

Modeling Synchronization Problems: From Composed Petri Nets to Provable Linear Sequents

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Abstract: Component-based programming has become a popular and frequently used method for software development, prepared from independent components by a composition. Our paper presents an illustration of how a composition of components can cause the emergence of new problems that should be solved, in order to obtain the desired results. We introduce a transformation of Petri nets to corresponding provable sequents of linear logic and then we show how a composition of simple Petri nets causes arising of synchronization problems. Transformation to provable linear sequents that ensures a verified behavior for such composed systems.

Keywords: linear logic; petri nets; component composition

1 Introduction

In the last decades, a new method of software development, a component-based programming, has become very popular. It can be characterized as a construction of program systems from working entities by their composition. There are many publications in the area of software engineering discussing basic principles of this method and providing practical guides for how to prepare such program systems, e.g. [21, 22, 23, 27, 29]. Among the basic properties of components is their independency, i.e. that they can be executed separately, can be reused, and should satisfy rules of composition (contracts and dependencies) to ensure that the whole system produces desired results. One of the important properties of a composition is that after it is composed, new problems can arise. The aim of our paper is to illustrate this situation on known examples of synchronization. We used two formal tools; Petri nets (PNs) and linear logic. Both tools are useful and frequently employed in modeling and behavioral description of program systems. We show how the behavior of PNs can be expressed by provable sequents of linear logic, and simultaneously, we show how the synchronization problems arise from the composition of simple components.

Petri nets are well-known mathematical and graphical tool for behavioral modeling of processes. They were designed especially for modeling systems with interacting concurrent processes [20, 30]. They are sometimes called place/transition nets and they enable graphical expression of the system execution. Petri nets nowadays have a wide spectrum of applications, not only in concurrent programming, but also in business process modeling, data analysis, software design, simulation, and many others [2, 3, 9, 10]. The expressive power of Petri nets has been studied and compared with several other formal methods for the specification and description of systems. Such systems include algebraic specification in [24], which leads to the extension of the notion of tokens to structural ones, or with B-language [11], in which the transformation of Petri nets to B-language is defined for software development, from specification to implementation. In our paper we would like to present another correspondence, namely how PNs can be transform into provable linear logic sequents.

Linear logic is a logical system introduced by Jean-Yves Girard in 1987 [6, 7]. It enables description of processes as they behave in real world. It is capable of describing the dynamic of processes, parallelism, external and internal nondeterminism, consecutive processes, and it is also able to handle the resources on syntactic level. Thanks to these properties, linear logic can be considered as a bridge between computing science and logic [15]. Propositional linear logic is available for program systems description [1, 16], their behavior [26], and their extension with modal operators enables modeling of knowledge achievement [17, 18] mainly in intrusion detection systems to improve network reliability [28]. Linear logic has greater expressive power than classical logic, thanks to more connectives with special properties. Moreover, every formula of classical propositional logic can be expressed in linear logic. One of the most important properties of linear logic is its ability to describe the dynamic of processes. By linear implication $\multimap$ it is possible to express sequentiality and causality of processes.

Another important property of linear logic is its ability to handle resources - logical space and logical time [14, 19]. It allows us to express the internal structure of the resources, their consumption, together with a continuation of processes in incremental time.

In our research, we were inspired by the approach published in [5], where PNs are defined as models of linear logic. The reverse property is in [13]. We follow up on this approach in a way by which each significant fragment of a PN can be described by a linear sequent. We formulate a transformation of Petri nets to provable linear sequents. To illustrate composition problems, we define a trivial working PN and show its behavior by corresponding provable linear sequent. Composing two and five trivial PNs causes new problems to arise, namely synchronization problems of mutual exclusion, and deadlock. These problems are similar to the ones in the process of component composition in component-based systems. The examples of synchronization problems appear frequently in

textbooks or papers concerning with Petri nets [9, 11, 20, 25]. To illustrate the transformation from PNs to linear logic together with the appearance of synchronization problems in component composition, is our main aim that is not published yet in scientific publications.

2 Principles of Petri Nets

A Petri net is a known formal tool used mainly for modeling the behavior of concurrent systems as state-transition systems. Their advantage is that these models can be represented graphically, by directed bipartite graphs. A PN graph has two types of nodes: places and transitions. *Places* are represented by circles and *transitions* by arrows (arcs). Places express possible states of a system, and transitions represent changes of states, i.e. events. Places can contain special marks called *tokens*. A transition is enabled, i.e. it can be *fired*, if all places of input arcs contain required number of tokens. When a transition is fired, it produces tokens in all places on output arcs. Generally, execution of a PN is nondeterministic: when more than one transition is enabled, any of them can be fired. Any distribution of tokens over places represents a configuration of a given PN called *marking*. For any place p of a PN its marking is a function $m: P \rightarrow \mathbb{N}_0$ returning a number of tokens in p . $\mathbb{N}_0$ denotes the set of natural numbers with zero. A marking of a PN is defined as a tuple

$$m = (m(p_1), \dots, m(p_n)) \quad (1)$$

of markings of all places in a PN.

A PN has two functions: *pre* and *post*. The *pre* function for each place and transition returns a number of arcs from a given place to a given transition. The *post* function for each place and transition returns a number of arcs outgoing from a given transition to a given place. Formally, a Petri net is defined as a tuple

$$PN = (P, T, pre, post, m_0), \quad (2)$$

where $P = \{p_1, \dots, p_n\}$ is a finite set of places, $T = \{t_1, \dots, t_n\}$ is a finite set of transitions, $pre: P \times T \rightarrow \mathbb{N}_0$ and $post: T \times P \rightarrow \mathbb{N}_0$ are pre- resp. post-conditions and m_0 is initial marking before a PN starts its execution.

The execution of a PN is based on following two rules:

- *enabling rule* formulates the condition under which a transition is allowed to be fired. A transition can be fired if each of its input places contains a number of tokens greater or equal than the given threshold
- *firing rule* defines modification of a marking caused by firing a transition. When a transition t is fired, a token from each input place is deleted, and to each output place a token is added

A *behavior* of a PN can be described as a sequence of markings reached during the execution of PN.

3 Basic Concepts of Linear Logic

Linear logic belongs to the new logical systems that are useful for describing and verifying of real systems. It facilitates the formulation of dynamic processes, nondeterminism, concurrency, and handling of resources such as time and space on syntactic level [12]. In this section we introduce the basic definitions of logical connectives and the deduction system of linear logic. Elementary propositions of linear logic can be considered as actions or resources.

Let $Prop = \{p_1, p_2, \dots\}$ be a countable set of elementary propositions. In this paper we use the following syntax of linear formulas:

$$\varphi ::= p \mid \mathbf{1} \mid \mathbf{0} \mid \top \mid \varphi \otimes \psi \mid \varphi \oplus \psi \mid \varphi \& \psi \mid \varphi \multimap \psi \mid \varphi^\perp \quad (3)$$

where

- $\varphi \otimes \psi$ is the *multiplicative conjunction* with neutral element $\mathbf{1}$. This formula expresses that both actions perform simultaneously or both resources are available at once.
- $\varphi \& \psi$ is the *additive conjunction* with neutral element $\top$. This formula expresses that only one of the actions performs, but we can deduce which one from the environment. Additive conjunction describes external nondeterminism.
- $\varphi \oplus \psi$ is the *additive disjunction* with neutral element $\mathbf{0}$. This formula expresses that only one of the actions performs but we cannot anticipate which one. Additive disjunction describes internal nondeterminism.
- $\varphi^\perp$ is the *linear negation* and it describes a reaction of an action φ or a consumption of a resource φ . Linear negation has the property of involution, i.e. $(\varphi^\perp)^\perp \equiv \varphi$.
- $\varphi \multimap \psi$ is the *linear implication*. This formula describes that the first action φ is a cause of the second (re)action ψ or in the case of resources it expresses that the first resource is consumed after linear implication.

For linear formulas, we use *sequent calculus*. A sequent has the form

$$\Gamma \vdash \varphi, \quad (4)$$

that expresses that a formula φ is deducible from the formulas in the context $\Gamma = \varphi_1, \dots, \varphi_n$. The formulas on the left side of a sequent are assumptions, therefore we consider them as multiplicative conjunction $\otimes$. The formula φ on the right side is deducible from the assumptions.

The sequent deduction system consists of basic rules, rules for the connectives, rules for neutral elements and structural rules:

1. Basic rule:

$$\frac{}{\varphi \vdash \varphi} (id)$$

2. Rule for linear negation:

$$\varphi^\perp \equiv \varphi \multimap \perp \quad ((\)^\perp)$$

3. Rules for neutral elements:

$$\frac{}{\Gamma \vdash \top} (\top_{-r}) \quad \frac{}{\Gamma, 0 \vdash \varphi} (0_{-l}) \quad \frac{\Gamma \vdash \varphi}{\Gamma, 1 \vdash \varphi} (1_{-l}) \quad \frac{}{\vdash 1} (1_{-r})$$

4. Rules for connectives:

$$\begin{array}{ll} \frac{\Gamma_1 \vdash \varphi_1 \quad \Gamma_2, \varphi_2 \vdash \psi}{\Gamma_1, \varphi_1 \multimap \varphi_2, \Gamma_2 \vdash \psi} (\multimap_{-l}) & \frac{\Gamma, \varphi_1 \vdash \varphi_2}{\Gamma \vdash \varphi_1 \multimap \varphi_2} (\multimap_{-r}) \\[10pt] \frac{\Gamma, \varphi_1, \varphi_2 \vdash \psi}{\Gamma, \varphi_1 \otimes \varphi_2 \vdash \psi} (\otimes_{-l}) & \frac{\Gamma_1 \vdash \varphi_1 \quad \Gamma_2 \vdash \varphi_2}{\Gamma_1, \Gamma_2 \vdash \varphi_1 \otimes \varphi_2} (\otimes_{-r}) \\[10pt] \frac{\Gamma, \varphi_1 \vdash \psi}{\Gamma, \varphi_1 \& \varphi_2 \vdash \psi} (\&_{-l1}) & \frac{\Gamma, \varphi_2 \vdash \psi}{\Gamma, \varphi_1 \& \varphi_2 \vdash \psi} (\&_{-l2}) \\[10pt] \frac{\Gamma, \varphi_1 \vdash \psi \quad \Gamma, \varphi_2 \vdash \psi}{\Gamma, \varphi_1 \& \varphi_2 \vdash \psi} (\&_{-r}) & \frac{\Gamma \vdash \varphi_1 \quad \Gamma \vdash \varphi_2}{\Gamma \vdash \varphi_1 \& \varphi_2} (\&_{-r}) \\[10pt] \frac{\Gamma, \vdash \varphi_1}{\Gamma \vdash \varphi_1 \otimes \varphi_2} (\otimes_{-r1}) & \frac{\Gamma \vdash \varphi_2}{\Gamma \vdash \varphi_1 \otimes \varphi_2} (\otimes_{-r2}) \end{array}$$

5. Structural rules:

$$\frac{\Gamma, \varphi_1, \varphi_2 \vdash \psi}{\Gamma, \varphi_2, \varphi_1 \vdash \psi} (exch) \quad \frac{\Gamma_1 \vdash \varphi \quad \Gamma_2 \vdash \varphi}{\Gamma_1, \Gamma_2 \vdash \varphi} (\otimes_{-r})$$

The basic rule is the axiom of identity, linear negation is expressed as linear implication. The rules of connectives introduce connectives on the left or on the right part of a sequent. The only structural rules are exchange and cut rules. We note that in linear logic it is important which resources and how many of them we have. Therefore, the obvious structural rules of weakening and contraction are not allowed, only in controlled way using special unary connectives, exponentials. In this paper, we do not use exponentials; their definition together with

corresponding deduction rules is in [8]. A proof in sequent calculus is a tree, where the root is a proven sequent, and every step is the application of an appropriate deduction rule. A sequent is provable if all of the leaves of its proof tree are identities.

4 Transformation of Petri Net Patterns to Linear Logic Sequents

In this section we define transformations of some parts, the patterns of PNs, to the corresponding linear formulas. We select several significant patterns that occur in synchronization PNs and we define corresponding linear logic sequents. All other patterns can be transformed similarly using this idea.

We introduce the following notation. A place p of a PN containing one token, i.e. with the marking $m(p) = 1$, we denote by the elementary proposition p of linear logic. Marking expressing that a place p_1 contains one token and a place p_2 contains two tokens, can be denoted using multiplicative conjunction:

$$p_1 \otimes p_2 \otimes p_2 \tag{5}$$

For describing of a PN transition by linear formula we use linear implication $\multimap$. The premise of the implication is a marking that makes a transition t to be enabled and the conclusion is the marking that arises after firing of t . Linear implication expresses change of a state, caused by firing a transition together with the consumed resources (tokens) on the left side and the produced resources (tokens) on the right side of implication [4]. For instance, if t is a transition enabled when the places p_1 and p_2 have both one token and after firing t the place p_3 obtains a token, then this transition can be denoted by the following linear implication:

$$t \equiv p_1 \otimes p_2 \multimap p_3 \tag{6}$$

A behavior of a PN is described by the sequents of linear logic in the form:

$$m, l \vdash m', \tag{7}$$

where

- m is a marking before firing a transition
- l is a list of enabled transitions expressed by linear implications defined above
- m' is a marking after firing a transition

Such sequents express that the marking m' is produced from a marking m by firing a transition from l .

Now, we consider the characteristic fragments of PNs representing their possible structure and we formulate the corresponding linear formulas and sequents.

Precisely:

- places of a PN are transformed into linear formulas
- transitions of a PN are transformed into linear implications

We choose a *sequence* illustrated in Figure 1 as the first pattern. The transition t is enabled if the place p_1 contains at least one token. After firing t , the place p_2 obtains one token.



Figure 1
Sequence

This pattern can be transformed to the following sequent:

$$p_1, t \vdash p_2, \quad (8)$$

where $t \equiv p_1 \multimap p_2$. We call this sequent *causality*, because p_1 is a cause of p_2 .

The pattern in Figure 2 depicts a situation of *furcation*:

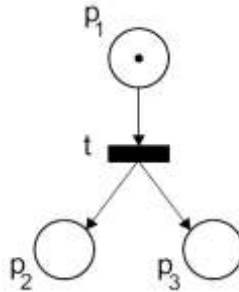


Figure 2
Furcation

This pattern has one transition t that is enabled if at least one token is in p_1 . Firing of t produces one token in both p_2 and p_3 , simultaneously. Therefore, the corresponding sequent expresses *concurrency*:

$$p_1, t \vdash p_2 \otimes p_3 \quad (9)$$

The pattern in Figure 3 illustrates a situation of *rendezvous*. To be t enabled the places p_1 and p_2 have to have a token and after firing t one token is produced in p_3 .

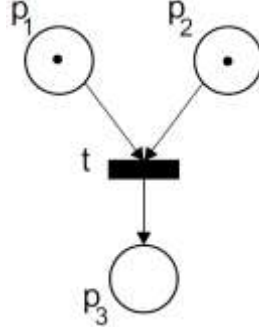


Figure 3

Rendezvous

We transform this pattern to the following sequent expressing *synchronization*:

$$p_1, p_2, t \vdash p_3 \quad (10)$$

Up to now, all patterns were deterministic because they have only one enabled transition.

The next two patterns express nondeterministic behavior. The first of them in Figure 4 is *free choice*. Either t_1 or t_2 are enabled but we cannot decide which of them.

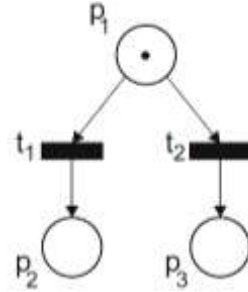


Figure 4

Free choice

We transform this pattern to the sequent using additive disjunction $\oplus$ between formulas describing enabled transitions on the left side, because only one of t_1 or t_2 can be fired, but we do not know which one. It expresses *internal nondeterminism*. Producing tokens on the right side is expressed by linear formula by additive conjunction because a token can be obtained either in p_2 or in p_3 depending on previous action:

$$p_1, t_1 \oplus t_2 \vdash p_2 \& p_3. \quad (11)$$

The last pattern that we consider is *dependent choice* in Figure 5. Dependent or environmental choice expresses the situation when only one transition of t_1 or t_2 can be fired, but it depends on the occurrence of a token either in p_1 or in p_2 . In the other words, this choice depends on the given environment. Firing any of transition t_1 or t_2 produces one token in the place p_3 .

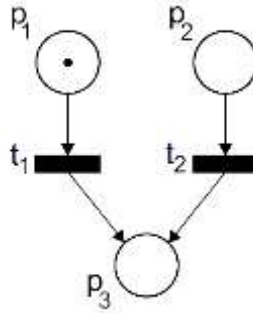


Figure 5
Dependent choice

We transform this pattern to the linear sequent with additive conjunction describing transitions on the left side, because firing of t_1 or t_2 depends on the situation in p_1 or p_2 , respectively:

$$p_1 \& p_2, t_1 \& t_2 \vdash p_3 \quad (12)$$

5 Synchronization Problems Arising from PN Composition and Verifying by Proofs

In this section, we present the main aim of our paper. First, we define a trivial PN that works, i.e. its transitions can be enabled and fired. Considering a trivial PN as a component, when we compose two such PNs a new problem arises, that is known as *mutual exclusion*. We transform such composed PN into linear sequent and verify it by a proof. Second, we compose five trivial PNs that lead to arising of a known case of dining philosophers, i.e. deadlock problem. Again, we transform this composed PN into linear sequent and verify it by a proof. To summarize, we illustrate not only transformation of PNs to corresponding linear sequents, but also that composition of components together can cause arising of new problems that have to be solved in order to reach desired system behavior.

We start with a trivial PN in Figure 6. It is clear that this PN works and its behavior is deterministic. With a little imagination, we can call this PN, a *dining philosopher*.

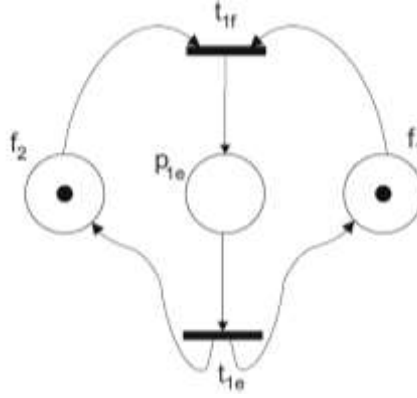


Figure 6
A dining philosopher

This trivial PN consists of three places, where f_1 and f_2 represent forks and p_{1e} represents an eating philosopher. This PN has two transitions t_{1e} and t_{1f} and its initial marking is $m_0 = (1,0,1)$. If both forks f_1 and f_2 are available, i.e. both corresponding places have a token, the transition t_{1f} is enabled and after firing, the place p_{1e} obtains a token, i.e. the philosopher is eating. In this state the transition t_{1f} is enabled and after firing, the philosopher releases the forks and starts to think.

The behavior of this PN can be expressed by the linear sequent:

$$f_2, f_1, (f_2 \otimes f_1) \multimap p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_2 \otimes f_1 \quad (13)$$

with the following proof in the Figure 7:

$$\frac{\frac{\frac{f_2 \vdash f_2 \quad (id) \quad f_1 \vdash f_1 \quad (id)}{f_2, f_1 \vdash f_2 \otimes f_1} (\otimes -r) \quad \frac{p_{1e} \vdash p_{1e} \quad (\otimes -r) \quad \frac{\frac{f_2 \vdash f_2 \quad (id) \quad f_1 \vdash f_1 \quad (id)}{f_2, f_1 \vdash f_2 \otimes f_1} (\otimes -r) \quad \frac{f_2 \otimes f_1 \vdash f_2 \otimes f_1 \quad (\otimes -l)}{f_2 \otimes f_1 \vdash f_2 \otimes f_1} (\otimes -l)}{p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_2 \otimes f_1} (\multimap -l)}{f_2, f_1, (f_2 \otimes f_1) \multimap p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_2 \otimes f_1} (\multimap -l)$$

Figure 7
Proof of dining philosopher

Now we consider the previous PN in Figure 6 as a component. By composing two such components (Fig. 8), we get the well-known problem of *mutual exclusion* (mutex). The interaction between the components is represented by the place f_2 . The principle of mutex is that only one of the processes can be executed in one moment, in other words, if one philosopher is eating (i.e. he possesses his left and right forks), the second is thinking and vice versa. Let the initial marking of this PN be $m_0 = (1,0,1,0,1)$.

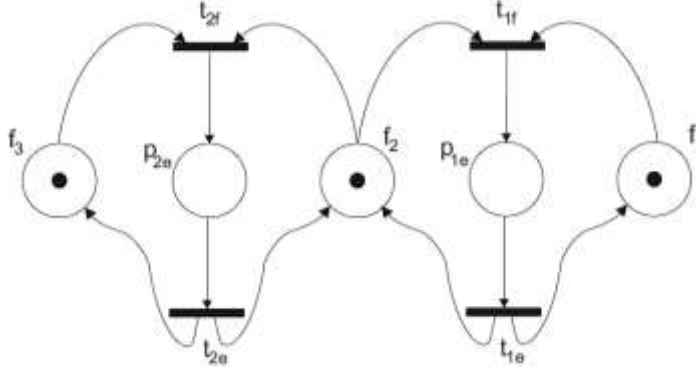


Figure 8
Mutual exclusion

There are two possibilities how this PN works:

- either t_{2f} is fired, which corresponds to the linear logic sequent:

$$f_3, f_2, f_1, (f_3 \otimes f_2) \multimap p_{2e} \vdash p_{2e} \otimes f_1 \quad (14)$$

- or t_{1f} is fired, this case is expressed by linear logic sequent:

$$f_3, f_2, f_1, (f_2 \otimes f_1) \multimap p_{1e} \vdash p_{1e} \otimes f_3 \quad (15)$$

The behavior of mutex can be described by the following linear logic sequent:

$$f_3, f_2, f_1, ((f_2 \otimes f_1) \multimap p_{1e}) \oplus ((f_3 \otimes f_2) \multimap p_{2e}) \vdash (p_{1e} \otimes f_3) \& (p_{2e} \otimes f_1),$$

where we use internal nondeterminism on the left side, i.e. additive disjunction $\oplus$ between transitions t_{2f} and t_{1f} . On the right side of this sequent, we use additive conjunction $\&$ between tokens, because they depend on which of the transitions t_{2f} and t_{1f} was actually fired. This sequent is provable and we present a left branch of this proof tree depicted in the Figure 9.

$$\frac{\frac{\frac{f_1 \vdash f_1 \quad (id)}{f_1, f_2, f_3, (f_3 \otimes f_2) \multimap p_{2e} \vdash (f_1 \otimes p_{2e})} \quad \dots \quad \dots}{f_1, f_2, f_3, ((f_3 \otimes f_2) \multimap p_{2e}) \oplus ((f_1 \otimes f_2) \multimap p_{1e}) \vdash (f_1 \otimes p_{2e}) \& (f_3 \otimes p_{1e})} \quad (\oplus_{-r}) \quad \dots}{f_1, f_2, f_3, ((f_3 \otimes f_2) \multimap p_{2e}) \oplus ((f_1 \otimes f_2) \multimap p_{1e}) \vdash (f_1 \otimes p_{2e}) \& (f_3 \otimes p_{1e})} \quad (\oplus_{-r}) \quad \dots$$

Figure 9
Proof of mutual exclusion

The right branch of the proof tree can be constructed similarly. Provability of this sequent ensures that we have a solution of mutual exclusion.

Now, we compose five trivial PNs (components) together and here a new problem arises, known as the problem of *five dining philosophers*, i.e. *deadlock problem* (Figure 10).

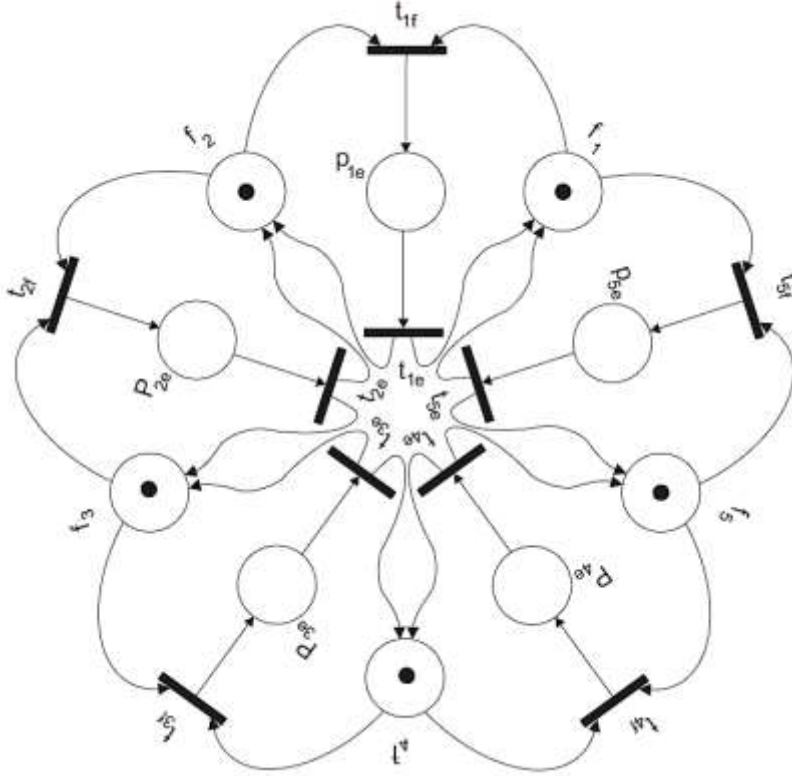


Figure 10
Problem of five dining philosophers

If we assume the order of places $p_{1e}, p_{2e}, p_{3e}, p_{4e}, p_{5e}, f_1, f_2, f_3, f_4, f_5$, then the initial marking is $m_0 = (0, 0, 0, 0, 0, 1, 1, 1, 1, 1)$. If a place p_i , $i = 1, \dots, 5$ has a token, the philosopher i is eating, if it is empty, he is thinking. The places f_1, f_2, f_3, f_4, f_5 serve for forks, the places $p_{1e}, p_{2e}, p_{3e}, p_{4e}, p_{5e}$ mean that corresponding philosophers eat.

This system works if every philosopher can eat, i.e. each process in a system can be executed. The problem occurs, when each philosopher takes its right fork and then they are waiting forever for the second fork; or in other words, if each process needs a certain resource to be executed, but any of them cannot release resources before finishing their execution. This problem is known as *deadlock*.

From the previous ideas it is clear that either one philosopher can eat, or two not neighbor philosophers can eat at one moment. We describe one of the possible solutions of this problem.

Consider that in the first step one philosopher, e.g. p_{1e} is eating. That means, he takes both forks f_1 and f_2 and the transition t_{1f} is fired. Figure 11 illustrates the system after firing t_{1f} .

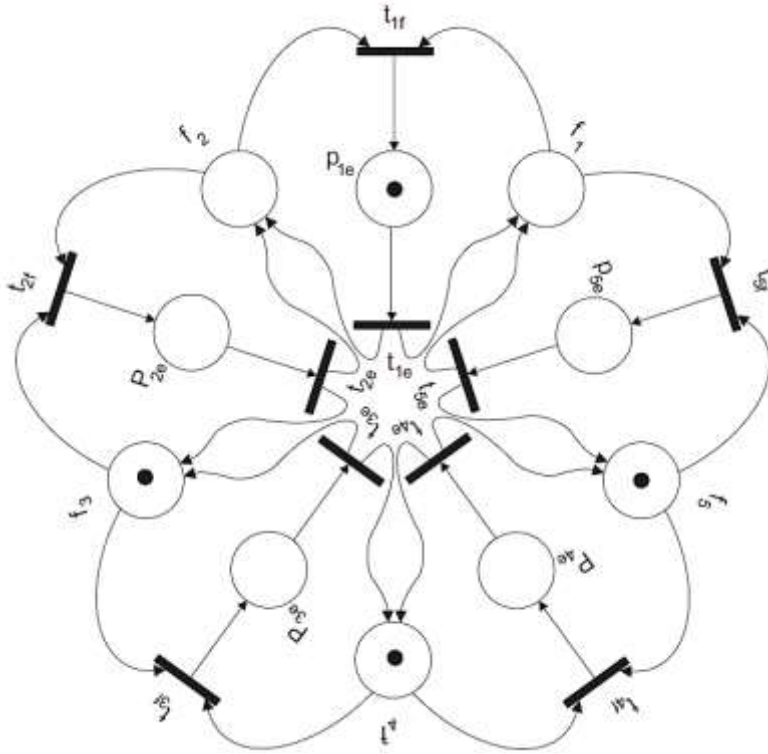


Figure 11
Single dining philosopher

We describe this action by the linear sequent

$$f_1, f_2, f_3, f_4, f_5, f_1 \otimes f_2 \multimap p_{1e} \vdash f_5 \otimes (f_4 \otimes (p_{1e} \otimes f_3)) \quad (16)$$

together with its (fragment of) proof depicted in the Figure 12:

$$\begin{array}{c}
\frac{\overline{f_1 \vdash f_1} \text{ (id)} \quad \overline{f_2 \vdash f_2} \text{ (id)}}{f_1, f_2 \vdash f_1 \otimes f_2} \text{ } \quad \frac{}{p_{1e} \vdash p_{1e}} \text{ (id)} \\
\frac{}{f_1, f_2, f_1 \otimes f_2 \multimap p_{1e} \vdash p_{1e}} \text{ } \quad \frac{}{f_3 \vdash f_3} \text{ (id)} \\
\frac{}{f_1, f_2, f_3, f_1 \otimes f_2 \multimap p_{1e} \vdash p_{1e} \otimes f_3} \text{ } \quad \frac{}{f_4 \vdash f_4} \text{ (id)} \\
\frac{}{f_1, f_2, f_3, f_4, f_1 \otimes f_2 \multimap p_{1e} \vdash f_4 \otimes (p_{1e} \otimes f_3)} \text{ } \quad \frac{}{f_5 \vdash f_5} \text{ (id)} \\
\frac{}{f_1, f_2, f_3, f_4, f_5, f_1 \otimes f_2 \multimap p_{1e} \vdash f_5 \otimes (f_4 \otimes (p_{1e} \otimes f_3))} \text{ }
\end{array}$$

Figure 12

Proof of single dining philosopher sequent

We again omit the left branches of this proof consisting of identities $f_5 \vdash f_5$ and $f_4 \vdash f_4$.

After finishing his work (eating), p_{1e} releases both forks, i.e. t_{1e} is fired and we get the initial marking of PN, which is described by the sequent:

$$f_3, f_4, f_5, p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_5 \otimes (f_4 \otimes (f_3 \otimes (f_2 \otimes f_1))), \quad (17)$$

and proven by the following (fragment of) proof in Figure 13:

$$\begin{array}{c}
\frac{}{f_2 \vdash f_2} \text{ (id)} \quad \frac{}{f_1 \vdash f_1} \text{ (id)} \\
\frac{}{f_2, f_1 \vdash f_2 \otimes f_1} \text{ } \quad \frac{}{f_2 \otimes f_1 \vdash f_2 \otimes f_1} \text{ } \\
\frac{}{p_{1e} \vdash p_{1e}} \text{ (id)} \quad \frac{}{f_2 \otimes f_1 \vdash f_2 \otimes f_1} \text{ } \\
\frac{}{p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_2 \otimes f_1} \text{ } \quad \frac{}{f_3 \vdash f_3} \text{ (id)} \\
\frac{}{f_3, p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_3 \otimes (f_2 \otimes f_1)} \text{ } \quad \frac{}{f_4 \vdash f_4} \text{ (id)} \\
\frac{}{f_3, f_4, p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_4 \otimes (f_3 \otimes (f_2 \otimes f_1))} \text{ } \quad \frac{}{f_5 \vdash f_5} \text{ (id)} \\
\frac{}{f_3, f_4, f_5, p_{1e}, p_{1e} \multimap (f_2 \otimes f_1) \vdash f_5 \otimes (f_4 \otimes (f_3 \otimes (f_2 \otimes f_1)))} \text{ }
\end{array}$$

Figure 13

Proof of single dining philosopher after finishing work

Again, the missing left branches of the proof denoted by ... contain identities for f_5, f_4 and f_3 .

The second step is to enable two philosophers, e.g. p_2 and p_4 , to eat as it is in Figure 15. In this step two transitions t_{2f} and t_{4f} can be fired simultaneously, because p_{2e} and p_{4e} have available both forks f_2, f_3 and f_4, f_5 , respectively.

The corresponding linear logic formula:

$$f_1, f_2, f_3, f_4, f_5, (f_3 \otimes f_2 \multimap p_{2e}) \otimes (f_5 \otimes f_4 \multimap p_{4e}) \vdash f_1 \otimes (p_{4e} \otimes p_{2e}), (18)$$

and its proof can be constructed in similar way as the proofs above depicted in Figure 14.

$$\begin{array}{c}
\frac{}{f_2 \vdash f_2} \text{(id)} \quad \frac{}{f_3 \vdash f_3} \text{(id)} \quad \frac{}{p_{4e} \vdash p_{4e}} \text{(id)} \quad \frac{}{p_{2e} \vdash p_{2e}} \text{(id)} \\
\frac{f_2, f_3 \vdash f_2 \otimes f_3}{f_2, f_3, p_{4e}, f_2 \otimes f_3 \multimap p_{2e}, \vdash p_{4e} \otimes p_{2e}} (\multimap -_1) \quad \frac{}{p_{4e}, p_{2e} \vdash p_{4e} \otimes p_{2e}} (\otimes -_1) \\
\vdots \quad \frac{f_2, f_3, p_{4e}, f_2 \otimes f_3 \multimap p_{2e}, \vdash p_{4e} \otimes p_{2e}}{f_2, f_3, f_4, f_5, f_4 \otimes f_5 \multimap p_{4e}, f_2 \otimes f_3 \multimap p_{2e} \vdash p_{4e} \otimes p_{2e}} (\multimap -_1) \\
\vdots \quad \frac{f_2, f_3, f_4, f_5, (f_4 \otimes f_5 \multimap p_{4e}) \otimes (f_2 \otimes f_3 \multimap p_{2e}) \vdash p_{4e} \otimes p_{2e}}{f_1, f_2, f_3, f_4, f_5, (f_4 \otimes f_5 \multimap p_{4e}) \otimes (f_2 \otimes f_3 \multimap p_{2e}) \vdash f_1 \otimes (p_{4e} \otimes p_{2e})} (\otimes -_1)
\end{array}$$

Figure 14

Proof of two dining philosophers

After finishing their dinner, the philosophers p_{2e} and p_{4e} release their forks, i.e. the transition t_{2e} and t_{4e} are fired simultaneously. The corresponding linear logic sequent and its proof can be constructed as above.

As the last step we consider that remaining philosophers p_3 and p_5 will eat. The corresponding linear sequent and its proof can be constructed similarly as in the previous steps. Now we have the solution of PN, because all philosophers had their dinner and we translated the behavior into corresponding provable linear sequents.

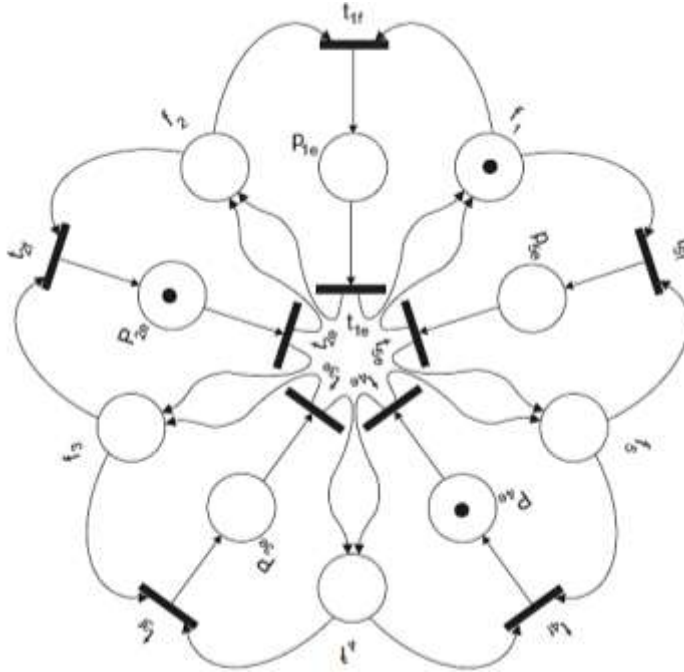


Figure 15

Two dining philosophers

Conclusions

In this paper, we presented an illustration on how the actual problem of component composition, used in component-based systems, can cause the advent of new problems. These problems need to be identified and solved. For achieving this aim, we apply a method of Petri nets transformation to the corresponding provable linear sequents. The proofs of constructed sequents ensure the correctness, they can be used as a specification of a system and they can help in achieving reliable software products. In our examples, we are concerned with only one kind of such problems, namely synchronization problems of mutual exclusion and deadlock that appear after the compositions of trivial working Petri nets. Our approach enables to formulate the solutions by corresponding provable sequents. We hope that our approach can be useful for education purposes, because it is simple, uses known concepts of PNs and linear logic, and is illustrative to comprehend component composition.

There are several open problems and possible ideas for solving them, by extending our approach. One of the advantages of linear logic is its resource character. First, we would like to formulate a transformation of timed Petri nets to linear formulas using polarization and focalization of the proof steps enabling to express time incrementally. After further study of Girard's theory of Ludics and its handling another resource, a space, we would like to transform explicit information about data types in colored Petri nets to linear logic proofs.

It is a challenge for us to work out our approach also for colored Petri nets, i.e. to define transformation from Petri nets, to the sequents of linear logic and illustrate it on significant examples.

The main result of our work is a systematically, worked out solution, for practical programmers, respectively, for students, on how different various known formal tools can be combined and proved, together with an illustration of component composition.

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