UNIVERSITY OF LA RIOJA

Security in Petri nets sharing and storage: subnets, privacy, integrity, authentication and non repudiation

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Declaration of Authorship

I, Iñigo LEÓN, declare that this thesis titled, 'Security in Petri nets sharing and storage: subnets, privacy, integrity, authentication and non repudiation' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.

- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

- Where I have consulted the published work of others, this is always clearly attributed.

- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

- I have acknowledged all main sources of help.

- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

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Date: July 2015

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Abstract

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Security in Petri nets sharing and storage: subnets, privacy, integrity, authentication and non repudiation

by Iñigo LEÓN

In this thesis I approach the study of Petri nets from the point of view of the security. There several goals in this thesis. First of all, I will define a subnetting process by building a framework of definitions and notations to create subnets from the original Petri net. Then, the creation of a PNML extension that allows the representation of subnets. In this work only the structure of the network is processed. The study of markings and properties of nets with hidden pieces will we analyzed in further works.

One application of this subnetting and PNML representation is the possibility of hiding part of a Petri net, facing a possible distribution, maintaining the privacy of the critical, secret, or complex parts of the system. However this hidden information is not eliminated from the net, but encrypted inside. Other application explained is the possibility of digital signature of subnets, providing security services to the net and/or subnets.

My original contribution to knowledge are:

1. Comprehensive study of subnets, abstracting their internal structure from the exterior by using front-ends. A method to build these subnets from the complete Petri net is explained and analyzed matrixed.

2. PNML has no way to represent subnets, so I approach a possible PNML extension to do it.

3. Subnetting and PNML extension to represents subnets allow to apply several security technics that offers encryption, data integrity, authentication and non repudiation

Acknowledgements

Thanks to my years of personal study and my curiosity for new knowledge, I fought to combine my job, my family and studies. I has been a difficult work, but the result has been worth it.

Thanks to my wife Nuria, and my daughters Valvanera and Blanca for putting up with me in my days of little sleep.

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Contents

List of Figures

Chapter 1

Introduction

1.1   Background of the research

Petri nets are widespread for modeling many classes of systems, such as manufacturing logistics processes and services [1, 2], concurrent systems [3], etc. However, all these nets are described in a comprehensive way and must have the information of the entire net to determine its evolution. Furthermore, these nets can be modified with no control of integrity or authoring, for example.

1.2   Research problem

The problem occurs when somebody doesn't want to describe the whole subnet. Or, maybe, is wanted one part of the process to be only accessible for one specific person or entity.

The first approach to solve this problem is to take two Petri nets:

- one Petri Net with only the public information, extracting the private data. This is an incomplete model of the process

- another Petri Net with the whole information for the interested person or entity.

As you can notice, this is not an efficient way to publish this kind of Petri Nets.

Other problem appears when I want to protect parts of the net from undesired modifications or ensure the authoring of some parts (or the whole net).

1.3 Justification of the research

It would be interesting to provide security to a Petri net:

- hiding a part of it. This can be useful, for example, distributing a process we want to be secret [4], or simply to be a part of the net to be complex and do not interest handle for any reason [4].

- avoiding not allowed changes in it (or a part of it).

- authenticating it (or a part of it). Useful to ensure who has developed a Petri net or subnet.

- avoiding the possibility of supplant other people in the authority of the Petri net or some of its parts.

So here is my contribution. I have researched the possibilities of hiding a part of a Petri Net so that everybody can access the public information, maintaining the secret of the private data. This private data is accessible only for authorized people. And not only that: I ensure data integrity, authentication and non repudiation to Petri nets or subnets.

Some authors study the possibilities of Petri nets reduction [5, 6, 7, 8, 9, 10], grouping in one place or transition a subnet, so that what happens on this subnet, is encapsulated in a single point of execution. However, we want to go further by defining parts of the net that are hidden (not clustered) and what are the implications, studied within network properties.

The main objective of this thesis is to extract parts (subnets) of a Petri net and provide them of wide security (privacy, integrity, authentication and non repudiation).

1.4 Methodology

In order to achieve this goal, I have defined three milestones:

1. Extend Petri Nets in order to define subnets, abstracting the internal structure from the the rest of the net using front-ends, focussing on hiding information.

2. Choose a lossless and extendible representation of this kind of Petri Nets

3. Define a hiding and signing method for this representation

For the first milestone, I work for the creation of the theoretical basis for further study of Petri nets in which certain parts are hidden. So we setup a generic framework of definitions and notations that allow us to deepen in the study of the characteristics and properties of Petri nets and their subnets [11, 12]. Also mention work already carried by other researchers in which we rely for our goal (i.e. [3, 13, 14, 15]). All of this will be necessary to create the framework that allows us to study occultation in Petri nets. We will expand the vision of Petri nets, providing them with greater functionality, such us attachable subnet.

The next step in this work is to choose (or define) a flexible representation of Petri nets that allows us to translate the previous extended nets. This representation has to be really extendible and flexible in order to be able to show actual and future characteristics of Petri nets. I can advance you that the selected representation is the standard PNML and I have to define and extension for it in order to represent subnets that are going to be secured.

Once selected this representation, the last step is the hiding and signing method(digital signature provide integrity, authentication and no repudiation services). Once more, I bet for standard protocols like XMLEncryption and XMLSignature.

This is a very basic investigation because I extend the very early definitions of Petri nets. Because of it, the results of this thesis is very probably extensible to any other development whose base are the classic Petri Nets. For example, I am not going to study colored Petri nets, neither timed Petri nets, etc. But it is very easy to see that the results achieved in this thesis can be applied to them with little problems.

1.5   Delimitations of scope and key assumptions

For this work we will always deal with ordinary and pure networks, unless otherwise expressly. This assumption is only for clarity reasons, because the protocols and methods described in this work are perfectly extensible to other kind of Petri nets, as long as these Petri nets are representable in PNML format.

Chapter 2

Literature review

In this chapter I am going to go over the ancient Petri net history. This work is a very basic investigation on Petri nets. This means that the most of the references are quite general.

For this literature review, I will follow the structure of this thesis:

1. First of all, I am going to describe some generalities of Petri nets as an introduction.

2. Then I will describe subnets and the process of subnetting (splitting Petri nets into several subnets). Some of the defined subnets (or the complete net) are going to be secured.

3. The next step is to explain some possible Petri net representations and my choice of PNML for the securizing process.

4. Once selected PNML, I am going to extend this language to support the subnets defined before.

5. The last step is the securing properly speaking. To do this, I will use the standard XMLEncryption for ciphering the secret information and XMLSignature for integrity, authentication and non repudiation.

2.1   Introduction. Petri nets

In the 60's, Carl Adam Petri invented a new way to describe distributed systems called Petri nets [16, 17, 18]. Many net theories are based on those works[19]. Nowadays, Petri nets are really extended to represent discrete systems [20, 21, 22, 23, 24]. There are lots of applications of Petri nets:

- Modelling of sequential processes[25], concurrent systems[26, 27], manufacturing [13, 28, 29, 30, 31], logistic processes [2], discrete event systems [32], ...

- Simulation of industrial applications [33, 34], logistic and production systems [1],...

This work is not about Petri nets applications, so I am not going to deepen this field. However I really mind the intrinsic structure of them. Since the definition of Petri nets, many authors investigated about them. The basic basis of my work are some of the best Petri net researchers of the world, who are included in this review:

- Murata, T [11, 35, 36]

- Silva, M [12, 31, 37]

- Peterson, JL [15]

And not only general Petri nets. Any kind of extensions are well received

- Lien [38]: Generalized Petri nets

- Jensen, K [3, 26, 39]: High level Petri nets, coloured Petri nets

- Silva [24, 40]: Continuous Petri nets

- Khomenko, V [41]: High level Petri nets

- Ratzer [42]: Coloured Petri nets

- Kristensen [27, 43]: Coloured Petri nets

- Silva [44]: Fluid Petri nets

- Latorre [22, 23]: Aggregation Petri nets and coloured Petri nets

- Campos [45]: Stochastic Petri net models

- Recalde [46]: Continuous Petri nets

- David [14]: Discrete, continuous and hybrid Petri nets

- Fraca [47]: Fluid and untimed Petri nets

- Vazquez [48, 49]: Stochastic continuous Petri nets and fluid Petri nets

The study of subnetting and securing of all of them are outside the scope of this work, but as all of these Petri nets extensions are reproducible by a graph, they are susceptible of applying the same described methods with light variations (like color, arc types, ...).

Several authors studied properties of Petri nets and they have been very useful as [50, 51, 52, 53, 54]. But they don't contribute in the main goal of my work. They are general references for the theoretical development.

Other sources are authors that studied general theory on structure of systems, such as Teruel [55] is.

But this work is not oriented towards studying all of these Petri net type. I want my work so general that it is easily exported to practically any kind of existing Petri nets or future Petri nets types that maybe are not defined still.

2.2   Subnets

The study of subnets is very ancient with general works by Silva [12, 31], Murata [11, 35] and Peterson [15]. All of them have been very useful for my preparation and they are the theoretical basics of my work. But there are other more specific works that study several aspects of subnets.

The first approach was presented by Valette [5], who studied the possibility and properties of replacing places or transitions by subnets. Suzuki (in collaboration with Murata) [6] continued it with a method for expanding and reducing Petri nets. Basically, they wanted to substitute places and transitions by subnet and viceversa, maintaining the properties of the net. Druzhinin (and Yuditskii) [8] completed these works explaining how to construct regular Petri nets from standard subnets. But basically it is an algorithm to replace places or transitions with well-formed Petri nets. My contribution in this field is the description of a way to replace subnets (not only places or transitions) with other subnets. Their work can be seen as a particular case of my description of macroplace an macrotrasition. However I don't deepen the properties because it is not my goal. This topic can be object of further investigations.

Other important works in this section are Fahmy's ones [7, 9]. At first sight (only reading the title), it seems to be the same I explain in the chapter 3. But this is not true. These two articles by Famhy are about the analysis of large Petri nets by cutting them into pieces. The second one [9] is and extension of the first one [7]. The idea is "divide and conquer" over the net. The partitioning of a net is useful because it preserves the properties of the original whole net. He centers the interest on the characteristics of the

net and the partitions. But he doesn't make an extensive study of subnets, that is what I do in my work. Basically, it is something like the previous paragraph: it can be seen as a particular case of my study.

Other work of interest is Hsieh' one [56], where he analyzes non-ordinary Petri nets for flexible assembly/disassembly processes based on structural decomposition, but it is not a net decomposition but a process decomposition. So it has no more interest for my work.

The last entrance in this section is the work of Xia [10]. His objective is to encapsulate a subnet in one place or transition. Then he study several ways of simplify that subnet or erasing redundant information. These subnets are grouped into a single point of execution. I want to go further by defining hidden (not grouped) parts of the net. However, this work has much to do with macroplaces and macrotransitions introduced in chapter 3.

2.3   Petri net representation

Other important question in this thesis is the election of a Petri net representation that allows us to translate defined subnets into that format in order to apply posterior operations over those subnets.

Apart from the general works of Petri nets named before introduced by Petri, Murata, Peterson and Silva [11, 12, 15, 16, 17, 18, 31, 35, 36, 37], there are other specific articles in this field:

- Hura [57] introduced the state space representation of Petri nets, but with no possibility of subnet representation

- Anishimov and Perchuk [58] in their work "Representation of exchange protocols and Petri using finite sequential machine nets" didn't do exactly what the title says. They used High level Petri nets in order to define interaction protocols between two objects. These protocols are seen as more precise formal languages. Definitely, nothing seemed to my goal.

- Das [59] defined the reflexive incidence matrix (RIM) representation of Petri nets, The possibilities of represent subnets in this case is basically the same as normal incidence matrices. So my method can be applied in the same way with this representation.

- Malyugin [60] worked in an arithmetical representation of Petri nets, but, as I said with Hura, there is no easy implementation of subnet representation. So this representation is not useful for my work.

- Kaushal [61] introduced a new formulation for state equation representation for Petri nets. The problem is the same as with Hura and Malyugin: no subnet representation.

- Kiritsis and Xirouchakis [62] defined a new matrix implementation of Petri nets for process planning. As it is matrix representation my method can be applied in the same way, as I said with Das.

2.4 PNML

PNML is a W3C standard for representation of Petri nets. Because of that, the main source of information is internet. In particular the official site `www.pnml.org` [63] has all the necessary information to work with it.

After several years of study, in 2004 the ISO/IEC 15909-1 [64] appeared to define conceptually and mathematically a xml representation of Petri nets: PNML [65]. It is explained in a less formal way by Billington [66].

So all the Petri nets that I am able to draw can be stored in PNML. Because of that, it is one of the most supported formats in almost every program that draw Petri nets.

PNML [63] is an implementation defined by the standard ISO/IEC 15909-2:2014 [67] that complement the anterior ISO/IEC 15909-1. The goal of this standard ISO is to define a transfer format of Place/Transition nets, High-level Petri nets and Symmetric nets. However, it is designed in such way that it can be easily extended, so that other versions of Petri nets can be supported later.

2.5 PNML extensions

There are ways to define these extensions in a graphical way, using eclipse as intermediate named ePNK, explained by Kindler [68] and Hillah [69]. Additionally, Moutinho [70] and Ribeiro [71] defined several PNML extensions for several kinds of Petri nets.

But this is not the main goal of my work. My intention is to describe the subnet extension in a theoretical way. Once described, it could be implemented with that kind of tools.

2.6   Securize information on Petri nets

There is very little literature about this topic (except my own work [4]). There are a couple of articles that seems to threat the theme, but with a deeper study we can see that the achievements are not what I am looking for.

Mahulea [72] point the problem of observability of timed CPNs, but not with the same meaning of my vision. His problem is that in determined circumstances it is difficult to estimate the initial/ actual state/marking of a Petri net. Anything like my work.

By his side, Saabori [73] approach the topic of hiding but not in Petri net structure, but in states of the Petri net. So it doesn't help.

Other work that at first sight may be interesting is one article from Velilla [74] that define a mechanism for safe implementation of concurrent systems. But this safety is for the process itself, not for the safety of the implementation. So it doesn't contribute to my work.

My intention is to securize part of a Petri net in two ways: hide and sign. The way to achieve this goal is cutting the net in subnets, represent them in PNML and then one or more of this goals:

- hide it.

- avoid unwanted changes.

- ensure identity of the custodian of the Petri net.

- avoid the impersonation of the custodian.

But there is not literature about the PNML representation for subnets, so this is new knowledge.

2.7   Security: XMLEncryption and XMLSignature

Both XMLEncryption and XMLSignature are W3C recommendations.

XMLEncryption is a way to cipher xml content. And not only that. Actually, it is a way to encrypt any kind of information and store it in xml format. In the same way, XMLSignature is a standard mode to sign xml or non xml content.

There are thousands of articles and applications of it, but, as they are W3C recommendation, they are completely defined. The last version of XMLEncryption and XMLSignature definition are [75, 76] respectively.

In this work, I apply these technologies in order to achieve the next goals

- Privacy: hide a entire or a part of a petri net.

- Integrity: nobody should modify concrete parts of a Petri net without being detected.

- Authentication: guarantee that nobody can impersonate another, for example stealing the creation of a Petri net or part of it.

- Non repudiation: ensure that nobody but a concrete person has done something in a Petri net (or part of it), for example, sign a Petri net.

In particular, encryption provides privacy and digital signature provides integrity, authentication and non repudiation.

My contribution to knowledge in this case is to mix two different knowledge areas as Petri nets and information security (encryption/digital signature) are.

So there are no literature about this topic, because nobody has developed it until I do.

Chapter 3

Private information in Petri nets. Subnets

3.1 Introduction

By default, a Petri net is described in a comprehensive and public way. In this chapter I am going to describe a way to declare private information of a Petri net. This information is candidate to be hidden, complying in this way with the goal of privacy. Furthermore, this theory can be applied afterwards in order to sign parts of a Petri net (subnets) achieving the objectives of integrity, authentication and non repudiation.

First of all I have to create a like framework of definitions, properties and methodologies in order to achieve this goal. The main idea is the concept of subnet an its interaction front-end.

Once defined this subnets, the Petri net can be divided into public and private chunks only by ordering the places and transitions in one subnet or another.

3.2 Petri subnets

3.2.1 Definitions and properties

Let P and T the non-empty finite sets of places and transitions of a Petri net, respectively. Let $|P| = n$ (the number of places of the net) and $|T| = m$ (number of transitions of the net). Let α and β pre and post incidence matrices respectively. Let $N = \langle P, T, \alpha, \beta \rangle$ be a Petri net and let C the incidence matrix of N

Definition 3.1 (Subnet [12])**.** A subnet of $N = \langle P, T, \alpha, \beta \rangle$ is a net $\overline{N} = \langle \overline{P}, \overline{T}, \overline{\alpha}, \overline{\beta} \rangle$ so that $\overline{P} \subseteq P$ y $\overline{T} \subseteq T$, $\overline{\alpha}$ y $\overline{\beta}$ are restrictions of α and β over $\overline{P} \times \overline{T}$.

In other words, a subnet is a subset of places and transitions together with the arches that connect them together.

Let's look at the implications of the latter definition since it is one of the most important with regard to this work.

A subnet corresponds [4, 12], in terms of matrices, with the resulting submatrix keeping only the rows and columns corresponding to places and transitions of the selected subnet.

Example 3.1. *Let's take the Petri net which has the following incidence matrix:*

$$
C = \begin{array}{c}
\\ p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6
\end{array}
\begin{array}{cccccc}
t_1 & t_2 & t_3 & t_4 & t_5 & t_6 \\
\left(\begin{array}{cccccc}
-1 & 0 & 1 & 0 & 0 & 0 \\
-1 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & -1 & 0 & 0 & 0 \\
0 & 1 & 0 & -1 & -1 & 1 \\
0 & 0 & 0 & 0 & 1 & -1
\end{array} \right)
\end{array}
$$

If we select the places p_1, p_3, p_4 and p_5 and transitions t_1, t_2, and t_6 we have the subnet defined by this incidence matrix

$$
C' = \begin{array}{c}
\\ p_1 \\ p_3 \\ p_4 \\ p_5
\end{array}
\begin{array}{ccc}
t_1 & t_2 & t_6 \\
\left(\begin{array}{ccc}
-1 & 0 & 0 \\
1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 1 & 1
\end{array} \right)
\end{array}
$$

by simply erasing p_2 and p_6 rows and t_3, t_4 and t_5 columns.

In [4] is shown that the set of all possible permutations of rows and/or columns of a matrix of incidence corresponding to a Petri net, either the pre or post incidence matrix, make an equivalence relation. In other words, given an incidence matrix, both rows and columns can be rearranged and this rearrangement describes exactly the original Petri net.

In this way, we can study the incidence matrices reordering rows and columns as preferred one at any time, without loss of generality.

$$
\begin{array}{c}
\quad\ \ t_1\ \ \ t_2\ \ \ t_3\ \ \ t_4\ \ \ t_5\ \ \ t_6 \\
\begin{array}{c}p_1\\p_2\\p_3\\p_4\\p_5\\p_6\\p_7\\p_8\end{array}
\left(\begin{array}{cccccc}
-1 & 0 & 1 & 0 & 0 & 0\\
-1 & 0 & 0 & 1 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & 0\\
1 & -1 & 0 & 0 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & 0\\
0 & 0 & -1 & 0 & 0 & 0\\
0 & 0 & 0 & -1 & -1 & 1\\
0 & 0 & 0 & 0 & 1 & -1
\end{array}\right)
\end{array}
\equiv
\begin{array}{c}
\quad\ \ t_1\ \ \ t_6\ \ \ t_3\ \ \ t_5\ \ \ t_4\ \ \ t_2 \\
\begin{array}{c}p_8\\p_1\\p_3\\p_6\\p_4\\p_5\\p_2\\p_7\end{array}
\left(\begin{array}{cccccc}
0 & -1 & 0 & 1 & 0 & 0\\
-1 & 0 & 1 & 0 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & -1 & 0 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & -1\\
0 & 0 & 0 & 0 & 0 & 1\\
-1 & 0 & 0 & 0 & 1 & 0\\
0 & 1 & 0 & -1 & -1 & 0
\end{array}\right)
\end{array}
$$

FIGURE 3.1: Two equivalent incidence matrices to describe the same Petri net

From all these definitions and proofs we can draw several trivial conclusions:

1. A subnet, like generic Petri net does not have to be square.

2. If a row or column of the incidence matrix of the subnet is all zeros, it doesn't mean that that place or that transition is isolated. This occurs only with pure nets. If there is an arc from one transition to a place and an arc from that place to the same transition with the same weight, the sum (the matrix element associated to that place/transition) is zero , but there are two arcs.

3. It does not matter the number of places and transitions that are chosen for the subnet, as long as they are not empty sets and have, at least one place and one transition. If it had only a place, it is a link place (there is an isolated row in the incidence matrix) and, if it had only a transition it would be a link transition (there is an isolated column in the incidence matrix).

3.2.2 Subnetting: splitting a net into subnets

Let $N = \langle P, T, \alpha\beta \rangle$ a Petri net where $|P| = n$ and $|T| = m$. So $P = \{p_1, p_2...p_n\}$ and $T = \{t_1, t_2...t_m\}$. Select two subsets $P' \subseteq P$ and $T' \subseteq T$ so that $|P'| = r \leq n$ and $|T'| = s \leq m$. With these premises divide into two subnets the original one.

We have seen that we can identify a subnet by simply removing rows and/or columns (places/transitions) of an incidence matrix. Taking advantage of the equivalence relation defined in [4], we reorder the incidence matrix so that places and transitions of the subnet are in the top-left. Without loss of generality, and for convenience, places and transitions can be renamed so that the incidence matrix is as follows:

$$
C = \begin{array}{c} \\ p_1 \\ \vdots \\ p_r \\ p_{r+1} \\ \vdots \\ p_n \end{array}
\begin{array}{ccccccc}
t_1 & \cdots & t_s & t_{s+1} & \cdots & t_m \\
\left(\begin{array}{ccc|ccc}
a_{11} & \cdots & a_{1s} & a_{1(s+1)} & \cdots & a_{1m} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
a_{r1} & \cdots & a_{rs} & a_{r(s+1)} & \cdots & a_{rm} \\
\hline
a_{(r+1)1} & \cdots & a_{(r+1)s} & a_{(r+1)(s+1)} & \cdots & a_{(r+1)m} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
a_{n1} & \cdots & a_{ns} & a_{n(s+1)} & \cdots & a_{nr}
\end{array}\right)
\end{array}
$$

We now have the net divided into two disjoint and complementary subnets. They are disjoint because there is no place and no common transition, and complementary because the union of the two we gives the complete net. At this point note that the incidence matrix is divided into four blocks $C = \begin{pmatrix} N_1 & PIM_{12} \\ TIM_{12} & N_2 \end{pmatrix}$. The interpretation is as follows:

- N_1 subnet made up of places $p_1..p_r$ and transitions $t_1..t_s$

- N_2 subnet that is complementary to N_1, made up of the places $p_{r+1}..p_n$ and transitions $t_{s+1}..t_m$

- PIM_{12} (Places Influence Matrix) is the matrix that defines the interaction of the N_1 places with N_2 transitions. Basically it is the matrix whose elements are those that are in the same rows of N_1 but outside of it (rows $1..s$ and columns $s+1..m$).

- TIM_{12} (Transitions Influence Matrix) is the matrix that defines the interaction of N_1 transitions with N_2 places. It is the matrix whose elements are in the same columns of N_1 elements but outside of it (rows $r+1..n$ and columns $1..s$).

We can notice that $PIM_{12} = TIM_{21}$ and $PIM_{21} = TIM_{12}$ by applying the definition.

This can be generalized to multiple disjoint and complementary subnets without further to re-apply the same process to any of the subnets already defined. Thus, generically we can divide a network into i subnetworks, so we'll have a matrix of this style:

$$
\left(
\begin{array}{ccc|ccc|c|ccc}
a_{11} & \cdots & a_{1s} & a_{1(s+1)} & \cdots & a_{1t} & & a_{1u} & \cdots & a_{1m} \\
\vdots & \mathbf{N_1} & \vdots & \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\
a_{p1} & \cdots & a_{ps} & a_{p(s+1)} & \cdots & a_{pt} & & a_{pu} & \cdots & a_{pm} \\
\hline
a_{(p+1)1} & \cdots & a_{(p+1)s} & a_{(p+1)(s+1)} & \cdots & a_{(p+1)t} & & a_{(p+1)u} & \cdots & a_{(p+1)m} \\
\vdots & \ddots & \vdots & \vdots & \mathbf{N_2} & \vdots & \cdots & \vdots & \ddots & \vdots \\
a_{q1} & \cdots & a_{qs} & a_{q(s+1)} & \cdots & a_{qt} & & a_{qu} & \cdots & a_{qm} \\
\hline
& \vdots & & & \vdots & & \ddots & & \vdots & \\
\hline
a_{r1} & \cdots & a_{rs} & a_{r(s+1)} & \cdots & a_{rt} & & a_{ru} & \cdots & a_{rm} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \cdots & \vdots & \mathbf{N_i} & \vdots \\
a_{n1} & \cdots & a_{ns} & a_{n(s+1)} & \cdots & a_{nt} & & a_{nu} & \cdots & a_{nm}
\end{array}
\right)
$$

In this situation, if we select two subnets N_j and N_k, we locate the zones of influence of each with respect to the other:

$$
\left(
\begin{array}{c|c|c|c|c}
\ddots & \cdots & \cdots & \cdots & \cdots \\
\hline
\vdots & SN_j & \cdots & PIM_{jk} = TIM_{jk} & \cdots \\
\hline
\vdots & \cdots & \ddots & \cdots & \cdots \\
\hline
\vdots & TIM_{jk} = PIM_{kj} & \cdots & SN_k & \cdots \\
\hline
\vdots & \vdots & \cdots & \vdots & \ddots
\end{array}
\right)
$$

Thus, the submatrix PIM_{jk} represents the arcs that connect places of the submatrix N_j with N_k transitions and the matrix TIM_{kj} represents the arcs that connect places of SN_k to SN_j transitions.

Notation. For simplicity, we will call

- PIM_i to all the elements in the same rows of N_i but outside of it.

- TIM_i to all the elements in the same columns of N_i but outside of it.

We can notice again that $PIM_{jk} = TIM_{kj}$ and $PIM_{kj} = TIM_{jk}$ by applying the definition.

Definition 3.2 (Partition of a Petri net into subnets). We say that a set $P = \{N_1 N_2 ... N_k\}$ is a partition into subnets of N if the following holds:

- $N_1 \cup N_2 \cup ... \cup N_k = N$

- $\forall i, j | 1 \leqslant i, j \leqslant k \Rightarrow N_i \cap N_j = \emptyset$ (pairwise disjointed)

3.2.3   Subnet classification

Depending on how each of the four pieces of matrix (N_1, N_2, PIM and TIM) are, we can see some special cases.

3.2.3.1   Disjoint subnets

Definition 3.3 (Disjointed subnet). Pure subnet said disjointed if there is no arc between its own places and transitions

Suppose that in the incidence matrix divided into the four pieces explained, are N_1 or N_2 be a null matrix. In this case the interpretation is that there arcs between places and transitions of the subnet, which would simply places and/or no transitions related to each other but with the additional subnetwork. Subnet talk then disjointed.

Proposition 3.4. *A subnet is disjoint iif its incidence submatrix is the null matrix.*

The demonstration is trivial.

Example 3.2. *Consider the next well-printed Petri net and its incidence matrix:*

$$
C = \begin{array}{c} \\ p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{array}
\begin{array}{cccc}
t_1 & t_2 & t_3 & t_4 \\
\left(\begin{array}{cccc}
-1 & 1 & 0 & 1 \\
1 & -1 & 1 & 0 \\
0 & 1 & -1 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1
\end{array} \right)
\end{array}
$$
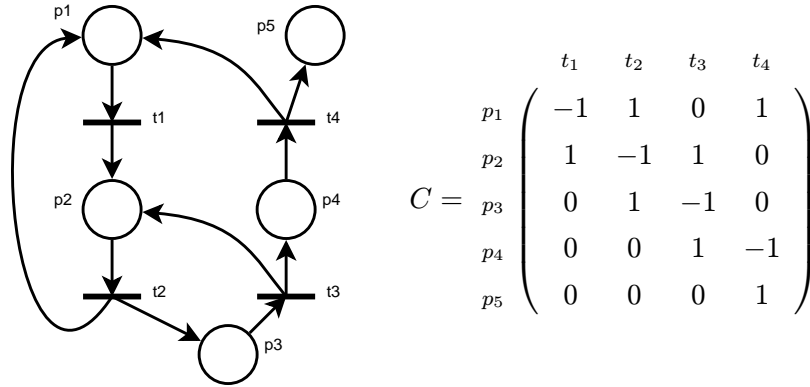
We assume that we select as subnet the one formed by 4th and 5th places and transitions 1 and 2. Then the graph and the incidence matrix are thus:

$$C = \begin{array}{c} \\ \\ p_4 \\ p_5 \\ \hline p_1 \\ p_2 \\ p_3 \end{array} \begin{array}{cc|cc} t_1 & t_2 & t_3 & t_4 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ \hline -1 & 1 & 0 & 1 \\ 1 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \end{array}$$
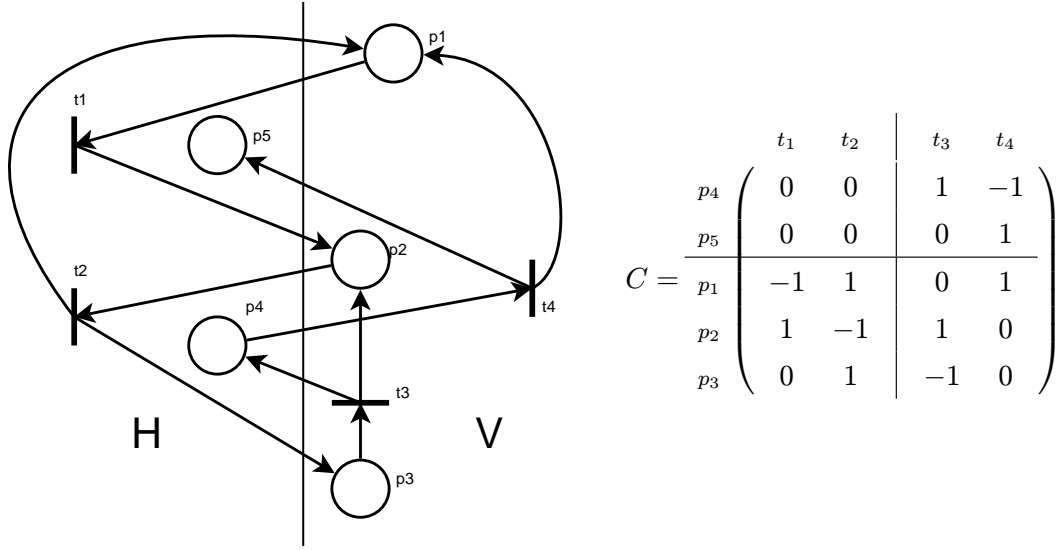
Here we can see that although really p_4, p_5, t_1 and t_2 are not isolated, there is no arc that connects them together. In the incidence matrix, the corresponding submatrix is the zero matrix. Therefore, whether or not there are elements isolated in the net, total subnet formed by p_4, p_5, t_1 and t_2 is a disjointed subnet.

We can extend this definition to a subnet that is part of a bigger net. It doesn't matter in how many subnets it is separated: if one subnet is the null matrix, this subnet is disjointed. This characteristic is implicit to the selected subnet and it doesn't depend on the rest of the net.

3.2.3.2   Macroplace

Once subnet concept is introduced, we can classify them by some properties. In this case, a subnet which behaviour is like a place, relating only to transitions can be defined as macroplace.

Definition 3.5 (Macroplace). A macroplace is a subnet that meets the following:

1. arcs entering any node of the subnet from an external node come from a transition.

2. arcs leaving any node on the subnet to an external node go to a transition.

Proposition 3.6. *A subnet N_1 is a macroplace iif its transitions influence matrix (TIM) is the null matrix. In the same way, N_2 is a macroplace iif its places influence matrix (PIM) is the null matrix*

$$N_1 \ is \ macroplace \iff \forall a_{ij} \in TIM_1, a_{ij} = 0$$

$$C = \begin{array}{c} \\ p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{array} \begin{array}{cccc} t_1 & t_2 & t_3 & t_4 \\ \left(\begin{array}{c|ccc} -1 & 1 & 0 & 1 \\ 1 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{array} \right) \end{array}$$
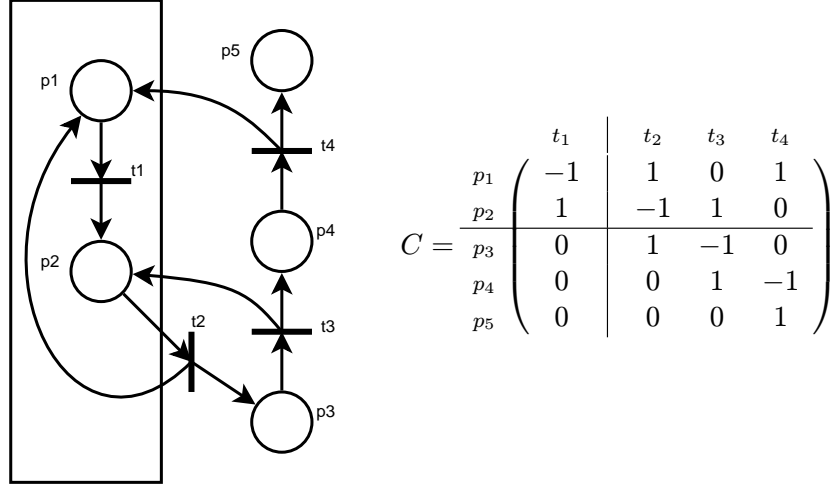
FIGURE 3.2: Macroplace

$$N_2 \ \text{is macroplace} \iff \forall a_{ij} \in PIM_1, a_{ij} = 0$$

The demonstration is trivial.

Suppose that the incidence matrix divided into the four pieces explained, TIM appears to be the zero matrix. Then we conclude that the subnet N_1 is only related by arcs with places of subnet N_2. All arcs entering N_1 come from transitions of N_2 and all arcs coming out from N_1 go to transitions of N_2. Stated another way, the subnet N_1 behaves like a place, but may contain places and transitions.

Note that this is not really a place, and that the subnet has not marked as such. The marking is on the places within the subnet and depends on the arches of arrival.

Example 3.3 (Macroplace). *If we take the figure 3.2 we can see that the subnet inside the rectangle N_1 is related to the rest of the net only through transitions, it is to say, there is no arc from an external place or from an internal transition. Furthermore, TIM_1 is the null matrix. So this subnet is a macroplace.*

We can extend this definition to a subnet that is part of a bigger net too. However, in this time, it does matter the way in which the bigger net is separated. This characteristic is not implicit to the selected subnet and depends on the rest of the net.

3.2.3.3   Macrotransition

In the same way as macroplaces, a subnet which behaviour is like a transition, relating only to places can be defined as macrotransition.

Definition 3.7 (Macrotransition)*.* A macrotransition is a subnet that meets with the following:

1. arcs entering any node of the subnet from an external node come from a place.

2. arcs leaving any node on the subnet to an external node go to a place.

Proposition 3.8. *A subnet N_1 is a macrotransition iif its places influence matrix (PIM) is the null matrix. In the same way, N_2 is a macrotransition iif its transitions influence matrix (TIM) is the null matrix*

$$N_1 \ is \ macrotransition \iff \forall a_{ij} \in PIM_1, a_{ij} = 0$$

$$N_2 \ is \ macrotransition \iff \forall a_{ij} \in TIM_1, a_{ij} = 0$$

The demonstration is trivial

This is other option that can happen is that in the incidence matrix: PIM appears to be the zero matrix. Then we conclude that the subnet N_1 is only related by arcs with places of subnet N_2. All arcs entering N_1 come from places of N_2 and all arcs coming out from N_1 go to places of N_2. Stated another way, the subnet N_1 behaves like a transition, but may contain places and transitions.

Like macroplaces, macrotransitions are not transitions as such. It is not necessary that all entries are marked to fire the macrotransition, and not all output places are marked after entering it. Everything depends on the inner workings of the macrotransition.

Example 3.4 (Macrotransition)*. If we take the figure 3.3 we can see that the subnet inside the rectangle N_2 is related to the rest of the net only through places, it is to say, there is no arc from an external transition or from an internal place. Furthermore, TIM_1 is the null matrix. So this subnet is a macrotransition.*

We can extend this definition again to a subnet that is part of a bigger net too. Like with macroplaces, it does matter the way in which the bigger net is separated.

3.2.3.4 Sinkhole subnet

Another thing that can happen is that arrive only arcs to the selected subnet. Then we find that you can not leave the subnet. We speak then of a sinkhole subnet.

Definition 3.9 (Sinkhole subnet)*.* It is said that a subnet is a sinkhole subnet if no arc has its origin in an internal node (place or transition) of the subnet.

$$C = \begin{array}{c|ccc} & t_1 & t_2 & t_3 & t_4 \\ \hline p_1 & -1 & 1 & 0 & 1 \\ p_2 & 1 & -1 & 1 & 0 \\ p_3 & 0 & 1 & -1 & 0 \\ p_4 & 0 & 0 & 1 & -1 \\ p_5 & 0 & 0 & 0 & 1 \end{array}$$

FIGURE 3.3: Macrotransition

It is easy to see that a subnet is sinkhole if and only if all elements of PIM are greater or equal to zero and all elements of TIM are less than or equal to zero.

$$N_1 \text{ is sinkhole } \iff \forall a_{ij} \in PIM_1, a_{ij} \geq 0 \wedge \forall a_{pq} \in TIM_1, a_{pq} \leq 0$$

The demonstration is trivial

Example 3.5 (Sinkhole Subnet). *If we have a look to the figure 3.4, we can see that there is no arc leaving the subnet N_1 defined by the rectangle. Furthermore, $\forall a_{ij} \in PIM_1, a_{ij} \geq 0 \wedge \forall a_{pq} \in TIM_1, a_{pq} \leq 0$, so we have a sinkhole subnet.*

If we can extend this definition to a subnet that is part of a bigger net, in this case, it does matter the way in which the bigger net is separated. This characteristic is not implicit to the selected subnet and depends on the other subnets.

3.2.3.5   Source subnet

If instead of this what happens is no arc gets into the subnet, we have a source subnet. In a source subnet we can not enter.

Definition 3.10 (Source subnet). It is said that a subnet is a source subnet if no arc has its destination in an internal node (place or transition) of the subnet.
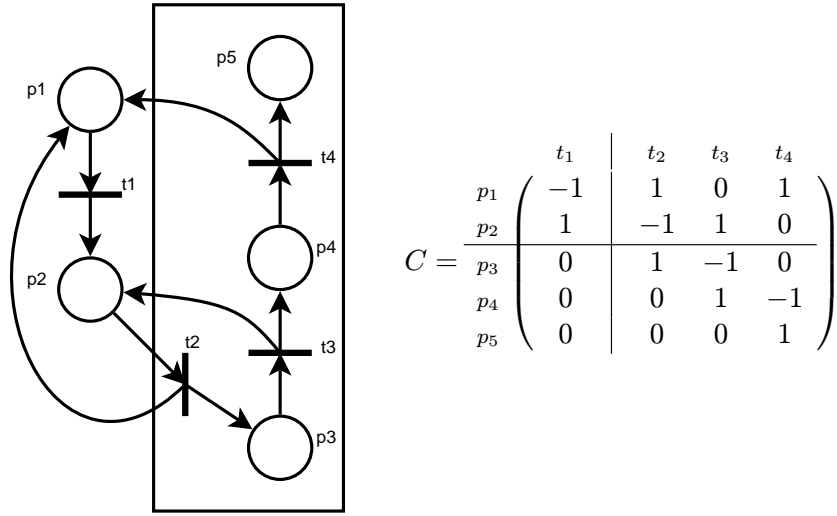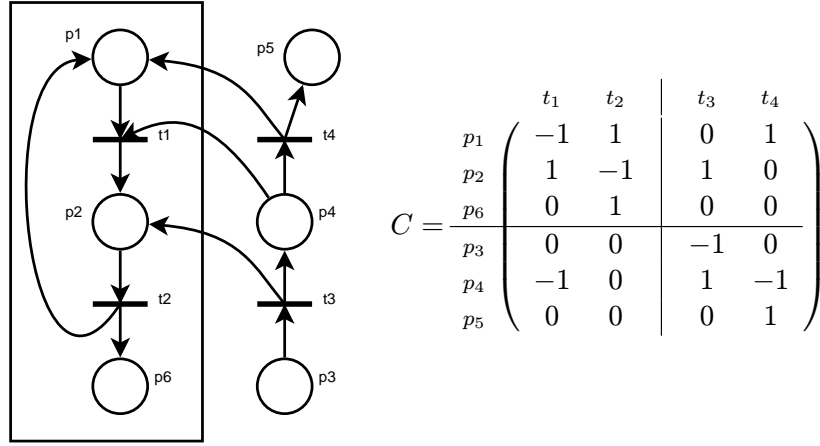
FIGURE 3.4: Sinkhole subnet

$$C = \begin{array}{c} \\ p_1 \\ p_2 \\ p_6 \\ p_3 \\ p_4 \\ p_5 \end{array} \begin{array}{cc} t_1 \quad t_2 \end{array} \begin{array}{cc} t_3 \quad t_4 \end{array} \left(\begin{array}{cc|cc} -1 & 1 & 0 & 1 \\ 1 & -1 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 0 & -1 & 0 \\ -1 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{array} \right)$$

FIGURE 3.5: Source subnet

$$C = \begin{array}{c} \\ p_3 \\ p_4 \\ p_5 \\ p_1 \\ p_2 \\ p_6 \end{array} \begin{array}{cc} t_3 \quad t_4 \end{array} \begin{array}{cc} t_1 \quad t_2 \end{array} \left(\begin{array}{cc|cc} -1 & 0 & 0 & 0 \\ 1 & -1 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 1 & -1 & 1 \\ 1 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{array} \right)$$
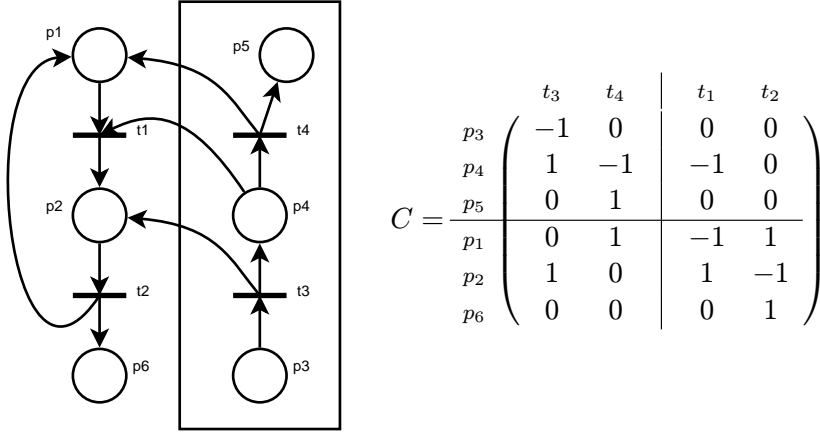
It is easy to see that a subnet is source if and only if all elements of TIM are greater than or equal to zero and all elements of PIM are less than or equal to zero.

$$N_1 \text{ is source} \iff \forall a_{ij} \in TIM_1, a_{ij} \geq 0 \wedge \forall a_{pq} \in PIM_1, a_{pq} \leq 0$$

The demonstration is trivial

Example 3.6 (Source Subnet). *In the same way that with the sinkhole subnet explained before, if we take the figure 3.5 we can see that the subnet N_1 inside the rectangle has no arc leaving it and $\forall a_{ij} \in TIM_1, a_{ij} \geq 0 \wedge \forall a_{pq} \in PIM_1, a_{pq} \leq 0$ so we have a source subnet.*

3.2.4 Matrix parts description once defined the subnets

As places and transitions can be reordered smoothly, we study a network N divided into 2 subnets, for simplicity and without loss of generality. At this moment I am going to study several topic in order to approach privacy, by hiding a subnet. For consistency with [4] we will follow this notation:

$$\left(\begin{array}{c|c} H & HP \\ \hline HT & V \end{array} \right)$$

where

- H (Hidden Subnet) is the subnet wanted to be hidden.

- V (Visible Subnet) is the subnet that is visible.

- HT (Hidden Transitions Submatrix) are the relationships between places of V and H transitions

- HP (Hidden Places Submatrix) are the relations between transitions of V and H sites

Note. Following this notation can be convenient because it is clear what is each of the submatrices. However, elsewhere in the document be referenced as N_1 and N_2 for be more clarifying or being something generic and independent networks concealment. However, using N_1 and N_2 the notation of subnets of influence with respect to the other is more diffuse.
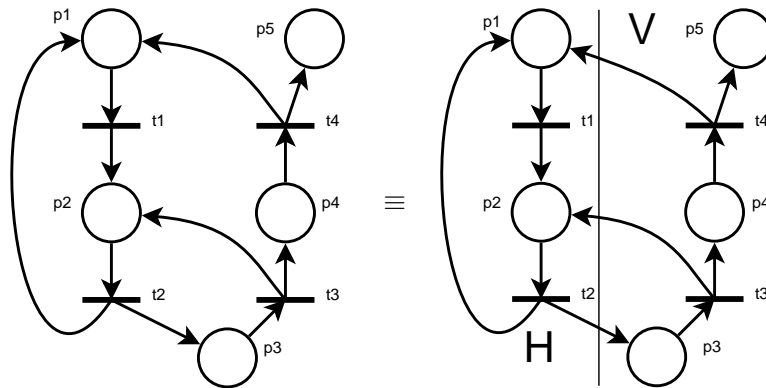

FIGURE 3.6: Selecting subnet to hide

Example 3.7. *Consider the Petri net of the figure 3.6 with the next incidence matrix:*

$$
\begin{array}{c}
\begin{array}{cccc} t_1 & t_2 & t_3 & t_4 \end{array} \\
\begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{array}
\left(
\begin{array}{cccc}
-1 & 1 & 0 & 1 \\
1 & -1 & 1 & 0 \\
0 & 1 & -1 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1
\end{array}
\right)
\end{array}
$$

The subnet we want to hide is formed by places p_1 and p_2 and transitions t_1 and t_2. Graphically, separate places and transitions to hide (H) from the rest of the network (V)

The incidence matrix is already sorted by the places and transitions to the top of it. Here are the four parts described above.

$$
\begin{array}{c}
\begin{array}{cccc} t_1 & t_2 & t_3 & t_4 \end{array} \\
\begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{array}
\left(
\begin{array}{cc|cc}
-1 & 1 & 0 & 1 \\
1 & -1 & 1 & 0 \\
\hline
0 & 1 & -1 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1
\end{array}
\right)
\end{array}
$$

In this matrix we can see:

- $H = \begin{array}{c} \begin{array}{cc} t_1 & t_2 \end{array} \\ \begin{array}{c} p_1 \\ p_2 \end{array} \left(\begin{array}{cc} -1 & 1 \\ 1 & -1 \end{array} \right) \end{array}$ *is the subnet we want to hide. It is the same as N_1*

- $V = \begin{array}{c} \begin{array}{cc} t_3 & t_4 \end{array} \\ \begin{array}{c} p_3 \\ p_4 \\ p_5 \end{array} \left(\begin{array}{cc} -1 & 0 \\ 1 & -1 \\ 0 & 1 \end{array} \right) \end{array}$ *is the subnet that is visible. It is the same as N_2*

- $HP = \begin{array}{c} \begin{array}{cc} t_3 & t_4 \end{array} \\ \begin{array}{c} p_1 \\ p_2 \end{array} \left(\begin{array}{cc} 0 & 1 \\ 1 & 0 \end{array} \right) \end{array}$ *are the relationships between transitions of V and H places.*
  It is the equivalent to PIM_1 or TIM_2

$$
\bullet \ HT = \begin{array}{c} \\ p_3 \\ p_4 \\ p_5 \end{array} \begin{array}{cc} t_1 & t_2 \\ \left(\begin{array}{cc} 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{array} \right) \end{array} \ \text{are the relationships between places of } V \text{ and } H \text{ transitions.}
$$

It is the equivalent to TIM_1 or PIM_2

At this moment, it is easy to see that we can choose any subset of places and transitions in order to hide it, simply reordering rows and columns.

Example 3.8. In the previous example we have seen a fairly simple option selection subnet and we have chosen the place p_1 and p_2 and transitions t_1 and t_2. However, we can choose any other subset of places and transitions. In this example we will select places p_2, p_3 and p_5 and the transitions t_1 and t_3. Thus, in the graph of the previous example move the locations and transitions to hide on one side and the rest on the other.
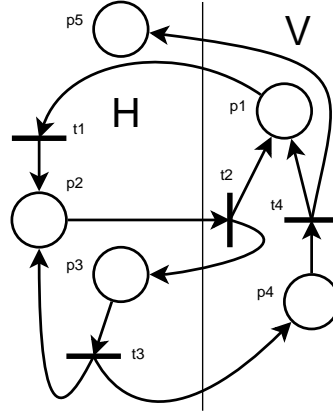
Although more confusing, can be seen that the graph is the same as the incidence matrix is the same (not just part of the equivalence class, it is exactly the same). Now, in this matrix move places p_2, p_3 and p_5, and transitions t_1 and t_3 at the beginning of the matrix:

$$
\begin{array}{c} \\ p_2 \\ p_3 \\ p_5 \\ p_1 \\ p_4 \end{array}
\begin{array}{ccc|cc}
t_1 & t_3 & & t_2 & t_4 \\
\left(\begin{array}{cc} 1 & 1 \end{array} \right. & & & \left. \begin{array}{cc} -1 & 0 \end{array} \right) \\
\end{array}
$$

	t_1	t_3	t_2	t_4
p_2	1	1	−1	0
p_3	0	−1	1	0
p_5	0	0	0	1
p_1	−1	0	1	1
p_4	0	1	0	−1

Interpreting each of the chunks of the matrix is similar to the previous example.

3.2.5 Front-end interaction with the subnet. Input and output functions

Once you have defined all this environment, we will try to go a little further. Let's assume that we want to export a subnet we have hidden in another network, like a black box. Our intention is to connect this hidden network to another network, and can thus be reused subnets. For example, let's assume that we have a process modeling with Petri net modeling and in this there is a subnet we want to hide, but, at the same time, we want to reuse it in other Petri nets.

In this case we have a problem, and once hidden network disappears half the information input or output arcs of the same. In particular, we do not know the source nodes and arcs that leave the target nodes of the arcs that enter the network until no visible again. But if we want to reuse it on other networks, can not wait to make it visible. Should remain hidden, but should be able to connect to other networks.

We will try to solve this problem. This way we can reuse hidden networks like plug-in modules on other networks. However, we will not need the actual implementation of the source or destination nodes of the arcs that leave or enter the network, respectively. The solution is to define a facade or front-end input and output of the network. This front-end will contain the information needed to interact with the network hidden, but hide the specifics of implementation. To define this behavior going from some assumptions.

3.2.5.1 Previous definitions

Let $N = \langle P, T, \alpha, \beta \rangle$ be a Petri net and let $P = \{N_1, N_2\}$ be a partition of N.

Definition 3.11 (Input place). Let p_i a place of N_1. p_i is an input place of N_1 if it is the destination of an arc coming from a N_2 transition, ie,

$$p_i \text{ is an input place of } N_1 \text{ if } \exists t_j \in N_2 \mid c_{ij} > 0$$

Definition 3.12 (Input transition). Let t_i a transition of N_1. t_i is an input transition of N_1 if it is the destination of an arc coming from a N_2 place, ie,

$$t_i \text{ is an input transition of } N_1 \text{ if } \exists p_j \in N_2 | c_{ji} < 0$$

Definition 3.13 (Input node). An input node of N_1 is an input place or transition of N_1.

Definition 3.14 (Output place). Let p_i be a place of N_1. p_i is an output place of N_1 if an arc leaves it towards a transition of N_2, ie,

$$p_i \text{is an output place of } N_1 \text{ if } \exists t_j \in N_2 | c_{ij} < 0$$

Definition 3.15 (Output transition). let t_i be a transition of N_1. t_i is an output transition of N_1 if an arc leaves it towards a place of N_2, ie,

$$t_i \text{ is an output transition of } N_1 \text{ if } \exists p_j \in N_2 | c_{ji} > 0$$

Definition 3.16 (Output node). An output node of N_1 is an output place or transition of N_1.

After defining these concepts, we can define the sets thereof.

Notation. We denote the sets of the elements defined above:

- Let $IP(N) \subseteq \overline{P}$ (Input Places) be the set of input places of a subnet.
- Let $IT(N) \subseteq \overline{T}$ (Input Transitions) be the set of input transitions of a subnet.
- Let $IN(N) \subseteq \overline{P} \cup \overline{T}$ (Input Nodes) be the set of input nodes of a subnet.
- Let $OP(N) \subseteq \overline{P}$ (Output Places) the set of output places of a subnet.
- Let $OT(N) \subseteq \overline{T}$ (Output Transitions) be the set of output transitions of a subnet.
- Let $ON(N) \subseteq \overline{P} \cup \overline{T}$ (Output Nodes) be the set of output nodes of a subnet.

Note. Recall that a node in a Petri net can be both a place and a transition, depending on the context.

Notation. Denote as n_i to a node of a Petri net.

As we have generic definitions, no problem in applying to a network divided into H, V, HN and HT, as the set $\{H, V\}$ is a partition of N.

3.2.5.2 Subnet Front-end

Once all these concepts, we create the front-end input/output of a Petri subnet. A front-end of the Petri net will be a intermediate facade that allows us to physically divide that subnet from the rest of the net. Thus, in order to enter or leave the subnet, you need to make it through this front-end.

Let IA (input arcs) the set of arcs that enter the subnet N_1 and let OA (output arcs) the set of arcs leaving N_1.

The matrix shown in the figure:
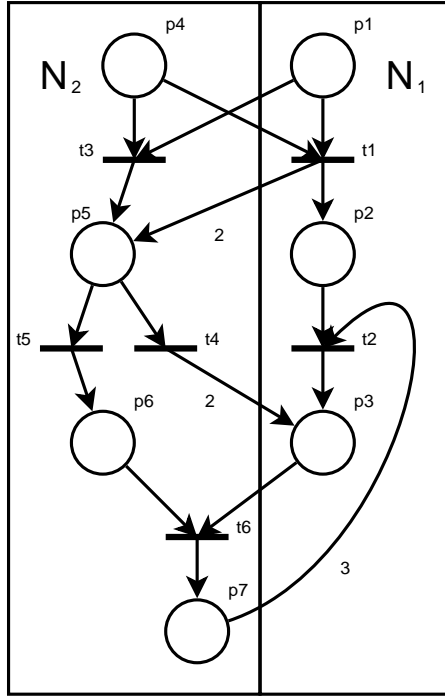
$$C = \begin{array}{c|cc|cccc} & t_1 & t_2 & t_3 & t_4 & t_5 & t_6 \\ \hline p_1 & -1 & 0 & -1 & 0 & 0 & 0 \\ p_2 & 1 & -1 & 0 & 0 & 0 & 0 \\ p_3 & 0 & 1 & 0 & 2 & 0 & -1 \\ \hline p_4 & -1 & 0 & -1 & 0 & 0 & 0 \\ p_5 & 2 & 0 & 1 & -1 & -1 & 0 \\ p_6 & 0 & 0 & 0 & 0 & 1 & -1 \\ p_7 & 0 & -3 & 0 & 0 & 0 & 1 \end{array}$$

FIGURE 3.7: Subnets with input and output nodes

Definition 3.17 (Input gate of a net). Let $a_i \in IA$ an arc of entrance to N_1. We define an input gate to N_1, and denote by ig_i, as a new logical node that is identified with an arc of entrance to the net. For each input arc, defines an input gate with the same weight, regardless of the origin and destination of the arc. If the source is a transition, we denote igt_i and if a place, igp_i.

Definition 3.18 (Output gate of a net). Let $a_i \in OA$ output arc N_1. We define an output gate of N_1, and denote by og_i, as a new logical node that is identified with an exit arc of the net. For each exit arc is defined an output gate with the same weight, regardless of the origin and destination of the arc. If the source is a transition, we denote ogt_i and if it is a place, ogp_i.

In this way we can divide the input arcs and output into two parts: a N_1 internal and external to N_1. If we take an arc of entrance a_i that has an origin in n_j and destination in n_k, we define an input gate through a point of entry so that the original arc a_i is divided into two parts.

- a_{i1} (external to N_1) with origin in n_j and destination in igt_i or igp_i depending on if n_j is a transition or a place, and the same weight as the input gate.

- a_{i2} (internal to N_1) with destination in igt_i or igp_i depending on if n_j is a transition or a place respectively, and the same weight as the input gate.

Similarly, if we take an exit arc a_i that has an origin in n_k and destination in n_j, we define an output gate og_i so that the original arc a_i is divided into two parts:

- a_{i1} (internal to N_1) with origin in n_k and destination in ogt_i or ogt_i depending on if n_j is a transition or a place, and the same weight as the output gate.

- a_{i2} (external to N_1) with destination in n_j and origin in igt_i or igp_i depending on if n_j is a transition or a place respectively, and the same weight as the output gate.

Example 3.9. *Consider the net in figure 3.7. In this network we have three arcs entering and three arcs leaving. For each of those that leave, I define output gates and for each coming one, we define input gates. The weight of each gate (if it is different than 1) is placed in a little square inside. The subnet N_1 becomes:*
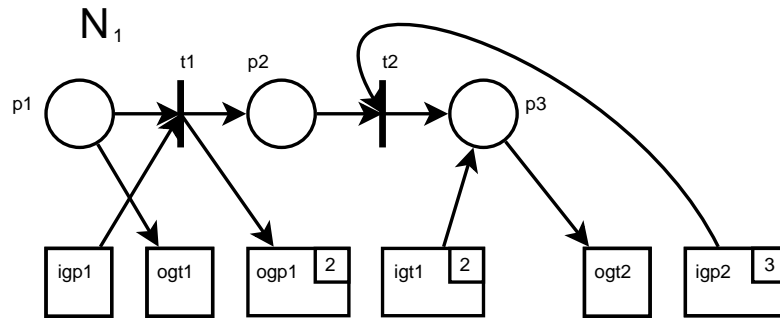
and in the complete net, arcs entering and leaving are divided into two pieces:
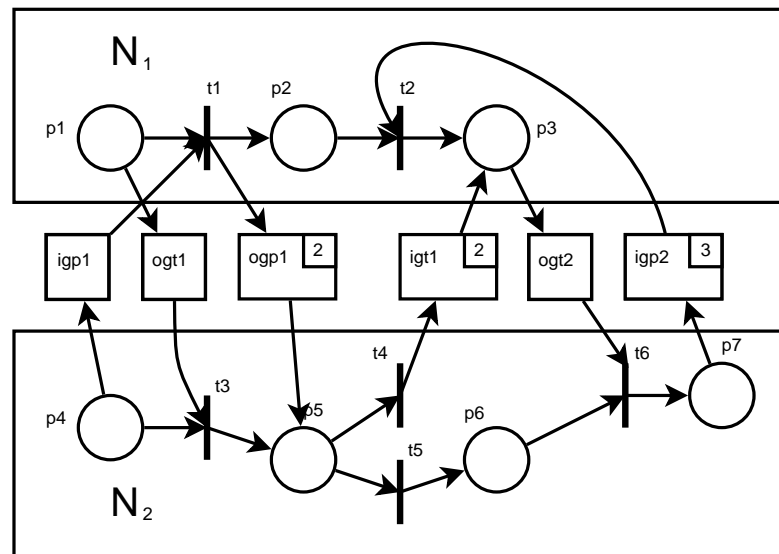
Definition 3.19 (Input Front-end of a net). The input front-end (or input interface) of a subnet N_1 is the set of all input gates of N_1. We denote by IF of N_1.

Definition 3.20 (Output Front-end of a net). The output front-end (or output interface)of a subnet N_1 is the set of all output gates of N_1. We denote by OF of N_1.

Definition 3.21 (Front-end of a net). The front-end (or interface) of a net N_1 is the pair of IF and OF of N_1. We denote by F of N_1.

$$F = \langle IF, OF \rangle$$

Example 3.10. *Taking the net of the example 3.9 and applying these new definitions, we would have N_1 net along with its front-end as shown in Figure 3.8.*
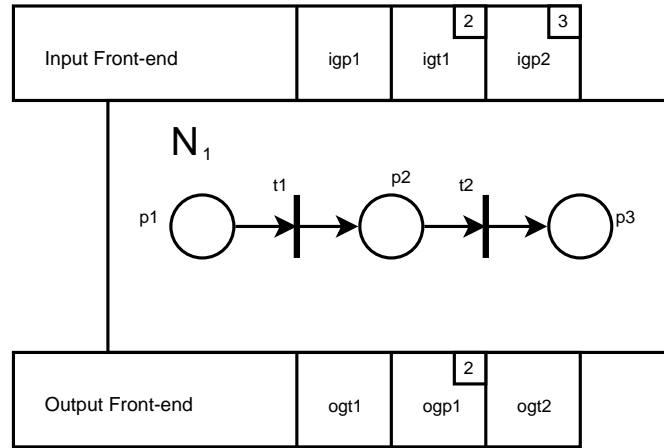
FIGURE 3.8: Net Front-end

3.2.5.3   Input/output functions

Once all these input and output concepts defined, we will introduce a few key concepts for our purpose.

Let N a Petri net and let $\{N_1, N_2\}$ a partition of N. Let $F = \langle IF, OF \rangle$ the front-end of N_1.

Definition 3.22 (Petri net Input function). We define the input function f_i of N_1 as:

$$f_i : F \longrightarrow IN$$

such that for each input gate igt_i you mapped one or no input place N_1 and each input gate igp_j you mapped one or no input transition N_1.

Definition 3.23 (Petri net Output function). We define the output function f_o of N_1 as:

$$f_o : ON \longrightarrow F$$

such that each output place N_1 you mapped one or no output gate ogt_i of N_1 and each output transition N_1 you mapped one or no output gate ogp_j to N_1

The input function can be defined for all the input gates and the output function should be surjective because if not, some door would not be connected. Anyway that is not essential. If a front-end door is not connected with any element of your network, simply by solving the final network, the arcs connected to that door disappear. Note also that the input function is not necessarily injective: Multiple input gates can be associated to the same node of N_1.

Example 3.11. *Consider the net N_1 in figure 3.7 with its front-end in figure 3.8. The input and output functions are:*

- *Input function:* $\dfrac{F \quad\begin{array}{ccc} igp_1 & igt_1 & igp_2 \end{array}}{IN \quad\begin{array}{ccc} t_1 & p_3 & t_2 \end{array}}$

- *Output function:* $\dfrac{ON \quad\begin{array}{ccc} p_1 & t_1 & p_3 \end{array}}{F \quad\begin{array}{ccc} ogt_1 & ogp_1 & ogt_2 \end{array}}$

3.2.5.4   Attachable net

By joining the subnet R_1 along with its front-end and its input and output functions f_i and f_o we grouped both the internal network with external communication. This way we can "extract" a subnet and "implant" it in another net. You only need this destination network is to communicate with the front-end. So naturally appears the following definition.

Definition 3.24 (Attachable Petri net). An Attachable Petri net is a quadruple $R_a = \langle R, F, f_i, f_o \rangle$

From these definitions, it is clear that you can create attachable subnets taking a subnet of another given and applying the whole process we have defined. But it is also possible to create from scratch, starting from a network, defining a front-end for that network and declaring the input and output functions. So you can create Petri nets modules providing functionality and out through a front-end without requiring the actual implementation.

Example 3.12. *The attachable net in figure 3.7 would be the next:*
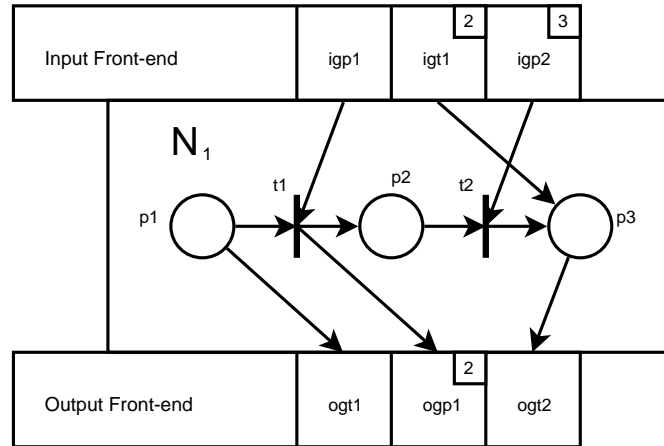
It can be seen as a private black box with visible input and output connectors that are "plugged" to other networks. In a attachable net, the private part would be N_1, f_i and f_o. The public part of the front-end would be F. All a net need to know is the input/output front-end.

A utility of these nets is that its definition is simple, since only the front-end is needed to define its operation. This makes possible to create nets using attachable nets in certain areas where they do not know their actual implementation, but its behavior. Additionally, it is possible to use different implementations of "network providers" of the same attachable nets, using at each moment the most appropriate one.

Example 3.13. *Consider now the following Petri net*
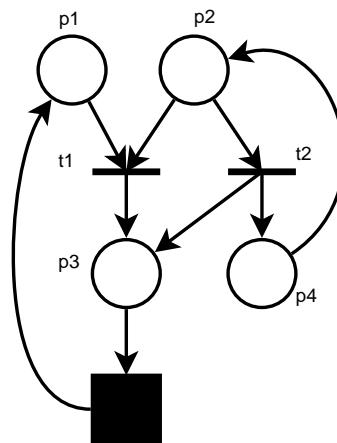
to which we want to connect an attachable net in the black box. Let's assume we have
two equivalent alternatives described in Example 3.16:
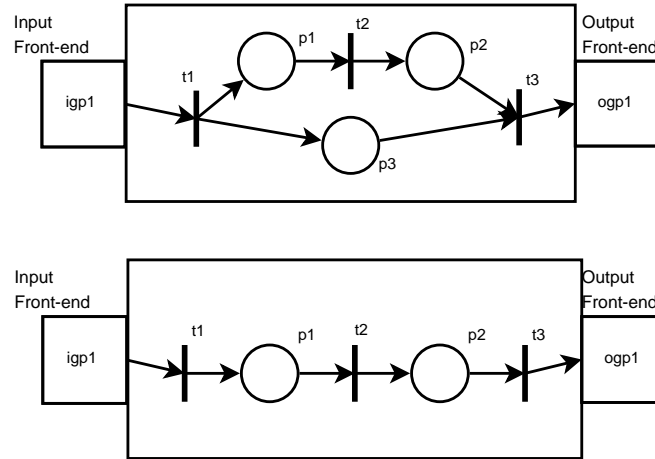
We Can "plug" either because their front-ends are equivalent and remains in figure 3.9.
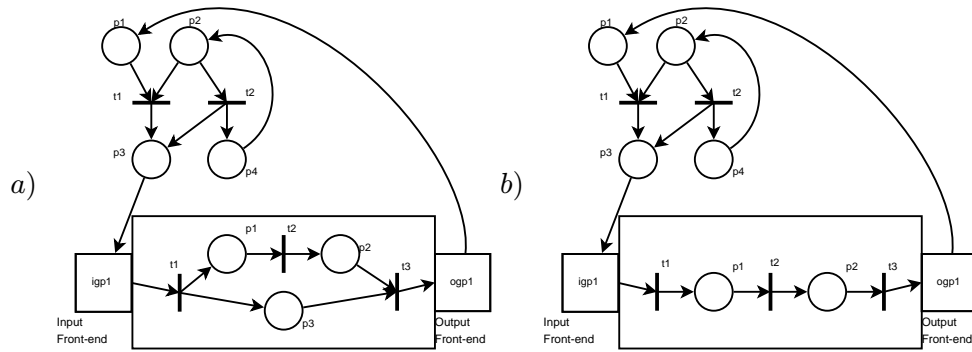
FIGURE 3.9: Two different implementations of attachable nets

In this case, the behavior of the net will be the same, but does not have to be. That will
decide who connects nets. For example, you could create a "foo" net that does nothing
at first and replace it later by the real one.

3.3   Private information. Hiding a subnet

Once we have defined subnets and front-ends we can select one of them to securize it
by hiding. We proceed to the occultation as such [4]. Graphically, it seems simple.
Just replace the subnet to hide by a black box and modify some arcs according to the
following rules:

1. The arcs originating in a place or transition within the black box, and target a place or transition out of it will have the black box as the source.

2. The arcs originating in a place or transition out of the black box, and target a place or transition within it, are replaced by the black box as a destination.

Example 3.14. *We consider the Petri net of the Figure 3.6. The result of hiding the part of the graph H is the following:*
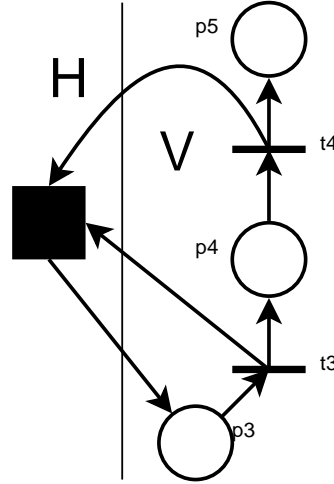
In the associated incidence matrix also replace the H elements by a black box:

$$
\begin{array}{c}
\quad\;\; t_1 \quad t_2 \;\;\bigm|\;\; t_3 \quad t_4 \\
\begin{array}{c} p_1 \\ p_2 \\ \hline p_3 \\ p_4 \\ p_5 \end{array}
\left(\begin{array}{cc|cc}
\blacksquare & \blacksquare & 0 & 1 \\
\blacksquare & \blacksquare & 1 & 0 \\
\hline
0 & 1 & -1 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1
\end{array}\right)
\end{array}
$$

However, in this matrix notation is given information should also be hidden: it gives us information about the number of places and transitions of the hidden subnet, besides indicating hidden places and transitions with which it interacts. To solve this problem we proceed as follows. We can group all rows for the screened subnet into one. In each row position examine all elements of the original rows corresponding to that position, and will put:

- If all these elements are zero, in the grouped row will be a zero.

- If one and only one of those elements is nonzero, will put that item.

- If there are several non-zero elements, we will post a list of these items separated by commas, creating a d-dimensional element (in d dimensions).

In the same way we have done with the rows, proceed with columns. Thus, if the hidden subnet has i columns and j rows, we will get a matrix like this:

$$\begin{pmatrix} \begin{array}{c|ccc} \blacksquare & a_{1(i+1)} & \cdots & a_{1m} \\ \hline a_{(j+1)1} & & & \\ \vdots & & V & \\ a_{n1} & & & \end{array} \end{pmatrix}$$

where $\forall p, \forall q | i + 1 \le p \le m \wedge j + 1 \le q \le n$

$$a_{1p} = \begin{cases} 0 & \text{if } \forall r | 1 \le r \le j, c_{rp} = 0 \\ c_{rp} & \text{if } \exists! r, 1 \le r \le j | c_{rp} \ne 0 \\ (c_{r_1 p}, c_{r_2 p}, ...) & \text{if } \exists r_1 \ne r_2 \ne ..., 1 \le r_1, r_2, ... \le j | c_{r_1 p}, c_{r_2 p}, ... \ne 0 \end{cases}$$

$$a_{q1} = \begin{cases} 0 & \text{if } \forall s | 1 \le s \le i, c_{qs} = 0 \\ c_{qs} & \text{if } \exists! s, 1 \le s \le i | c_{qs} \ne 0 \\ (c_{q s_1}, c_{q s_2}, ...) & \text{if } \exists s_1 \ne s_2 \ne ..., 1 \le s_1, s_2, ... \le s | c_{q s_1}, c_{q s_2}, ... \ne 0 \end{cases}$$

So we hide the number of places and transitions of the hidden subnet and their relationships. Yes, some information is given about the hidden network. Really if this resulting matrix some node that is d-dimensional, at least in the hidden network must exist d nodes of this type.

Furthermore, each nonzero element define part of the front-end of the subnet. If we take the elements of the first row (the first element of the column is the hidden subnet):

- any element greater than zero defines an *ogt* towards the transition related to the column

- any element less than zero defines an *igt* from the transition related to the column

If we take the elements of the first column (the first element of the column is the hidden subnet):

- any element greater than zero defines an *igp* towards the place related to the row

- any element less than zero defines an *ogp* from the place related to the row

With this information we can build the entire front-end of the subnet.

Example 3.15. *We consider the Petri net defined by the following incidence matrix, separated into H,V,HT and HP.*

	t_1	t_2	t_3	t_4	t_5	t_6
p_1	-1	0	1	0	0	0
p_2	-1	0	0	1	0	1
p_3	1	0	0	-1	0	0
p_4	1	-1	0	2	0	0
p_5	0	1	0	0	0	0
p_6	3	0	-1	0	0	0
p_7	0	0	0	-1	-1	1
p_8	0	0	0	0	1	-1

After applying the above steps for the group, we would have the following:

		t_4	t_5	t_6
	■	$(1,-1,2)$	0	1
p_5	1	0	0	0
p_6	$(3,-1)$	0	0	0
p_7	0	-1	-1	1
p_8	0	0	1	-1

Here we see that the information about the number of hidden places and transitions is minimized. So we know that at least there are two hidden transitions and at least three hidden places (there is a transition of dimension 3). However, we do not know the exact number of either.

Now we can build the front-end. The elements of the first row are $(1,-1,2)$ and 1. So we have three ogt and one igt. The elements of the first column are 1 and $(3,-1)$, so defines two igp and one ogp like this. This is the subnet front-end, having hidden its inner content.

Input Front-end	igt1	igp1	igp2 (3)	

Output Front-end	ogt1	ogt2	ogt3 (2)	ogp1
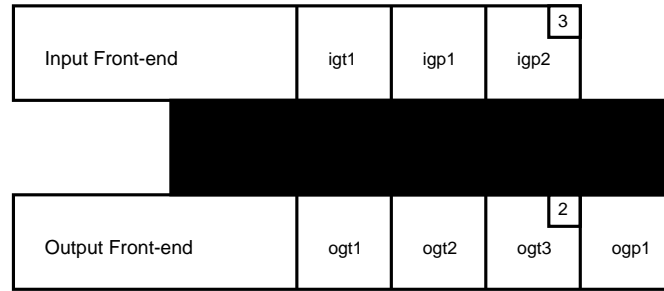
So, any subnet with the same front-end could replace this subnet in the original net (attachable subnet) even though we know nothing about the internal structure of the subnet, because it is hidden.

3.3.1   Hiding vs. Reduction

Both Silva works [12, 13] as in the article by Xia [10] discusses possible Petri nets reductions for grouping and simplifying, under certain circumstances, places and/or transitions. These reductions can be structural (only dependent on the structure and initial marking of the net) or depending on the interpretation of the Petri net.

Should be clear that these reductions are not the same thing we are describing. We do not try to simplify the network together elements to have more or fewer places or transitions or to make it easier. What we want is to hide part of the network, regardless of how simple or complicated it is.

Here we have an example of what a reduction is.

Example 3.16 (Reduction of an implicit place [12]). *In a marked Petri net, an implicit place is one that meets the following:*

1. *its marking can be calculated from other points marking*
2. *never is the only place that prevents the enabling of its output transitions*

If we consider the following Petri net
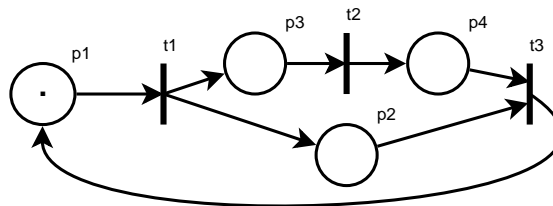
we can notice that p_2 is an implicit place because its marking can be calculated as a function of p_3 y p_4:

$$M(p_2) = M(p_3) + M(p_4)$$

Moreover, by this same formula, it is clear that $M(p_2) \geq M(P_4)$ (marking cannot be negative) so the only place that can prevent enabling of T_3 is P_4. Thus eliminating p_2 does not alter the behavior of the network, which would be as follows:
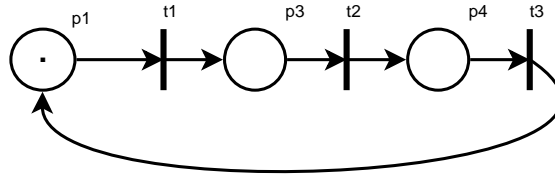
In this network elements have been removed, no hidden. This example helps us to see the difference between hiding and a reduction.

3.4   Conclusions

As we have seen, any Petri net can be divided into any number of subnets, only limited by the number of places and transitions. Furthermore, each one of this Petri subnets has its own input and output front-ends in order to connect with the rest of the Petri net. Of course, the main application of this definitions in this thesis is that the private information of this Petri net is stored in one or more of these defined subnets.

So I have reached the first milestone: to extend Petri Nets definition in order to define the public and the private information.

Chapter 4

Petri net representation for subnets support. PNML

4.1 Introduction

Once explained how to split a net in several subnets, the next step is to define a way to secure one or more of those subnets.

There is not literature about this topic. Because of that I have to do a previous work about Petri net representation. First of all, a way to represent subnet must be defined. Depending on the selected representation, the way to occult subnets may be different or even impossible.

4.2 Petri net representations

There are four standard ways to represent Petri nets. Each one of them have their properties, advantages and disadvantages. But I want to select one that I am able to represent any kind of Petri net, its subnets and allow to hide information without erasing it.

4.2.1 Graphic representation

This is the clearest and extended way to represent Petri nets. It has a very important advantage and it is that a picture is worth a thousand words.

Subnets can be defined simply drawing a vertical line. The right part is one subnet and the left part is other subnet. Places and transitions can be moved from one location to another depending on the subnet they are situated. This is only an example. Other way would be to use colors for the nodes (same color indicates same subnet) or use rectangles, etc.

Example 4.1 (Graphic representation of a hidden subnet). *Let's take the following Petri net.*
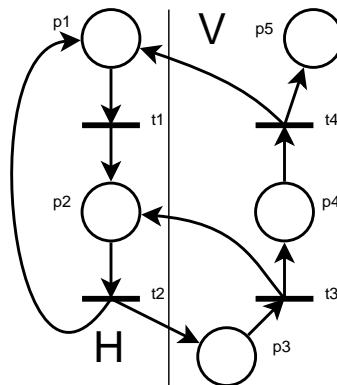
I want to occult the part marked with an H, so the result is this graphic
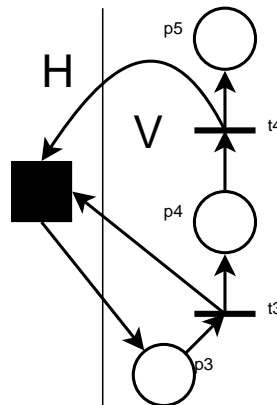
And now, how can I maintain the H subnet information on the black box? If I want to distribute this Petri net I should send something more to that people I want to access the hidden subnet. I have not found a way to embed that information in the graphic so that some people can access it but other people can't.

So this representation is useful in order to show at one sight the Petri net structure, but I can't choose it for my goals. I have not been able to discover a way to show some people the hidden information (the hidden subnet). However I will continue using it where a clear idea of the Petri structure if necessary.

4.2.2 Matrix representation

This representation is very useful to study properties and evolution of a Petri net, independently of its graphic representation. As we have seen before (in chapter 3), we can reorder rows and columns and define subnets in the matrix.

Example 4.2 (Matrix representation of a hidden subnet). *This is the matrix representation of the Petri net in the previous example 4.1.*

$$
\begin{array}{c}
 & \begin{array}{cccc} t_1 & t_2 & t_3 & t_4 \end{array} \\
\begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{array}
\left(\begin{array}{cccc}
-1 & 1 & 0 & 1 \\
1 & -1 & 1 & 0 \\
0 & 1 & -1 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1
\end{array}\right)
\end{array}
$$

As we can see before, If I occult the part marked with an H, so the result is:

$$
\begin{array}{c}
 & \begin{array}{cccc} t_1 & t_2 & t_3 & t_4 \end{array} \\
\begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{array}
\left(\begin{array}{cc|cc}
\blacksquare & \blacksquare & 0 & 1 \\
\blacksquare & \blacksquare & 1 & 0 \\
\hline
0 & 1 & -1 & 0 \\
0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1
\end{array}\right)
\end{array}
$$

or this other one, grouping the places and transitions of the hidden subnet as seen in chapter 3

$$
\begin{array}{c}
 & \begin{array}{cc} t_3 & t_4 \end{array} \\
\begin{array}{c} \\ p_3 \\ p_4 \\ p_5 \end{array}
\left(\begin{array}{c|cc}
\blacksquare & 1 & 1 \\
\hline
1 & -1 & 0 \\
0 & 1 & -1 \\
0 & 0 & 1
\end{array}\right)
\end{array}
$$

And now I have the same problems as in graphic mode: how can I keep information in the black box?

With this representation it is possible to study properties and it may be really important as a complement to graphic mode. With both representations together, everyone has a clear idea of the Petri net structure and properties. But I haven't found a way to store information inside the black box.

4.2.3   Equation representation

The third representation way for Petri nets is the equation representation. Basically, transitions are selected and, for each one, the tokens of the places connected to that transition are modified. This is very useful to compute the evolution of a Petri net, choosing the transition fired.

However it is difficult to find a way for representing subnets with this notation. And, of course, if a subnet cannot be represented, it cannot be hidden.

Example 4.3 (Equation representation of a hidden subnet). *Let's take again the Petri net from the previous examples 4.1. This is It's equation representation:*

```
if (p1>0) then
        p1 <- p1 - 1
        p2 <- p2 + 1
if (p2>0) then
        p2 <- p2 - 1
        p1 <- p1 + 1
        p3 <- p3 + 1
if (p3>0) then
        p3 <- p3 - 1
        p2 <- p2 + 1
        p4 <- p4 + 1
if (p4>0) then
        p4 <- p4 - 1
        p1 <- p1 + 1
        p5 <- p5 + 1
```

As we can see, we should hide several lines. In particular all that includes places p_1 and p_2, resulting something like this (strikethrough text would be part of the subnet):

```
~~if (p1>0) then~~
        ~~p1 <- p1 - 1~~
        ~~p2 <- p2 + 1~~
~~if (p2>0) then~~
        ~~p2 <- p2 - 1~~
        ~~p1 <- p1 + 1~~
        p3 <- p3 + 1
if (p3>0) then
        p3 <- p3 - 1
        ~~p2 <- p2 + 1~~
        p4 <- p4 + 1
if (p4>0) then
        p4 <- p4 - 1
        ~~p1 <- p1 + 1~~
        p5 <- p5 + 1
```

This is probably the strangest way to represent Petri nets and it is difficult to define subnets over it.

I have tried to think about these ways of representation but, in my opinion, no one of them is suitable enough to represent subnets in a clear way than can be occulted. Because of that I have chosen the fourth representation, which is PNML, and that is explained in the next section.

4.3   PNML. Petri Net Marked Language

As I have explained in the Literature review in the chapter 2, PNML is a way to represent Petri nets as xml content.

The advantages over the other three representation ways described before are clear. By one side, XML is a widely extended format to represent almost everything. And not only that. XML is a robust technology free of errors and it is really flexible. Its flexibility come from the possibility of adding any kind of labels and functionality with a very little amount of work. Its robustness come from the strict specification of the schemas declared to define completely the XML files that support. Once the schema is defined, the XML files have no way to get out of this definition, so we can know if a XML file is correct given its schema. And this is not all. If you have an XML file, you can extract information and complete it to create a schema for that file.

Originally, with basic Petri nets, the structure of a Petri net was fully provided. The only thing that is not supported in comparison with graphic mode is the graphical appearance of Petri nets: the position of nodes and transitions was not important, but with the arrival of High level Petri nets and Petri nets design software, it is necessary to store this kind of information.

In this work, I am going to study only basic Petri nets, but that concept and the method is easily exportable to other kind of nets, such as Symmetric nets and High Level Petri nets (that are representable in PNML format too.)

4.3.1   Scope

The scope of this work in this section is basically bounded by the original and basic Petri nets, that is:

- there are places, transitions and arcs between them.

- places can have tokens on them (but this does not influence the hiding process).

- transitions can be fired, but there is only one type of transition (not messages, not time, etc.).

Furthermore, I am going to explain several concepts for a specific graphical design of the Petri net (that will not influence the process either).

There are other options such as specific information for the design tool that I am not going to discuss because the tools have no interest in this work.

4.3.2   Description

Petri Net Marked Language is an xml language created to represent Petri Nets. With it, we can take a Petri Net and store it into an xml file without loss of information.

One of the best properties of PNML is that, as it is an xml based schema, it can be extended with more functionality extending the grammar. Virtually, any extension over Petri nets can be translated into PNML in a logical and natural way. Moreover, this extension is defined by Petri net type definition [66, 67].

In this case PNML hasn't got a way to represent subnets. There is something named `<page>` that is used to represent several nets in the same PNML file. But, by default, a node inside a page cannot connect with a node of other page. So it cannot be used as "subnets". So I am going to extend the language in order to get several goals:

1. Represent subnets of a Petri Net.

2. Include input and output interfaces for every subnet.

As we can think, definition of several subnets of a Petri net is possible and the connection over them are always through their respective interfaces.

4.3.3   PNML grammar

As PNML is an xml based language it has to be described by an schema that define the creation rules of the PNML representation of a Petri net.

The grammar is defined since 2009 and updated until 2012, which is the most recent revision. I am not going to do and extensive explanation of all the possibilities of the grammar, but the most important. As we can see later, anything we think is useful can

be added to the process with little effort. So I am going to study only the most basic elements of a Petri net. The rest of the element can be attached later with facility.

4.3.3.1 PNML basics

In this section I am going to explain several characteristics of PNML files. With these explanations it is going to be easier the understanding of PNML structure.

First of all, as PNML files are xml files, there several things to know:

1. A xml file normally starts with a line defining some characteristics of the file, like the version and the encoding type. It has an aspect like this[1]:

   ```
   <?xml version="1.0" encoding="utf-8"?>
   ```

2. A root node must exist. In this case, the root node is `<pnml>`. So every PNML files has to start with the tag `<pnml>` and end with the tag `</pnml>`. Below this tag, there is a new tag `<net>` that can contain:

   - Type: the type of the Petri net as an attribute. In this case, as I am going to study only Place/Transition nets, it will be `ptnet`

   - Name of the net: New tag `<name><text>...</text></name>`

   - Pages: one page is an invention to store several Petri nets inside an unique PNML file, but usually there is only one page for file. It is nested inside a `<page>` tag. Furthermore, we cannot link elements from different pages.

3. Each element in PNML has to have a unique id inside the net to be identified unambiguously. So there cannot be two elements with the same id.

With this three observations, we can have an idea about how a PNML file is structured:

```
<?xml version="1.0" encoding="utf-8"?>
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <name>
      <text> My new net </text>
    </name>
    <page id="page1">
      .......
    </page>
  </net>
</pnml>
```

LISTING 4.1: Example of general PNML file

---

[1]For clarity, in the following examples, this line can be deleted.

Once this structure is defined, I am going to explain the next stage, that is the most important one in this work.

4.3.3.2 Places, transitions and arcs in PNML

As Petri nets have three main elements (places, transitions and arcs), PNML has them too. These three elements have several things in common in an PNML file:

- They are all nested in a tag `<page>` .

- Places and transitions (not arcs) can contain a tag `<name>` with its name. This tag has been defined before for the net's name. It can store information about the text of the name and the graphical position of this label in this way:

```
<name >
  <text > Element Name </text >
  <graphics >
    <offset x="22" y="-10"/>
  </graphics >
</name >
```

- They can contain information about its position and dimension in a tag `<graphics>`:

```
<graphics >
  <position x="100" y="200"/>
  <dimension x="40" y="40"/>
</graphics >
```

These are the common properties of places, transitions and arcs. Now let's go on the particular characteristics of each one of them.

Places are represented with the tag `<place>` and the can have a marking with the tag `<initialMarking>`. Here we have an example of a place with two tokens in PNML:

```
<place id="p1">
  <name >
    <text > Place number one </text >
    <graphics >
      <offset x="130" y="130"/>
    </graphics >
  </name >
  <graphics >
    <position x="130" y="90"/>
    <dimension x="40" y="40"/>
  </graphics >
  <initialMarking >
    <text > 2 </text >
  </initialMarking >
```

```
</place>
```

LISTING 4.2: PNML representation for places

Transitions are represented with the tag `<transition>`. Except the initial marking, it is really similar to a place. This is an example of a transition in PNML:

```
<transition id="t1">
  <name>
    <text> Transition number one </text>
    <graphics>
      <offset x="270" y="140"/>
    </graphics>
  </name>
  <graphics>
    <position x="270" y="100"/>
    <dimension x="40" y="40"/>
  </graphics>
</transition>
```

LISTING 4.3: PNML representation for transitions

Arcs are represented with the tag `<arc>`. Arc have to have a source and a target, which are defined by the attributes `source` and `target` that have to point to a transition and a place, identified by their `id`. Furthermore, the arc weight can be fixed by the tag `<inscription>`. If the weight is one, the tag inscription is not necessary because this is the default value. This is an example of the arc with weight 3 that connects the place and the transition of the previous examples in PNML:

```
<arc id="a1" source="p1" target="t1">
  <inscription> 3 </inscription>
</arc>
```

LISTING 4.4: General PNML representation for arcs with arbitrary weight

And this is the same example but with weight 1, that is obviated:

```
<arc id="a1" source="p1" target="t1">
</arc>
```

LISTING 4.5: PNML representation for arcs of weight 1

or the same

```
<arc id="a1" source="p1" target="t1"/>
```

LISTING 4.6: PNML representation for arcs of weight 1

If we take the last examples all together, we can represent the following Petri net:
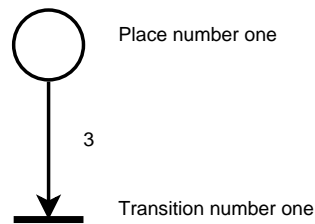

```xml
<?xml version="1.0" encoding="utf-8"?>
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <name>
      <text> My new net </text>
    </name>
    <page id="page1">
      <place id="p1">
        <name>
          <text> Place number one </text>
          <graphics>
            <offset x="130" y="130"/>
          </graphics>
        </name>
        <graphics>
          <position x="130" y="90"/>
          <dimension x="40" y="40"/>
        </graphics>
        <initialMarking>
          <text> 2 </text>
        </initialMarking>
      </place>
      <transition id="t1">
        <name>
          <text> Transition number one </text>
          <graphics>
            <offset x="270" y="140"/>
          </graphics>
        </name>
        <graphics>
          <position x="270" y="100"/>
          <dimension x="40" y="40"/>
        </graphics>
      </transition>
      <arc id="a1" source="p1" target="t1">
        <inscription> 3 </inscription>
      </arc>
    </page>
  </net>
</pnml>
```

LISTING 4.7: Complete PNML representation for a basic Petri net

For clarity, I am going to obviate several options. I am not going to draw the graphic information and the names, but the id. So this last example is as follows:
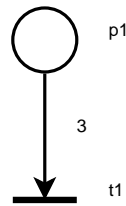

```xml
<?xml version="1.0" encoding="utf-8"?>
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <place id="p1">
        <initialMarking>
          <text> 2 </text>
        </initialMarking>
      </place>
      <transition id="t1"/>
      <arc id="a1" source="p1" target="t1">
        <inscription> 3 </inscription>
      </arc>
    </page>
  </net>
</pnml>
```

LISTING 4.8: Basic PNML representation for a basic Petri net

I think that this last listing is clear enough to understand the rest of the process. But not only that. For even more clarity, the tags `<?xml>`, `<pnml>`, `<net>` and `<page>` are going to be obviated too. So in many of the later examples they will not be present. Applying this criterium, the listing 4.8 change to:

```xml
<place id="p1">
  <initialMarking>
    <text> 2 </text>
 </initialMarking>
</place>
<transition id="t1"/>
<arc id="a1" source="p1" target="t1">
  <inscription> 3 </inscription>
</arc>
```

LISTING 4.9: Simplified PNML representation for a basic Petri net

4.3.4   PNML examples

Now I am going to present some Petri nets in format PNML, in order to get used to work with this type of representation. As I said before, one thing to have in mind is that, in PNML, each element can have a name (tag `<name>`) and a position (tag `<graphics>`). Even the tag `<name>` itself can have its own `<graphics>` inside. As a result, a PNML representation grows in size with lots and lots of elements `<graphics>`, although they have only information about the elements position: they have no influence (at first) over the net behaviour.

So in all of these following Petri nets examples, I am going to eliminate, at least, the information about the exact situation of the elements, keeping only the internal structure of the net, in order to be shorter and clearer. So all the tags `<graphics>` are going to be obviated.

Anyway, obviously, in a real case, this information can be stored and processed with no problem. It is the very nature of the net who is going to demand the exact information to be processed.

4.3.4.1   The dining philosophers

One famous example of Petri net is the model of the dining philosophers problem. This problem, formulated by Edsger Dijkstra in 1965 says:

"Five silent philosophers sit at a round table with bowls of spaghetti. Forks are placed between each pair of adjacent philosophers.

Each philosopher must alternately think and eat. However, a philosopher can only eat spaghetti when he has both left and right forks. Each fork can be held by only one philosopher and so a philosopher can use the fork only if it is not being used by another philosopher. After he finishes eating, he needs to put down both forks so they become available to others. A philosopher can take the fork on his right or the one on his left as they become available, but cannot start eating before getting both of them.

Eating is not limited by the remaining amounts of spaghetti or stomach space; an infinite supply is assumed.

The problem is how to design a discipline of behavior (a concurrent algorithm) such that each philosopher will not starve; i.e., can forever continue to alternate between eating and thinking, assuming that any philosopher cannot know when others may want to eat or think."

It is a classic problem modelled by the well known Petri net in figure 4.1:
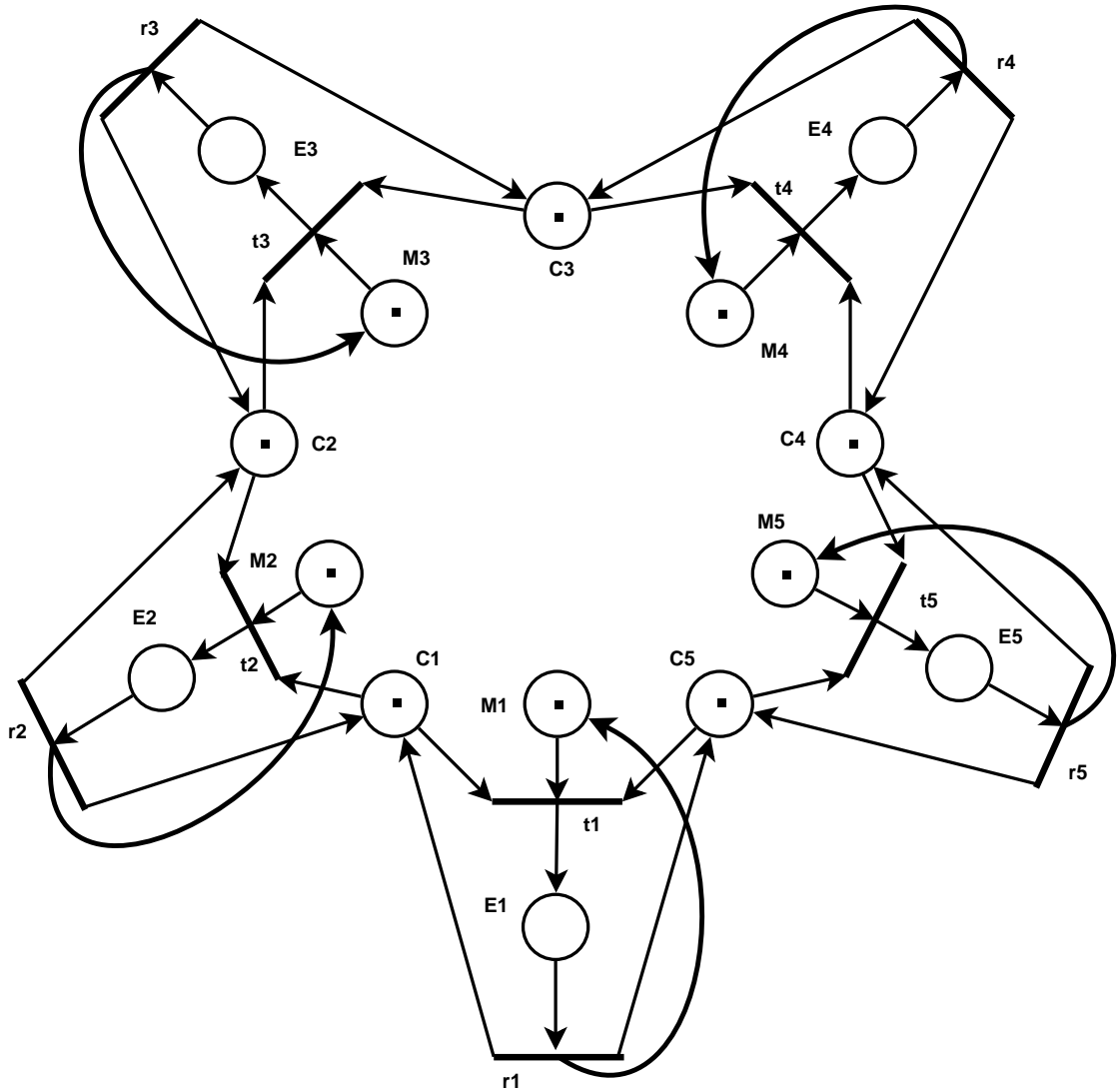

FIGURE 4.1: Dining philosophers Petri net

Here are the descriptions of each element:

- M1..M5: philosophers waiting

- C1..C5: forks

- E1..E5: philosopher eating

- t1..t5 - r1..r5: transitions

Obviating the graphics information about the exact position of the elements, the PNML content that represents this Petri net is as follows:

Note. This PNML content is in two columns for space and clarity reasons.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="5Philo"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <place id="p7">
        <name>
          <text>E2</text>
        </name>
      </place>
      <place id="p6">
        <name>
          <text>C2</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p5">
        <name>
          <text>M2</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p4">
        <name>
          <text>E1</text>
        </name>
      </place>
      <place id="p3">
        <name>
          <text>C1</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p2">
        <name>
          <text>M1</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p1">
        <name>
          <text>C5</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p10">
        <name>
          <text>E3</text>
        </name>
      </place>
      <place id="p9">
        <name>
          <text>C3</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p8">
        <name>
          <text>M3</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p16">
        <name>
          <text>E5</text>
        </name>
      </place>
      <place id="p14">
        <name>
          <text>M5</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p13">
        <name>
          <text>E4</text>
        </name>
      </place>
      <place id="p12">
        <name>
          <text>C4</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <place id="p11">
        <name>
          <text>M4</text>
        </name>
        <initialMarking>
          <text>1</text>
        </initialMarking>
      </place>
      <transition id="t3">
        <name>
          <text>t3</text>
        </name>
      </transition>
      <transition id="t2">
        <name>
          <text>t2</text>
        </name>
      </transition>
      <transition id="t1">
        <name>
          <text>t1</text>
        </name>
      </transition>
      <transition id="t10">
        <name>
          <text>r4</text>
        </name>
      </transition>
      <transition id="t11">
        <name>
          <text>r5</text>
        </name>
      </transition>
      <transition id="t4">
        <name>
          <text>t4</text>
        </name>
      </transition>
      <transition id="t5">
```

```
      <name>                                    <arc id="a2" source="p2" target="t1"/>
        <text>t5</text>                         <arc id="a33" source="t10" target="p12"/>
      </name>                                   <arc id="a3" source="t1" target="p4"/>
    </transition>                               <arc id="a32" source="t10" target="p9"/>
    <transition id="t7">                        <arc id="a4" source="p4" target="t7"/>
      <name>                                    <arc id="a5" source="t7" target="p2"/>
        <text>r1</text>                         <arc id="a38" source="t11" target="p12"/>
      </name>                                   <arc id="a6" source="p1" target="t1"/>
    </transition>                               <arc id="a37" source="t11" target="p14"/>
    <transition id="t8">                        <arc id="a7" source="p3" target="t1"/>
      <name>                                    <arc id="a18" source="p8" target="t3"/>
        <text>r2</text>                         <arc id="a19" source="t3" target="p10"/>
      </name>                                   <arc id="a8" source="t7" target="p3"/>
    </transition>                               <arc id="a36" source="p16" target="t11"/>
    <transition id="t9">                        <arc id="a51" source="t11" target="p1"/>
      <name>                                    <arc id="a52" source="p1" target="t5"/>
        <text>r3</text>                         <arc id="a31" source="p12" target="t4"/>
      </name>                                   <arc id="a30" source="p9" target="t4"/>
    </transition>                               <arc id="a25" source="t9" target="p9"/>
    <arc id="a41" source="p12" target="t5"/>    <arc id="a26" source="p11" target="t4"/>
    <arc id="a20" source="p10" target="t9"/>    <arc id="a27" source="t4" target="p13"/>
    <arc id="a16" source="t8" target="p3"/>     <arc id="a28" source="p13" target="t10"/>
    <arc id="a9" source="t7" target="p1"/>      <arc id="a21" source="t9" target="p8"/>
    <arc id="a17" source="t8" target="p6"/>     <arc id="a22" source="p6" target="t3"/>
    <arc id="a14" source="p6" target="t2"/>     <arc id="a23" source="p9" target="t3"/>
    <arc id="a15" source="p3" target="t2"/>     <arc id="a24" source="t9" target="p6"/>
    <arc id="a12" source="p7" target="t8"/>     <arc id="a29" source="t10" target="p11"/>
    <arc id="a13" source="t8" target="p5"/>    </page>
    <arc id="a10" source="p5" target="t2"/>   </net>
    <arc id="a11" source="t2" target="p7"/>  </pnml>
    <arc id="a35" source="t5" target="p16"/>
    <arc id="a34" source="p14" target="t5"/>
```

As we can see, the size of the PNML representation for a relative small Petri net, is significant big, even the graphics content is deleted. But this is not a problem because this PNML representation is oriented to computer processing.

4.3.4.2   Mengchu Zhou benmarch

This other example is a famous Petri net modelled by Mengchu Zhou. The graphical representation is the figure 4.2.

Again, this is the PNML representation, obviating the data associated to graphical position and labels, in order to be clearer

```
                                              <place id="p44"/>
<?xml version="1.0" encoding="UTF-8"?>        <place id="p47"/>
<pnml                                         <place id="p46"/>
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">  <place id="p49"/>
  <net id="MengchuZhou"                       <place id="p48"/>
      type="http://www.pnml.org/version-2009/grammar/ptnet">  <place id="p31"/>
    <page id="page1">                         <place id="p32"/>
      <place id="p5"/>                        <place id="p30"/>
      <place id="p4"/>                        <place id="p36"/>
      <place id="p3"/>                        <place id="p35"/>
      <place id="p2"/>                        <place id="p34"/>
      <place id="p1"/>                        <place id="p33"/>
      <place id="p40"/>                       <place id="p39"/>
      <place id="p41"/>                       <place id="p38"/>
      <place id="p42"/>                       <place id="p37"/>
      <place id="p43"/>                       <place id="p20"/>
      <place id="p45"/>                       <place id="p21"/>
```

FIGURE 4.2: Mengchu Zhou's Petri net

```xml
<place id="p27"/>                          <transition id="t15"/>
<place id="p26"/>                          <transition id="t16"/>
<place id="p29"/>                          <transition id="t17"/>
<place id="p28"/>                          <transition id="t18"/>
<place id="p23"/>                          <transition id="t19"/>
<place id="p22"/>                          <transition id="t71"/>
<place id="p25"/>                          <transition id="t72"/>
<place id="p24"/>                          <transition id="t70"/>
<place id="p99"/>                          <transition id="t76"/>
<place id="p18"/>                          <transition id="t75"/>
<place id="p17"/>                          <transition id="t74"/>
<place id="p16"/>                          <transition id="t73"/>
<place id="p90"/>                          <transition id="t79"/>
<place id="p15"/>                          <transition id="t78"/>
<place id="p14"/>                          <transition id="t77"/>
<place id="p13"/>                          <transition id="t80"/>
<place id="p12"/>                          <transition id="t81"/>
<place id="p11"/>                          <transition id="t82"/>
<place id="p95"/>                          <transition id="t4"/>
<place id="p96"/>                          <transition id="t9"/>
<place id="p97"/>                          <transition id="t3"/>
<place id="p98"/>                          <transition id="t2"/>
<place id="p91"/>                          <transition id="t1"/>
<place id="p92"/>                          <transition id="t61"/>
<place id="p93"/>                          <transition id="t67"/>
<place id="p94"/>                          <transition id="t66"/>
<place id="p19"/>                          <transition id="t69"/>
<place id="p88"/>                          <transition id="t68"/>
<place id="p89"/>                          <transition id="t63"/>
<place id="p83"/>                          <transition id="t62"/>
<place id="p82"/>                          <transition id="t65"/>
<place id="p81"/>                          <transition id="t64"/>
<place id="p87"/>                          <arc id="a63" source="p27" target="t24"/>
<place id="p86"/>                          <arc id="a64" source="p43" target="t37"/>
<place id="p85"/>                          <arc id="a61" source="t22" target="p27"/>
<place id="p84"/>                          <arc id="a62" source="t23" target="p27"/>
<place id="p111"/>                         <arc id="a60" source="t22" target="p25"/>
<place id="p110"/>                         <arc id="a120" source="p82" target="t62"/>
<place id="p113"/>                         <arc id="a121" source="p82" target="t69"/>
<place id="p112"/>                         <arc id="a123" source="p81" target="t62"/>
<place id="p114"/>                         <arc id="a122" source="p91" target="t69"/>
<place id="p109"/>                         <arc id="a125" source="t70" target="p88"/>
<place id="p108"/>                         <arc id="a59" source="t23" target="p30"/>
<place id="p107"/>                         <arc id="a124" source="t64" target="p95"/>
<place id="p102"/>                         <arc id="a58" source="t21" target="p28"/>
<place id="p101"/>                         <arc id="a127" source="p97" target="t24"/>
<place id="p100"/>                         <arc id="a57" source="t25" target="p28"/>
<place id="p106"/>                         <arc id="a126" source="p96" target="t15"/>
<place id="p105"/>                         <arc id="a56" source="p28" target="t19"/>
<place id="p104"/>                         <arc id="a129" source="t24" target="p99"/>
<place id="p103"/>                         <arc id="a55" source="p28" target="t17"/>
<place id="p50"/>                          <arc id="a128" source="t15" target="p98"/>
<transition id="t33"/>                     <arc id="a54" source="p26" target="t19"/>
<transition id="t34"/>                     <arc id="a72" source="p36" target="t33"/>
<transition id="t35"/>                     <arc id="a73" source="p47" target="t28"/>
<transition id="t36"/>                     <arc id="a74" source="t28" target="p45"/>
<transition id="t30"/>                     <arc id="a75" source="p45" target="t38"/>
<transition id="t31"/>                     <arc id="a110" source="p84" target="t65"/>
<transition id="t32"/>                     <arc id="a70" source="p42" target="t31"/>
<transition id="t37"/>                     <arc id="a71" source="t31" target="p36"/>
<transition id="t38"/>                     <arc id="a119" source="p87" target="t62"/>
<transition id="t20"/>                     <arc id="a114" source="t64" target="p83"/>
<transition id="t21"/>                     <arc id="a113" source="t70" target="p83"/>
<transition id="t24"/>                     <arc id="a69" source="t35" target="p42"/>
<transition id="t25"/>                     <arc id="a112" source="p90" target="t70"/>
<transition id="t22"/>                     <arc id="a111" source="t65" target="p90"/>
<transition id="t23"/>                     <arc id="a118" source="p87" target="t69"/>
<transition id="t28"/>                     <arc id="a66" source="p44" target="t36"/>
<transition id="t29"/>                     <arc id="a117" source="t65" target="p87"/>
<transition id="t26"/>                     <arc id="a65" source="t37" target="p44"/>
<transition id="t10"/>                     <arc id="a116" source="t61" target="p87"/>
<transition id="t11"/>                     <arc id="a68" source="p41" target="t35"/>
<transition id="t12"/>                     <arc id="a115" source="p83" target="t68"/>
<transition id="t13"/>                     <arc id="a67" source="t36" target="p41"/>
<transition id="t14"/>                     <arc id="a140" source="p104" target="t76"/>
```
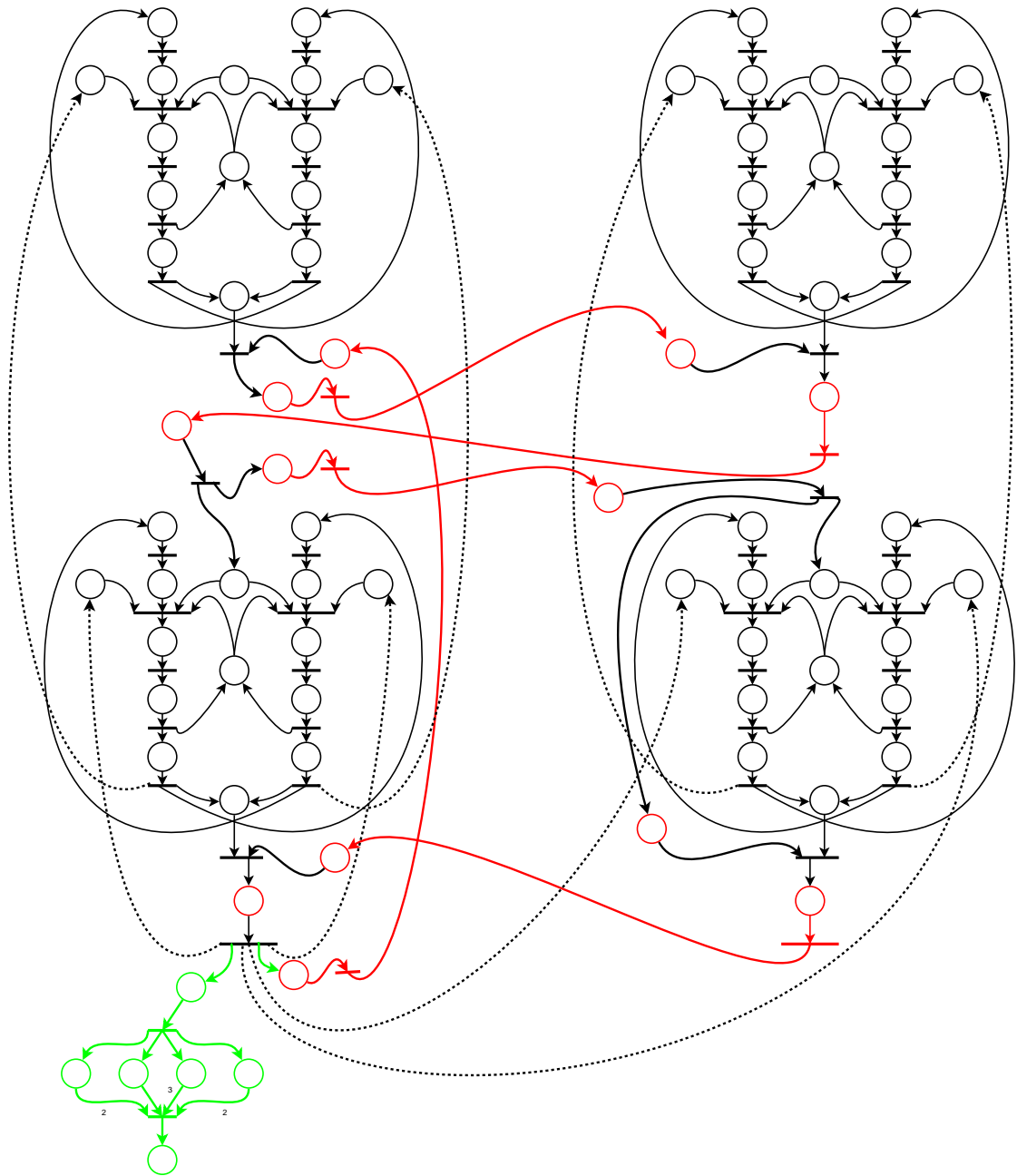
```xml
<arc id="a141" source="t76" target="p106"/>
<arc id="a142" source="t76" target="p107"/>
<arc id="a143" source="t76" target="p108"/>
<arc id="a41" source="p30" target="t20"/>
<arc id="a42" source="t20" target="p31"/>
<arc id="a40" source="p21" target="t23"/>
<arc id="a9" source="p16" target="t10"/>
<arc id="a149" source="p105" target="t78"/>
<arc id="a35" source="t17" target="p23"/>
<arc id="a1" source="p1" target="t1"/>
<arc id="a148" source="p109" target="t77">
  <inscription>
    <text>2</text>
  </inscription>
</arc>
<arc id="a34" source="p24" target="t17"/>
<arc id="a2" source="t1" target="p2"/>
<arc id="a33" source="t18" target="p24"/>
<arc id="a3" source="p2" target="t2"/>
<arc id="a32" source="p25" target="t18"/>
<arc id="a4" source="t2" target="p3"/>
<arc id="a145" source="p106" target="t77">
  <inscription>
    <text>2</text>
  </inscription>
</arc>
<arc id="a39" source="t25" target="p21"/>
<arc id="a5" source="p3" target="t3"/>
<arc id="a144" source="t76" target="p109"/>
<arc id="a38" source="p22" target="t25"/>
<arc id="a6" source="t3" target="p4"/>
<arc id="a147" source="p108" target="t77">
  <inscription>
    <text>3</text>
  </inscription>
</arc>
<arc id="a37" source="t16" target="p22"/>
<arc id="a7" source="p4" target="t4"/>
<arc id="a146" source="p107" target="t77"/>
<arc id="a36" source="p23" target="t16"/>
<arc id="a8" source="t4" target="p5"/>
<arc id="a131" source="p101" target="t68"/>
<arc id="a132" source="t30" target="p102"/>
<arc id="a130" source="p100" target="t30"/>
<arc id="a50" source="p35" target="t17"/>
<arc id="a51" source="p29" target="t17"/>
<arc id="a53" source="p29" target="t19"/>
<arc id="a44" source="t19" target="p32"/>
<arc id="a139" source="t74" target="p105"/>
<arc id="a43" source="p31" target="t19"/>
<arc id="a138" source="t74" target="p104"/>
<arc id="a46" source="t26" target="p33"/>
<arc id="a137" source="p103" target="t75"/>
<arc id="a45" source="p32" target="t26"/>
<arc id="a136" source="p102" target="t74"/>
<arc id="a48" source="t21" target="p34"/>
<arc id="a135" source="p99" target="t73"/>
<arc id="a47" source="p33" target="t21"/>
<arc id="a134" source="p98" target="t72"/>
<arc id="a133" source="t68" target="p103"/>
<arc id="a49" source="p34" target="t22"/>
<arc id="a98" source="t69" target="p86"/>
<arc id="a99" source="p86" target="t66"/>
<arc id="a20" source="p17" target="t2"/>
<arc id="a161" source="t80" target="p113"/>
<arc id="a160" source="t79" target="p39"/>
<arc id="a163" source="t82" target="p82"/>
<arc id="a162" source="p113" target="t82"/>
<arc id="a165" source="t33" target="p19"/>
<arc id="a164" source="t82" target="p101"/>
<arc id="a166" source="t74" target="p48"/>
<arc id="a16" source="t9" target="p12"/>
<arc id="a167" source="t32" target="p20"/>
<arc id="a17" source="p12" target="t12"/>
<arc id="a168" source="t74" target="p38"/>
<arc id="a14" source="t10" target="p13"/>
<arc id="a169" source="t64" target="p35"/>
<arc id="a15" source="p13" target="t9"/>
<arc id="a12" source="t11" target="p14"/>
<arc id="a13" source="p14" target="t10"/>
<arc id="a10" source="p16" target="t2"/>
<arc id="a11" source="p15" target="t11"/>
<arc id="a18" source="t12" target="p11"/>
<arc id="a19" source="p17" target="t10"/>
<arc id="a150" source="t75" target="p100"/>
<arc id="a31" source="p18" target="t15"/>
<arc id="a30" source="t14" target="p15"/>
<arc id="a154" source="t79" target="p111"/>
<arc id="a153" source="p110" target="t79"/>
<arc id="a152" source="t72" target="p97"/>
<arc id="a151" source="t78" target="p96"/>
<arc id="a157" source="p112" target="t81"/>
<arc id="a25" source="t13" target="p18"/>
<arc id="a26" source="t14" target="p18"/>
<arc id="a155" source="p111" target="t80"/>
<arc id="a27" source="p19" target="t2"/>
<arc id="a156" source="t73" target="p112"/>
<arc id="a28" source="p20" target="t10"/>
<arc id="a21" source="t12" target="p17"/>
<arc id="a22" source="t4" target="p17"/>
<arc id="a159" source="t81" target="p110"/>
<arc id="a23" source="p11" target="t13"/>
<arc id="a24" source="p5" target="t14"/>
<arc id="a29" source="t13" target="p1"/>
<arc id="a76" source="t38" target="p46"/>
<arc id="a77" source="p46" target="t34"/>
<arc id="a78" source="t34" target="p50"/>
<arc id="a79" source="p50" target="t29"/>
<arc id="a80" source="t29" target="p49"/>
<arc id="a82" source="p39" target="t36"/>
<arc id="a81" source="p49" target="t32"/>
<arc id="a84" source="t38" target="p38"/>
<arc id="a83" source="p39" target="t38"/>
<arc id="a86" source="p40" target="t36"/>
<arc id="a85" source="p48" target="t36"/>
<arc id="a102" source="t61" target="p89"/>
<arc id="a89" source="t29" target="p40"/>
<arc id="a103" source="p89" target="t64"/>
<arc id="a100" source="t66" target="p85"/>
<arc id="a87" source="p40" target="t38"/>
<arc id="a101" source="p85" target="t61"/>
<arc id="a88" source="t31" target="p40"/>
<arc id="a106" source="p93" target="t62"/>
<arc id="a107" source="t62" target="p94"/>
<arc id="a104" source="p95" target="t71"/>
<arc id="a105" source="t71" target="p93"/>
<arc id="a108" source="p94" target="t67"/>
<arc id="a173" source="t77" target="p114"/>
<arc id="a109" source="t67" target="p84"/>
<arc id="a172" source="t70" target="p26"/>
<arc id="a171" source="t74" target="p81"/>
<arc id="a170" source="t74" target="p91"/>
<arc id="a93" source="t32" target="p43"/>
<arc id="a92" source="t37" target="p30"/>
<arc id="a91" source="t33" target="p37"/>
<arc id="a90" source="t32" target="p37"/>
<arc id="a97" source="p92" target="t69"/>
<arc id="a96" source="t63" target="p92"/>
<arc id="a95" source="p88" target="t63"/>
<arc id="a94" source="t33" target="p47"/>
      </page>
    </net>
  </pnml>
```

Again, we can see the size and the strange format for a person, but, as I said before, it is oriented to computers.

4.3.4.3   Abstract example

This last triple example is going to be the base of some other future examples. It is based on Latorre's PhD [77] and represents three nets and will be used later for the other purposes of this thesis. I introduce these nets because they are quite simple and the examples will be very clear and not too big. These nets are shown in the figure 4.3
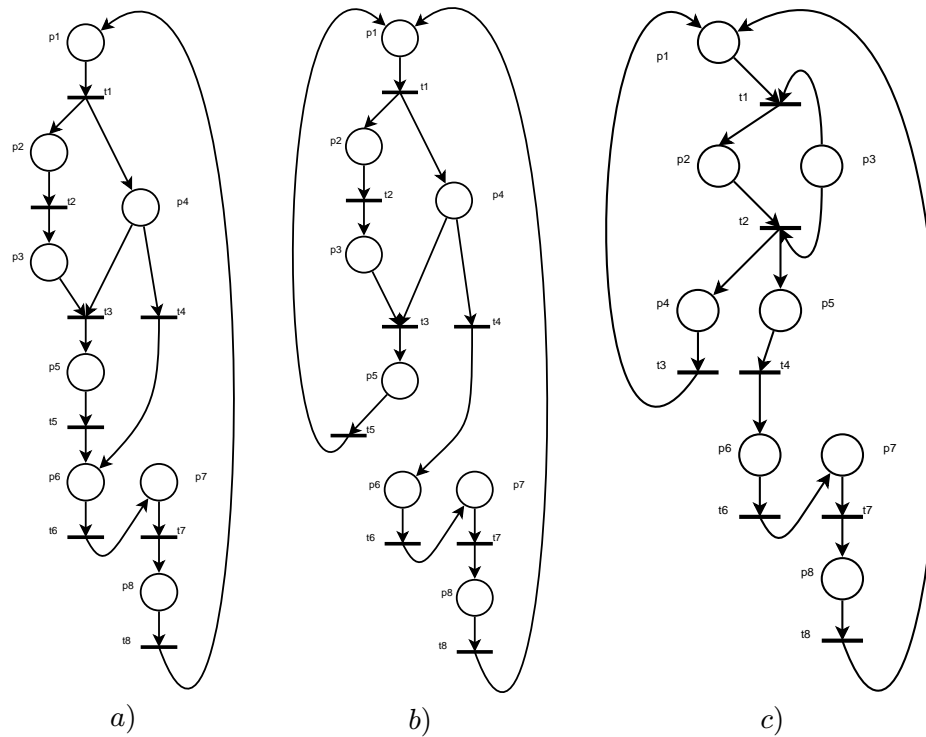
FIGURE 4.3: Three Petri net examples

Note that they have common or very similar parts. For example, a) and b) area almost the same net, but with a little difference in an arc. And they all three have an equal part with the places p_6, p_7 and p_8. This characteristics will be important in the next chapters.

The PNML representation of the a) net is:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
```

```xml
      <subnet id="N1">
        <content id="N1_content">
        </content>
      </subnet>
      <subnet id="N2">
        <content id="N2_content">
        </content>
      </subnet>
      <place id="p1"/>
      <place id="p2"/>
      <place id="p3"/>
      <place id="p4"/>
      <place id="p5"/>
      <place id="p6"/>
      <place id="p7"/>
      <place id="p8"/>
      <transition id="t1"/>
      <transition id="t2"/>
      <transition id="t3"/>
      <transition id="t4"/>
      <transition id="t5"/>
      <transition id="t6"/>
      <transition id="t7"/>
      <transition id="t8"/>
      <arc id="a1" source="p1" target="t1"/>
      <arc id="a2" source="t1" target="p2"/>
      <arc id="a3" source="p2" target="t2"/>
      <arc id="a4" source="t2" target="p3"/>
      <arc id="a5" source="t1" target="p4"/>
      <arc id="a6" source="p3" target="t3"/>
      <arc id="a7" source="p4" target="t4"/>
      <arc id="a8" source="p4" target="t3"/>
      <arc id="a9" source="t3" target="p5"/>
      <arc id="a10" source="p5" target="t5"/>
      <arc id="a11" source="t5" target="p6"/>
      <arc id="a12" source="p6" target="t6"/>
      <arc id="a13" source="t6" target="p7"/>
      <arc id="a14" source="p7" target="t7"/>
      <arc id="a15" source="t7" target="p8"/>
      <arc id="a16" source="p8" target="t8"/>
      <arc id="a17" source="t8" target="p1"/>
      <arc id="a18" source="t4" target="p6"/>
    </page>
  </net>
</pnml>
```

The PNML representation of the b) net is:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre2"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <place id="p1"/>
```

```xml
        <place id="p2"/>
        <place id="p3"/>
        <place id="p4"/>
        <place id="p5"/>
        <place id="p6"/>
        <place id="p7"/>
        <place id="p8"/>
        <transition id="t1"/>
        <transition id="t2"/>
        <transition id="t3"/>
        <transition id="t4"/>
        <transition id="t5"/>
        <transition id="t6"/>
        <transition id="t7"/>
        <transition id="t8"/>
        <arc id="a1" source="p1" target="t1"/>
        <arc id="a2" source="t1" target="p2"/>
        <arc id="a3" source="p2" target="t2"/>
        <arc id="a4" source="t2" target="p3"/>
        <arc id="a5" source="t1" target="p4"/>
        <arc id="a6" source="p3" target="t3"/>
        <arc id="a7" source="p4" target="t4"/>
        <arc id="a8" source="p4" target="t3"/>
        <arc id="a9" source="t3" target="p5"/>
        <arc id="a10" source="p5" target="t5"/>
        <arc id="a11" source="p6" target="t6"/>
        <arc id="a12" source="t6" target="p7"/>
        <arc id="a13" source="p7" target="t7"/>
        <arc id="a14" source="t7" target="p8"/>
        <arc id="a15" source="p8" target="t8"/>
        <arc id="a16" source="t8" target="p1"/>
        <arc id="a17" source="t4" target="p6"/>
        <arc id="a18" source="t5" target="p1"/>
      </page>
    </net>
</pnml>
```

The PNML representation of the c) net is:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre3"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <place id="p1"/>
      <place id="p2"/>
      <place id="p3"/>
      <place id="p4"/>
      <place id="p5"/>
      <place id="p6"/>
      <place id="p7"/>
      <place id="p8"/>
      <transition id="t1"/>
      <transition id="t2"/>
```

```
        <transition id="t3"/>
        <transition id="t4"/>
        <transition id="t5"/>
        <transition id="t6"/>
        <transition id="t7"/>
        <arc id="a1"  source="p1"  target="t1"/>
        <arc id="a2"  source="t1"  target="p2"/>
        <arc id="a3"  source="p2"  target="t2"/>
        <arc id="a4"  source="p4"  target="t3"/>
        <arc id="a5"  source="p6"  target="t5"/>
        <arc id="a6"  source="t5"  target="p7"/>
        <arc id="a7"  source="p7"  target="t6"/>
        <arc id="a8"  source="t6"  target="p8"/>
        <arc id="a9"  source="p8"  target="t7"/>
        <arc id="a10"  source="t7"  target="p1"/>
        <arc id="a11"  source="t4"  target="p6"/>
        <arc id="a12"  source="p3"  target="t1"/>
        <arc id="a13"  source="p3"  target="t2"/>
        <arc id="a14"  source="t2"  target="p4"/>
        <arc id="a15"  source="t3"  target="p1"/>
        <arc id="a16"  source="p5"  target="t4"/>
        <arc id="a17"  source="t2"  target="p5"/>
      </page>
    </net>
</pnml>
```

4.3.5   PNML extension for representing subnets

In this section I am going to define new tags and structures in PNML. At this point, I have developed all the necessary to extend PNML in order to represent subnets inside a concrete Petri net.

Let's take simple Petri net of the figure 4.4. It will serve us to explain the method to achieve a subnet representation and the PNML extension associated to it parting from a determinate Petri net:

The PNML code for this net is:

```
<place id="p1"/>
<place id="p2"/>
<place id="p3"/>
<transition id="t1"/>
<transition id="t2"/>
<transition id="t3"/>
<arc id="a1" source="p1" target="t1">
  <inscription>
    <text> 3 </text>
  </inscription>
</arc>
<arc id="a2" source="t1" target="p2"/>
<arc id="a3" source="t1" target="p3"/>
```

FIGURE 4.4: Subnet to represent in PNML

```
<arc id="a4" source="p3" target="t2">
  <inscription>
    <text>2</text>
  </inscription>
</arc>
<arc id="a5" source="t3" target="p3"/>
<arc id="a6" source="p2" target="t3"/>
<arc id="a7" source="t2" target="p1"/>
```
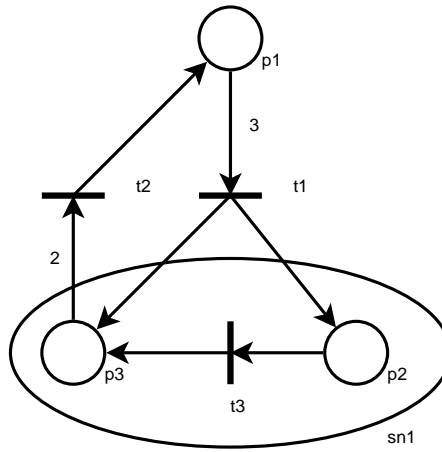
I want the ellipse region to be a subnet, so I have to specify a subnet with the elements inside the ellipse.

The first step is to define a new tag `<subnet>`. This tag will have an id, as the rest of PNML elements. And now we proceed in this way:

1. The places and transitions inside the subnet are moved into the tag `<subnet>`.

2. The arcs linking two elements that are both inside the subnet will be moved to into this new tag too.

3. The arcs entering or leaving the subnet will be copied inside the tag. This mean that there are arcs duplicated inside and outside the tag.

If we apply these rules to the example:

1. $p2$, $p3$ and $t3$ are moved into the tag `<subnet>`.

2. $a5$ and $a6$ are put inside the tag.

3. *a2*, *a3* and *a4* are copied inside the tag.

and we have this other PNML extended code:

```
<subnet id="sn1">
  <place id="p2"/>
  <place id="p3"/>
  <transition id="t3"/>
  <arc id="a2" source="t1" target="p2"/>
  <arc id="a3" source="t1" target="p3"/>
  <arc id="a4" source="p3" target="t2">
    <inscription>
      <text> 2 </text>
    </inscription>
  </arc>
  <arc id="a5" source="t3" target="p3"/>
  <arc id="a6" source="p2" target="t3"/>
</subnet>
<place id="p1"/>
<transition id="t1"/>
<transition id="t2"/>
<arc id="a1" source="p1" target="t1">
  <inscription>
    <text> 3 </text>
  </inscription>
</arc>
<arc id="a2" source="t1" target="p2"/>
<arc id="a3" source="t1" target="p3"/>
<arc id="a4" source="p3" target="t2">
  <inscription>
    <text> 2 </text>
  </inscription>
</arc>
<arc id="a7" source="t2" target="p1"/>
```

Now this is one of the most important moment in this work: I will separate the inside and the outside of the subnet completely. Taking advantage of the process described in chapter 3, I have to extract the front-end from this subnet.

In this case I have two `igp` (input gate to a place) and an `ogt` (output gate to a transition) with weight 2. The figure 4.5 illustrates the interface associated:

And the figure 4.6 is the complete net including the subnet and its front-end.

And now that I have the graphic, how can I represent it in PNML? To answer this question I will define four new tags: `<interface>`, `<gate>`, `<inscription>` and `<content>`. Let's explain them.

As its name says, `<interface>` is the tag name for encapsulate the front-end. This tag has no attributes (just the id, of course) but it has embedded the gates inside of it.
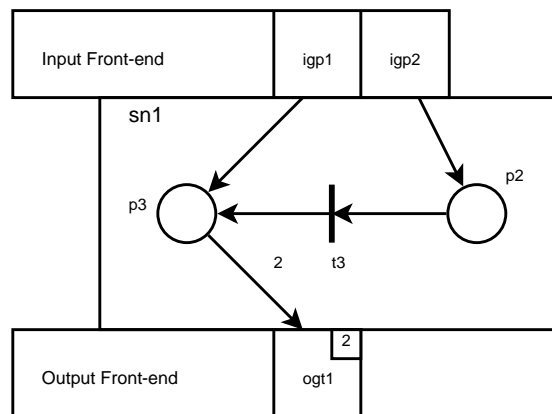
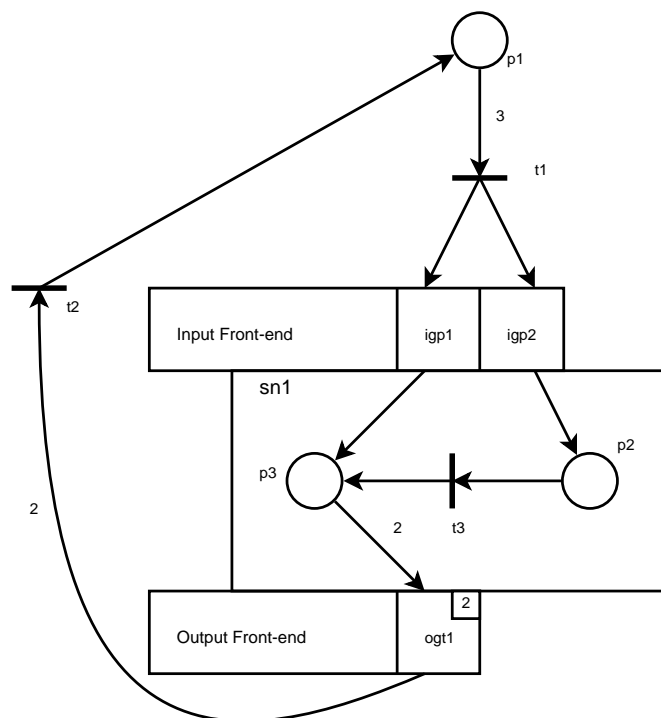FIGURE 4.5: Subnet with its interface

FIGURE 4.6: Petri net with subnet

These gates are represented by `<gate>`. This tag has two new attributes: `action` and `type`. These two attributes have information about the gates. The attribute `action` can take two different values: `input` and `output`. It indicates whether the gate is an input or an output gate. The other attribute, `type`, can take other two values: `place` and `transition`. As arcs have weight, gates have it too. For being in accordance, I define the tag `<inscription>` embedded in the tag `<gate>`. It has the weight of the arc associated. In the same way that with arcs, if they have weight 1 this tag can be obviated.

There is one other tag `<content>` that probably at this moment seems useless, but it is necessary for the rest of the process, as we will see in the next chapter. So I am going to introduce it now. This tag is used to encapsulate the rest of the subnet outside the interface. That is, `<subnet>` has two children: `<interface>` and `<content>`, that have the input/output place/transition gates and the rest of the elements, respectively.

Applying this definition to the example, we will have this code:

```
<subnet id="sn1">
  <interface id="sn1-interface">
    <gate id="igp1" action="input" type="place"/>
    <gate id="igp2" action="input" type="place"/>
    <gate id="ogt1" action="output" type="transition">
      <inscription>
        <text> 2 </text>
      </inscription>
    </gate>
  </interface>
  <content id="sn1-content">
    <place id="p2"/>
    <place id="p3"/>
    <transition id="t3"/>
    <arc id="a2" source="t1" target="p2"/>
    <arc id="a3" source="t1" target="p3"/>
    <arc id="a4" source="p3" target="t2">
      <inscription>
        <text> 2 </text>
      </inscription>
    </arc>
    <arc id="a5" source="t3" target="p3"/>
    <arc id="a6" source="p2" target="t3"/>
  </content>
</subnet>
<place id="p1"/>
<transition id="t1"/>
<transition id="t2"/>
<arc id="a1" source="p1" target="t1">
  <inscription>
    <text> 3 </text>
  </inscription>
</arc>
<arc id="a2" source="t1" target="p2"/>
```

```
<arc id="a3" source="t1" target="p3"/>
<arc id="a4" source="p3" target="t2">
  <inscription>
    <text> 2 </text>
  </inscription>
</arc>
<arc id="a7" source="t2" target="p1"/>
```

At this moment I have to do only one thing more. The last step is to modify the arcs that are repeated inside and outside the net changing their id and source or target, depending on where is it:

- Change the name of one of the copies of the arc.

- If the arc is **entering** the subnet

  - For the `<arc>` tag inside the tag `<subnet>`, the **source** attribute of the arc is changed by the **input** gate associated

  - For the `<arc>` tag outside the tag `<subnet>`, the **target** attribute of the arc is changed by the **output** gate associated

- If the arc is **leaving** the subnet

  - For the `<arc>` tag inside the tag `<subnet>`, the **target** attribute of the arc is changed by the **input** gate associated

  - For the `<arc>` tag outside the tag `<subnet>`, the **source** attribute of the arc is changed by the **output** gate associated

Applying again this rule to the example we have the definitive code for this Petri net:

```
<subnet id="sn1">
  <interface id="sn1-interface">
    <gate id="igp1" action="input" type="place"/>
    <gate id="igp2" action="input" type="place"/>
    <gate id="ogt1" action="output" type="transition">
      <inscription>
        <text> 2 </text>
      </inscription>
    </gate>
  </interface>
  <content id="sn1-content">
    <place id="p2"/>
    <place id="p3"/>
    <transition id="t3"/>
    <arc id="sn1-a2" source="igp2" target="p2"/>
    <arc id="sn1-a3" source="igp1" target="p3"/>
    <arc id="sn1-a4" source="p3" target="ogt1">
      <inscription>
```

```xml
        <text> 2 </text>
      </inscription>
    </arc>
    <arc id="a5" source="t3" target="p3"/>
    <arc id="a6" source="p2" target="t3"/>
  </content>
</subnet>
<place id="p1"/>
<transition id="t1"/>
<transition id="t2"/>
<arc id="a1" source="p1" target="t1">
  <inscription>
    <text> 3 </text>
  </inscription>
</arc>
<arc id="a2" source="t1" target="igp2"/>
<arc id="a3" source="t1" target="igp1"/>
<arc id="a4" source="ogt1" target="t2">
  <inscription>
    <text> 2 </text>
  </inscription>
</arc>
<arc id="a7" source="t2" target="p1"/>
```

LISTING 4.10: Final PNML representation

Once this is done, the only way to enter or leave the subnet is crossing the front-end, and I have reached my goal.

This is a comprehensive definition of how to represent subnets in PNML. Now there are several ways to create a grammar extension that frame this structure of xml. For example, we can define a dtd file[78], and xsd file [79, 80] or, by coherence with the original grammar of PNML, a Relax NG file [81]. I have defined a way to represent subnets, but the formal grammar is outside the scope of my work because of the wide casuistry of these Petri net types. However, the method is explained enough in order to each one of these types to define their own extension.

4.3.5.1   Examples of PNML subnets

Let's take the examples of 4.3. The coloured subnets in the figure 4.7 are going to be represented.

The first net a) is going to be split in two subnets:

- N_1 made up of the places p_2, p_3, p_4 and p_5 an the transitions t_1, t_2, t_3 and t_5

- N_2 made up of the places p_7 and p_8 and the transitions t_6 and t_7
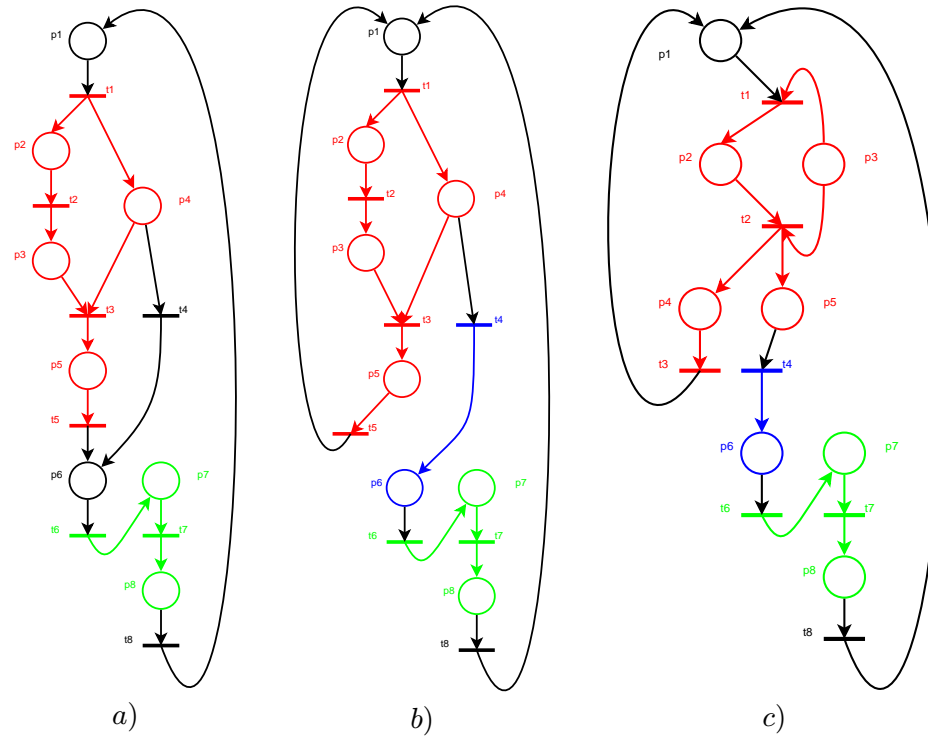
FIGURE 4.7: Three Petri subnet examples

- remain outside the subnets the places p_1 and p_6 and the transitions

Let's apply the method explained before.

First, we create two new tags `<subnet>` with different id with tags `<interface>` and `<content>` inside:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
        </interface>
        <content id="N1-content">
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N1-interface">
        </interface>
        <content id="N2-content">
        </content>
      </subnet>
      <place id="p1"/>
```

```xml
          <place id="p2"/>
          <place id="p3"/>
          <place id="p4"/>
          <place id="p5"/>
          <place id="p6"/>
          <place id="p7"/>
          <place id="p8"/>
          <transition id="t1"/>
          <transition id="t2"/>
          <transition id="t3"/>
          <transition id="t4"/>
          <transition id="t5"/>
          <transition id="t6"/>
          <transition id="t7"/>
          <transition id="t8"/>
          <arc id="a1" source="p1" target="t1"/>
          <arc id="a2" source="t1" target="p2"/>
          <arc id="a3" source="p2" target="t2"/>
          <arc id="a4" source="t2" target="p3"/>
          <arc id="a5" source="t1" target="p4"/>
          <arc id="a6" source="p3" target="t3"/>
          <arc id="a7" source="p4" target="t4"/>
          <arc id="a8" source="p4" target="t3"/>
          <arc id="a9" source="t3" target="p5"/>
          <arc id="a10" source="p5" target="t5"/>
          <arc id="a11" source="t5" target="p6"/>
          <arc id="a12" source="p6" target="t6"/>
          <arc id="a13" source="t6" target="p7"/>
          <arc id="a14" source="p7" target="t7"/>
          <arc id="a15" source="t7" target="p8"/>
          <arc id="a16" source="p8" target="t8"/>
          <arc id="a17" source="t8" target="p1"/>
          <arc id="a18" source="t4" target="p6"/>
      </page>
  </net>
</pnml>
```

Now I place their places, transitions and arcs between them inside the correspondent `<content>` as shown:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
        </interface>
        <content id="N1_content">
          <place id="p2"/>
          <place id="p3"/>
          <place id="p4"/>
          <place id="p5"/>
```

```xml
            <transition id="t1"/>
            <transition id="t2"/>
            <transition id="t3"/>
            <transition id="t5"/>
            <arc id="a2" source="t1" target="p2"/>
            <arc id="a3" source="p2" target="t2"/>
            <arc id="a4" source="t2" target="p3"/>
            <arc id="a5" source="t1" target="p4"/>
            <arc id="a6" source="p3" target="t3"/>
            <arc id="a8" source="p4" target="t3"/>
            <arc id="a9" source="t3" target="p5"/>
            <arc id="a10" source="p5" target="t5"/>
          </content>
        </subnet>
        <subnet id="N2">
          <interface id="N2-interface">
          </interface>
          <content id="N2_content">
            <place id="p7"/>
            <place id="p8"/>
            <transition id="t6"/>
            <transition id="t7"/>
            <arc id="a13" source="t6" target="p7"/>
            <arc id="a14" source="p7" target="t7"/>
            <arc id="a15" source="t7" target="p8"/>
          </content>
        </subnet>
        <place id="p1"/>
        <place id="p6"/>
        <transition id="t4"/>
        <transition id="t8"/>
        <arc id="a1" source="p1" target="t1"/>
        <arc id="a7" source="p4" target="t4"/>
        <arc id="a11" source="t5" target="p6"/>
        <arc id="a12" source="p6" target="t6"/>
        <arc id="a16" source="p8" target="t8"/>
        <arc id="a17" source="t8" target="p1"/>
        <arc id="a18" source="t4" target="p6"/>
      </page>
    </net>
</pnml>
```

Then I define the input and output gates of each subnet. In this case, I look for the arcs entering or leaving each subnet and the gates that are defined.

- The arc a_1 is entering $N1$ from a place, so it defines an *igp*

- The arc a_7 is leaving $N1$ towards a transition, so they defines an *ogt*

- The arc a_{11} is leaving $N1$ towards a place, so it defines an *ogp*

- The arc a_{12} is entering N_2 from a place, so it defines an *igp*

- The arc a_{16} is leaving N_2 towards a transition, so it defines an *ogt*

I put these gates in their location inside the correspondent `<subnet><interface>`

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
          <gate id="N1-igp1" action="input" type="place"/>
          <gate id="N1-ogt1" action="output" type="transition"/>
          <gate id="N1-ogp1" action="output" type="place"/>
        </interface>
        <content id="N1_content">
          <place id="p2"/>
          <place id="p3"/>
          <place id="p4"/>
          <place id="p5"/>
          <transition id="t1"/>
          <transition id="t2"/>
          <transition id="t3"/>
          <transition id="t5"/>
          <arc id="a2" source="t1" target="p2"/>
          <arc id="a3" source="p2" target="t2"/>
          <arc id="a4" source="t2" target="p3"/>
          <arc id="a5" source="t1" target="p4"/>
          <arc id="a6" source="p3" target="t3"/>
          <arc id="a8" source="p4" target="t3"/>
          <arc id="a9" source="t3" target="p5"/>
          <arc id="a10" source="p5" target="t5"/>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate id="N2-igp1" action="input" type="place"/>
          <gate id="N2-ogt1" action="output" type="transition"/>
        </interface>
        <content id="N2_content">
          <place id="p7"/>
          <place id="p8"/>
          <transition id="t6"/>
          <transition id="t7"/>
          <arc id="a13" source="t6" target="p7"/>
          <arc id="a14" source="p7" target="t7"/>
          <arc id="a15" source="t7" target="p8"/>
        </content>
      </subnet>
      <place id="p1"/>
      <place id="p6"/>
      <transition id="t4"/>
      <transition id="t8"/>
      <arc id="a1" source="p1" target="t1"/>
```

FIGURE 4.8: a) Subnet and interfaces

```
      <arc id="a7" source="p4" target="t4"/>
      <arc id="a11" source="t5" target="p6"/>
      <arc id="a12" source="p6" target="t6"/>
      <arc id="a16" source="p8" target="t8"/>
      <arc id="a17" source="t8" target="p1"/>
      <arc id="a18" source="t4" target="p6"/>
    </page>
  </net>
</pnml>
```
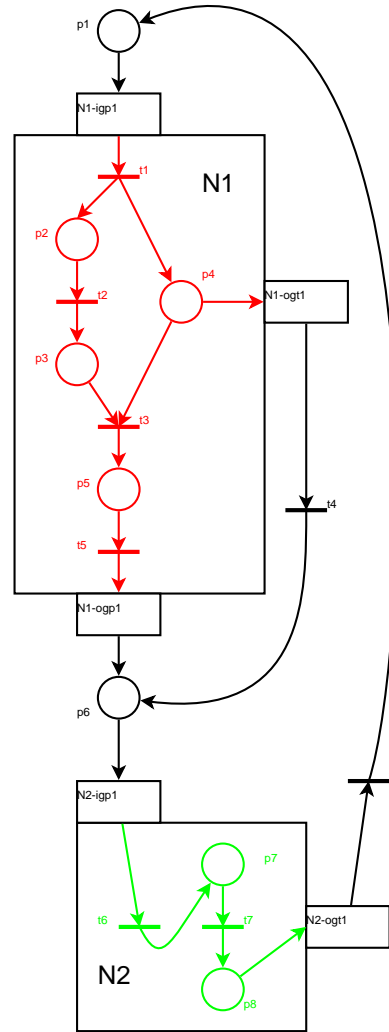
Then I duplicate the arcs entering or leaving each subnet and change their source and/or the target for the interface to be an intermediate and their id in order not to have elements with the same id.

So the figure 4.8 is the final graphical and PNML representation for de a) net:

```
<?xml version="1.0" encoding="UTF-8"?>
```

```xml
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
          <gate id="N1-igp1" action="input" type="place"/>
          <gate id="N1-ogt1" action="output" type="transition"/>
          <gate id="N1-ogp1" action="output" type="place"/>
        </interface>
        <content id="N1_content">
          <place id="p2"/>
          <place id="p3"/>
          <place id="p4"/>
          <place id="p5"/>
          <transition id="t1"/>
          <transition id="t2"/>
          <transition id="t3"/>
          <transition id="t5"/>
          <arc id="a2" source="t1" target="p2"/>
          <arc id="a3" source="p2" target="t2"/>
          <arc id="a4" source="t2" target="p3"/>
          <arc id="a5" source="t1" target="p4"/>
          <arc id="a6" source="p3" target="t3"/>
          <arc id="a8" source="p4" target="t3"/>
          <arc id="a9" source="t3" target="p5"/>
          <arc id="a10" source="p5" target="t5"/>
          <arc id="N1-a1" source="N1-igp1" target="t1"/>
          <arc id="N1-a7" source="p4" target="N1-ogt1"/>
          <arc id="N1-a11" source="t5" target="N1-ogp1"/>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate id="N2-igp1" action="input" type="place"/>
          <gate id="N2-ogt1" action="output" type="transition"/>
        </interface>
        <content id="N2_content">
          <place id="p7"/>
          <place id="p8"/>
          <transition id="t6"/>
          <transition id="t7"/>
          <arc id="a13" source="t6" target="p7"/>
          <arc id="a14" source="p7" target="t7"/>
          <arc id="a15" source="t7" target="p8"/>
          <arc id="N2-a12" source="N2-igp1" target="t6"/>
          <arc id="N2-a16" source="p8" target="N2-ogt1"/>
        </content>
      </subnet>
      <place id="p1"/>
      <place id="p6"/>
      <transition id="t4"/>
      <transition id="t8"/>
      <arc id="a1" source="p1" target="N1-igp1"/>
```

```
        <arc id="a7" source="N1-ogt1" target="t4"/>
        <arc id="a11" source="N1-ogp1" target="p6"/>
        <arc id="a12" source="p6" target="N2-igp1"/>
        <arc id="a16" source="N2-ogt1" target="t8"/>
        <arc id="a17" source="t8" target="p1"/>
        <arc id="a18" source="t4" target="p6"/>
      </page>
    </net>
</pnml>
```

The b) net has three subnets instead of two. The process y the same, but there is a little difference with a). There are arcs from one output gate of a subnet to one input gate of other subnet, so an original arc is cut in three parts instead of two. The figure 4.9 is the graphical result of subnetting
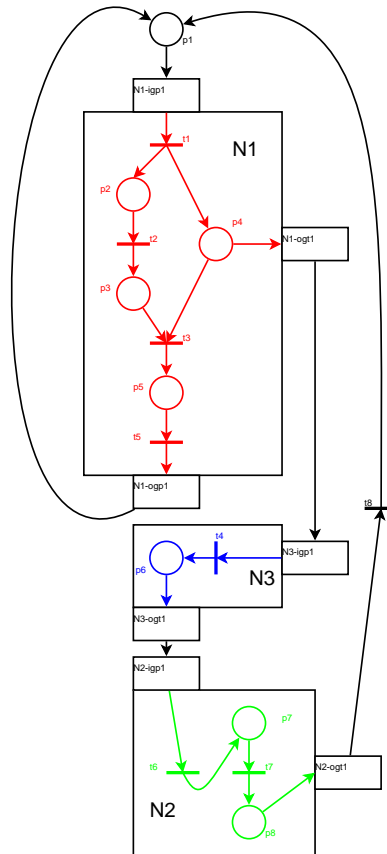

FIGURE 4.9: b) Subnet and interfaces

And this is the final result of the PNML representation:

```
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
```

```xml
<subnet id="N1">
  <interface id="N1-interface">
    <gate id="N1-igp1" action="input" type="place"/>
    <gate id="N1-ogt1" action="output" type="transition"/>
    <gate id="N1-ogp1" action="output" type="place"/>
  </interface>
  <content id="N1_content">
    <place id="p2"/>
    <place id="p3"/>
    <place id="p4"/>
    <place id="p5"/>
    <transition id="t1"/>
    <transition id="t2"/>
    <transition id="t3"/>
    <transition id="t5"/>
    <arc id="a2" source="t1" target="p2"/>
    <arc id="a3" source="p2" target="t2"/>
    <arc id="a4" source="t2" target="p3"/>
    <arc id="a5" source="t1" target="p4"/>
    <arc id="a6" source="p3" target="t3"/>
    <arc id="a8" source="p4" target="t3"/>
    <arc id="a9" source="t3" target="p5"/>
    <arc id="a10" source="p5" target="t5"/>
    <arc id="N1-a1" source="N1-igp1" target="t1"/>
    <arc id="N1-a7" source="p4" target="N1-ogt1"/>
    <arc id="N1-a11" source="t5" target="N1-ogp1"/>
  </content>
</subnet>
<subnet id="N2">
  <interface id="N2-interface">
    <gate id="N2-igp1" action="input" type="place"/>
    <gate id="N2-ogt1" action="output" type="transition"/>
  </interface>
  <content id="N2_content">
    <place id="p7"/>
    <place id="p8"/>
    <transition id="t6"/>
    <transition id="t7"/>
    <arc id="a13" source="t6" target="p7"/>
    <arc id="a14" source="p7" target="t7"/>
    <arc id="a15" source="t7" target="p8"/>
    <arc id="N2-a12" source="N2-igp1" target="t6"/>
    <arc id="N2-a16" source="p8" target="N2-ogt1"/>
  </content>
</subnet>
<subnet id="N3">
  <interface id="N3-interface">
    <gate id="N3-igp1" action="input" type="place"/>
    <gate id="N3-ogt1" action="output" type="transition"/>
  </interface>
  <content id="N3_content">
    <place id="p6"/>
    <transition id="t4"/>
    <arc id="N3-a18" source="t4" target="p6"/>
  </content>
```

```
            </subnet>
            <place id="p1"/>
            <place id="p6"/>
            <transition id="t4"/>
            <transition id="t8"/>
            <arc id="a1" source="p1" target="N1-igp1"/>
            <arc id="a7" source="N1-ogt1" target="N3-igp1"/>
            <arc id="a11" source="N1-ogp1" target="p1"/>
            <arc id="a12" source="N3-ogt1" target="N2-igp1"/>
            <arc id="a16" source="N2-ogt1" target="t8"/>
            <arc id="a17" source="t8" target="p1"/>
        </page>
    </net>
</pnml>
```
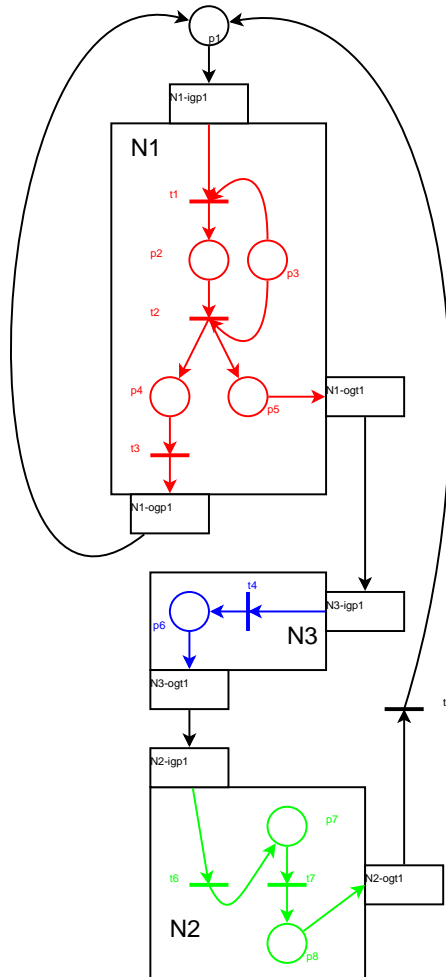
The last example is the c) net. It is going to be cut in three subnets too. The graphical result is the figure 4.10:

FIGURE 4.10: c) Subnet and interfaces

And the PNML representation is:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml
    xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1"
      type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
          <gate id="N1-igp1" action="input" type="place"/>
          <gate id="N1-ogt1" action="output" type="transition"/>
          <gate id="N1-ogp1" action="output" type="place"/>
        </interface>
        <content id="N1_content">
          <place id="p2"/>
          <place id="p3"/>
          <place id="p4"/>
          <place id="p5"/>
          <transition id="t1"/>
          <transition id="t2"/>
          <transition id="t3"/>
          <arc id="a2" source="t1" target="p2"/>
          <arc id="a3" source="p2" target="t2"/>
          <arc id="a4" source="t2" target="p3"/>
          <arc id="a5" source="t1" target="p4"/>
          <arc id="a6" source="p3" target="t3"/>
          <arc id="a8" source="p4" target="t3"/>
          <arc id="a9" source="t3" target="p5"/>
          <arc id="a10" source="p5" target="t5"/>
          <arc id="N1-a1" source="N1-igp1" target="t1"/>
          <arc id="N1-a7" source="p4" target="N1-ogt1"/>
          <arc id="N1-a11" source="t5" target="N1-ogp1"/>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate id="N2-igp1" action="input" type="place"/>
          <gate id="N2-ogt1" action="output" type="transition"/>
        </interface>
        <content id="N2_content">
          <place id="p7"/>
          <place id="p8"/>
          <transition id="t6"/>
          <transition id="t7"/>
          <arc id="a13" source="t6" target="p7"/>
          <arc id="a14" source="p7" target="t7"/>
          <arc id="a15" source="t7" target="p8"/>
          <arc id="N2-a12" source="N2-igp1" target="t6"/>
          <arc id="N2-a16" source="p8" target="N2-ogt1"/>
        </content>
      </subnet>
      <subnet id="N3">
        <interface id="N3-interface">
          <gate id="N3-igp1" action="input" type="place"/>
          <gate id="N3-ogt1" action="output" type="transition"/>
```

```
      </interface>
      <content id="N3_content">
        <place id="p6"/>
        <transition id="t4"/>
        <arc id="N3-a18" source="t4" target="p6"/>
      </content>
    </subnet>
    <place id="p1"/>
    <place id="p6"/>
    <transition id="t4"/>
    <transition id="t8"/>
    <arc id="a1" source="p1" target="N1-igp1"/>
    <arc id="a7" source="N1-ogt1" target="N3-igp1"/>
    <arc id="a11" source="N1-ogp1" target="p1"/>
    <arc id="a12" source="N3-ogt1" target="N2-igp1"/>
    <arc id="a16" source="N2-ogt1" target="t8"/>
    <arc id="a17" source="t8" target="p1"/>
  </page>
 </net>
</pnml>
```

Note that the interfaces are exactly equals than the b) net. N2 and N3 are the same, but N1 is different, but with the same interface (attachable net). So I could replace one subnet for another with no problem.

4.4   Conclusions

In this section we have seen a way to represent subnets in PNML format. It has not been a formal definition, but general guidelines in order to make a more extended study of the Petri nets. There are lots of different Petri net types. Each one of them has their own particularities that have to be translated into the PNML format. The method explained here is based on the basic general Petri nets, but it can see viewed as an algorithm that allow these types to define their own tags.

Basically, four new xml tags are introduced

- `<subnet>`, for delimitating the scope (places and transitions) of the subnet

- `<interface>`, for defining the gates to enter or leave the subnet. Each arc entering or leaving the subnet is associated to a specific gate. Each gate is represented with the tag `<gate>` and can be of several types: input/output (depending on if the arcs enters or leaves the subnet) and place/transition (depending on if the arc is associated to a place or a transition outside the subnet)

- `<content>`, where the places and transitions inside the subnet are placed, in addition to the arcs between them.

The really important thing in this chapter is to identify the subnet and process it in order to extract and interface that is the only way to enter and leave the subnet. The details of each one of the different Petri net types are not specified because of the big casuistry of them.

Once the method is applied, there has to be one subnet content and one subnet interface. There are two rules that must be accomplished:

1. no arc can join nodes inside the subnet with nodes outside and viceversa

2. the interface has to support all the arcs entering and leaving the subnet with the same information of the arcs replaced.

If these two rules are complied, then the subnet is correctly defined. Obviously, this method can be applied several times in order to declare several subnets. the only restriction is that each place or transition can be only in one subnet: no place/transition can be stored in two or more.

Chapter 5

Security

5.1 Introduction

This is the second main goal, after subnetting. Once the possible subnets are defined it is the turn of securing them. It is possible to secure Petri subnets or the entire net.

With secure, I mean four goals:

- **Privacy**. Concrete parts of the net must be occulted: the content is secret, so not everybody should be able to know it.

- **Integrity**. Any change in the secured parts has to be detected. If any of these parts suffers any kind of modification, the information may have been compromised, and perhaps it is not valid or correct. But I cannot know what has been modified: I can only detect that the original content has been changed.

- **Authentication**. I can authenticate the source of that net/subnet (the signer, author or guarantor).

- **Non repudiation**. With this characteristic, the possibility of supplant other people is avoided. So the person that sign that part cannot say that he hadn't done it. The signer cannot deny it.

There can be several reasons for hiding information of a Petri net. For example:

- One subnet is a secret process that I want to hide from indiscrete eyes

- I have a main process that communicates with other processes. These processes are susceptible to be changed and the only information I need is the interface, so they can be easily replaced by other implementations.

But this information should be accessible to authorized people without necessity of supplying any other kind of data. So the whole information may be stored in the same file.

In the same way, there can be many reasons for the rest of the security characteristics. For example, suppose that we have a Petri net that several people can access an modify and:

- Some parts of that Petri net have been validated an accepted, so I want nobody to change them. In this case **integrity** is needed.

- I want to know who has developed a concrete chunk of the net. **Authentication** is required.

- There is a part of the Petri net that is bad defined and go wrong. The person responsible of this part says that he hasn't made it and somebody has supplant him. Then, **non repudiation** is needed.

The best way to reach these goals is using standard and proved technologies. In this case, the selected technologies are:

- XMLEncryption[75] for privacy.

- XMLSignature [76] for integrity, authentication and non repudiation.

5.2 XMLEncryption

5.2.1 XMLEncryption revision

XMLEncryption is a World Wide Web Consortium (W3C) Recommendation for encrypting xml or non xml content. It is a standard xml file cipher. Both symmetric and asymmetric ciphering can be used, but in this case, symmetric is preferred. The main idea of this encryption is to replace the xml element or elements we want to be ciphered by other xml code that contains the ciphered data, in addition to information of the algorithms and keys used for the encryption process. When a non xml file is ciphered, the only option is to encrypt it completely. But, when it is applied to xml content, this technology allows us to define concrete fragments of the document we want to hide. Moreover, the xml document can be transformed before applying the encryption, for example, in order to format the normalize the xml content. In this work, the pieces of

xml content susceptible to be ciphered are, obviously, the subnets represented in PNML format.

Regardless of the data source (xml or non xml) the result is always a xml element. Normal is that this xml encrypted chunk have the whole necessary information to be decrypted. Among that information we can find:

- Ciphering algorithm: it is the name of chosen method to encrypt the data. It can be not included. In this case, both ciphering and deciphering agents have to know which is the exact this algorithm.

- The ciphered data: obviously this parts is mandatory and has always to be present.

- Name of the chosen key: it is optional. It is used when a set of keys is known by both ciphering and deciphering agents.

- Key: it is optional. In this case there is a symmetric key in order to encrypt the data and an additional pair of keys: one (known by the cipher agent) to encrypt the symmetric key and the other (known by the decipher agent) to decrypt it.

Actually, there are several options to apply XMLEncryption, such as the algorithm or the key. The exact election of those option values is responsibility of the Petri net sender. For example:

- Maybe both parts (sender and receiver) have a common set of keys, so they can use it in order to encrypt and decrypt the subnet content.

- Other common use is that the key is defined inside the options but it is ciphered itself. If the receiver have a pair of keys (public and private) and an asymmetrical algorithm (such as Diffie-Hellman or RSA) , the symmetric key can be ciphered by the sender with the receiver's public key. In this case, only the receiver can decrypt it using his private key.

This section does not want to be an extensive explanation about XMLEncryption but a general idea about its functionality. So I am not going to deepen the whole characteristics of XMLEncryption. The final decision about which options use is responsibility of those people that want to apply this work, basing their decision on the requirements of their own Petri net.

Once this is said, here we have a basic example of XMLEncryption. Let's take this original xml document:

```xml
<?xml version='1.0'?>
<PaymentInfo xmlns='http://example.org/paymentv2'>
  <Name>John Smith</Name>
  <CreditCard Limit='5,000' Currency='USD'>
    <Number>4019 2445 0277 5567</Number>
    <Issuer>Example Bank</Issuer>
    <Expiration>04/02</Expiration>
  </CreditCard>
</PaymentInfo>
```

LISTING 5.1: Clear xml content

In this example, we want to hide the credit card number <Number>. Several options are going to be applied: with and without the ciphering information

First of all let's see which will be the aspect of the ciphered content without information about ciphering, only replacing the clear data by the encrypted data: we have not information about the key or the ciphering algorithm. This is the xml ciphered code:

```xml
<?xml version='1.0'?>
<PaymentInfo xmlns='http://example.org/paymentv2'>
  <Name>John Smith</Name>
  <CreditCard Limit='5,000' Currency='USD'>
    <Number>
      <xenc:EncryptedData xmlns='http://www.w3.org/2001/04/xmlenc#'
          Type='http://www.w3.org/2001/04/xmlenc#Content'>
        <xenc:CipherData>
          <xenc:CipherValue>A23B45C56</CipherValue>
        </CipherData>
      </EncryptedData>
    </Number>
    <Issuer>Example Bank</Issuer>
    <Expiration>04/02</Expiration>
  </CreditCard>
</PaymentInfo>
```

LISTING 5.2: Ciphered xml content without ciphering information

As we can see, the credit card number has been replaced by a new tag <EncryptedData> that contains the ciphered credit card number.

Note. A new namespace xenc appear that is the standard namespace for XMLEncryption. However, in further examples this namespace can be delete for clarity and for space problems without loss of generality.

And now let's see how does this same example with information about the algorithm:

```xml
<?xml version='1.0'?>
<PaymentInfo xmlns='http://example.org/paymentv2'>
  <Name>John Smith</Name>
  <CreditCard Limit='5,000' Currency='USD'>
```

```
    <Number>
      <xenc:EncryptedData xmlns='http://www.w3.org/2001/04/xmlenc#'
          Type='http://www.w3.org/2001/04/xmlenc#Content'>
        <xenc:EncryptionMethod
            Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"
            xmlns:xenc="http://www.w3.org/2001/04/xmlenc#" />
        <xenc:CipherData>
          <xenc:CipherValue>A23B45C56</CipherValue>
        </CipherData>
      </EncryptedData>
    </Number>
    <Issuer>Example Bank</Issuer>
    <Expiration>04/02</Expiration>
  </CreditCard>
</PaymentInfo>
```

LISTING 5.3: Ciphered xml content with algorithm information

As we can see, a new tag <EncryptedMethod> has appeared inside the <EncryptedData> tag with the algorithm used to cipher. In this case is aes128-cbc.

There is other method of Encryption that cipher the tag too. In this case, we would have the next code:

```
<?xml version='1.0'?>
<PaymentInfo xmlns='http://example.org/paymentv2'>
  <Name>John Smith</Name>
  <CreditCard Limit='5,000' Currency='USD'>
    <xenc:EncryptedData xmlns='http://www.w3.org/2001/04/xmlenc#'
        Type='http://www.w3.org/2001/04/xmlenc#Element'>
      <xenc:EncryptionMethod
          Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"
          xmlns:xenc="http://www.w3.org/2001/04/xmlenc#" />
      <xenc:CipherData>
        <xenc:CipherValue>A223B3B493G5C569M</CipherValue>
      </CipherData>
    </EncryptedData>
    <Issuer>Example Bank</Issuer>
    <Expiration>04/02</Expiration>
  </CreditCard>
</PaymentInfo>
```

LISTING 5.4: Ciphered xml content including the tag itself
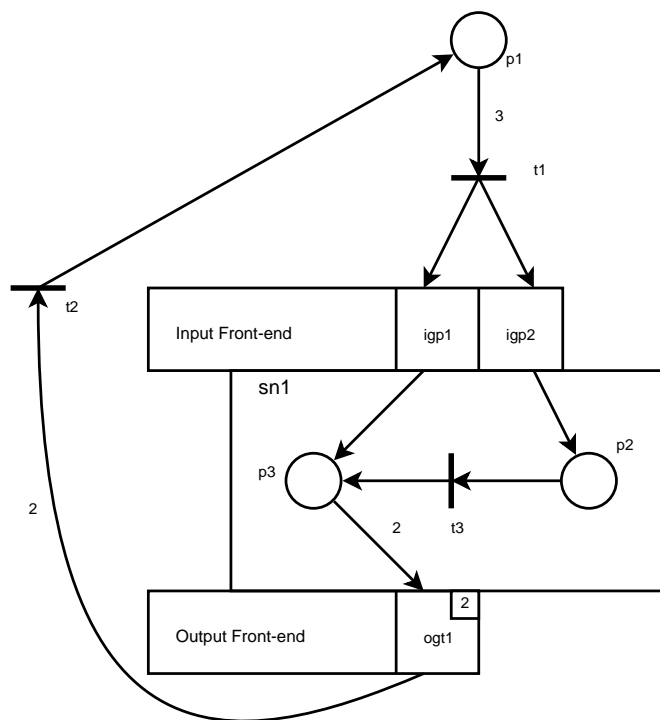
As we can see, the tag <Number> has disappeared and it has been included into the <CipherValue> of the <CipherData>.

This is a little approach to XMLEncryption functionality, but enough for understanding the next section.

5.2.2   XMLEncryption and Petri nets

Once described XMLEncryption it is time to apply it in order to hide part of a Petri net. Remembering the chapter 4, we have one Petri net with one or more subnets represented in a PNML file. These subnets are represented by a `<subnet>` tag that contains `<interface>` and `<content>`. This last tag contains the xml content that is going to be ciphered. Obviously, if we encrypt the interface we will have no way to connect the subnet with the rest of the net.

Let's take back the example used to explain the process of subnetting in the figure 4.6...

...and its PNML representation

```xml
<subnet id="sn1">
  <interface id="sn1-interface">
    <gate id="igp1" action="input" type="place"/>
    <gate id="igp2" action="input" type="place"/>
    <gate id="ogt1" action="output" type="transition">
      <inscription>
        <text> 2 </text>
      </inscription>
    </gate>
  </interface>
  <content id="sn1-content">
    <place id="p2"/>
    <place id="p3"/>
    <transition id="t3"/>
    <arc id="sn1-a2" source="igp2" target="p2"/>
```

```
    <arc id="sn1-a3" source="igp1" target="p3"/>
    <arc id="sn1-a4" source="p3" target="ogt1">
      <inscription>
        <text> 2 </text>
      </inscription>
    </arc>
    <arc id="a5" source="t3" target="p3"/>
    <arc id="a6" source="p2" target="t3"/>
  </content>
</subnet>
<place id="p1"/>
<transition id="t1"/>
<transition id="t2"/>
<arc id="a1" source="p1" target="t1">
  <inscription>
    <text> 3 </text>
  </inscription>
</arc>
<arc id="a2" source="t1" target="igp2"/>
<arc id="a3" source="t1" target="igp1"/>
<arc id="a4" source="ogt1" target="t2">
  <inscription>
    <text> 2 </text>
  </inscription>
</arc>
<arc id="a7" source="t2" target="p1"/>
```

The goal is to hide the internal content of the subnet. If we apply XMLEncryption to the data contained inside the tag <content>, we will get something like this, depending on the algorithm and key selected for the ciphering.

```
<subnet id="sn1">
  <interface id="sn1-interface">
    <gate id="igp1" action="input" type="place"/>
    <gate id="igp2" action="input" type="place"/>
    <gate id="ogt1" action="output" type="transition">
      <inscription>
        <text> 2 </text>
      </inscription>
    </gate>
  </interface>
  <content id="sn1-content">
    <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
        Type="http://www.w3.org/2001/04/xmlenc#Element">
        <xenc:EncryptionMethod
            Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"
            xmlns:xenc="http://www.w3.org/2001/04/xmlenc#" />
        <xenc:CipherData
            xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
            <xenc:CipherValue
                xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                    Wr1njyJlYYOM9lAYqcwGCWkw2L4pUjQD2GGVoU9lVZOwKqHY8y3lGY8FY4i5K
                    3GY8FY4i5K3G8grIe1HRFqe7RtkFiXZgGMeYnQp6oB6ckKp3KFKHVqtucc9rA
                    VzOgC7XAwe61HRFqe6RRVzXjNM9hlVZOwKqHY8y3l3GY8FY4i5K3G8grIe2xN
```

```
                         4u7x7fRtkFiXZgGMeYnQp6oB6ckKp3KFRRVzXjNAtVzOgC7XAw/oe61HRFqe6
                         RRVzXjNMLU5ZgGMeYny8NVPQmUSDX7NRtnR6YnQp6oB6GY8F=
                </xenc:CipherValue>
            </xenc:CipherData>
        </xenc:EncryptedData>
    </content>
</subnet>
<place id="p1"/>
<transition id="t1"/>
<transition id="t2"/>
<arc id="a1" source="p1" target="t1">
    <inscription>
        <text> 3 </text>
    </inscription>
</arc>
<arc id="a2" source="t1" target="igp2"/>
<arc id="a3" source="t1" target="igp1"/>
<arc id="a4" source="ogt1" target="t2">
    <inscription>
        <text> 2 </text>
    </inscription>
</arc>
<arc id="a7" source="t2" target="p1"/>
```

If we try to represent this Petri net we will have the interface of the subnet, but the content is a black box as shown in the figure 5.1.
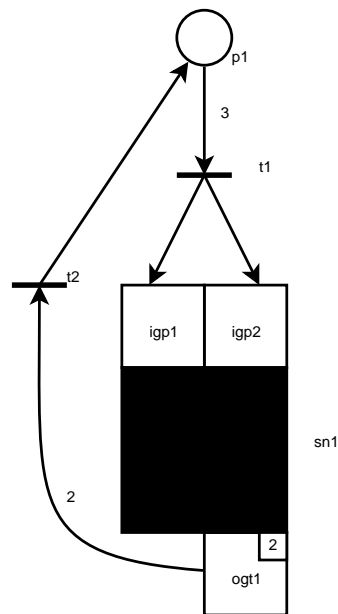

FIGURE 5.1: Petri net with hidden subnet

One important thing is that I can cipher several subnets of the same Petri net with distinct options. For example, if there are two subnets for both two distinct receivers each one of the subnets can be configured in order to each subnet can be decrypted by its own receiver.

5.2.3   Examples

5.2.3.1   Hiding several subnets

Let's take the Petri net from the figure 4.8. I want to occult the content of the subnets N1 and N2. The result should be, graphically, like this:

FIGURE 5.2: Petri net with two hidden subnets

The PNML content is this:

```
<?xml version="1.0" encoding="UTF-8"?>
<pnml xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
          <gate action="input" id="N1-igp1" type="place"/>
          <gate action="output" id="N1-ogt1" type="transition"/>
```
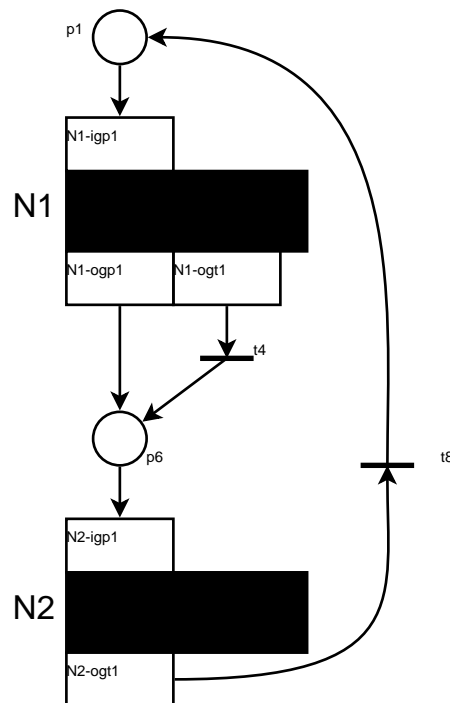
```xml
          <gate action="output" id="N1-ogp1" type="place"/>
        </interface>
        <content id="N1_content">
          <xenc:EncryptedData
              xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
              Type="http://www.w3.org/2001/04/xmlenc#Content">
            <xenc:EncryptionMethod
                Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
            <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
              <xenc:EncryptedKey xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                <xenc:EncryptionMethod
                    Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"/>
                <xenc:CipherData>
                  <xenc:CipherValue>
                    2F3hsIebAicJ6WaS34Hy0OGJKFMAaOoTel/n4jfctbg=
                  </xenc:CipherValue>
                </xenc:CipherData>
              </xenc:EncryptedKey>
            </ds:KeyInfo>
            <xenc:CipherData>
              <xenc:CipherValue>
7oMx5W4VDF6fzvGcvRl71evbyDjTlSRtRVeiNEQSywmWMKz8tunVQPc3uATf4RcuGVroBFNt/3wn
PPSw6uXNPd9CSaTE0qGLmLlmWMBx3ge8rZlohS7uXGwq+Nfvc9QDmtl4+p5KpQdCyp1F/wBhVkGH
ezDWEsSH4fRoLcIwBmHcvroUCNyZ+6Un2+BLWr0U6xl0V9iyCuvZhUKjASupBZ/M3V7s6VzrzPtr
vvxjrIV3dcIZ1dAFBa3CxGjKMF76dqV9x1x3T9S7BqXLdbpXRYfcjOtbeDvIk3Y/HzJAQjGZaVfB
b6fye7aNiBlXOLL0x18W4OvJc9Y66Q3oAuVNlsSlrZAcxmshbDKD0FzkPE/QP929YOEerIq11KGw
SmJOhxsfZuSx+2KL4ZfrCx7CIpO1lJyCKu9r4PL7xZt9rVmKJcIAX546Mks3QKO94cBiQOCh8GbE
hbC7mzPMN/U24hIZ5KUMDdLibwsDchs5abXD+DweEMmC2AV328lLhott1fZRLb8lZ+rtrrmvnHIM
ZF+lrmjfhL9+1PAsVyMBsY8oN7gdXsxzxNHUAhrq0zFbIA58Ro4YjeRZhuACmXx/1y9wYgNjKSwo
x+w17hoYCUdwkzM12iiBJa/QcZcAALcLX2RTF9McAJOElonRrNdUgi9SCBz5ZblgONGyC7Edla7f
7P+QCFJaGFAoKYmDZF9OjTBQ4q+9FV+8/sUXSxqRnXUeUZEB7rhgVY68gyCp4L21aikXyEwQ2PkR
/GPZOWz/Yb7Sbq1pN/G6wqNbsepKWG9EV6n9rjSfiOocvy9wL8m1I0HmAp2l4FRTGKXLBluf0in+
7XvQIwaKz1dyoHGFESjr2Yt316K7LFakCqO6EC5dTIm1TwSuYuLOcNyz+HIOR1fPG1t1gbDok55R
WmJpZGtPciIWRjadmqyCSLHCgzMjAeIuUtf2GAowKsmTep7fUZ5jq3I59ggSKW9JCgjtc7oePQpG
lYxWfqO4oIlgONh+cIJKJMx+8VYh2a68GIkhn7816X2JlHNFjThlHF2rc31O17Wa6MA2eMO8zeyQ
ABsoUCx7BGHc0pzjxs5RF/lRh7rK7isFqUdDTgJAMX+bowZsGD2gDg93N/Yq/D/j0V4AcmWy5dAi
BmwY1WOPVjhgs0SIZhqfMvXo2o1pZvDRtvXEKALmVG6oBKZ+dQdLAIZW5xRlijYAEcwKfbTxosxE
1Gh5nw0tMAO9VxL9e1v1iW+ZdU9SLRf5FYULZ2+DtCqRQQvTP9AK5lJsh4rzV/f+YqQg1qq5IpMO
6OA3Z+OZcHtbZuRz1WyJM+240c8l9NpZILRYADj6Vz5/4FKmz7h1DGAr+TfBjqky7ZTqI+CzGQ==
              </xenc:CipherValue>
            </xenc:CipherData>
          </xenc:EncryptedData>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate action="input" id="N2-igp1" type="place"/>
          <gate action="output" id="N2-ogt1" type="transition"/>
        </interface>
        <content id="N2_content">
          <xenc:EncryptedData
              xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
              Type="http://www.w3.org/2001/04/xmlenc#Content">
            <xenc:EncryptionMethod
                Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
```

```
                <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
                  <xenc:EncryptedKey
                      xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                    <xenc:EncryptionMethod
                        Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"/>
                    <xenc:CipherData>
                      <xenc:CipherValue>
                        2F3hsIebAicJ6WaS34Hy0OGJKFMAaOoTel/n4jfctbg=
                      </xenc:CipherValue>
                    </xenc:CipherData>
                  </xenc:EncryptedKey>
                </ds:KeyInfo>
                <xenc:CipherData>
                  <xenc:CipherValue>
QbzkD9xHRIQVtHrpUQy4YHWcEuOXK135jCtnFHuHOTX4t9Bjwo29YR5GjmGNOjADZJvvQYcXasC3
PsBR/nymLyGvgnp8B/KNO6flN7f3FWGqPTo2oNpcckAryqCoi0Wy9wB6m/AfCAdVvmiUKzktEmLJ
Z8nyPk3n2pKyoKqLHSxtp1mu2Ll2gk6xpbdIgzy2aIT0KryrbRgcdLSSCI/L8om5d9MTstZGWVdr
2zl0ClAW68ef7/aqn6cyqJn/7czQvY8APFtQhWbQnBXjDMVCm1UH0FwfIffQfYENzi/8EhPB266P
ggj/2dv/Uk0TI+WB3BLhnbnrLoa0yIigSzYJYEz6EEn6D5deGOhnITxRdF9rgQliNxnirEeb+9ki
KlxFSB54h1TGzFV5UYQdHcuy0zf0XWBC2fQmdiCQtuzpvJqoOnQsdGmJhJjf65pZnFnvpNAPQF+S
RGN0tf4v8wP5ItSGl6O0GcSD2GRfkHfpfck6vAo/jxfzUs8j4qEOm9l9MB0TS1JLtQuNbBmTFTRz
3UgxChaDjBzR5s29uca9ZqirdZwnars+telyOVFD5qtBnWDTTVxSCLaeS7CEOgVWj9tQbUq7yqPK
fRnWhFyTZIuMCAuN+ybN3AWxsqwv499Q
                  </xenc:CipherValue>
                </xenc:CipherData>
              </xenc:EncryptedData>
            </content>
          </subnet>
          <place id="p1"/>
          <place id="p6"/>
          <transition id="t4"/>
          <transition id="t8"/>
          <arc id="a1" source="p1" target="N1-igp1"/>
          <arc id="a7" source="N1-ogt1" target="t4"/>
          <arc id="a11" source="N1-ogp1" target="p6"/>
          <arc id="a12" source="p6" target="N2-igp1"/>
          <arc id="a16" source="N2-ogt1" target="t8"/>
          <arc id="a17" source="t8" target="p1"/>
          <arc id="a18" source="t4" target="p6"/>
      </page>
    </net>
</pnml>
```
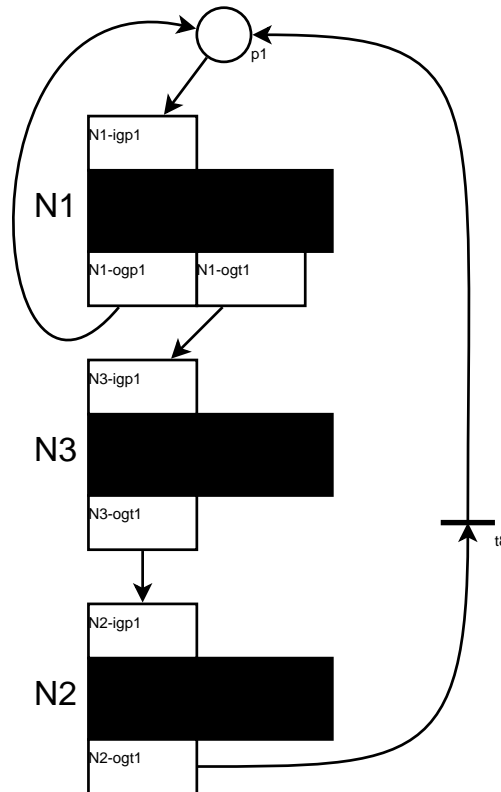
We can see that the content of the subnets has been replaced by a new XML content with ciphered information that cannot be decrypted unless we have the correct decrypting key.

5.2.3.2   Encrypted replacement

Other application of this encryption method is that I can replace ciphered content with other ciphered content without decrypting it. For example, let's take the net 4.9 and

let's cipher it. As in the previous example, the graphical representation is:

And the PNML content is:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
          <gate action="input" id="N1-igp1" type="place"/>
          <gate action="output" id="N1-ogt1" type="transition"/>
          <gate action="output" id="N1-ogp1" type="place"/>
        </interface>
        <content id="N1_content">
          <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
              Type="http://www.w3.org/2001/04/xmlenc#Content">
            <xenc:EncryptionMethod
                Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
            <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
              <xenc:EncryptedKey
                  xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                <xenc:EncryptionMethod
                    Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"/>
                <xenc:CipherData>
                  <xenc:CipherValue>
                    adSAmnteqXFUBdX3I6ClLoe27subXx/IPie9RUh3Viw=
                  </xenc:CipherValue>
                </xenc:CipherData>
```

```
              </xenc:EncryptedKey>
            </ds:KeyInfo>
            <xenc:CipherData>
              <xenc:CipherValue>
49adWIMQ3edEv8SArCsR6090GQU+2pjRhvkMH/kOlHDVcJmGw5Edu7jzIvZc7FF/4vzfKy8hgdXi
MIEQLhd7dbLdoBmkbZzZBnEZbD+JELC3lenV328xv0Y5jtx60vDM+cOEY94C8ctSlGmswlTC7m/h
pXyXtMtAipKcPBtqU6HiXW90gpEIosnEhat6+hyjpESgiQgbuHkYmSeCCqwMWvIR++UkB7Sf6hzP
er4QLUwZfuAbLH9NbReLmLbjpumGhWnMbvKXvwYAWnl1sjrtqnU2NZBWBLV8Uo3EMrTajI/2KA6o
XBo/piONJDEK5Q1lkpLm/+RFD+V1D7iKIXzUVdkOx4RbpOQarrz6bfnwfUBpPSDT+W1qz+8IILmd
DfXvyKGAefKzeOMiHf3YnSso+a5rm61XSmTVClBv2kYqcuADuh9GMsSVG1Uu94eg2C67DWKXFADK
dELk4g/W7FFDn77pqtcSG0BRb4NbGWaOz+m+hrXm/C8S8Ha/36A2DV1ysoAjrJlWsSxIPqf9gxL+
vWXpBr1d7KdD93g15natV4X80BD+2sWu23ZUlSavjLsOfNcocxIzlSXWlwGYyHoHGuHPcRzjn8Sr
hQ4s4gypOKlisc6EgRjbc+UlvLkVnc91LHHWKOhJuvCdgiodl6w//qf7J8X6ase0fhFBkHIUoOMz
XOQekOPKRgzHgz3iIkynwzShSpxSIaADynlJq6zUbbN77aOV4JyXJQRvyizZBCQz/kea8r1zBHJU
hPafRtTW1gZADB2C6xhrkE2KmMXlPzRwDGzPcRIfMo1frpg8PwJkNUhoFZSiZVvTOioB/jf4ITIO
Z/ffRxNokOVWHInjzjE09S5vyDli8VOq2fe1SOnjp/vKGZgv6cYxh6TrtjKGsC8J3nGgIb6PcSKR
+hzGCr8ZwGL3W8O5HogAELLDOC/u6knAdsOwCVPFcK72NroFPJu5O9ulGAJqNUoMlXLMAq1PfPmL
zdJPFcHSglOW/QvVtB3i7CyZrakyE2AiGZfmJko+pzFOI9VqkN989XHkchpF6gcQ1Zwcnxf8bben
fqT5zUVqStA4xJGCVHtyWIkIWGdbmIpzdEpiDUuozj+HzmC2zTS3r7EaViii34TOJkbOFt6IfTDn
NNX+LeH8P3JGxKEv27drQmchpWXrvithwt78csYPB6G395Wnpo+joQcQ7Bv7TREpu1n+OKdydZ3K
aGyozTHOkGMKoL1NCAVoj9f/4chjn/k9NM58KF63F0BtIDWS70k69iQb2rs5kAyA2SJ7YCkE6OI3
LXgAFjgOrXqjF9NSlwt3eEFsDWRdhn/epVGbkexdnjXBOnGW79AFcClYsVkj1vsSmJx5EvkvIw==
              </xenc:CipherValue>
            </xenc:CipherData>
          </xenc:EncryptedData>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate action="input" id="N2-igp1" type="place"/>
          <gate action="output" id="N2-ogt1" type="transition"/>
        </interface>
        <content id="N2_content">
          <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
              Type="http://www.w3.org/2001/04/xmlenc#Content">
            <xenc:EncryptionMethod
                Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
            <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
              <xenc:EncryptedKey xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                <xenc:EncryptionMethod
                    Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"/>
                <xenc:CipherData>
                  <xenc:CipherValue>
                    adSAmnteqXFUBdX3I6ClLoe27subXx/IPie9RUh3Viw=
                  </xenc:CipherValue>
                </xenc:CipherData>
              </xenc:EncryptedKey>
            </ds:KeyInfo>
            <xenc:CipherData>
              <xenc:CipherValue>
f3qOP5rBe3h/B4j1ruwdyBHDf59hu1Z27UhN9U4VgUisgzKcFcT6dO6GGtveXBoSHKv/oi8ZVCsS
9XWuAVZsMk7LB4M2A3hKsDqEpGsPWD1S+9Z84vNZbq1YGaukA/VqeCV/tmTEIS9p5ygFJwszS9Ri
o81rQ+dyOB9GsyLl1HQbaeRAvbY5mut5z+wdgOeiBmdTLkbJ+WGqv0RNK/X8lxGmTdqNiczWvHQ7
cozZbJo0nG2UqtUqLRNnLIfHL3YTORLpEEwg09rUIgxHr9eNv/Q7Nxxi4Rv3DeGL9LGWoZm2F8a6
rUQ8vxoQBPzTkvcAFcMyD2VWx3YfirCE+CsIW1rNEm8YKRsbix4TDBjkAzU7shnHtlCR+AwSF24V
```

```xml
TtqMSZEvdDBoTYaublqqwpuwjejIyJ72oswQgKDPYdgVNZrtUL5Cf7VLXVzD7gTlg2rRFaEPUlID
jDQiHE7JHNmKWlk4MaJ/XKnQ/uyEdFNF7BDpykwZhWkDZsM+rXSauG72bmtBc6xljdrllwMtE9pV
Q/T4PO6Q3zORLQ6+vTlYDCQ9NOAsPNt481I2cOg/T/qOteTk2/vavoU8fO2e/RKDjLSzznRe52aV
GTfbLnbjNgewPcIFp8qFUPhWBExfs2Pa
                </xenc:CipherValue>
              </xenc:CipherData>
            </xenc:EncryptedData>
          </content>
        </subnet>
        <subnet id="N3">
          <interface id="N3-interface">
            <gate action="input" id="N3-igp1" type="place"/>
            <gate action="output" id="N3-ogt1" type="transition"/>
          </interface>
          <content id="N3_content">
            <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
                Type="http://www.w3.org/2001/04/xmlenc#Content">
              <xenc:EncryptionMethod
                  Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
              <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
                <xenc:EncryptedKey
                    xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                  <xenc:EncryptionMethod
                      Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"/>
                  <xenc:CipherData>
                    <xenc:CipherValue>
                      adSAmnteqXFUBdX3I6ClLoe27subXx/IPie9RUh3Viw=
                    </xenc:CipherValue>
                  </xenc:CipherData>
                </xenc:EncryptedKey>
              </ds:KeyInfo>
              <xenc:CipherData>
                <xenc:CipherValue>
OBQYbCoHJjFPwKoFK6WbZ/0z0GT16QoHSJnJ8S2KSuKaXrbKrX7i+mAEXWqPIkBiOFZg18FwHlba
BD2lD3B+MOOJe+Jvig1r7rxwVtI4ZkCDlDBi7cC0uzB3E6f3WmD1Rz8PyigMfAwkUW8bHnblqU+R
SzRZEyjt9B8NEe3rCtuEEQRs/HGa/WTrYP9wUjxOKKYkLTD5PUz3tAsHFTpFOTlw9jMgIq5QC9eP
wuufPGQ=
                </xenc:CipherValue>
              </xenc:CipherData>
            </xenc:EncryptedData>
          </content>
        </subnet>
        <place id="p1"/>
        <place id="p6"/>
        <transition id="t4"/>
        <transition id="t8"/>
        <arc id="a1" source="p1" target="N1-igp1"/>
        <arc id="a7" source="N1-ogt1" target="N3-igp1"/>
        <arc id="a11" source="N1-ogp1" target="p1"/>
        <arc id="a12" source="N3-ogt1" target="N2-igp1"/>
        <arc id="a16" source="N2-ogt1" target="t8"/>
        <arc id="a17" source="t8" target="p1"/>
      </page>
  </net>
</pnml>
```

Now, suppose that we have other subnet ciphered with the same interface as N1. For example:

```xml
<subnet id="N5">
  <interface id="N5-interface">
    <gate action="input" id="N5-igp1" type="place"/>
    <gate action="output" id="N5-ogt1" type="transition"/>
    <gate action="output" id="N5-ogp1" type="place"/>
  </interface>
  <content id="N5_content">
    <xenc:EncryptedData
        xmlns:xenc="http://www.w3.org/2001/04/xmlenc#"
        Type="http://www.w3.org/2001/04/xmlenc#Content">
      <xenc:EncryptionMethod
          Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
      <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
        <xenc:EncryptedKey xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
          <xenc:EncryptionMethod
              Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"/>
          <xenc:CipherData>
            <xenc:CipherValue>
              7fw3o2IsAjwMotze2QUnYLQKm0KawfqhEMd2pLUGvd8=
            </xenc:CipherValue>
          </xenc:CipherData>
        </xenc:EncryptedKey>
      </ds:KeyInfo>
      <xenc:CipherData>
        <xenc:CipherValue>
iRTrqnS0l66bI0R71gU6wY8kASLqCsF43Ljbpe72Ne2JDENTBp1I6oapcgxr8pLfDD2XpzFKV9cE
EXyBHcuS2MG2YVrf0QVoHNIvp7y0246bWei6HlXPZH4sGVOtlSZKqlU5kWtV3k++ZQ9yyJ0F7pG1
KdqCaOGJ0j64wpf/UO+KQeDVhVc9toD4vj9HxGqAMa6pFizHmqg0B/iNjz6fFXN7JFkevjx6a/e8
QPHlpR/bLR/43P4Q7lWOJt9FTU/GAd3bOoIOY3qMhN3hgLTcWv47Uh6gymAgnXhAqygBNcYyHS79
4fXjQUh8DFW2AlE6Bx4hHC/tNd+shRGbaZZ4hmLqVhSe7DWB3px9WDtpN2JMeDGen3TvSSNPjAnk
h5lkchzCajgFRCAAxxHMmm9BtVBdQ+4ZejKBJKas8kXcDwc2hYQEnK31p2SXNMmCJwpTSoiNIR7s
9YS6R6r4IJlmvR/hlKxGF/ZGxAFBtFRjsBoN5aI03L6wwmOfxOgl2sNvpjpvU3xYb7+fFP9s1eJ5
pJW6ZGMAegsUd+VPDq+QolcLXs9jBW6ADTcPP3ZgLDX75+PTTVOqnYYrQhLz5fqDC9iwzWzI68bc
moUqy7yKq8wDdtlSh0TPMYg33O5u6S9UcI7Pc0bElRu8rLS0JU+eAt/+v7PfXXLqM/J1Oux9MGcJ
eivcx9OTX3xx6BTjRee6GrNy0/jiv51Q8MWncWfbu+lPhmYyWtWJAOC8ixXHQpYNHVoFJm1QOOaA
KolYfVbgIsS1868HGkTPtAb5/8pJIyi8X2h1VmHPbbxwjAmOA/zNEWjY+uv2x/lkZ3BN86wcsvW2
4LaKU/kaiAasPANHazl6RzoTqEtBMO6E/ihwmpHaQSOJebG0YzexJ4v66PxyCgPMzEoz8xtwQeQs
7d4Nrtebhj5ZiAWdtDi2uwt/6i9RzOLdXSQC10pqDALSYlQQYa1hLm8+li4a9xkkA3jcuqYXaIku
d88wfI8lSeLzCSyJfTZYORtPrn5QwxcyNQulrIDJlQgyY2r/CENKqIcN5nAuOQnwEQx5GvihSEEk
aV1gy1Ji1GDaQkMbNAVJmkMZZWlhUC3+ODMChKT1r6jH7U0OlylOnZCOiWL7j9P9wbsN1WR+49CE
yKOi7HNSjqzIk71U7Z2HiIOCAOmY0T5Lb6j2K19xVYH5wYqqV5acqqKSz7/2wDY4NycfB56y2Uor
uO5YakMbNM6TWvOIi6hkTsF83gI4cEfPjw4t18fRw1eb9ULJ7Qk0o3S64FvbUuxYQrgjHg/MfM9d
WLOBzHiDdw==
        </xenc:CipherValue>
      </xenc:CipherData>
    </xenc:EncryptedData>
  </content>
</subnet>
```

As the encryption only affect to the replaced content, I can take this subnet and replace it in the other net, instead of N1. The only thing I have to do is to change the origin or

target of the arcs. Normally, the gates ids are different and this has to be reflected in the code. So this PNML content is valid too:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N5">
        <interface id="N5-interface">
          <gate action="input" id="N5-igp1" type="place"/>
          <gate action="output" id="N5-ogt1" type="transition"/>
          <gate action="output" id="N5-ogp1" type="place"/>
        </interface>
        <content id="N5_content">
          <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#" Type="http://www.w3
            <xenc:EncryptionMethod Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
            <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
              <xenc:EncryptedKey xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
                <xenc:EncryptionMethod Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"
                <xenc:CipherData>
                  <xenc:CipherValue>
                7fw3o2IsAjwMotze2QUnYLQKm0KawfqhEMd2pLUGvd8=
                </xenc:CipherValue>
                  </xenc:CipherData>
                </xenc:EncryptedKey>
            </ds:KeyInfo>
            <xenc:CipherData>
              <xenc:CipherValue>
iRTrqnS0l66bIOR71gU6wY8kASLqCsF43Ljbpe72Ne2JDENTBp1I6oapcgxr8pLfDD2XpzFKV9cE
EXyBHcuS2MG2YVrf0QVoHNIvp7y0246bWei6HlXPZH4sGVOtlSZKqlU5kWtV3k++ZQ9yyJ0F7pG1
KdqCa0GJ0j64wpf/UO+KQeDVhVc9toD4vj9HxGqAMa6pFizHmqg0B/iNjz6fFXN7JFkevjx6a/e8
QPHlpR/bLR/43P4Q7lWOJt9FTU/GAd3bOoIOY3qMhN3hgLTcWv47Uh6gymAgnXhAqygBNcYyHS79
4fXjQUh8DFW2AlE6Bx4hHC/tNd+shRGbaZZ4hmLqVhSe7DWB3px9WDtpN2JMeDGen3TvSSNPjAnk
h5lkchzCajgFRCAAxxHMmm9BtVBdQ+4ZejKBJKas8kXcDwc2hYQEnK31p2SXNMmCJwpTSoiNIR7s
9YS6R6r4IJlmvR/hlKxGF/ZGxAFBtFRjsBoN5aI03L6wwmOfxOgl2sNvpjpvU3xYb7+fFP9s1eJ5
pJW6ZGMAegsUd+VPDq+QolcLXs9jBW6ADTcPP3ZgLDX75+PTTVOqnYYrQhLz5fqDC9iwzWzI68bc
moUqy7yKq8wDdtlSh0TPMYg33O5u6S9UcI7Pc0bElRu8rLS0JU+eAt/+v7PfXXLqM/J1Oux9MGcJ
eivcx9OTX3xx6BTjRee6GrNy0/jiv51Q8MWncWfbu+lPhmYyWtWJAOC8ixXHQpYNHVoFJm1QOOaA
KolYfVbgIsS1868HGkTPtAb5/8pJIyi8X2h1VmHPbbxwjAmOA/zNEWjY+uv2x/lkZ3BN86wcsvW2
4LaKU/kaiAasPANHazl6RzoTqEtBMO6E/ihwmpHaQSOJebG0YzexJ4v66PxyCgPMzEoz8xtwQeQs
7d4Nrtebhj5ZiAWdtDi2uwt/6i9Rz0LdXSQC10pqDALSYlQQYa1hLm8+li4a9xkkA3jcuqYXaIku
d88wfI8lSeLzCSyJfTZYORtPrn5QwxcyNQulrIDJlQgyY2r/CENKqIcN5nAuOQnwEQx5GvihSEEk
aV1gy1Ji1GDaQkMbNAVJmkMZZWlhUC3+ODMChKT1r6jH7U00lylOnZCOiWL7j9P9wbsN1WR+49CE
yKOi7HNSjqzIk71U7Z2HiIOCA0mY0T5Lb6j2K19xVYH5wYqqV5acqqKSz7/2wDY4NycfB56y2Uor
uO5YakMbNM6TWvOIi6hkTsF83gI4cEfPjw4t18fRw1eb9ULJ7Qk0o3S64FvbUuxYQrgjHg/MfM9d
WLOBzHiDdw==
              </xenc:CipherValue>
            </xenc:CipherData>
          </xenc:EncryptedData>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate action="input" id="N2-igp1" type="place"/>
          <gate action="output" id="N2-ogt1" type="transition"/>
```

```
      </interface>
      <content id="N2_content">
        <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#" Type="http://www.w3
          <xenc:EncryptionMethod Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
          <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
            <xenc:EncryptedKey xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
              <xenc:EncryptionMethod Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"
              <xenc:CipherData>
                <xenc:CipherValue>
                  adSAmnteqXFUBdX3I6ClLoe27subXx/IPie9RUh3Viw=
                </xenc:CipherValue>
              </xenc:CipherData>
            </xenc:EncryptedKey>
          </ds:KeyInfo>
          <xenc:CipherData>
          <xenc:CipherValue>
f3qOP5rBe3h/B4j1ruwdyBHDf59hu1Z27UhN9U4VgUisgzKcFcT6dO6GGtveXBoSHKv/oi8ZVCsS
9XWuAVZsMk7LB4M2A3hKsDqEpGsPWD1S+9Z84vNZbq1YGaukA/VqeCV/tmTEIS9p5ygFJwszS9Ri
o81rQ+dyOB9GsyLl1HQbaeRAvbY5mut5z+wdgOeiBmdTLkbJ+WGqvORNK/X8lxGmTdqNiczWvHQ7
cozZbJo0nG2UqtUqLRNnLIfHL3YTORLpEEwg09rUIgxHr9eNv/Q7Nxxi4Rv3DeGL9LGWoZm2F8a6
rUQ8vxoQBPzTkvcAFcMyD2VWx3YfirCE+CsIW1rNEm8YKRsbix4TDBjkAzU7shnHtlCR+AwSF24V
TtqMSZEvdDBoTYaublqqwpuwjejIyJ72oswQgKDPYdgVNZrtUL5Cf7VLXVzD7gTlg2rRFaEPUlID
jDQiHE7JHNmKWlk4MaJ/XKnQ/uyEdFNF7BDpykwZhWkDZsM+rXSauG72bmtBc6xljdrllwMtE9pV
Q/T4PO6Q3zORLQ6+vTlYDCQ9NOAsPNt481I2cOg/T/qOteTk2/vavoU8fO2e/RKDjLSzznRe52aV
GTfbLnbjNgewPcIFp8qFUPhWBExfs2Pa
          </xenc:CipherValue>
          </xenc:CipherData>
        </xenc:EncryptedData>
      </content>
    </subnet>
    <subnet id="N3">
      <interface id="N3-interface">
        <gate action="input" id="N3-igp1" type="place"/>
        <gate action="output" id="N3-ogt1" type="transition"/>
      </interface>
      <content id="N3_content">
        <xenc:EncryptedData xmlns:xenc="http://www.w3.org/2001/04/xmlenc#" Type="http://www.w3
          <xenc:EncryptionMethod Algorithm="http://www.w3.org/2001/04/xmlenc#aes128-cbc"/>
          <ds:KeyInfo xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
            <xenc:EncryptedKey xmlns:xenc="http://www.w3.org/2001/04/xmlenc#">
              <xenc:EncryptionMethod Algorithm="http://www.w3.org/2001/04/xmlenc#kw-tripledes"
              <xenc:CipherData>
                <xenc:CipherValue>
                  adSAmnteqXFUBdX3I6ClLoe27subXx/IPie9RUh3Viw=
                </xenc:CipherValue>
              </xenc:CipherData>
            </xenc:EncryptedKey>
          </ds:KeyInfo>
          <xenc:CipherData>
          <xenc:CipherValue>
OBQYbCoHJjFPwKoFK6WbZ/Oz0GT16QoHSJnJ8S2KSuKaXrbKrX7i+mAEXWqPIkBiOFZg18FwHlba
BD2lD3B+MOOJe+Jvig1r7rxwVtI4ZkCDlDBi7cCOuzB3E6f3WmD1Rz8PyigMfAwkUW8bHnblqU+R
SzRZEyjt9B8NEe3rCtuEEQRs/HGa/WTrYP9wUjx0KKYkLTD5PUz3tAsHFTpFOTlw9jMgIq5QC9eP
wuufPGQ=
          </xenc:CipherValue>
```

```
                </xenc:CipherData>
              </xenc:EncryptedData>
          </content>
        </subnet>
        <place id="p1"/>
        <place id="p6"/>
        <transition id="t4"/>
        <transition id="t8"/>
        <arc id="a1" source="p1" target="N5-igp1"/>
        <arc id="a7" source="N5-ogt1" target="N3-igp1"/>
        <arc id="a11" source="N5-ogp1" target="p1"/>
        <arc id="a12" source="N3-ogt1" target="N2-igp1"/>
        <arc id="a16" source="N2-ogt1" target="t8"/>
        <arc id="a17" source="t8" target="p1"/>
      </page>
    </net>
</pnml>
```

5.3 XMLSignature

5.3.1 Introduction

Although privacy is a solved question with XMLEncryption, there are other aspects of the security that XMLEncryption can't cover. For example:

- We want nobody to modify parts of a Petri net.

- I want to put on record that I am the Petri net author or responsible.

- Maybe I want to be sure that the author of a Petri net is somebody with no doubt.

To solve these questions, we can use digital signature. It gives us several interesting characteristics:

- **Integrity**: The data integrity will appear if we are able to avoid, or at least detect, any non authorized modification of the information

- **Authentication**: authentication guarantee that somebody is who says that he is. Basically, with digital signature nobody can impersonate another.

- **Non repudiation**: with this characteristic, we can avoid that somebody says he hasn't signed something if he really did. Only that person can have done it.

In this case I want to sign a whole Petri net or concrete parts of it. Obviously, if I sign only a fragment of a Petri net, this part keeps integrity, authentication and non repudiation, but the rest of net doesn't.

As with XMLEncryption, the best way to achieve this goals is using standard technologies. For signing, the method chosen is XMLSignature [76].

5.3.2   XMLSignature revision

XMLSignature is a digital signing standard. With XMLSignature we can sign any kind of content but the result is XML content. It requires the use of digital certificates and a set of public/private keys, using asymmetrical ciphering algorithms for the process.

It has three possibilities:

1. **Enveloped**: The result of the signing is the original xml file with a new attached signature element inside.

2. **Enveloping**: The result of the signing is a new xml file with the digital signature, and, inside it, the original signed elements of the initial xml file.

3. **Detached**: The result of the signature is a new independent file. The original xml file remains inalterable, The new file contains the sign.

It is indifferent which of this three methods use. They are only different ways to organize the generated signature.

XMLSignature forces a digital signature to have:

- **Canonicalization method**: Basically, we have an equivalent relationship that is able to detect if two xml files are equivalent each other. A canonicalization method transforms a xml file into a canonicalized one that is the representant of the equivalence class. All the equivalent xml files are transformed in this representant. This transform has to be applied before signing. If no method is declared, there is one defined by default.

- **Reference**: there can be several references in one only signature. Each reference indicates a part of the document that has to be signed and the digest algorithm used[1]. It is important to say that each reference doesn't generate a signature, but all of these references are signed together and generates only one signature.

---

[1] A digest algorithm generates a fixed length bytes sequence from arbitrary length contents. This bytes sequence is different for each content

- **Key information**: Optionally, the signature can include necessary information to be validated. In this part we can indicate the public key directly, by a bytes sequence, by an URL or the most usual X.509 digital certificates.

- **Transforms**: It is possible that what we want to sign is not the whole document, but concrete information obtained from it (but not the content itself): e.g. encoding/decoding, select only certain parts, modify the XML structure, include fragments of other documents,... Transforms is a ordered list of processing steps that has to be applied to the content before being digested. This feature is optional but in this case it will be necessary.

A XML signature consists of a tag `<Signature>` that is defined in the following namespace: `http://www.w3.org/2000/09/xmldsig#`

The basic structure of the element signature is:

```
<Signature>
  <SignedInfo>
    <CanonicalizationMethod />
    <SignatureMethod />
    <Reference>
      <Transforms>
        <Transform />
      </Transforms>
      <DigestMethod>
      <DigestValue>
    </Reference>
    <Reference /> etc.
  </SignedInfo>
  <SignatureValue />
  <KeyInfo />
  <Object />
</Signature>
```

The element `<Object>` is used only in enveloping signature to store the signed data. In this case I am going to use enveloped signature, so this element will no be present in the examples.

The final aspect of a complete XMLSignature element is like this example:

```
<Signature xmlns="http://www.w3.org/2000/09/xmldsig#">
  <SignedInfo xmlns="http://www.w3.org/2000/09/xmldsig#">
    <CanonicalizationMethod
        Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315"
        xmlns="http://www.w3.org/2000/09/xmldsig#" />
    <SignatureMethod
        Algorithm="http://www.w3.org/2000/09/xmldsig#dsa-sha1"
        xmlns="http://www.w3.org/2000/09/xmldsig#" />
    <Reference URI=""
        xmlns="http://www.w3.org/2000/09/xmldsig#">
```

```
        <Transforms
            xmlns="http://www.w3.org/2000/09/xmldsig#">
         <Transform
             Algorithm="http://www.w3.org/2000/09/xmldsig#enveloped-signature"
             xmlns="http://www.w3.org/2000/09/xmldsig#" />
        </Transforms>
        <DigestMethod
            Algorithm="http://www.w3.org/2000/09/xmldsig#sha1"
            xmlns="http://www.w3.org/2000/09/xmldsig#" />
        <DigestValue
            xmlns="http://www.w3.org/2000/09/xmldsig#">
         Oyyx+K28+cp7kuUgcnANtTBdUwg=
        </DigestValue>
       </Reference>
     </SignedInfo>
     <SignatureValue xmlns="http://www.w3.org/2000/09/xmldsig#">
       ZVzRud7G4mEZsDnBavbnZoFUmm5J2OBDkQ+IooDLn95ndGYdrq6uPQ==
     </SignatureValue>
     <KeyInfo xmlns="http://www.w3.org/2000/09/xmldsig#">
       <X509Data xmlns="http://www.w3.org/2000/09/xmldsig#">
        <X509Certificate
            xmlns="http://www.w3.org/2000/09/xmldsig#">
         IICmDCCAlYCBEfrim8wCwYHKoZIzjgEAwUAMDIxCzAJBgNVBAYTAkVTMREwDwYDVQQKEwhBd
         pYTEQMA4GA1UEAxMHVXN1YXJpbzAeFw0wODAzMjcxMTUyMTVaFw0wOTAzMjcxMTUyMTVaMDI
         BgNVBAYTAkVTMREwDwYDVQQKEwhBdXRlbnRpY2EQMA4GA1UEAxMHVXN1YXJpbzCCAbcwggEs
         BgcqhkjOOAQBMIIBHwKBgQD9f1OBHXUSKVLfSpwu7OTn9hG3UjzvRADDHj+AtlEmaUVdQCJR
         jVj6v8X1ujD2y5tVbNeBO4AdNG/yZmC3a5lQpaSfn+gEexAiwk+7qdf+t8Yb+DtX58aophUP
         9tPFHsMCNVQTWhaRMvZ1864rYdcq7/IiAxmd0UgBxwIVAJdgUI8VIwvMspK5gqLrhAvwWBz1
         APfhoIXWmz3ey7yrXDa4V7l5lK+7+jrqgvlXTAs9B4JnUVlXjrrUWU/mcQcQgYC0SRZxI+hM
         t88JMozIpuE8FnqLVHyNKOCjrh4rs6Z1kW6jfwv6ITVi8ftiegEkO8yk8b6oUZCJqIPf4Vrl
         i2ZegHtVJWQBTDv+zOkqA4GEAAKBgDUPDwxDZFXMrZha74VNmgyFslLMO1wKw17nbt9UFTJA
         iPpozeZMP2u0SoYst2nbxkCs1hziiuaNJnykzcjVf3+PmL3sQES8SxwJBRUME2UTA2006WD3
         iZ9yibcWQimB8eKIJyBBxSk5TueAzvTA8HN2+Rvgh8RMaOzhMAsGByqGSM44BAMFAAMvADAs
         4+nQZdFvlvsfyOfq1t02h9MJEgIUEvYDfxeygKCmrIlA0sQLtaCs0Qo=
        </X509Certificate>
       </X509Data>
       <KeyValue xmlns="http://www.w3.org/2000/09/xmldsig#">
        <DSAKeyValue
            xmlns="http://www.w3.org/2000/09/xmldsig#">
         <P xmlns="http://www.w3.org/2000/09/xmldsig#">
          /X9TgR11EilS30qcLuzk5/YRt1I870QAwx4/gLZRJmlFXUAiUftZPY1Y+r/F9bow9subVWz
          HTRv8mZgt2uZUKWkn5/oBHsQIsJPu6nX/rfGG/g7V+fGqKYVDwT7g/bTxR7DAjVUE1oWkTL
          K2HXKu/yIgMZndFIAcc=
         </P>
         <Q xmlns="http://www.w3.org/2000/09/xmldsig#">
          l2BQjxUjC8yykrmCouuEC/BYHPU=
         </Q>
         <G xmlns="http://www.w3.org/2000/09/xmldsig#">
          9+GghdabPd7LvKtcNrhXuXmUr7v6OuqC+VdMCz0HgmdRWVeOutRZT+ZxBxCBgLRJFnEj6Ew
          zwkyjMim4TwWeotUfIOo4KOuHiuzpnWRbqN/C/ohNWLx+2J6ASQ7zKTxvqhRkImog9/hWuW
          Zl6Ae1UlZAFMO/7PSSo=
         </G>
         <Y xmlns="http://www.w3.org/2000/09/xmldsig#">
          NQ8PDENkVcytmFrvhU2aDIWyUszTXArDXudu31QVMkAuTvWI+mjN5kw/a7RKhiy3advGQKz
          5oOmfKTNyNV/f4+YvexARLxLHAkFFQwTZRMDbTTpYPfE3L2Jn3KJtxZCKYHx4ognIEHFKTl
```

```
                  9MDwc3b5G+CHxExo7OE=
            </Y>
        </DSAKeyValue>
    </KeyValue>
  </KeyInfo>
</Signature>
```

At first sight it seems very complicated, but it isn't. First of all, the attribute xmlns that is in almost all the tags is only the namespace. From here, for more clarity it can be obviated. So the example is as follows:

```
<Signature>
  <SignedInfo>
    <CanonicalizationMethod
        Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315" />
    <SignatureMethod
        Algorithm="http://www.w3.org/2000/09/xmldsig#dsa-sha1" />
    <Reference URI="">
      <Transforms>
        <Transform
            Algorithm="http://www.w3.org/2000/09/xmldsig#enveloped-signature"/>
      </Transforms>
      <DigestMethod
          Algorithm="http://www.w3.org/2000/09/xmldsig#sha1" />
      <DigestValue>
          Oyyx+K28+cp7kuUgcnANtTBdUwg=
      </DigestValue>
    </Reference>
  </SignedInfo>
  <SignatureValue>
    ZVzRud7G4mEZsDnBavbnZoFUmm5J2OBDkQ+IooDLn95ndGYdrq6uPQ==
  </SignatureValue>
  <KeyInfo>
    <X509Data>
      <X509Certificate>
        IICmDCCAlYCBEfrim8wCwYHKoZIzjgEAwUAMDIxCzAJBgNVBAYTAkVTMREwDwYDVQQKEwhBd
        pYTEQMA4GA1UEAxMHVXN1YXJpbzAeFw0wODAzMjcxMTUyMTVaFw0wOTAzMjcxMTUyMTVaMDI
        BgNVBAYTAkVTMREwDwYDVQQKEwhBdXRlbnRpYTEQMA4GA1UEAxMHVXN1YXJpbzCCAbcwggEs
        BgcqhkjOOAQBMIIBHwKBgQD9f1OBHXUSKVLfSpwu7OTn9hG3UjzvRADDHj+AtlEmaUVdQCJR
        jVj6v8X1ujD2y5tVbNeBO4AdNG/yZmC3a5lQpaSfn+gEexAiwk+7qdf+t8Yb+DtX58aophUP
        9tPFHsMCNVQTWhaRMvZ1864rYdcq7/IiAxmd0UgBxwIVAJdgUI8VIwvMspK5gqLrhAvwWBz1
        APfhoIXWmz3ey7yrXDa4V7l5lK+7+jrqgvlXTAs9B4JnUVlXjrrUWU/mcQcQgYCOSRZxI+hM
        t88JMozIpuE8FnqLVHyNKOCjrh4rs6Z1kW6jfwv6ITVi8ftiegEkO8yk8b6oUZCJqIPf4Vrl
        i2ZegHtVJWQBTDv+zO0kqA4GEAAKBgDUPDwxDZFXMrZha74VNmgyFslLM01wKw17nbt9UFTJA
        iPpozeZMP2u0SoYst2nbxkCs1hziiuaNJnykzcjVf3+PmL3sQES8SxwJBRUME2UTA2006WD3
        iZ9yibcWQimB8eKIJyBBxSk5TueAzvTA8HN2+Rvgh8RMaOzhMAsGByqGSM44BAMFAAMvADAs
        4+nQZdFvlvsfyOfq1t02h9MJEgIUEvYDfxeygKCmrIlAOsQLtaCs0Qo=
      </X509Certificate>
    </X509Data>
    <KeyValue>
      <DSAKeyValue>
        <P>
           /X9TgR11EilS30qcLuzk5/YRt1I870QAwx4/gLZRJmlFXUAiUftZPY1Y+r/F9bow9subVWz
           HTRv8mZgt2uZUKWkn5/oBHsQIsJPu6nX/rfGG/g7V+fGqKYVDwT7g/bTxR7DAjVUE1oWkTL
```

```
          K2HXKu/yIgMZndFIAcc=
      </P>
      <Q>
        l2BQjxUjC8yykrmCouuEC/BYHPU=
      </Q>
      <G>
        9+GghdabPd7LvKtcNrhXuXmUr7v6OuqC+VdMCz0HgmdRWVeOutRZT+ZxBxCBgLRJFnEj6Ew
        zwkyjMim4TwWeotUfI0o4KOuHiuzpnWRbqN/C/ohNWLx+2J6ASQ7zKTxvqhRkImog9/hWuW
        Zl6Ae1UlZAFMO/7PSSo=
      </G>
      <Y>
        NQ8PDENkVcytmFrvhU2aDIWyUszTXArDXudu31QVMkAuTvWI+mjN5kw/a7RKhiy3advGQKz
        5oOmfKTNyNV/f4+YvexARLxLHAkFFQwTZRMDbTTpYPfE3L2Jn3KJtxZCKYHx4ognIEHFKTl
        9MDwc3b5G+CHxExo7OE=
      </Y>
    </DSAKeyValue>
  </KeyValue>
  </KeyInfo>
</Signature>
```

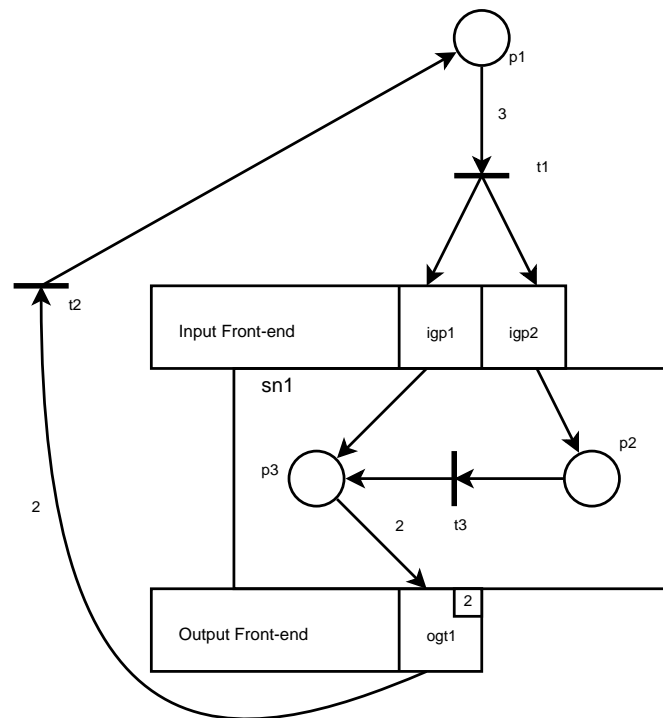### 5.3.3   XMLSignature and Petri nets

In this case I am going to use enveloped signature, so the result of the signature is stored in a new tag inside the original PNML file. As I explained before, we have to select which parts of the PNML file are going to be signed.

Many times we will need to sign the whole Petri net, but it will be very usual to sign only certain parts of a Petri net, for example a critical subprocess. The modus operandi here is similar to XMLEncryption. First of all, the content to be signed should be grouped in a subnet and then, this subnet is signed.

The standard way to indicate a subnet to sign in XMLSignature is through a XPath [82] expression. In XMLSignature, the way to specify XPath addresses is using XMLSignature XPath Filter [83]. XPathFilter returns the node set that is going to be signed and it is placed into `/Signature/SignedInfo/Reference/Transforms` as a new `<Transform>`.

I am not going to explain all the possibilities of XPath Filter. I will explain only those main configurations useful to my objective. The exact configuration depends on the particular necessities of each case.

In order to illustrate the process, let's take the figure 4.6 as example again:

and its full PNML representation:

```xml
<?xml version="1.0" encoding="utf-8"?>
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <name>
      <text> My new net </text>
    </name>
    <page id="page1">
      <subnet id="sn1">
        <interface id="sn1-interface">
        <gate id="igp1" action="input" type="place"/>
        <gate id="igp2" action="input" type="place"/>
        <gate id="ogt1" action="output" type="transition">
          <inscription>
          <text> 2 </text>
          </inscription>
        </gate>
        </interface>
        <content id="sn1-content">
        <place id="p2"/>
        <place id="p3"/>
        <transition id="t3"/>
        <arc id="sn1-a2" source="igp2" target="p2"/>
        <arc id="sn1-a3" source="igp1" target="p3"/>
        <arc id="sn1-a4" source="p3" target="ogt1">
          <inscription>
          <text> 2 </text>
          </inscription>
```

```
      </arc>
      <arc id="a5" source="t3" target="p3"/>
      <arc id="a6" source="p2" target="t3"/>
      </content>
    </subnet>
    <place id="p1"/>
    <transition id="t1"/>
    <transition id="t2"/>
    <arc id="a1" source="p1" target="t1">
      <inscription>
      <text> 3 </text>
      </inscription>
    </arc>
    <arc id="a2" source="t1" target="igp2"/>
    <arc id="a3" source="t1" target="igp1"/>
    <arc id="a4" source="ogt1" target="t2">
      <inscription>
      <text> 2 </text>
      </inscription>
    </arc>
    <arc id="a7" source="t2" target="p1"/>
  </page>
 </net>
</pnml>
```

The first option is to sign the whole net. In XPath, the expression to represent the entire document is:

```
/
```

If we apply XMLSignature with this XPath expression, the result is

```
<?xml version="1.0" encoding="UTF-8"?>
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <name>
      <text> My new net </text>
    </name>
    <page id="page1">
      <subnet id="sn1">
        <interface id="sn1-interface">
          <gate action="input" id="igp1" type="place"/>
          <gate action="input" id="igp2" type="place"/>
          <gate action="output" id="ogt1" type="transition">
            <inscription>
              <text> 2 </text>
            </inscription>
          </gate>
        </interface>
        <content id="sn1-content">
          <place id="p2"/>
          <place id="p3"/>
          <transition id="t3"/>
          <arc id="a2" source="igp2" target="p2"/>
          <arc id="a3" source="igp1" target="p3"/>
          <arc id="a4" source="p3" target="ogt1">
            <inscription>
              <text> 2 </text>
            </inscription>
          </arc>
```

```xml
            <arc id="a5" source="t3" target="p3"/>
            <arc id="a6" source="p2" target="t3"/>
          </content>
        </subnet>
        <place id="p1"/>
        <transition id="t1"/>
        <transition id="t2"/>
        <arc id="a1" source="p1" target="t1">
          <inscription>
            <text> 3 </text>
          </inscription>
        </arc>
        <arc id="a2" source="t1" target="igp2"/>
        <arc id="a3" source="t1" target="igp1"/>
        <arc id="a4" source="ogt1" target="t2">
          <inscription>
            <text> 2 </text>
          </inscription>
        </arc>
        <arc id="a7" source="t2" target="p1"/>
    </page>
  </net>
  <ds:Signature xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
    <ds:SignedInfo>
      <ds:CanonicalizationMethod Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315"/>
      <ds:SignatureMethod Algorithm="http://www.w3.org/2000/09/xmldsig#rsa-sha1"/>
      <ds:Reference URI="">
        <ds:Transforms>
          <ds:Transform Algorithm="http://www.w3.org/2000/09/xmldsig#enveloped-signature"/>
          <ds:Transform Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315#WithComments"/>
          <ds:Transform Algorithm="http://www.w3.org/2002/06/xmldsig-filter2">
            <dsig-xpath:XPath xmlns:dsig-xpath="http://www.w3.org/2002/06/xmldsig-filter2" Filter="union">
              /
            </dsig-xpath:XPath>
          </ds:Transform>
        </ds:Transforms>
        <ds:DigestMethod Algorithm="http://www.w3.org/2000/09/xmldsig#sha1"/>
        <ds:DigestValue>LIMSPHwtGpK3hlDEdfaAv7D39KU=</ds:DigestValue>
      </ds:Reference>
    </ds:SignedInfo>
    <ds:SignatureValue>
      W3C5nlPSYcR2qvx2bOwpGy8CGMuOvWPTZCIQVkYuGUA52lRmtyFRInlRmOG+d+eqQHBwtvMophte
      HWPsPiOl+Bwc/C3HTHj2XBc9P1bcFUtVM91rLhLZhI/ZAl9t6VfLoQ+Cduu8sQJh6qiH24CiYGjc
      FaOlQbQOsYBvGXoBhEk=
    </ds:SignatureValue>
    <ds:KeyInfo>
      <ds:X509Data>
        <ds:X509Certificate>
          MIICgTCCAeqgAwIBAgIETfh4CTANBgkqhkiG9w0BAQUFADCBhDELMAkGA1UEBhMCRVMxETAPBgNV
          BAgTCExBIFJJT0pBMREwDwYDVQQHDAhMT0dST8KlTzEgMB4GA1UEChMXVU5JVkVSU0lEQUQgREUg
          TEEgUklPSkExDDAKBgNVBAsTA1BGQzEfMBOGA1UEAwwWScKlSUdPIExFFw6BOIFNBTUFOSUVHTzAe
          Fw0xMTA2MTUwOTE0ODlaFw0xMTA5MTMwOTE4ODlaMIGEMQswCQYDVQQGEwJFUzERMA8GA1UECBMI
          TEEgUklPSkExETAPBgNVBAcMCExPR1JPwqVPMSAwHgYDVQQKExdVTklWRVJTSURBRCBERSBMQSBS
          SU9KQTEMMAoGA1UECxMDUEZDMR8wHQYDVQQDDBZJwqVJR08gTEXDoE4gU0FNQU5JRUdPMIGfMAOG
          CSqGSIb3DQEBAQUAA4GNADCBiQKBgQChePFNVCIfphFlyXQ9BysiR5BfXIuv3AnAK8OFuw4tTFwC
          nVUjJeGnkUYQO32oUu+fEBK8WsEqjeH8A7zrHTRQjfYZWyuGWrM8gJXOa/POMROPm/c/H8b5a6Nx
          1/+zLwR0tYkqLI2xqDOFII2RwK5L2yGeV4T4y8i3h1U0OFTSEwIDAQABMAOGCSqGSIb3DQEBBQUA
          A4GBAIDOvAAdOCaTpy+83bGB2KmngMJrNxxWDpAi5LGFrN8iCShmbTpIeIbYBUAaBpZtdhOnhq4n
          wD5QOENSFipQcdH5GEpPM9Rquy6xMwfda9EU5UfOSEmbk4fK2vaIOVjynpQsJ9P99enO2smQlyvw
          /hBa7Xacz6qDut8ghUeuV5Js
        </ds:X509Certificate>
      </ds:X509Data>
      <ds:KeyValue>
        <ds:RSAKeyValue>
          <ds:Modulus>
            oXjxTVQiH6YRZcl0PQcrIkeQX1yLr9wJwCvNBbsOLUxcAp1VIyXhp5FGEDt9qFLvnxASvFrBKo3h
            /AO86x00UI32GVsrhlqzPICVzmvz9DETj5v3Px/G+Wujcdf/sy8EdLWJKiyNsagzhSCNkcCuS9sh
            nleE+MvIt4dVNDhU0hM=
          </ds:Modulus>
          <ds:Exponent>AQAB</ds:Exponent>
        </ds:RSAKeyValue>
      </ds:KeyValue>
    </ds:KeyInfo>
  </ds:Signature>
</pnml>
```

In the generated tag `<Signature>` a XMLSignature XPath Filter tag has appeared as a new `<Transform>`

```xml
<ds:Transform Algorithm="http://www.w3.org/2002/06/xmldsig-filter2">
  <dsig-xpath:XPath
      xmlns:dsig-xpath="http://www.w3.org/2002/06/xmldsig-filter2"
      Filter="union">
    /
  </dsig-xpath:XPath>
</ds:Transform>
```

It is easy to see the behaviour of this element: the union of "/" XPath expression, that is to say, the union of the entire document.

The set of nodes returned by this expression is

```xml
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <name>
      <text> My new net </text>
    </name>
    <page id="page1">
      <subnet id="sn1">
        <interface id="sn1-interface">
        <gate action="input" id="igp1" type="place"></gate>
        <gate action="input" id="igp2" type="place"></gate>
        <gate action="output" id="ogt1" type="transition">
          <inscription>
          <text> 2 </text>
          </inscription>
        </gate>
        </interface>
        <content id="sn1-content">
        <place id="p2"></place>
        <place id="p3"></place>
        <transition id="t3"></transition>
        <arc id="sn1-a2" source="igp2" target="p2"></arc>
        <arc id="sn1-a3" source="igp1" target="p3"></arc>
        <arc id="sn1-a4" source="p3" target="ogt1">
          <inscription>
          <text> 2 </text>
          </inscription>
        </arc>
        <arc id="a5" source="t3" target="p3"></arc>
        <arc id="a6" source="p2" target="t3"></arc>
        </content>
      </subnet>
      <place id="p1"></place>
      <transition id="t1"></transition>
      <transition id="t2"></transition>
      <arc id="a1" source="p1" target="t1">
        <inscription>
```

```
        <text> 3 </text>
        </inscription>
      </arc>
      <arc id="a2" source="t1" target="igp2"></arc>
      <arc id="a3" source="t1" target="igp1"></arc>
      <arc id="a4" source="ogt1" target="t2">
        <inscription>
        <text> 2 </text>
        </inscription>
      </arc>
      <arc id="a7" source="t2" target="p1"></arc>
    </page>
  </net>
</pnml>
```

It is the full document (without the first row xml definition) node set.

Other important configuration in this work is the signing of a concrete subnet. In this case, it is a little different as in XMLEncryption. Remember that in XMLEncryption, if I want to mask a subnet I don't process the `<subnet>` tag but the `subnet/content`. This is because the interface has to be visible. But in a signature I want to sign the complete subnet, including the interface. Suppose that this subnet has `id="sn1"`. The XPath expression that represents it is:

`/pnml/net/page/subnet[@id="sn1"]`

The node set in this case is

```
<subnet id="sn1">
  <interface id="sn1-interface">
    <gate action="input" id="igp1" type="place"/>
    <gate action="input" id="igp2" type="place"/>
    <gate action="output" id="ogt1" type="transition">
      <inscription>
        <text> 2 </text>
      </inscription>
    </gate>
  </interface>
  <content id="sn1-content">
    <place id="p2"/>
    <place id="p3"/>
    <transition id="t3"/>
    <arc id="sn1-a2" source="igp2" target="p2"/>
    <arc id="sn1-a3" source="igp1" target="p3"/>
    <arc id="sn1-a4" source="p3" target="ogt1">
      <inscription>
        <text> 2 </text>
      </inscription>
    </arc>
    <arc id="a5" source="t3" target="p3"/>
    <arc id="a6" source="p2" target="t3"/>
  </content>
</subnet>
```

and the signature result is

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml>
  <net id="myNet" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <name>
      <text> My new net </text>
    </name>
    <page id="page1">
      <subnet id="sn1">
        <interface id="sn1-interface">
          <gate action="input" id="igp1" type="place"/>
          <gate action="input" id="igp2" type="place"/>
          <gate action="output" id="ogt1" type="transition">
            <inscription>
              <text> 2 </text>
            </inscription>
          </gate>
        </interface>
        <content id="sn1-content">
          <place id="p2"/>
          <place id="p3"/>
          <transition id="t3"/>
          <arc id="sn1-a2" source="igp2" target="p2"/>
          <arc id="sn1-a3" source="igp1" target="p3"/>
          <arc id="sn1-a4" source="p3" target="ogt1">
            <inscription>
              <text> 2 </text>
            </inscription>
          </arc>
          <arc id="a5" source="t3" target="p3"/>
          <arc id="a6" source="p2" target="t3"/>
        </content>
      </subnet>
      <place id="p1"/>
      <transition id="t1"/>
      <transition id="t2"/>
      <arc id="a1" source="p1" target="t1">
        <inscription>
          <text> 3 </text>
        </inscription>
      </arc>
      <arc id="a2" source="t1" target="igp2"/>
      <arc id="a3" source="t1" target="igp1"/>
      <arc id="a4" source="ogt1" target="t2">
        <inscription>
          <text> 2 </text>
        </inscription>
      </arc>
      <arc id="a7" source="t2" target="p1"/>
    </page>
  </net>
  <ds:Signature xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
    <ds:SignedInfo>
      <ds:CanonicalizationMethod Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315"/>
      <ds:SignatureMethod Algorithm="http://www.w3.org/2000/09/xmldsig#rsa-sha1"/>
      <ds:Reference URI="">
        <ds:Transforms>
          <ds:Transform Algorithm="http://www.w3.org/2000/09/xmldsig#enveloped-signature"/>
          <ds:Transform Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315#WithComments"/>
          <ds:Transform Algorithm="http://www.w3.org/2002/06/xmldsig-filter2">
            <dsig-xpath:XPath xmlns:dsig-xpath="http://www.w3.org/2002/06/xmldsig-filter2" Filter="intersect">
              /pnml/net/page/subnet[@id="sn1"]
            </dsig-xpath:XPath>
          </ds:Transform>
        </ds:Transforms>
        <ds:DigestMethod Algorithm="http://www.w3.org/2000/09/xmldsig#sha1"/>
        <ds:DigestValue>prCzhLgTCZ1ck6MjQnFy6cASCZw=</ds:DigestValue>
      </ds:Reference>
    </ds:SignedInfo>
    <ds:SignatureValue>
      QoO7mQmGBFTg2UxgiZnzlsnKi8V477JC0v12JPItL53zIOCpjhOwLoyxENl6v8lCLoJ9WwFHlBKk
      r3GdqrgZimNXMUjwR4zkd9FVNcIrn85DuRjHA/zDwSuPMq9w0N5AO7c0xJ24uvn9+zpbQxfblYTb
      kiy08+SOpqczU/bv5+g=
    </ds:SignatureValue>
    <ds:KeyInfo>
```

```
<ds:X509Data>
  <ds:X509Certificate>
    MIICgTCCAeqgAwIBAgIETfh4CTANBgkqhkiG9w0BAQUFADCBhDELMAkGA1UEBhMCRVMxETAPBgNV
    BAgTCExBIFJJTOpBMREwDwYDVQQHDAhMT0dST8K1TzEgMB4GA1UEChMXVU5JVkVSU01EQUQgREUg
    TEEgUklPSkExDDAKBgNVBAsTA1BGQzEfMB0GA1UEAwwWScK1SUdPIExFw6BOIFNBTUFOSUVHTzAe
    Fw0xMTA2MTUwOTE0ND1aFw0xMTA5MTMwOTE0NDlaMIGEMQswCQYDVQQGEwJFUzERMA8GA1UECBMI
    TEEgUklPSkExETAPBgNVBAcMCExPR1JPwqVPMSAwHgYDVQQKExdVTk1WRVJTSURBRCBERSBMQSBS
    SU9KQTEMMAoGA1UECxMDUEZDMR8wHQYDVQQDDBZJwqVJR08gTEXDoE4gUOFNQU5JRUdPMIGfMA0G
    CSqGSIb3DQEBAQUAA4GNADCBiQKBgQChePFNVCIfphFlyXQ9BysiR5BfXIuv3AnAK8OFuw4tTFwC
    nVUjJeGnkUYQO32oUu+fEBK8WsEqjeH8A7zrHTRQjfYZWyuGWrM8gJXOa/POMROPm/c/H8b5a6Nx
    1/+zLwR0tYkqLI2xqDOFII2RwK5L2yGeV4T4y8i3h1UOOFTSEwIDAQABMA0GCSqGSIb3DQEBBQUA
    A4GBAIDOvAAdOCaTpy+83bGB2KmngMJrNxxWDpAi5LGFrN8iCShmbTpIeIbYBUAaBpZtdhOnhq4n
    wD5QOENSFipQcdH5GEpPM9Rquy6xMwfda9EU5UfOSEmbk4fK2vaIOVjynpQsJ9P99enO2smQlyvw
    /hBa7Xacz6qDut8ghUeuV5Js
  </ds:X509Certificate>
</ds:X509Data>
<ds:KeyValue>
  <ds:RSAKeyValue>
    <ds:Modulus>
      oXjxTVQiH6YRZcl0PQcrIkeQX1yLr9wJwCvNBbsOLUxcAp1VIyXhp5FGEDt9qFLvnxASvFrBKo3h
      /AO86x00UI32GVsrhlqzPICVzmvz9DETj5v3Px/G+Wujcdf/sy8EdLWJKiyNsagzhSCNkcCuS9sh
      nleE+MvIt4dVNDhUOhM=
    </ds:Modulus>
    <ds:Exponent>AQAB</ds:Exponent>
  </ds:RSAKeyValue>
</ds:KeyValue>
      </ds:KeyInfo>
    </ds:Signature>
</pnml>
```

In this case, the Transform associated to the XPath expression is

```
<ds:Transform Algorithm="http://www.w3.org/2002/06/xmldsig-filter2">
  <dsig-xpath:XPath
      xmlns:dsig-xpath="http://www.w3.org/2002/06/xmldsig-filter2"
      Filter="intersect">
    /pnml/net/page/subnet[@id="sn1"]
  </dsig-xpath:XPath>
</ds:Transform>
```

As we can see, the resultant node set is the intersection of the entire document and the nodes returned by `/pnml/net/page/subnet[@id="sn1"]`, that is, the nodes returned by `/pnml/net/page/subnet[@id="sn1"]`.

5.3.4   Example. Signing all the subnets of a Petri net

Other important configuration is to sign all the subnets defined in a PNML file. Let's take the example Petri net of the figure 4.8 again. The goal is to sign all the subnets, so we are going to use this XPath expression:

```
/pnml/net/page/subnet
```

Then we have the following Petri net
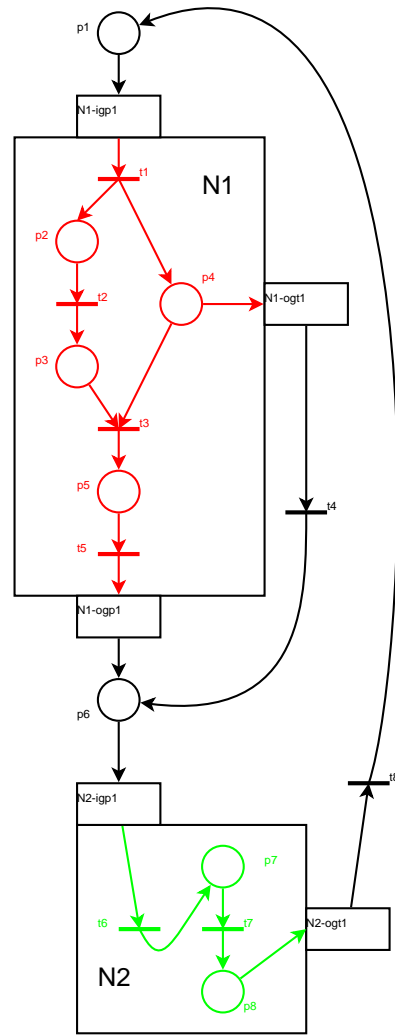
and this is the XML content with the signature of all the subnets:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<pnml xmlns="http://www.pnml.org/version-2009/grammar/pnml">
  <net id="latorre1" type="http://www.pnml.org/version-2009/grammar/ptnet">
    <page id="page1">
      <subnet id="N1">
        <interface id="N1-interface">
          <gate action="input" id="N1-igp1" type="place"/>
          <gate action="output" id="N1-ogt1" type="transition"/>
          <gate action="output" id="N1-ogp1" type="place"/>
        </interface>
        <content id="N1_content">
          <place id="p2"/>
          <place id="p3"/>
          <place id="p4"/>
          <place id="p5"/>
          <transition id="t1"/>
          <transition id="t2"/>
          <transition id="t3"/>
          <transition id="t5"/>
          <arc id="a2" source="t1" target="p2"/>
          <arc id="a3" source="p2" target="t2"/>
          <arc id="a4" source="t2" target="p3"/>
          <arc id="a5" source="t1" target="p4"/>
          <arc id="a6" source="p3" target="t3"/>
          <arc id="a8" source="p4" target="t3"/>
          <arc id="a9" source="t3" target="p5"/>
          <arc id="a10" source="p5" target="t5"/>
```

```xml
          <arc id="N1-a1" source="N1-igp1" target="t1"/>
          <arc id="N1-a7" source="p4" target="N1-ogt1"/>
          <arc id="N1-a11" source="t5" target="N1-ogp1"/>
        </content>
      </subnet>
      <subnet id="N2">
        <interface id="N2-interface">
          <gate action="input" id="N2-igp1" type="place"/>
          <gate action="output" id="N2-ogt1" type="transition"/>
        </interface>
        <content id="N2_content">
          <place id="p7"/>
          <place id="p8"/>
          <transition id="t6"/>
          <transition id="t7"/>
          <arc id="a13" source="t6" target="p7"/>
          <arc id="a14" source="p7" target="t7"/>
          <arc id="a15" source="t7" target="p8"/>
          <arc id="N2-a12" source="N2-igp1" target="t6"/>
          <arc id="N2-a16" source="p8" target="N2-ogt1"/>
        </content>
      </subnet>
      <place id="p1"/>
      <place id="p6"/>
      <transition id="t4"/>
      <transition id="t8"/>
      <arc id="a1" source="p1" target="N1-igp1"/>
      <arc id="a7" source="N1-ogt1" target="t4"/>
      <arc id="a11" source="N1-ogp1" target="p6"/>
      <arc id="a12" source="p6" target="N2-igp1"/>
      <arc id="a16" source="N2-ogt1" target="t8"/>
      <arc id="a17" source="t8" target="p1"/>
      <arc id="a18" source="t4" target="p6"/>
    </page>
  </net>
  <ds:Signature xmlns:ds="http://www.w3.org/2000/09/xmldsig#">
    <ds:SignedInfo>
      <ds:CanonicalizationMethod Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315"/>
      <ds:SignatureMethod Algorithm="http://www.w3.org/2000/09/xmldsig#rsa-sha1"/>
      <ds:Reference URI="">
        <ds:Transforms>
          <ds:Transform Algorithm="http://www.w3.org/2000/09/xmldsig#enveloped-signature"/>
          <ds:Transform Algorithm="http://www.w3.org/TR/2001/REC-xml-c14n-20010315#WithComments"/>
          <ds:Transform Algorithm="http://www.w3.org/2002/06/xmldsig-filter2">
            <dsig-xpath:XPath xmlns:dsig-xpath="http://www.w3.org/2002/06/xmldsig-filter2"
                 Filter="intersect">/pnml/net/page/subnet</dsig-xpath:XPath>
          </ds:Transform>
        </ds:Transforms>
        <ds:DigestMethod Algorithm="http://www.w3.org/2000/09/xmldsig#sha1"/>
        <ds:DigestValue>2jmj7l5rSw0yVb/vlWAYkK/YBwk=</ds:DigestValue>
      </ds:Reference>
    </ds:SignedInfo>
    <ds:SignatureValue>
      PIwJ414XUFjfd5IYFcJBKeCmYJfanN7Wcus5F5PJRl1yMGVcfeocqQv1nTAn86pQW4NxhYrXEEnD
      zO5Dic/aKC/jt8zgnCZ81DVLCnJLmtc61ltKezEs0ekE6A9PsRjPODusqtVKL4C2miiFiPsL3enn
      rXBk3ZPYpLcXZw5q/js=
    </ds:SignatureValue>
    <ds:KeyInfo>
      <ds:X509Data>
        <ds:X509Certificate>
          MIICgTCCAeqgAwIBAgIETfh4CTANBgkqhkiG9w0BAQUFADCBhDELMAkGA1UEBhMCRVMxETAPBgNV
          BAgTCExBIFJJT0pBMREwDwYDVQQHDAhMT0dST8KlTzEgMB4GA1UEChMXVU5JVkVSU0lEQUQgREUg
          TEEgUklPSkExDDAKBgNVBAsTA1BGQzEfMB0GA1UEAwwWScKlSUdPIExFw6BOIFNBTUFOSUVHTzAe
          Fw0xMTA2MTUwOTE0NDlaFw0xMTA5MTMwOTE0NDlaMIGEMQswCQYDVQQGEwJFUzERMA8GA1UECBMI
          TEEgUklPSkExDzAPBgNVBAcMCExPR1JPwqVPMSAwHgYDVQQKExdVTklWRVJTSURBRCBERSBMQSBS
          SU9KQTEMMAoGA1UECxMDUEZDMR8wHQYDVQQDDBZJwqVJR08gTEXDoE4gU0FNQU5JRUdPMIGfMA0G
          CSqGSIb3DQEBAQUAA4GNADCBiQKBgQChePFNVCIfphFlyXQ9BysiR5BfXIuv3AnAK8OFuw4tTFwC
          nVUjJeGnkUYQO32oUu+fEBK8WsEqjeH8A7zrHTRQjfYZWyuGWrM8gJXOa/POMROPm/c/H8b5a6Nx
          1/+zLwR0tYkqLI2xqDOFII2RwK5L2yGeV4T4y8i3h1U0OFTSEwIDAQABMA0GCSqGSIb3DQEBBQUA
          A4GBAIDOvAAdOCaTpy+83bGB2KmngMJrNxxWDpAi5LGFrN8iCShmbTpIeIbYBUAaBpZtdhOnhq4n
          wD5QOENSFipQcdH5GEpPM9Rquy6xMwfda9EU5UfOSEmbk4fK2vaIOVjynpQsJ9P99enO2smQlyvw
          /hBa7Xacz6qDut8ghUeuV5Js
        </ds:X509Certificate>
      </ds:X509Data>
      <ds:KeyValue>
```

```
        <ds:RSAKeyValue >
          <ds:Modulus >
            oXjxTVQiH6YRZcl0PQcrIkeQX1yLr9wJwCvNBbsOLUxcAp1VIyXhp5FGEDt9qFLvnxASvFrBKo3h
            /AO86x00UI32GVsrhlqzPICVzmvz9DETj5v3Px/G+Wujcdf/sy8EdLWJKiyNsagzhSCNkcCuS9sh
            nleE+MvIt4dVNDhUOhM=
          </ds:Modulus >
          <ds:Exponent >AQAB </ds:Exponent >
        </ds:RSAKeyValue >
      </ds:KeyValue >
    </ds:KeyInfo >
  </ds:Signature >
</pnml >
```

5.4 Complete security

In this section I am going to explain several important questions. Until now, I have described the two security operation separately: hiding and signing. I want some parts to be hidden and other parts to be signed. But, what would happen if I want to hide and sign the same parts? In this case, the result is different depending on the order selected. Let's see the differences.

Suppose first cipher and then sign. If this order is applied, the cipher has no problem, but the sign has a obvious but important detail: the signed content is encrypted itself. What does it mean? Well, you don't see what you are signing. The implications are simple: you don't know exactly what you are signing. This order is useful in order to guarantee the integrity, but you have to be sure that what you are signing is exactly what you want.

The other order is: first signing and then ciphering. In this case, signing has no problem. The special characteristic is the ciphering. As explained before in this chapter, after signing, appears a new tag `<Signature>` appended to the original content. Then, if I encrypt the signed content, this tag is still visible but the signature cannot be verified, because the encrypting process replace the original content, so there is a modification of the signed data and it is detected by the signature, avoiding a correct verification of it.

The selected order depends on the responsible of each part. Anyway, there is a W3C recommendation that describes a XMLSignature decryption transform [84] that permits to differentiate between ciphered content that were encrypted before signing (and must not be decrypted) and ciphered content that were encrypted after signing (and must be decrypted). So the XML applications are able to interpret the correct way to validate the signature. As it is a particular case of configuration, and my intention is explain the general guidelines, I am not going to explain it here. Again, the responsible of the net/subnet is who has to decide the concrete configuration, but maintaining the general rules that I explain in this thesis.

5.5   Conclusions

As we have seen, one of the applications of subnetting Petri nets and represent them in PNML is that I can apply standard processes based on XML. In this case, once defined and represented a subnet in PNML, I have applied XMLEncryption in order to hide the internal structure of the subnet and XMLSignature for signing the subnet.

The use of standard and widely extended technologies like XMLEncryption and XMLSignature enables that everybody has access to them, so the processes explained here are perfectly usable.

One important conclusion in the encryption section is that several subnets in the same net can be ciphered with different options. This is used, for example, for one receiver to decrypt the subnet addressed to him but no other one.

Other important use is that with a PNML file with encrypted subnets, I can replace one ciphered subnet by other ciphered subnet without the necessity of decrypt any of them: we can work with encrypted subnets if the interfaces are the same. With the explained in this chapter, the privacy of parts of a Petri net is guarantied.

In XMLSignature, integrity, authentication and non repudiation is assured. A big difference with XMLEncryption is that the signature is attached to the original file, instead of replace part of the net. In this case I have used enveloped signature, but if we use the detached way, the signature is in other file, separating signature and signed content. In signature it makes no sense replace one signature by another, but we can have as many signatures as we want, including different signatures of the same contents.

Using both technologies XMLEncryption and XMLSignature together we can reach very high security levels, but we have to be careful with the order of the processes, because depending on the selected order, the acquired properties will be different.

The last conclusion, but very important one is that the responsible of the net has to choose the concrete configurations of XMLEncryption and XMLSignature, the transforms and the order of the actions in order to achieve his particular objectives.

Chapter 6

Conclusions

Throughout this paper I have enriched Petri nets with definitions and properties. From this initial presentation, have been building a series of elements as a basis for further investigation. We defined subnets, subnets classifications have been studied, we have defined front-ends (interfaces) for those subnets, etc.. From this point is possible a further study of these subnets (their properties, utilities,....) and the methodological study of securing parts of Petri nets.

In the first chapter of this thesis I have introduced the research problem. The nets are represented in a comprehensive way, so that the whole information is visible to everybody. Furthermore, these nets are not prepared to avoid undesired changes or to ensure the authoring of them.

So here is my contribution to the knowledge: to provide security to a Petri net. The aspects covered by this investigation are:

- to occult a part of the net (or entire). The secret is maintained, and all the information is stored in the same file, but hidden. This information is only available to accredited people.

- to avoid unwanted changes. Any modification is, at least, detected.

- to authenticate the net (or a part of it). We know who has developed a Petri net or subnet.

- to avoid the possibility of supplant other people in the authority of the Petri net or some of its parts.

The next chapter is the state of the art. In this chapter, the literature about subnets, hiding, encryption, Petri net representation, PNML extensions, Petri net securing, etc.

are grouped and analyzed in order to understand the general knowledge about these topics, related to my objectives. The general conclusions in this part are:

- There are lots of authors and contents about Petri nets but very few about subnets.

- There is no standard way to represent subnets in a form that is not graphical.

- Many works studied security using Petri nets, but there is not literature about security over Petri nets themselves.

- In particular there is not material on how to hide parts of a Petri nets and either about integrity, authentication or non repudiation.

Once reviewed the state of the art, I enter into the study of subnets. The main goal is to find a structure of Petri subnets that is easily represented in other formats in addition to graphical mode.

In this chapter I explain how to cut a Petri net into several subnets using the incidence matrix. The method of cutting into two subnets is studied. This method split the incidence matrix into four parts: the subnets per se and two other parts that defined the interaction between this two subnets (N_1, N_2, PIM and TIM). This will allow us to define the front-end of a subnet in order to abstract is content from the rest of the net.

Once explained subnets, I make a subnet classification. This classification is based on the structure properties. So we can talk about:

- disjoint subnets, if there are not arcs between the element of the subnet.

- macroplaces, if the only way to enter the subnet is from a transition outside towards a place inside.

- macrotransitions, if the only way to enter the subnet is from a place outside towards a transition inside.

- sinkhole, if there is no arc leaving the subnet.

- source, if there is no arc entering the subnet

Then, one of the main parts of the thesis is studied: the subnet front-end. It is a very important concept because the rest of the thesis is based on it: if I define a subnet with its own front-end, I can know its behaviour without the necessity of knowing the internal structure. In this chapter, I introduce the critical concepts of front-end, input

and output gates from places or transitions and attachable net that are going to be used later.

This part of the Petri subnets theory is finished, so I can go on the representation of this kind of subnets. As one of my goals is to hide parts of a Petri net, but not erasing information, the main problem is to find a way to represent a subnet in order to cipher information. From my point of view, the only alternative nowadays to solve this problem is the use of PNML. Other representations cannot maintain or recover the original information once is hidden.

PNML is a xml standard way to represent Petri nets. But it has a problem: there is noway to represent subnets. So I have explained a possible PNML extension that support this kind of information. The key is the definition of several custom xml tags: `<subnet>`, `<interface>`, `<gate>` and `<content>`. These four tags are enough to my goals. But Petri nets are a really wide knowledge area. So i don't define a closed PNML extension, but a way for each person to extend it as needed.

At this moment I have the basis to secure a Petri net (or parts of it). The next step is the securization itself. The first step is the privacy of the whole net or only of a part. The technology that I have selected to reach this goal is XMLEncryption. As it is an standard, it is widely extended and well known. It has de possibility of symmetric and asymmetric ciphering so the confidentiality of the information is ensured. This method of encryption replace tags in the xml file by encrypted content, only accessible by people that knows the right decrypting key. In this case, the tag replaced is `<content>`, inside the tag `<subnet>`. Once this is done only the front-end of the subnet is exposed, maintaining two properties:

- The structure of the entire net is not affected, because the interaction with elements of the subnet is always through the front-end.

- The information has been not deleted. It is hidden, waiting for somebody with the correct key.

- I can change one subnet by another if they have the same front-end, even though they are ciphered.

The other goals of security are data integrity (not allow unwanted modifications), authentication (know the author or responsible), and non repudiation (nobody can be supplanted by another one). All of these goals can be achieved by a digital signature. In this case I my proposition is the use of XMLSignature, that is going to allow to sign the entire Petri net or only parts of it (the secured ones) by using XPath expressions.

XMLSignature is a standard too, so it has been widely probed and examined by the community. With XMLSignature the signed content is not replaced. Instead of that, a new xml element appears in the PNML file with the necessary information to validate the signature.

And this is the final stage of this thesis. There several ways to follow in further works. For example:

- In this thesis I have worked with very basic Petri nets, with only places, transitions, arcs and weights. This work can be extended to other kind of Petri nets, such as coloured Petri nets, High level Petri nets, fluid Petri nets, ...

- The properties of Petri nets replacing subnets with other subnets can other field of investigation.

- The properties of the subnets have not been studied from the point of view of the behaviour, contemplating markings and evolutions.

Appendix A

PNML grammar

The official PNML grammar is available in www.pnml.org. It is written in RELAX NG format. These are the main parts that I use in this work.

A.1 RELAX NG implementation of PNML Core Model

```xml
<?xml version="1.0" encoding="UTF-8"?>

<grammar ns="http://www.pnml.org/version-2009/grammar/pnml"
  xmlns="http://relaxng.org/ns/structure/1.0"
  xmlns:a="http://relaxng.org/ns/compatibility/annotations/1.0"
  datatypeLibrary="http://www.w3.org/2001/XMLSchema-datatypes">

  <a:documentation>
    Petri Net Markup Language (PNML) schema.
    RELAX NG implementation of PNML Core Model.

    File name: pnmlcoremodel.rng
    Version: 2009
    (c) 2001-2009
    Michael Weber,
    Ekkart Kindler,
    Christian Stehno,
    Lom Hillah (AFNOR)
    Revision:
    July 2008 - L.H
  </a:documentation>

  <include href="http://www.pnml.org/version-2009/grammar/anyElement.rng"/>

  <start>
    <ref name="pnml.element"/>
  </start>

  <define name="pnml.element">
```

```
    <element name="pnml">
      <a:documentation>
        A PNML document consists of one or more Petri nets.
        It has a version.
      </a:documentation>
      <oneOrMore>
        <ref name="pnml.content"/>
      </oneOrMore>
    </element>
</define>

<define name="pnml.content">
  <ref name="net.element"/>
</define>

<define name="net.element">
  <element name="net">
    <a:documentation>
      A net has a unique identifier (id) and refers to
      its Petri Net Type Definition (PNTD) (type).
    </a:documentation>
    <ref name="identifier.content"/>
    <ref name="nettype.uri"/>
    <a:documentation>
      The sub-elements of a net may occur in any order.
      A net consists of at least a top-level page which
      may contain several objects. A net may have a name,
      other labels (net.labels) and tool specific information in any order.
    </a:documentation>
    <interleave>
      <optional>
        <ref name="Name"/>
      </optional>
      <ref name="net.labels"/>
      <oneOrMore>
        <ref name="page.content"/>
      </oneOrMore>
      <zeroOrMore>
        <ref name="toolspecific.element"/>
      </zeroOrMore>
    </interleave>
  </element>
</define>

<define name="identifier.content">
  <a:documentation>
    Identifier (id) declaration shared by all objects in any PNML model.
  </a:documentation>
  <attribute name="id">
    <data type="ID"/>
  </attribute>
</define>

<define name="nettype.uri">
  <a:documentation>
```

```
      The net type (nettype.uri) of a net should be redefined in the grammar
      for a new Petri net Type.
      An example of such a definition is in ptnet.pntd, the grammar
      for P/T Nets. The following value is a default.
    </a:documentation>
    <attribute name="type">
      <value>http://www.pnml.org/version-2009/grammar/pnmlcoremodel</value>
    </attribute>
  </define>


  <define name="net.labels">
    <a:documentation>
      A net may have unspecified many labels. This pattern should be used
      within a PNTD to define the net labels.
    </a:documentation>
    <empty/>
  </define>


  <define name="basicobject.content">
    <a:documentation>
      Basic contents for any object of a PNML model.
    </a:documentation>
    <interleave>
      <optional>
        <ref name="Name"/>
      </optional>
      <zeroOrMore>
        <ref name="toolspecific.element"/>
      </zeroOrMore>
    </interleave>
  </define>



  <define name="page.content">
    <a:documentation>
      A page has an id. It may have a name and tool specific information.
      It may also have graphical information. It can also have many arbitrary labels.
      Note: according to this definition, a page may contain other pages.
      All these sub-elements may occur in any order.
    </a:documentation>
    <element name="page">
      <ref name="identifier.content"/>
      <interleave>
        <ref name="basicobject.content"/>
        <ref name="page.labels"/>
        <zeroOrMore>
          <ref name="netobject.content"/>
        </zeroOrMore>
        <optional>
          <element name="graphics">
            <ref name="pagegraphics.content"/>
          </element>
        </optional>
      </interleave>
    </element>
```

```xml
  </define>

  <define name="netobject.content">
    <a:documentation>
      A net object is either a page, a node or an arc.
      A node is a place or a transition, a reference place of
      a reference transition.
    </a:documentation>
    <choice>
      <ref name="page.content"/>
      <ref name="place.content"/>
      <ref name="transition.content"/>
      <ref name="refplace.content"/>
      <ref name="reftrans.content"/>
      <ref name="arc.content"/>
    </choice>
  </define>

  <define name="page.labels">
    <a:documentation>
      A page may have unspecified many labels. This pattern should be used
      within a PNTD to define new labels for the page concept.
    </a:documentation>
    <empty/>
  </define>

  <define name="place.content">
    <a:documentation>
      A place may have several labels (place.labels) and the same content
      as a node.
    </a:documentation>
    <element name="place">
      <ref name="identifier.content"/>
      <interleave>
        <ref name="basicobject.content"/>
        <ref name="place.labels"/>
        <ref name="node.content"/>
      </interleave>
    </element>
  </define>

  <define name="place.labels">
    <a:documentation>
      A place may have arbitrary many labels. This pattern should be used
      within a PNTD to define the place labels.
    </a:documentation>
    <empty/>
  </define>

  <define name="transition.content">
    <a:documentation>
      A transition may have several labels (transition.labels) and the same
      content as a node.
    </a:documentation>
    <element name="transition">
```

```
      <ref name="identifier.content"/>
      <interleave>
        <ref name="basicobject.content"/>
        <ref name="transition.labels"/>
        <ref name="node.content"/>
      </interleave>
    </element>
  </define>


  <define name="transition.labels">
    <a:documentation>
      A transition may have arbitrary many labels. This pattern should be
      used within a PNTD to define the transition labels.
    </a:documentation>
    <empty/>
  </define>


  <define name="node.content">
    <a:documentation>
      A node may have graphical information.
    </a:documentation>
    <optional>
      <element name="graphics">
        <ref name="nodegraphics.content"/>
      </element>
    </optional>
  </define>


  <define name="reference">
    <a:documentation>
      Here, we define the attribute ref including its data type.
      Modular PNML will extend this definition in order to change
      the behavior of references to export nodes of module instances.
    </a:documentation>
    <attribute name="ref">
      <data type="IDREF"/>
    </attribute>
  </define>


  <define name="refplace.content">
    <a:documentation>
      A reference place is a reference node.
    </a:documentation>
    <a:documentation>
      Validating instruction:
      - _ref_ MUST refer to _id_ of a reference place or of a place.
      - _ref_ MUST NOT refer to _id_ of its reference place element.
      - _ref_ MUST NOT refer to a cycle of reference places.
    </a:documentation>
    <element name="referencePlace">
      <ref name="refnode.content"/>
    </element>
  </define>

  <define name="reftrans.content">
```

```xml
        <a:documentation>
          A reference transition is a reference node.
        </a:documentation>
        <a:documentation>
          Validating instruction:
          - The reference (ref) MUST refer to a reference transition or to a
          transition.
          - The reference (ref) MUST NOT refer to the identifier (id) of its
          reference transition element.
          - The reference (ref) MUST NOT refer to a cycle of reference transitions.
        </a:documentation>
        <element name="referenceTransition">
          <ref name="refnode.content"/>
        </element>
    </define>


    <define name="refnode.content">
        <a:documentation>
          A reference node has the same content as a node.
          It adds a reference (ref) to a (reference) node.
        </a:documentation>
        <ref name="identifier.content"/>
        <ref name="reference"/>
        <ref name="basicobject.content"/>
        <ref name="node.content"/>
    </define>


    <define name="arc.content">
        <a:documentation>
          An arc has a unique identifier (id) and
          refers both to the node's id of its source and
          the node's id of its target.
          In general, if the source attribute refers to a place,
          then the target attribute refers to a transition and vice versa.
        </a:documentation>
        <element name="arc">
          <ref name="identifier.content"/>
          <attribute name="source">
            <data type="IDREF"/>
          </attribute>
          <attribute name="target">
            <data type="IDREF"/>
          </attribute>
          <a:documentation>
            The sub-elements of an arc may occur in any order.
            An arc may have a name, graphical and tool specific information.
            It may also have several labels.
          </a:documentation>
          <interleave>
            <optional>
              <ref name="Name"/>
            </optional>
            <ref name="arc.labels"/>
            <optional>
              <element name="graphics">
```

```
              <ref name="edgegraphics.content"/>
            </element>
          </optional>
          <zeroOrMore>
            <ref name="toolspecific.element"/>
          </zeroOrMore>
        </interleave>
      </element>
  </define>


  <define name="arc.labels">
    <a:documentation>
      An arc may have arbitrary many labels. This pattern should be used
      within a PNTD to define the arc labels.
    </a:documentation>
    <empty/>
  </define>


  <define name="pagegraphics.content">
    <a:documentation>
      A page graphics is actually a node graphics
    </a:documentation>
    <ref name="nodegraphics.content"/>
  </define>


  <define name="nodegraphics.content">
    <a:documentation>
      The sub-elements of a node's graphical part occur in any order.
      At least, there may be one position element.
      Furthermore, there may be a dimension, a fill, and a line element.
    </a:documentation>
    <interleave>
      <ref name="position.element"/>
      <optional>
        <ref name="dimension.element"/>
      </optional>
      <optional>
        <ref name="fill.element"/>
      </optional>
      <optional>
        <ref name="line.element"/>
      </optional>
    </interleave>
  </define>


  <define name="edgegraphics.content">
    <a:documentation>
      The sub-elements of an arc's graphical part occur in any order.
      There may be zero or more position elements.
      Furthermore, there may be a line element.
    </a:documentation>
    <interleave>
      <zeroOrMore>
        <ref name="position.element"/>
      </zeroOrMore>
```

```xml
      <optional>
        <ref name="line.element"/>
      </optional>
    </interleave>
  </define>


  <define name="simpletext.content">
    <a:documentation>
      This definition describes the contents of simple text labels
      without graphics.
    </a:documentation>
    <optional>
      <element name="text">
        <a:documentation>
          A text should have a value.
          If not, then there must be a default.
        </a:documentation>
        <text/>
      </element>
    </optional>
  </define>


  <define name="annotationstandard.content">
    <a:documentation>
      The definition annotationstandard.content describes the
      standard contents of an annotation.
      Each annotation may have graphical or tool specific information.
    </a:documentation>
    <interleave>
      <optional>
        <element name="graphics">
          <ref name="annotationgraphics.content"/>
        </element>
      </optional>
      <zeroOrMore>
        <ref name="toolspecific.element"/>
      </zeroOrMore>
    </interleave>
  </define>


  <define name="simpletextlabel.content">
    <a:documentation>
      A simple text label is an annotation to a net object containing
      arbitrary text.
      Its sub-elements occur in any order.
      A simple text label behaves like an attribute to a net object.
      Furthermore, it contains the standard annotation contents which
      basically defines the graphics of the text.
    </a:documentation>
    <interleave>
      <ref name="simpletext.content"/>
      <ref name="annotationstandard.content"/>
    </interleave>
  </define>
```

```
<define name="Name">
  <a:documentation>
    Label definition for a user given name of an
    element.
  </a:documentation>
  <element name="name">
    <ref name="simpletextlabel.content"/>
  </element>
</define>

<define name="annotationgraphics.content">
  <a:documentation>
    An annotation's graphics part requires an offset element describing
    the offset the center point of the surrounding text box has to
    the reference point of the net object on which the annotation occurs.
    Furthermore, an annotation's graphic element may have a fill, a line,
    and font element.
  </a:documentation>
  <ref name="offset.element"/>
  <interleave>
    <optional>
      <ref name="fill.element"/>
    </optional>
    <optional>
      <ref name="line.element"/>
    </optional>
    <optional>
      <ref name="font.element"/>
    </optional>
  </interleave>
</define>

<define name="position.element">
  <a:documentation>
    A position element describes Cartesian coordinates.
  </a:documentation>
  <element name="position">
    <ref name="coordinate.attributes"/>
  </element>
</define>

<define name="offset.element">
  <a:documentation>
    An offset element describes Cartesian coordinates.
  </a:documentation>
  <element name="offset">
    <ref name="coordinate.attributes"/>
  </element>
</define>

<define name="coordinate.attributes">
  <a:documentation>
    The coordinates are decimal numbers and refer to an appropriate
    xy-system where the x-axis runs from left to right and the y-axis
    from top to bottom.
```

```xml
    </a:documentation>
    <attribute name="x">
      <data type="decimal"/>
    </attribute>
    <attribute name="y">
      <data type="decimal"/>
    </attribute>
  </define>

  <define name="dimension.element">
    <a:documentation>
      A dimension element describes the width (x coordinate) and height
      (y coordinate) of a node.
      The coordinates are actually positive decimals.
    </a:documentation>
    <element name="dimension">
      <attribute name="x">
        <ref name="positiveDecimal.content"/>
      </attribute>
      <attribute name="y">
        <ref name="positiveDecimal.content"/>
      </attribute>
    </element>
  </define>

  <define name="positiveDecimal.content" ns="http://www.w3.org/2001/XMLSchema-datatypes">
    <a:documentation>
      Definition of a restricted positive decimals domain with a total digits
      number of 4 and 1 fraction digit. Ranges from 0 to 999.9
    </a:documentation>
    <data type='decimal'>
      <param name='totalDigits'>4</param>
      <param name='fractionDigits'>1</param>
      <param name='minExclusive'>0</param>
    </data>
  </define>

  <define name="fill.element">
    <a:documentation>
      A fill element describes the interior colour, the gradient colour,
      and the gradient rotation between the colors of an object.  If an
      image is available the other attributes are ignored.
    </a:documentation>
    <element name="fill">
      <optional>
        <attribute name="color">
          <ref name="color.type"/>
        </attribute>
      </optional>
      <optional>
        <attribute name="gradient-color">
          <ref name="color.type"/>
        </attribute>
      </optional>
      <optional>
```

```xml
            <attribute name="gradient-rotation">
              <choice>
                <value>vertical</value>
                <value>horizontal</value>
                <value>diagonal</value>
              </choice>
            </attribute>
          </optional>
          <optional>
            <attribute name="image">
              <data type="anyURI"/>
            </attribute>
          </optional>
      </element>
  </define>


  <define name="line.element">
    <a:documentation>
      A line element describes the shape, the colour, the width, and the
      style of an object.
    </a:documentation>
    <element name="line">
        <optional>
          <attribute name="shape">
            <choice>
              <value>line</value>
              <value>curve</value>
            </choice>
          </attribute>
        </optional>
        <optional>
          <attribute name="color">
            <ref name="color.type"/>
          </attribute>
        </optional>
        <optional>
          <attribute name="width">
            <ref name="positiveDecimal.content"/>
          </attribute>
        </optional>
        <optional>
          <attribute name="style">
            <choice>
              <value>solid</value>
              <value>dash</value>
              <value>dot</value>
            </choice>
          </attribute>
        </optional>
      </element>
  </define>


  <define name="color.type">
    <a:documentation>
      This describes the type of a color attribute. Actually, this comes
```

```xml
        from the CSS2 (and latest versions) data type system.
    </a:documentation>
    <text/>
</define>


<define name="font.element">
    <a:documentation>
      A font element describes several font attributes, the decoration,
      the alignment, and the rotation angle of an annotation's text.
      The font attributes (family, style, weight, size) should be conform
      to the CSS2 and latest versions data type system.
    </a:documentation>
    <element name="font">
      <optional>
        <attribute name="family">
          <text/>  <!-- actually, CSS2 and latest versions font-family -->
        </attribute>
      </optional>
      <optional>
        <attribute name="style">
          <text/>  <!-- actually, CSS2 and latest versions font-style -->
        </attribute>
      </optional>
      <optional>
        <attribute name="weight">
          <text/>  <!-- actually, CSS2 and latest versions font-weight -->
        </attribute>
      </optional>
      <optional>
        <attribute name="size">
          <text/>  <!-- actually, CSS2 and latest versions font-size -->
        </attribute>
      </optional>
      <optional>
        <attribute name="decoration">
          <choice>
            <value>underline</value>
            <value>overline</value>
            <value>line-through</value>
          </choice>
        </attribute>
      </optional>
      <optional>
        <attribute name="align">
          <choice>
            <value>left</value>
            <value>center</value>
            <value>right</value>
          </choice>
        </attribute>
      </optional>
      <optional>
        <attribute name="rotation">
          <data type="decimal"/>
        </attribute>
```

```
        </optional>
      </element>
  </define>


  <define name="toolspecific.element">
    <a:documentation>
      The tool specific information refers to a tool and its version.
      The further substructure is up to the tool.
    </a:documentation>
    <element name="toolspecific">
      <attribute name="tool">
        <text/>
      </attribute>
      <attribute name="version">
        <text/>
      </attribute>
      <zeroOrMore>
        <ref name="anyElement"/>
      </zeroOrMore>
    </element>
  </define>

</grammar>
```

LISTING A.1: RELAX NG implementation of PNML Core Model

A.2 RELAX NG implementation of Petri Net Type Definition for Place/Transition nets

```xml
<?xml version="1.0" encoding="UTF-8"?>

<grammar ns="http://www.pnml.org/version-2009/grammar/pnml"
  xmlns="http://relaxng.org/ns/structure/1.0"
  xmlns:a="http://relaxng.org/ns/compatibility/annotations/1.0">

  <a:documentation>
    RELAX NG implementation of Petri Net Type Definition for Place/Transition nets.
    This PNTD re-defines the value of nettype.uri for P/T nets.

    File name: ptnet.pntd
    Version: 2009
    (c) 2007-2009
    Lom Hillah (AFNOR)
    Revision:
    July 2008 - L.H
  </a:documentation>

  <a:documentation>
    The PT Net type definition.
    This document also declares its namespace.
    All labels of this Petri net type come from the Conventions document.
    The use of token graphics as tool specific feature is possible.
  </a:documentation>

  <include href="http://www.pnml.org/version-2009/grammar/conventions.rng"/>

  <!--
  <include href="http://www.pnml.org/version-2009/grammar/pnmlextensions.rng"/>
    We do not need to include this, because the pnmlcoremodel.rng covers any
    toolspecific extension.
  -->

  <include href="http://www.pnml.org/version-2009/grammar/pnmlcoremodel.rng"/>

  <define name="nettype.uri" combine="choice">
    <a:documentation>
      The URI value for the net type attribute,
      declaring the type of P/T nets.
    </a:documentation>
    <attribute name="type">
      <value>http://www.pnml.org/version-2009/grammar/ptnet</value>
    </attribute>
  </define>


  <define name="PTMarking">
    <a:documentation>
      Label definition for initial marking in nets like P/T-nets.
      <contributed>Michael Weber</contributed>
      <date>2003-06-16</date>
```

```
      <reference>
        W. Reisig: Place/transition systems. In: LNCS 254. 1987.
      </reference>
    </a:documentation>
    <element name="initialMarking">
      <ref name="nonnegativeintegerlabel.content"/>
    </element>
  </define>

  <define name="PTArcAnnotation">
    <a:documentation>
      Label definition for arc inscriptions in P/T-nets.
      <contributed>Michael Weber, AFNOR</contributed>
      <date>2003-06-16</date>
      <reference>
        W. Reisig: Place/transition systems. In: LNCS 254. 1987.
      </reference>
    </a:documentation>
    <element name="inscription">
      <ref name="positiveintegerlabel.content"/>
    </element>
  </define>

  <define name="place.labels" combine="interleave">
    <a:documentation>
      A place of a P/T net may have an initial marking.
    </a:documentation>
    <optional><ref name="PTMarking"/></optional>
  </define>

  <define name="arc.labels" combine="interleave">
    <a:documentation>
      An arc of a P/T net may have an inscription.
    </a:documentation>
    <optional><ref name="PTArcAnnotation"/></optional>
  </define>

</grammar>
```

LISTING A.2: RELAX NG implementation of PNTD for Place/Transition nets

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