1,6.) ;   7 : H2 := QL(.K1,8.)
              END
      END ;
    (*                                                  *)
    (*     the main program of procedure REACHABILITY   *)
    (*                                                  *)
    BEGIN
       PREP ;                        (*  call PREP to initial-data  *)
       K1:= 1 ;
100 :  IF GG = 1 THEN RECEIVE;(* to receive new values of var.*)
       CHECK ;                       (*  to check token properties  *)
       FIND ;                        (* to find firable transitions  *)
       L1 := 0 ;  L2 := 0 ;  K0 := 0 ;  K3 := 0 ;
       J := 1 ;
200:   WRITELN(' 200: K1=',K1:2) ;
       IF TT (.K1,J.) <> 0
         THEN BEGIN
                (*                                  *)
                (*   when Tj is firable             *)
                (*                                  *)
                FIRING (J) ;     (*  to firing Tj    *)
                LEAF (J,XX) ;    (*  to determine type of leaf *)
                IF XX=1 THEN GOTO 100
                        ELSE  IF J<N THEN BEGIN
                                            J := J + 1 ;
                                            GOTO 200
                                          END
                                ELSE BEGIN
                                       (*  detect locks  *)
                                       LOCK (J,YY) ;
                                       IF YY = 0
                                         THEN BEGIN
```

```
                                    (* trace back *)
                                     K1 := K1 - 1 ;
                                     FLAG := 0  ;
                          WHILE (K1>=1) AND (FLAG=0) DO
                            BEGIN
                               J := Q(.K1.) + 1 ;
                              IF J <= N THEN FLAG := 1
                                        ELSE K1:= K1-1
                             END ;
                            IF FLAG = 1
                            THEN BEGIN
                                   L1 := 0 ;
                                   (* get old values *)
                                   VARIABLES ;
                                   IF K1 < K4 + 1  THEN
                                     BEGIN
                                      FOR K:=1 TO L DO
                                       FOR I:=1 TO M DO
                                       QK(.I,K.) := 0 ;
                                            K4 := 0
                                        END ;
                                       GOTO 200
                                     END
                                 ELSE GOTO 300
                                END
                    END
          END
     ELSE BEGIN
            (*                                    *)
            (*    when Tj is not firable          *)
            (*                                    *)
           L1 := L1 + 1 ; (* sum unfirable num. of trans. *)
           IF J < N
             THEN BEGIN
                    J := J + 1;  (* try next transition *)
                    GOTO 200
                  END
             ELSE BEGIN
                    (*   when no more transition left  *)
                    LOCK (J YY) ;      (*  detect locks  *)
                    IF YY = 0  THEN BEGIN
                                      (*.  trace back   *)
                                     K1 := K1 - 1 ;
                                     FLAG := 0 ;
                                WHILE (K1>=1) AND (FLAG=0) DO
                                  BEGIN
                                    J := Q(.K1.) + 1 ;
                                    IF J <= N THEN FLAG := 1
                                              ELSE K1 := K1 - 1
                                  END;
                                IF FLAG=1 THEN BEGIN
                                                 L1 := 0 ;
                                                 VARIABLES ;
                                             IF K1 < K4 + 1 THEN
```

```
                                                BEGIN
                                                 FOR K:=1 TO L DO
                                                   FOR I:=1 TO M DO
                                                    BEGIN
                                                     QK(.I,K.) := 0;
                                                     K4 := 0
                                                    END ;
                                                    GOTO 200
                                                END
                                            END
                                    END
                            END ;

(*   check the last marking is in a live-loop or not     *)
300 :  IF K0 <> 0 THEN
         BEGIN
           R := Q1(.K3.) - 1  ;
           WRITE('          M<',K3:2,',',R:2,'>  = ') ;
           WRITE(' M<',K0:2,',',Q1(.K0.)-1:2,'>  :')  ;
           FOR I:=K0 TO K3-1 DO
              WRITE(' M<',I:2,',',Q1(.I )-1:2,'> -->');
           WRITELN(' M<',K0:2,',',Q1(.K0.)-1:2,'>') ;
           WRITE('                          ') ;
           WRITELN('  --- LIVE-LOOPING  < TERMINAL NODE >') ;
           K0 := 0 ;  K3 := 0 ;  LVLP := 1
         END ;
        (*                                                 *)
        (*    printout the properties of the PN            *)
        (*                                                 *)
        WRITELN ;
        WRITELN('   THE REACHABILITY ANALYSIS RESULTS :') ;
        IF SAF = 1 THEN WRITELN ('  <1>  THE NET IS NOT SAFE .')
                   ELSE IF E3 = 0  THEN
                        WRITELN ('   <1>  THE  NET  IS  SAFE .')
                                ELSE
                  WRITELN('   <1> THE SAFENESS IS NOT DETECTED.');
        WRITELN ;
        IF E3 = 0 THEN
      WRITELN('   <2>  THE MAX NUMBER OF TOKENS IN EACH PLACE :')
                 ELSE
      WRITELN('   <2>  THE MAX NUMBER OF TOKENS IN EACH PLACE >=');
        FOR K:=1 TO L DO
          WRITELN ('          FOR COLOUR',K:1,' IS  ',BD(.K.):2);
        IF CFLAG = 0
          THEN IF E3 = 0 THEN
           BEGIN
             WRITELN ('   <3>  THE NET IS CONSERVED BY :')  ;
             FOR K:=1 TO L DO
               WRITELN('    FOR COLOUR',K:1,' IS  ',CS(.K.):2);
               WRITELN
           END
                      ELSE
             WRITELN (' <3>  THE CONSERVATION IS NOT DETECTED.')
```

```
      ELSE WRITELN (' <3>  THE NET IS NOT CONSERVED .')  ;
    WRITELN ('   <4>  EXECUTION TERMINALS :') ;
    IF DDLK=0 THEN
                  WRITELN('                    NO DEADLOCKS  ')
               ELSE
                  WRITELN('      THE NET HAS DEADLOCK<S>.');
    IF LVLK=0 THEN
                  WRITELN('                    NO LIVE-LOCKS .')
               ELSE
                  WRITELN('     THE NET HAS LIVE-LOCK<S>.');
    IF LVLP=0 THEN
                  WRITELN('                 NO LIVE-LOOPING .')
               ELSE
                  WRITELN('  THE NET HAS LIVE-LOOPING<S>.');
    IF HMST=0 THEN
                  WRITELN('            M0 IS NOT A HOME-STATE .')
               ELSE
                  WRITELN('          M0 IS A HOME-STATE .');
     WRITELN ('   ****************************************') ;
     WRITELN ('   *    END OF REACHABILITY ANALYSIS      *') ;
     WRITELN ('   ****************************************')
  END ;
(*****************************************************************)
(*  NAME :        INCIDENCE                                      *)
(*  FUNCTION :    To find the place and transition invariants    *)
(*                of the PN                                      *)
(*  PROGRAM IDENTIFIER :                                         *)
(*     FFLAG  -- 0/1, when procedure OMAGA/FAI calls SOLUTION    *)
(*  PROGRAM ARRAYS :                                             *)
(*          CM -- 40x40x9, CM = TARC - PARC                      *)
(*          CT -- 40x40x9, the transform of CM                   *)
(*          X  -- 40, solution of CM.X=0 or CT.X=0               *)
(*  PROCEDURES CALLED :    OMAGA                                 *)
(*                         FAI                                   *)
(*****************************************************************)
  PROCEDURE INCIDENCE ;
    VAR CM ,CT : CB ;
        X      : CF ;
        I,J,K : INTEGER ;
        V.L1,S.T: INTEGER ;
        FOUND, FLAG, FFLAG  : INTEGER ;
(*****************************************************************)
(*  NAME :        SOLUTION                                       *)
(*  FUNCTION :    To do the elementary operation for a           *)
(*                MxNxL matrix   (B5) .                          *)
(*  PROGRAM VARIABLES :                                          *)
(*        M1 --  integer, MIN.(MM,NN)                            *)
(*        LL  -- integer, rotaion variable                       *)
(*        TEMP -- integer, used as a tempral variable            *)
(*  PROGRAM IDENTIFIER :                                         *)
(*        KFLAG -- 1/0, column NO.(k) > total row no.(MM)/not    *)
(*  PROGRAM ARRAYS :                                             *)
(*        Y(I) -- 1X40, 1/0, I row has zero-element / not        *)
(*        Z(K) -- 1X40, 1/0, K-column, from K-row has no         *)
```

```
(*                              zero-element / has                    *)
(*                                                                    *)
(*  INPUT PARAMETERS :                                                *)
(*        B5  --  40X40 array, the matrix to be operated              *)
(*        WW(HH) --  40 array, original column no. in B5,             *)
(*                   for the HHth zero column in the current          *)
(*                   step of elmentary opration                       *)
(*        MM  --  integer, total number of rows in B5                 *)
(*        NN  --  integer, total number of columns in B5              *)
(*  OUTPUT PARAMETERS :                                               *)
(*        HH  --  integer, total number of zero-columns               *)
(*        HL  --  integer, total number of zero-rows                  *)
(**********************************************************************)
PROCEDURE SOLUTION (VAR B5: CA ; VAR WW: CF ;
                                 VAR MM,NN,HH,HL :INTEGER) ;
VAR     I Il, J, K, FOUND, FLAG, KFLAG : INTEGER ;
        T   TEMP,LL : INTEGER ;
        Y,Z : ARRAY (.1..40.) OF INTEGER ;
        INDEX, M1 : INTEGER ;
BEGIN
 WRITELN('   SOLUTION ') ;
     (*   get M1 = MIN (MM,NN)   *)
     IF MM < NN
       THEN  M1 := MM
       ELSE  M1 := NN ;
     (*   initialize Z(.I.) , HL    *)
     FOR I:=1 TO NN DO
        Z(.I.) := 0 ;
     INDEX := 0 ;  HL := 0 ;
     (*                              *)
     (*    elementary operation      *)
     (*                              *)
     FOR K:=1 TO NN DO
         BEGIN
           (*    for column k, initialize row i    *)
           FOUND := 0 ; KFLAG := 0 ;
           IF K=1
              THEN I:=K
              ELSE BEGIN
                     LL := 1 ; FLAG := 0 ;
                     WHILE (LL<K) AND (LL<=MM-HL) AND (FLAG=0) DO
                        BEGIN
                            IF Z(.LL.) =1
                               THEN IF B5(.LL,K.) <> 0
                                       THEN BEGIN
                                              FLAG := 1;
                                              I := LL
                                            END
                                    ELSE LL:= LL+1
                               ELSE LL := LL+1
                        END ;
                     IF FLAG = 0
                        THEN IF K <= MM THEN I:= K
                                        ELSE KFLAG := 1 ;
           END ;
```

```
IF KFLAG = 0 THEN
(*  find non-zero element in kth column : B5(index,k)<>0  *)
    WHILE (I<=MM-HL) AND (FOUND=0) DO
          IF  B5(.I,K.) <> 0
            THEN BEGIN
                  FOUND := 1; INDEX := I;(* found INDEX *)
                  IF B5(.I,K.) < 0  THEN
             (* change this non-zero element to positive *)
                  FOR J:=K TO NN DO
                    B5(.I,J.) := -B5(.I,J )
                END
            ELSE I := I + 1 ;
    IF FOUND = 1     (* kth column has non-zero element  *)
       THEN BEGIN
            IF K <= MM
              THEN BEGIN
                  (* exchange INDEX row and Kth row   *)
                    IF INDEX <> K
                      THEN FOR J := K TO NN DO
                             BEGIN
                          T := B5(.K,J.) ;
                          B5(.K,J ) := B5(.INDEX, J ) ;
                          B5(.INDEX,J.) := T
                             END ;
                (*  purge other elements in Kth row  *)
                    FOR I:=1 TO K-1 DO
                      IF Z(.I.) = 1
                        THEN BEGIN
                    TEMP := B5(.I,K.) ;  T := B5(.K,K.);
                          FOR J :=K TO NN DO
                          B5(.I,J.) := B5(.I,J.) * T -
                                       TEMP * B5(.K,J )

                          END ;
                   FOR I:= K+1 TO MM DO
                     BEGIN
                       TEMP := B5(.I K.) ;
                       T    := B5(.k,k.) ;
                       FOR J := K TO NN DO
            B5(.I J ) := B5(.I,J )*T-TEMP * B5(.K,J.)
                     END
                END
            ELSE BEGIN     (*  for MM<NN and K>MM  *)
           (* purge other elements in INDEX column *)
                  FOR I:=INDEX+1 TO MM DO
                    BEGIN
                     TEMP := B5(.I,K.) ;
                     T    := B5(.INDEX,k.) ;
                     FOR J:=1 TO NN DO
                B5(.I,J.) := B5(.I J )*T - B5(.INDEX
                                           ,J.)*TEMP

                     END ;
           (*  move INDEX row to the bottom, each    *)
           (*  of INDEX+1 to MM rows move up 1 row   *)
                  FOR J := 1 TO NN DO
```

```
                                BEGIN
                                  T := B5(.INDEX,J ) ;
                                  FOR I:=INDEX+1 TO MM DO
                                    B5(.I-1,J.) := B5(.I J ) ;
                                  B5(.MM,J ) := T
                                END ;
                              HL := HL + 1
                            END
                      END
                ELSE Z(.K.) := 1
(*    after each elementary operation, write the matrix     *)
(*      WRITELN('  Z',K:2,'=':3,Z(.K.) )                    *)
(*      WRITELN''    MATRIX D',K:2)                         *)
(*      FOR I:=1 TO MM DO                                   *)
(*        BEGIN                                             *)
(*          FOR J:=1 TO NN DO                               *)
(*            WRITE(B5(.I,J ):4)                            *)
(*          WRITELN                                         *)
(*          END                                             *)
(*     WRITELN                                              *)
    END ;
    (*    count the total number of zero-rows     *)
    HL := 0 ;
    FOR I:=1 TO MM DO
      BEGIN
        J := 1 ; FLAG := 0 ;
        WHILE (J <= NN ) AND (FLAG = 0) DO
        IF B5(.I J.) <> 0
          THEN FLAG := 1
          ELSE J := J+1 ;
        IF FLAG = 0
          THEN BEGIN
                 Y(.I.) := 1 ;
                 HL := HL + 1
               END
          ELSE Y(.I ) := 0
      END ;
    (*    count the total number of zero-columns     *)
    HH := 0 ;
    FOR K:=1 TO NN DO
      IF Z(.K.) = 1
        THEN BEGIN
               HH := HH + 1 ;
               WW(.HH ) := K
             END ;
  IF FFLAG=1
    THEN FOR I:=HH+1 TO HH+(NN-MM) DO
           WW(.I.) := MM+I-HH ;
  (*     move all the zero-rows to the bottom     *)
  FOR K:=1 TO MM-1 DO
  FOR I:=1 TO MM-1 DO
    IF Y(.I ) = 1
      THEN IF Y(.I+1.) = 0
             THEN BEGIN
```

```
                    Y(.I.) := 0 ; Y(.I+1.) := 1 ;
                    FOR J:= 1 TO NN DO
                      BEGIN
                        T := B5(.I+1,J.) ;
                        B5(.I+1,J ) := B5(.I J ) ;
                        B5(.I,J ) := T
                      END
                  END ;
(*  move up the non-zero rows who has less no. zero-element  *)
FOR K:=1 TO M1 DO
  IF B5(.K,K.) = 0
    THEN BEGIN
           J := K+1 ;  FOUND := 0 ;
           WHILE  (J<=NN) AND (FOUND=0) DO
             IF B5(.K,J.) = 0
               THEN BEGIN
                      I := K + 1 ;   FLAG := 0 ;
                      WHILE (I<=MM) AND (FLAG=0) DO
                        IF B5(.I,J.) <> 0
                          THEN BEGIN
                                 FLAG := 1 ;
                                 FOR LL:=1 TO NN DO
                                   BEGIN
                                     T := B5(.K,LL.) ;
                                     B5(.K,LL.) := B5(.I,LL.);
                                     B5(.I,LL.) := T
                                   END
                               END
                          ELSE I := I + 1 ;
                    IF FLAG = 0  THEN  J := J + 1
                  END
               ELSE FOUND := 1
         END
(*    write the final equivalent matrix     *)
(*        WRITELN('MATRIX D')                                    *)
(*        FOR I:= 1 TO MM DO                                     *)
(*            BEGIN                                              *)
(*               FOR J:= 1 TO NN DO                              *)
(*                   WRITE(B5(.I,J ):4)                          *)
(*               WRITELN                                         *)
(*            END                                                *)
(*        WRITELN ('   MAX ORDER =',MM-HL :2)                    *)
 END ;
(*************************************************************)
(*  NAME :       OMAGA                                       *)
(* FUNCTION :    To find the transition invariants by solving *)
(*                  CM.X=0                                   *)
(*  PROGRAM VARIABLES :                                      *)
(*        V  -- integer, total number of solution groups     *)
(*        H  -- integer, total number of 0-columns in AA1    *)
(*        H1 -- integer, total number of 0-rows in  AA1      *)
(*  PROGRAM IDENTIFIER :                                     *)
(*        XFLAG  --  0/1, solution X(INDEX) = integer  / not *)
(*  PROGRAM ARRAYS :                                         *)
```

```
(*            AA1  --  40X40, integer,  AA1 = AA for one k     *)
(*            W    --  1X40, integer,                          *)
(*            X    --  1X40, integer,                          *)
(*  INPUT PARAMENTER :                                         *)
(*            AA   --  40X40X9, integer,  AA = CM               *)
(*  PROCEDURE CALLED :     SOLUTION                            *)
(*************************************************************)
 PROCEDURE OMAGA (VAR AA : CB ) ;
   VAR AA1 : CA ;
       W,X : CF ;
       I,J,I1,I2,K2,LL,NN,H1,INDEX,XFLAG : INTEGER ;
   BEGIN
 WRITELN ('  OMAGA') ;
 writeln ('    * * * * * * * * * * * * * * * * * * * * * *') ;
 writeln ('    *          TRANSITION INVARIANTS          *') ;
 writeln ('    * * * * * * * * * * * * * * * * * * * * * *') ;
 writeln ;
     FOR K2:=1 TO L DO
       BEGIN
         (*    for each k, get AA1  from AA    *)
         FOR I:=1 TO M DO
           FOR J:=1 TO N DO
             AA1(.I,J.) := AA(.I J K2.) ;
         (*  call SOLUTION to do elementary operations on AA1 *)
         SOLUTION (AA1,W,M,N,H,H1) ;
(*    WRITELN('   0-COLUMN # H=',H:2,'   0-ROW # H1=',H1:2)    *)
   IF M-H >= N
     THEN WRITELN
      (' * THERE IS NOT ANY TRANSITION INVARIANT FOR THIS NET *')
     ELSE BEGIN
       (*   get the total number of possible 0/1 solutions     *)
       V := 1 ;
       K := 0 ;
       REPEAT
            V := V * 2 ;
            K := K+1
       UNTIL K = H ;
(*     WRITELN ('    V=',V)                                    *)
       I2 := 0 ;
       FOR LL:=1 TO V-1 DO
           (*   assign 0/1 to erch arbitary Xi                 *)
           (*                      in the LLth solution        *)
           BEGIN
             J := 1 ;
             S := LL ;
             REPEAT
                  X(.W(.J.).) := S MOD 2  ;
                  S := S DIV 2 ;
                  J := J + 1
             UNTIL J = H + 1 ;
(*           FOR J:=1 TO H DO                                  *)
(*             IF W(.J.)<=N                                    *)
(*               THEN                                          *)
(*                WRITELN('    X',W(.J.):2,'=':3,X(.W(J ).):2) *)
```

```
          L1:= M-H1;  XFLAG := 0 ;
(*        WRITELN('    NON-ZERO ROW # M-H1 = ',L1:2)                    *)
          WHILE (L1>0) AND (XFLAG=0) DO
           BEGIN
            (*          find first non-0-elemet                         *)
            (*                  in the last non-0-row                   *)
            J := 1 ; FOUND := 0 ; T := 0 ;
            WHILE (J<=N) AND (FOUND=0) DO
              IF AA1(.L1,J.) <> 0
                THEN BEGIN
                       FOUND := 1 ;
                       INDEX := J    (*  find the column #  *)
                     END
                ELSE J := J+1 ;
             (*    get the value of X(INDEX)      *)
             IF INDEX < N THEN
               BEGIN
                 FOR J:=INDEX +1 TO N DO
                   T := T-AA1(.L1,J.) * X(.J ) ;
                 X(.INDEX.) := T DIV AA1(.L1,INDEX.) ;
                 IF X(.INDEX.) * AA1(.L1,INDEX.) <> T
                   THEN XFLAG := 1 ;
                                 END
                            ELSE X(.INDEX.) := 0  ;
             L1 := L1-1
           END ;
         (*    to find only integer solutions      *)
         IF XFLAG = 0 THEN
           BEGIN
            (* to detemine whether this solution is 0/1 or not *)
            FLAG := 0 ;
            I := 1 ;
            WHILE (I<=N) AND (FLAG=0) DO
              IF (X(.I.)<>0) AND (X(.I.)<>1)
                THEN FLAG := 1
                ELSE I := I+1 ;
            (*  if it is 0/1 solution, printout the invariant  *)
            IF FLAG = 0
              THEN BEGIN
                     I2 := I2 + 1 ;
(*                   FOR I1:= 1 TO N DO                                *)
(*                     WRITELN('   X(',I1:3,')=':4,X(.I1.) )           *)
                     writeln ;
                     writeln ;
                     WRITELN('  TRANSITION INVARIANT ',I2:2,' :');
                     WRITE ('                                ') ;
                     NN := 0 ;
                     FOR I:=1 TO N DO
                       IF X(.I.)=1 THEN
                                    BEGIN
                                      WRITE('T':2,I:1) ;
                                      NN := NN + 1
                                    END ;
                     WRITELN ;
```

```
                    WRITE('                              ') ;
                    WRITE ('     M ') ;
                    FOR I:=1 TO NN DO
                                  WRITE('----') ;
                    WRITELN ('> M')

                  END
              END
            END
          END
        END
    END ;
(*****************************************************************)
(*  NAME :       FAI                                             *)
(*  FUNCTION :  To find the place invarints by solving           *)
(*                 CT.X=0                                        *)
(*  INPUT PARAMETER :                                            *)
(*     BB  --    40X40X9, integer, BB=CT                         *)
(*  PROGRAM VARIABLES :                                          *)
(*     H   --    integer, total number of 0-columns in BB1       *)
(*     H1  --    integer, total number of 0-rows in BB1          *)
(*  PROGRAM ARRAYS :                                             *)
(*     BB1 --  40X40, integer, BB1= BB for one k                 *)
(*     W   --  1X40, integer, w(i) is original # of ith 0-row    *)
(*     x   --  1X40, integer, the solution                       *)
(*  PROCEDURE CALLED :     SOLUTION                             *)
(*****************************************************************)
 PROCEDURE FAI (VAR BB : CB);
   VAR BB1 : CA ;
       W,X : CF ;
       SUM, INDEX, XFLAG :INTEGER ;
       I,J,I1,I2,K2,LL,H-H1: INTEGER ;
   BEGIN
 WRITELN('   FAI') ;
 writeln ('    * * * * * * * * * * * * * * * * * * * * * * * *') ;
 writeln ('    *              PLACE INVARIANTS               *') ;
 writeln ('    * * * * * * * * * * * * * * * * * * * * * * * *') ;
 writeln ;
     FOR K2:=1 TO L DO
       BEGIN
         (*     get BB1,  BB1 = BB(i,j,k2)     *)
         FOR I:=1 TO N DO
           FOR J:=1 TO M DO
             BB1(.I,J.) := BB(.I,J K2.) ;
         (*    call SOLUTION to do elementary operations    *)
         SOLUTION 'BB1,W,N,M,H,H1) ;
  IF N-H' >= M
    THEN WRITELN
        ('  * THERE IS NOT ANY PLACE INVARIANT FOR THIS  NET *')
    ELSE BEGIN
      (*    to count the total number of solutions     *)
      V := 1 ;
      K := 0  ;
      REPEAT
```

```
        V := V * 2 ;
        K := K + 1 ;
    UNTIL K = H  ;
    I2 := 0 ;
    FOR LL:=1 TO V-1 DO
        BEGIN
          (*  assign 0/1 to arbitary Xi in LL th solution   *)
          J := 0 ;
          S := LL ;
          REPEAT
                J := J + 1 ;
                X(.W(.J.).) := S MOD 2 ;
                S := S DIV 2
          UNTIL J=H ;
(*        FOR J:=1 TO H DO                                    *)
(*           WRITELN('   X',W(.J ):?,'=':3,X(.W(.J.).):3)   *)
          (*    bottom-up, to find LLth solution     *)
          L1:= N-H;  XFLAG := 0 ;
          WHILE (L1>0) AND (XFLAG=0) DO
           BEGIN
            (*      to find the fist non-0-element          *)
            (*                  in the last non-0-row       *)
            T := 0;
            J := 1 ; FOUND := 0 ;
            WHILE (J<=M) AND (FOUND=0) DO
              IF BB1(.L1,J.) <> 0
                THEN BEGIN
                       FOUND := 1 ;
                       INDEX := J (* found  comlunm # INDEX *)
                     END
                ELSE J := J+1 ;
              (*       to get the value of  X(INDEX)       *)
              IF INDEX < M THEN BEGIN
                           FOR J:=INDEX +1 TO M DO
                               T := T-BB1(.L1,J.) * X(.J ) ;
                           X(.INDEX.) := T DIV BB1(.L1,INDEX.);
                           IF X(.INDEX.) * BB1(.L1,INDEX.) <> T
                             THEN XFLAG := 1
                                END
                           ELSE  X(.INDEX.) := 0  ;
             L1 := L1-1
           END ;
          (*    consider only integer solution      *)
          IF XFLAG = 0 THEN
            BEGIN
             (*  check LLth solution is only 0/1 or not    *)
             FLAG := 0 ;  I := 1 ;
             WHILE (I<=M) AND ( FLAG=0) DO
               IF ( X(.I.) <> 0 ) AND ( X(.I ) <>1 )
                  THEN FLAG := 1
                  ELSE I := I + 1 ;
             (*    if only 0/1, printout the place invarint    *)
             IF FLAG = 0
               THEN BEGIN
```

```
                    I2 := I2 + 1 ;
(*                  FOR I1:= 1 TO M DO                                  *)
(*                    WRITELN('   X(',I1:3,')=':4,X(.I1.) )             *)
                    WRITELN ;
                    WRITELN('    PLACE INVARIANT ',I2:2,' :') ;
                    WRITE ('                    ') ;
                    FOR I:=1 TO M DO
                      BEGIN
                        FLAG := 0 ;  J := I + 1 ;
                        WHILE (J<=M) AND (FLAG=0) DO
                          IF X(.J.) <> 0
                            THEN FLAG :=1
                            ELSE J := J + 1 ;
                        IF X(.I.) <> 0
                          THEN IF FLAG=1
                             THEN WRITE (' M (P':4,I:3,') +':3)
                             ELSE WRITE (' M (P':4,I:3,')':2)
                      END ;
                    SUM := 0 ;
                    FOR I:=1 TO M DO
                      SUM := SUM + X(.I.) * P(.I K2.) ;
                    WRITELN('=':3 , SUM:3)
                  END ;
                WRITELN ;
              END
            END
        END
      END
    END ;
(*                                                                      *)
(*      the main program of procedure INCIDENCE                         *)
(*                                                                      *)
 BEGIN
   FFLAG := 0 ;
   WRITELN('     INCIDENCE') ;
      (*  get CM,  CM = TARC - PARC      *)
     FOR I:=1 TO M DO
       FOR J:=1 TO N DO
         FOR K:=1 TO L DO
           CM(.I,J,K.) := TARC(.I,J K.) - PARC(.I,J,K.) ;
(*  WRITELN('    CM')                                                   *)
(*  FOR I:=1 TO M DO                                                    *)
(*    BEGIN                                                             *)
(*      WRITE ('      ')                                              *)
(*      FOR J:=1 TO N DO                                                *)
(*        FOR K:=1 TO L DO                                              *)
(*            WRITE (CM(.I,J,K.):4)                                     *)
(*     WRITELN                                                          *)
(*    END                                                               *)
      (*      to get CT ,  CT = transform of CM      *)
      FOR K:=1 TO L DO
        FOR I:=1 TO N DO
          FOR J:=1 TO M DO
            CT(.I J,K.) := CM(.J I,K.) ;
```

```
(*    WRITELN('    CT')                                          *)
(*    FOR I:=1 TO N DO                                          *)
(*     BEGIN                                                    *)
(*      WRITE('     ')                                          *)
(*      FOR J:=1 TO M DO                                        *)
(*        FOR K:=1 TO L DO                                      *)
(*           WRITE (CT(.I,J,K.) :' )                            *)
(*      WRITELN                                                 *)
(*     aND                                                      *)
  OMAGA (CM) ;    (*  call OMAGA to find transition invariants  *)
  FFLAG := 1 ;
      FAI (CT) ; (*     call FAI to find place invariants      *)
      WRITELN('    ***************************************') ;
      WRITELN('    *       END OF INCIDENCE ANALYSIS      *') ;
      WRITELN('    ***************************************')
  END ;
(*****************************************************************)
(*  NAME :        ANEW                                           *)
(*  FUNCTION :    contain the options of process ANALYSIS        *)
(*****************************************************************)
  PROCEDURE ANEW ;
   BEGIN
     WRITELN ('             < MODULE  ANALYSIS >              ') ;
     WRITELN ('   ***************************************') ;
     WRITELN ('   *   DO YOU WANT TO DO :               *') ;
     WRITELN ('   *        1.  REACHABILITY ANALYSIS    *') ;
     WRITELN ('   *        2.  INCIDENCE ANALYSIS       *') ;
     WRITELN ('   ***************************************') ;
     WRITELN ('      *  ENTER YOUR SELECTION  * ') ;
     WRITE   ('      *  HIT ANY DIGIT OTHER THEN 1 AND 2 TO END ') ;
     WRITELN (' ANALYSIS  *') ;
   END ;
(*****************************************************************)
(*  NAME :        AINTO                                          *)
(*  FUNCTION :    To display the options on the terminal and     *)
(*                  get the user's selection                     *)
(*  PROCEDURE CALLED :    ANEW                                   *)
(*****************************************************************)
  PROCEDURE AINTO ;
   BEGIN
     T := 'N' ;
     WHILE T <> 'Y' DO
       BEGIN
         ANEW ;     (*   call ANEW to display options    *)
         READLN ;
         READ (R) ;     (*    accept user's selection     *)
         WRITELN ('      <',R:1,'>   OK  ?   --- Y OR N') ;
         READLN ;
         READ (T)       (*    accept user's Y/N decision  *)
       END
   END ;
(*                                                           *)
(*    the main program of procedure ANALYSIS                 *)
(*                                                           *)
```

```
BEGIN
  AINTO ;          (*     call AINTO to display options          *)
                   (*          and get user's selection          *)
  WHILE (R>0) AND (R<3) DO
    BEGIN
      IF R=1 THEN REACHABILITY
             ELSE IF R=2 THEN INCIDENCE ;
      AINTO   (*  call AINTO to get next selection from user  *)
    END ;
    WRITELN('     ***************************************') ;
    WRITELN('     *          END  OF  ANALYSIS          *') ;
    WRITELN('     ***************************************')
  END ;
```