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Place Dependency of a Petri Net Generating a Maximal Prefix Code*

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Abstract In this paper we deal with prefix codes, called CPN languages, defined on Petri nets. And the family CPN of all CPN languages is included in the family of all context-sensitive languages. The subclass mCPN and NmCPN of CPN are a family of prefix codes which are maximal prefix codes and a family of prefix codes defined on input-ordinal Petri nets. NmCPN is obviously included in mCPN. But its converse inclusion is still an open problem. We have already proved under some restricted Petri nets, for example, Petri nets have at most two places or at most one transition. We consider this problem in the case that Petri nets have more than two places.

1 Preliminaries

In this section, we state the definitions and the notations of formal languages and codes in this paper. And we introduce Petri net codes and their related codes.

Let $X$ be a nonempty finite set called an alphabet, $X^*$ be the free monoid generated by $X$ under the concatenation. An element of $X^*$ is called a word. The identity of $X^*$ is called the empty word, denoted by 1. We denote $X^* \setminus \{1\}$ by $X^+$, the concatenation of two words $x$ and $y$ by $xy$, and the length of a word $w \in X^*$ by $|w|$ (especially $|1| = 0$).

If for two words $w, u \in X^*$ there exists some word $v \in X^*$ (resp. $v \in X^+$) with $w = uv$, then $u$ is called a prefix (resp. a proper prefix) of $w$, we represent $u \leq_p w$ (resp. $u <_p w$). A language over $X$ is a subset of $X^*$. The concatenation of two languages $L_1$ and $L_2$ is defined by $L_1L_2 = \{w_1w_2 | w_1 \in L_1, w_2 \in L_2\}$. A nonempty language $L$ is a code if for any two integers $n, m \geq 1$ and $u_1, u_2, \ldots, u_n, v_1, v_2, \ldots, v_m \in L$,

$$u_1u_2 \cdots u_n = v_1v_2 \cdots v_m$$

implies

$$n = m \text{ and } u_i = v_i \text{ for } i = 1, \ldots, n.$$ 

A code $L$ is a prefix code if $u, uv \in L$ implies $v = 1$. A code $C \subseteq X^+$ is maximal (resp. maximal prefix) in $X$ if $C$ is not included by any other code (resp. prefix code) over $X$.

Remark A maximal and prefix code is clearly a maximal prefix code because it is not included in any other codes by the maximality. But a maximal prefix code is a prefix code, but is not necessarily a maximal code.

**DEFINITION 1.1 (Petri net)** A Petri net $PN$ is a quadruple $(P, X, W, \mu_0)$ satisfying the following conditions.

1. $P$ and $X$ are finite sets with $P \cap X = \emptyset$ and $P \cup X \neq \emptyset$.
2. $W$ is a weighting function from $(P \times X) \cup (X \times P)$ to the set $N$ of all the nonnegative integers.
3. $\mu_0$ is a function from $P$ to $N$, called an initial marking.

*This is an abstract and the paper will appear elsewhere.*
A marking is called **positive** (or **zero**) if it is a mapping from $P$ to $\mathbb{N}\setminus\{0\}$ (or a mapping from $P$ to $\{0\}$, respectively).

And $PN$ is **input-ordinal** if $W(p, a) \leq 1$ for any $(p, a) \in P \times X$. In the above Petri net $PN$, we may call $(p, a) \in P \times X$ an arc when $W(p, a) > 0$ holds, and then $W(p, a)$ is called the weight of the arc $(p, a)$. The similar definition is stated about $(a, p) \in X \times P$.

The transition $a \in X$ is called **enable** under the Petri net $PN$ if $W(p, a) \leq \mu(p)$ holds for each place $p \in P$. Then the new marking $\mu'$ is defined as follows:

$$
\mu'(p) = \mu(p) - W(p, a) + W(a, p) \text{ for } \forall p \in P.
$$

The transition function $\delta_{PN}$ of $PN$ is defined by $\delta_{PN}(\mu, a) = \mu'$. $\delta_{PN}(\mu, a)$ is undefined if $a \in X$ is not enable under $PN$. This function is extended from $P \times X \rightarrow \mathbb{N}$ to $P \times X^{*} \rightarrow \mathbb{N}$ as follows:

$$
\delta_{PN}(\mu, 1) = \mu \text{ and } \delta_{PN}(\mu, w) = \delta_{PN}(\delta_{PN}(\mu, u), a). \text{ We may denote } \delta_{PN} \text{ by } \delta \text{ if no confusion is possible.}
$$

$w \in X^{*}$ is called a **firing sequence** in $PN$ if $\delta_{PN}(\mu, w)$ is defined. $w \in X^{*}$ is called a **positive firing sequence** in $PN$ if $\delta_{PN}(\mu, w)$ is defined and $\delta_{PN}(\mu, u)$ is positive for any prefix $u$ of $w$. We denote the sets of all firing sequences in $PN$ and all positive firing sequences in $PN$ by $FSeq(PN)$ and $FSeq^{+}(PN)$ respectively. We denote $\{\delta(\mu_{0}, w) | w \in FSeq(PN)\}$ (or $\{\delta(\mu_{0}, w) | w \in FSeq^{+}(PN)\}$) by $Re(PN)$ (or $Re^{+}(PN)$ resp.).

**DEFINITION 1.2** Let $PN = (P, X, W, \mu_{0})$ be a Petri net, $\mu_{0}$ be a positive marking. Then we define the languages $C(P, X, W, \mu_{0})$ and $C_{0}(P, X, W, \mu_{0})$ as follows:

$$
C(P, X, W, \mu_{0}) = \{w \in FSeq(PN) | \delta(\mu, w) \text{ is not positive, } w = uv, v \in X^{+}, u \in FSeq^{+}(PN)\},
$$

$$
C_{0}(P, X, W, \mu_{0}) = \{w \in FSeq(PN) | \delta(\mu, w) \text{ is zero, } w = uv, v \in X^{+}, u \in FSeq^{+}(PN)\}. \quad \square
$$

If $C(P, X, W, \mu_{0})$ and $C_{0}(P, X, W, \mu_{0})$ are not empty, then they are prefix codes. Because both $u, uv$ are their elements and $v \neq 1$ yield a contradiction since $\delta(\mu, u)$ is positive. And we call $C(P, X, W, \mu_{0}) \neq \emptyset$ a Petri net code, $C_{0}(P, X, W, \mu_{0}) \neq \emptyset$ a strict Petri net code. The families of all the Petri net codes and all strict Petri net code are denoted by CPN and CPN0, respectively. Note that CPN0 is a subclass of CPN. Moreover a Petri net code is said to be **maximal** if it is maximal as a prefix code. The families of all the maximal Petri net codes and all the strict Petri net codes are denoted by mCPN and mCPN0, respectively.

A Petri net code is said to be **input-ordinal** if it is generated by some input-ordinal Petri net. The family of all the input-ordinal Petri net codes is denoted by NmCPN.

Since an input-ordinal Petri net code is clearly a maximal Petri net code, we get the inclusion relation $NmCPN \subset mCPN$. In this paper, we consider the following problem:

[Problem] mCPN ⊆ NmCPN?

Since it is too difficult to solve this problem in general Petri nets, in the next section we prove that the problem is solved affirmatively in a restricted Petri net.

## 2 Fundamental Properties

In this section we state some fundamental properties about strict Petri net codes and the structure of Petri nets which generate maximal Petri net codes.
2.1 Some Properties of Strict Petri net codes

At first we show that a strict Petri net code is a full uniform code if it is finite and maximal. For a Petri net \((P, X, W, \mu_0)\), \(p \in P\) and \(u = a_1a_2 \ldots a_r \in X^+\), we denote \(W(p, a_1) - W(a_1, p) + (W(p, a_2) - W(a_2, p)) + \cdots + (W(p, a_r) - W(a_r, p))\) by \(p(u)\).

LEMMA 2.1 [2] Let \(C = C(P, X, W, \mu_0)\) be a finite maximal Petri net code over \(X\). For any \(u, v \in C\), if there exists a \(p \in P\) such that \(\mu_0(p) = p(u) = p(v)\), then \(C\) is a full uniform code over \(X\), i.e. \(C = X^n\) for some \(n, n \geq 1\).

PROPOSITION 2.1 If a finite maximal Petri net code over \(X\) is strict, then it is a full uniform code over \(X\).

LEMMA 2.2 Let \(C = C_0(P, X, W, \mu_0)\) be a maximal strict Petri net code over \(X\). And let \(p\) be a place in \(P\). Then there exists a Petri net \((\{p\}, X, W', \mu_0)\) such that \(C(\{p\}, X, W', \mu_0) = C\).

Proof) Let \(W'\) be the restriction of \(W\) on \(\{p\} \times X \cup X \times \{p\}\), \(\mu_0'\) be the restriction of \(\mu_0\) on \(\{p\}\). Let \(\delta\) and \(\delta'\) be transition functions of \((P, X, W, \mu_0)\) and \((\{p\}, X, W', \mu_0)\) respectively. Since \(C\) is maximal, \(\delta(\mu_0, u)(q) > 0, \delta'(\mu_0, u)(p) > 0\) and \(\delta(\mu_0, w)(q) = \delta'(\mu_0, w)(p) = 0\) for each \(q \in P, w = uv \in C, v \in X^+\). Therefore \(C(\{p\}, X, W', \mu_0) = C\).

PROPOSITION 2.2 If a maximal Petri net code over \(X\) is strict, then it is input-ordinal.

A code in this proposition is given the formula (1) in the next chapter. Note that the Petri net code \(\{a^n, ab, ba\}\) is strict but not maximal.

2.2 Structure of maximal Petri net codes

DEFINITION 2.1 Let \(PN = (P, X, W, \mu_0)\) be a Petri net and \(\mu_0\) be a positive marking. For \(w \in X^+\), the set \(F_w \subset P \times X\) of \(PN\) is defined as follows:

\[
(p, a) \in F_w \iff
\begin{align*}
(i) & \ W(p, a) > 0, \forall b \in X(W(p, a) \geq W(p, b)), \\
(ii) & \ w \in F^+(PN), \mu = \delta(\mu_0, w), (\forall q \in P)(W(q, a) > 0 \Rightarrow \mu(p) / W(p, a) \leq \mu(q) / W'(q, a)).
\end{align*}
\]

\((p, a) \in F_w\) means that the continuous firing of \(a\) makes the number of tokens in \(p\) become zero under the marking \(\mu\) obtained by reading a positive firing sequence \(w\). We denote the set of all such pairs \((p, a)\) by \(F^*\), that is \(F^* \overset{\text{def}}{=} \bigcup_{w \in X^+} F_w\). \(F^*\) is called the active flow of \(PN\).

A \((p, a) \in F^*\) means that \(p\) is a place where the number of tokens first becomes zero when a fires continuously after reading a positive firing sequence \(w\).

LEMMA 2.3 (Fundamental Lemma) Let \(F^*\) be an active flow of a Petri net \((P, X, W, \mu_0)\), \(C = C(P, X, W, \mu_0)\) be a maximal Petri net code. Let \(p \in P\) and \(a, b \in X\).

\[
\begin{align*}
(i) & \ (p, a) \in F^* \Rightarrow W(p, a) \geq W(p, b), \\
(ii) & \ (p, a), (p, b) \in F^* \Rightarrow W(p, a) = W(p, b).
\end{align*}
\]
DEFINITION 2.2 (The Reachability Problem) For a given Petri net $PN = (P, X, W, \mu_0)$ and a given marking $\mu$, is $\mu \in \text{Re}(PN)$?

DEFINITION 2.3 (The Single-Place Zero-Reachability Problem) For a given Petri net $PN = (P, X, W, \mu_0)$ and a given place $p \in P$, does there exist $\mu \in \text{Re}(PN)$ with $\mu(p) = 0$?
DEFINITION 2.4 (The Single-Place First Zero-Reachability Problem) For a given Petri net \( PN = (P, T, W, \mu_0) \) and a given place \( p \in P \), let \( \delta \) be the transition function of \( PN \), then does there exist \( w \in X^* \) such that \( \delta(\mu_0, w)(p) = 0 \) and \( \delta(\mu_0, w')(q) > 0 \) for all \( w' \in P_r(w) \setminus \{w\}, \forall q \in P \) ?

Fact 2.1 (1) The reachability problem and the single-place zero-reachability problem are equivalent. [7]

(2) The reachability problem is decidable. [8], [9] Any algorithm to solve the problem requires at least an exponential amount of space for storage and an exponential amount of time. [10]


LEMMA 2.5 (Reduction rule of two-way arcs) Let \( PN = (P, X, W, \mu_0) \) be a Petri net and \( \mu_0 \) be a positive marking. Let \( C = C(P, X, W, \mu_0) \) be a maximal Petri net code. Let \( p \in P, a \in X \) with \( W(p, a) > 0 \) and \( W(a, p) > 0 \). Then the Petri net \( PN' = (P, X, W', \mu_0) \) is defined as follows, which is obtained by replacing the weights of the two arcs \((p, a)\) and \((a, p)\).

\[
\begin{align*}
W(p, a) &> W(a, p) \quad \Rightarrow \quad W'(p, a) = W(p, a) - W(a, p), \quad W'(a, p) = 0 \\
W(p, a) &< W(a, p) \quad \Rightarrow \quad W'(a, p) = W(a, p) - W(p, a), \quad W'(p, a) = 0 \\
W(p, a) &= W(a, p) \quad \Rightarrow \quad W'(p, a) = W(p, a) - W'(a, p) = W(p, a)
\end{align*}
\]

Then

\[ C(P, X, W, \mu_0) = C(P, X, W', \mu_0). \]

3 Maximal Petri net codes and input-ordinal Petri net code

Here we solve the problem whether mCPN \( \equiv \) mCPN holds or not under some conditions.

In a Petri net \( PN = (P, X, W, \mu_0) \), for a transition \( a \in X \), set \( I(a) = \{ p \in P | W(p, a) > 0 \} \) and \( O(a) = \{ p \in P | W(a, p) > 0 \} \). If \( I(a) \neq \emptyset \) and \( O(a) \neq \emptyset \), then \( a \) is called a consuming transition. If \( I(a) \neq \emptyset \) and \( O(a) = \emptyset \), then \( a \) is called a supplying transition. If \( I(a) = \emptyset \) and \( O(a) \neq \emptyset \), then \( a \) is called an isolated transition.

Through this section, without the loss of generality we may assume that a Petri net \( PN = (P, X, W, \mu_0) \) with a positive marking \( \mu_0 \) satisfies the following conditions. Such a Petri net is called a slim maximal Petri net.

(i) \( C(P, X, W, \mu_0) \) is a maximal Petri net code.
(ii) By lemma 2.4, there is no useless place in \( PN \).
(iii) By lemma 2.5, for any \( p \in P \) and any \( a \in X \), both the weight of \( (a, p) \) and the weight of \( (p, a) \) are not positive.
(iv) \( PN \) has no isolated transitions.

3.1 Case of \(|P| \leq 2 \) or \(|X| = 1 \)

At first we consider the case the number \(|P|\) of places equals 1 and the case the number \(|X|\) of transitions equals 1.
THEOREM 3.1 Let $PN = (P, X, W, \mu_0)$ be a Petri net and $\mu_0$ be a positive marking. Assume that $|X| = 1$ or $|P| = 1$. If $C = C(P, X, W, \mu_0)$ is a maximal Petri net code, then $C$ is an input-ordinal Petri net code.

Assume that $|P| = 1$, that is $P = \{p\}$ in this theorem. Setting $X_1 = \{a \in X | W(p, a) > 0, W(a, p) = 0\}$ and $X_2 = X - X_1$, Then

$$C(P, X, W, \mu_0) = (X_1^{n_1} \circ (\bigcup_{a \in X_1} a_1 X_1^{n_1})) X_2,$$  \hspace{1cm} (1)$$

where $n_i = W(a_i, p)/n_i$. $\circ$ is the shuffle product over two languages $L, K \subset X^*$ defined by $L \circ K = \bigcup_{x \in L, y \in K} x \circ y$, $x \circ y = \{x_1 y_1 x_2 y_2 \cdots x_n y_n | x = x_1 x_2 \cdots x_n, y = y_1 y_2 \cdots y_n, x_i, y_i \in X^* \text{for } 1 \leq i \leq n\}$ for $x, y \in X^*$ and $L^\circ$ is the shuffle closure of a language $L$, defined by $L^\circ = \bigcup_{i \geq 0} L^{\circ_i}, L^{\circ_0} = \{1\}$, $L^{\circ_{i+1}} = L^{\circ_i} \circ L$.

Especially, in the above example setting $X_1 = \emptyset$ and $X_2 = X$, $C = X^k = \{w \in X^* | |w| = k\}$. $X^k$ is called a (full) uniform code over $X$. Therefore a uniform code becomes an input-ordinal Petri net code.

In case that a Petri net has only a place or only a transition, we have proven $\text{NmCPN} = \text{mCPN}$. We get the following result in the case that a Petri net has two places. The first proposition is for the case without supplying transitions, the second is for the case with with supplying transitions.

PROPOSITION 3.1 Let $PN = (P, X, W, \mu_0)$ be a Petri net without supplying transitions, $\mu_0$ be positive and $|P| = 2$. If $C = C(P, X, W, \mu_0)$ is a maximal Petri net code, then $C$ is an input-ordinal Petri net code.

PROPOSITION 3.2 Let $PN = (P, X, W, \mu_0)$ be a Petri net with supplying transitions, $\mu_0$ be positive and $|P| = 2$. If $C = C(P, X, W, \mu_0)$ is a maximal Petri net code, then $C$ is an input-ordinal Petri net code.

We obtain the final result of this paper from the theorems 3.1 and 3.2.

THEOREM 3.2 Let $PN = (P, X, W, \mu_0)$ be a Petri net, $\mu_0$ be positive and $|P| = 2$. If $C = C(P, X, W, \mu_0)$ is a maximal Petri net code, then $C$ is an input-ordinal Petri net code.
4 Some results in case of $|P| > 2$

In this section, first we introduce some notation and define some dependency of places in a Petri net. Secondly we investigate the maximality of a special type of Petri net.

4.1 Place dependency

We introduce the following notations:

**DEFINITION 4.1** Let $a \in X, w \in X, U \subseteq X$, and $\Omega \subseteq 2^X$. Then, The number $C_{\Omega}(w)$ is defined as follows:

$$|w|_{U} \overset{\text{def}}{=} \sum_{a \in U} |w|_{a} (\leq |w|)$$

$$C_{\Omega}(w) \overset{\text{def}}{=} \max \{|w|_{U} | U \in \Omega\},$$

where $|w|_{a}$ means the number of occurrences of a letter $a$ in $w$. □

Then the following properties hold:

(1) $0 \leq C_{\Omega}(w) \leq |w|.$

(2) Let $k \geq 1$ and $L_{\Omega,k} = \{w \in X^* | C_{\Omega}(w) = k\} \neq \emptyset$.

$L_{\Omega,k}$ is commutative and regular.

$L_{\Omega,k}$ is finite $\iff X = \bigcup \Omega$.

$X \in \Omega \Rightarrow L_{\Omega,k} = X^k$. The converse is not necessarily true.

(3) $L_{\Omega,k} \cap X^l = \emptyset$ for any $\Omega \subseteq 2^X$ if $k > l$.

(4) $L_{\Omega,k} \cap X^k = X^k$ iff $k \geq |X| \Rightarrow X \in \Omega$ and $k < |X| \Rightarrow (\forall w \in X^*)(|w| = k \Rightarrow \exists U \in \Omega(\text{alph}(w) \subseteq U)).$

$\text{alph}(w)$ means the number of the distinct letters in $w$. The equivalence is due to [1].

**EXAMPLE 4.1** Let $X = \{a, b, c\}$ and $\Omega = \{q, r\} = \{\{a, b\}, \{a, c\}, \{b, c\}\}$. Then $L_{\Omega,2} \cap X^2 = X^2$. But $L_{\Omega,3} \cap X^3 \neq X^3$ because $abc \notin L_{\Omega,3}$. □

![fig3](image_url)

Fig. 3: A Petri net generating $L_{\Omega,k}$.

Now we introduce some notations to prepare to describe the following lemmas.

**NOTATIONS** Let $PN = (P, X, \omega_0)$ be a PN and $\omega_0$ be a positive marking. Let $p \in P$ be a place.
\[ \alpha(p) \overset{\text{def}}{=} \max\{W(p, a) | a \in X\}, \]
\[ p^* \overset{\text{def}}{=} \{a \in X | W(p, a) > 0\}, \]
\[ 1st(F_w) \overset{\text{def}}{=} \{p \in P | (p, a) \in F_w\}, \]
\[ \#_w(p) \overset{\text{def}}{=} \mu(p)/\alpha(p) \text{ and } \mu = \delta(\mu_0, w). \]

In only a slim maximal Petri net, the following fundamental lemmas are true.

**LEMMA 4.1** Let \((P, X, W, \mu_0)\) be a slim maximal PN. Let \(p \in P\) and \(a \in X\). Then,
\[ (p, a) \in F^* \iff W(p, a) = \alpha(p) > 0. \] \(\Box\)

**LEMMA 4.2** Let \((P, X, W, \mu_0)\) be a slim maximal PN. Let \(p \in P\) and \(b \in X\). If \(p \in 1st(F_w)\) for some \(w \in X^*\) and \(0 < W(p, b) < \alpha(p)\) hold, there exists \(q \in 1st(F_w)\) satisfying the following (i) or (ii):
(i) \(W(q, b) = \alpha(q) \wedge \#_w(q) = 1\) for all \(w \in X^*\) with \(p \in 1st(F_w)\),
(ii) \(W(q, b) = W(q, a) = \alpha(q) \wedge \#_w(p) = \#_w(q)\) for all \(w \in X^*\) with \(p \in 1st(F_w)\).

If (i) (or (ii)) holds, it is said that \(p\) strongly (or weakly) depends on \(q\), we write \(p \triangleright_S q\) (or \(p \triangleright W q\)).

**EXAMPLE 4.2** In the Petri net in Fig. 4, \(p \triangleright S q\), \(#_w(p) = \#_w(q) = 1\):

![Diagram](image-url)

Fig. 4: Explanation of the dependency \(\triangleright_S\).

**LEMMA 4.3** Let \((P, X, W, \mu_0)\) be a slim maximal PN code. Let \(p, q, r \in P\).
(i) \(\triangleright_S\) is transitive (\(\triangleright_W\) is not necessarily transitive).
(ii) \(p \triangleright W q\) and \(q \triangleright W p\) are incompatible.
(iii) \(p \triangleright_S q\) and \(q \triangleright W r \Rightarrow q \triangleright_S r\). \(\Box\)

### 4.2 Petri net of the special type

We define a Petri net of the special type.

**DEFINITION 4.2** A Petri net \((P, X, W, \mu_0)\) is called to be of type D if it satisfies:
(i) \(P = \{p\} + Q\) and \(X = Z + Y\).
(ii) \( W(p,a) = \alpha(p) , \quad 0 < W(p,b) < \alpha(p) \). \( W(q,a) = W(q,b) = \alpha(q) \) for all \( q \in Q , \ a \in Z \) and \( b \in Y \).

(iii) \( \mu_0(p) = k\alpha(p) \) and \( \mu_0(q) = k\alpha(q) \) for all \( q \in Q \).

We denote this Petri net by \((p;Q,Z;Y;W,k)\) and the code it generates by \( C(p;Q,Z;Y;W,k) \), where \( Q = \{q_1,q_2,\ldots,q_n\} \), \( Z = \{a_1,a_2,\ldots,a_s\} \) and \( Y = \{b_1,b_2,\ldots,b_t\} \).

**EXAMPLE 4.3** The following figure is an example of a Petri net \((p;Q,Z;Y;W,k)\) of type D. For each \( q_i \in Q = \{q_1,q_2,\ldots,q_n\} , p \triangleright_w q_i \) holds there.

![Figure 5: A Petri net of type D with parameter k.](image)

Let \( w = a_1a_2\ldots a_n \in X^* , \ a_i \in X (1 \leq i \leq n) \).

\[
\pi_p(w) \overset{\text{def}}{=} \sum_{i=1}^{n} W(p,a_i).
\]

\( \pi_p : (X^*,+) \rightarrow (\{0,1,2,\ldots\},+) \) is the monoid morphism. The next lemma is the main result of this paper.

**LEMMA 4.4** Let \((p;Q,Z;Y;W,k)\) be a Petri net of type D. If \( C(p;Q,Z;Y;W,k) \) is a maximal prefix code, the condition:

\[
\text{For all } w \in X^*, \ \pi_p(w) \geq (k-1)m + 1 \Rightarrow C_{\Omega}(w) \geq k
\]

holds, where \( m = \alpha(p) , X = Y \cup Z \) and \( \Omega = \{Z\} \cup \{q | q \in Q\} \). The converse is also true. \( \square \)

**EXAMPLE 4.4** Let \( C_k \) be the Petri net code with the number \( k \) of tokens in \( p \) in Fig.6. If \( k = 2 \), then \( C_k = \{a,a',b\}^2 \) is a maximal code. But If \( k = 3 \), then \( C_k \) is not a maximal prefix code. Because \( \pi_p(aa'b) = 5 > (3-1)2 + 1 \) but \( C_p(aa'b) = C_q(aa'b) = C_{q'}(aa'b) = 2 < k = 3 \)

![Figure 6: Petri net of type D with parameter k.](image)
References