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On the Intractability of Computing the Duquenne-Guigues Base

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Abstract: Implications of a formal context (G, M, I) obey Armstrong rules, which allows for definition of a minimal (in the number of implications) implication base, called Duquenne-Guigues or stem base in the literature. A long-standing problem was that of an upper bound for the size of a stem base in the size of the relation I. In this paper we give a simple example of a relation where this boundary is exponential. We also prove $\#P$-hardness of the problem of determining the size of the stem base (i.e., the number of pseudo-intents).
Key Words: implication base, computational complexity
Category: F.2, H.2

1 Main Definitions and Problem Statement

First we recall some basic notions of Formal Concept Analysis (FCA) [Wille 1982], [Ganter and Wille 1999].

Definition. Let G and M be sets, called the set of objects and the set of attributes, respectively. Let I be a relation $I \subseteq G \times M$ between objects and attributes: for $g \in G$, $m \in M$, gIm holds iff the object g has the attribute m. The triple $K = (G, M, I)$ is called a *(formal) context*. Formal contexts are naturally given by cross tables, where a cross for a pair (g, m) means that this pair belongs to the relation I. If $A \subseteq G$, $B \subseteq M$ are arbitrary subsets, then the *Galois connection* is given by the following *derivation operators*:

$$A' := \{m \in M \mid gIm \text{ for all } g \in A\},$$
$$B' := \{g \in G \mid gIm \text{ for all } m \in B\}.$$

The pair (A, B), where $A \subseteq G$, $B \subseteq M$, $A' = B$, and $B' = A$ is called a *(formal) concept (of the context K)* with *extent* A and *intent* B. For $g \in G$ and $m \in M$ the sets $\{g\}'$ and $\{m\}'$ are called *object intent* and *attribute extent*, respectively. The set of attributes B *is implied by the set of attributes* D, or an *implication* $D \to B$ holds, if all objects from G that have all attributes from the set D also have all attributes from the set B, i.e., $D' \subseteq B'$.

The operation $(\cdot)''$ is a closure operator [Ganter and Wille 1999], i.e., it is idempotent ($X'''' = X''$), extensive ($X \subseteq X''$), and monotone ($X \subseteq Y \Rightarrow X'' \subseteq$

Y''). Sets $A \subseteq G$, $B \subseteq M$ are called *closed* if $A'' = A$ and $B'' = B$. Obviously, extents and intents are closed sets. Since the closed sets form a closure system or a Moore space [Birkhoff 1979], the set of all formal concepts of the context K, forms a lattice, called a *concept lattice* and usually denoted by $\underline{\mathfrak{B}}(K)$ in FCA literature.

Implications obey Armstrong rules:

$$\frac{A \to B}{A \cup C \to B} \quad , \quad \frac{A \to B, A \to C}{A \to B \cup C} \quad , \quad \frac{A \to B, B \to C}{A \to C}.$$

A minimal (in the number of implications) subset of implications, from which all other implications of a context can be deduced by means of Armstrong rules was characterized in [Guigues and Duquenne 1986]. This subset is called Duquenne-Guigues or stem base in the literature. The premises of implications of the stem base can be given by pseudo-intents (see, e.g., [Ganter and Wille 1999]): a set $P \subseteq M$ is a **pseudo-intent** if $P \neq P''$ and $Q'' \subset P$ for every pseudo-intent $Q \subset P$. Since the introduction of the stem base, a long standing problem was that concerning the upper bound of the size of the stem base: whether the stem base can be exponential in the size of the input, i.e., in $|G| \times |M|$.

Now we recall some standard definitions. A **many-valued context** [Ganter and Wille 1999] is a tuple (G, M, W, I), where W is the set of attribute values, $I \subseteq G \times M \times W$, such that $(g, m, w) \in I$ and $(g, m, v) \in I$ implies $w = v$. Thus, instead of $(g, m, w) \in I$ one can write $g(m) = w$. By definition, $\mathrm{dom}(m) := \{g \in G \mid (g, m, w) \in I \text{ for some } w \in W\}$. An attribute m is **complete** if $\mathrm{dom}(m) = G$. A many-valued context is complete if all its attributes are complete. $X \to Y$ is a **functional dependency** in a complete many-valued context (G, M, W, I) if the following holds for every pair of objects $g, h \in G$:

$$(\forall m \in X \quad m(g) = m(h)) \Rightarrow (\forall n \in Y \quad n(g) = n(h)).$$

In [Ganter and Wille 1999] it was shown that having a complete many-valued context (G, M, W, I), one defines the context $K_N := (\mathcal{P}_2(G), M, I_N)$, where $\mathcal{P}_2(G)$ is the set of all pairs of different objects from G and I_N is defined by

$$\{g, h\} I_N m :\Leftrightarrow m(g) = m(h).$$

Then a set $Y \subseteq M$ is functionally dependent on the set $X \subseteq M$ iff the implication $X \to Y$ holds in the context K_N.

2 Counting pseudo-intents

A concept lattice can be exponential in the size of the context (e.g., when it is a Boolean one). Moreover, the problem of determining the size of a concept lattice is $\#P$-complete (see e.g. [Kuznetsov 2001]). There are several polynomial-delay algorithms for computing the set of all concepts (see e.g. review [Kuznetsov and Obiedkov 2002]). However, neither an efficient (polynomial-delay) algorithm, nor a good upper bound for the size of stem base was known. It is easy to show that there can be a stem base exponential in the size with respect to $|M|$, for example when object intents are exactly all possible subsets of size $|M|/2$. However, in this case $|G|$, as well as $|I|$, are also exponential in $|M|$, and the number of pseudo-intents is polynomial in $|I|$.

A solution to the question whether stem base can be exponential in the size of the context, i.e., in $|G| \times |M|$ is obtained by observing a fact about functional dependencies, namely that the size of a smallest base of functional dependencies can be exponential in the size of the relation [Mannila and Räihä 1992][1]. Although the reducibility of functional dependencies to implications implies similar statement for the implication base, a general form of a context that gives rise to exponentially large stem base was not clear. The reduction of a many-valued context (G, M, W, I) to a binary one $K_N = (\mathcal{P}_2(G), M, I_N)$ along the lines of [Ganter and Wille 1999] (see Section 1) results in contexts with $(2m+3)^2$ objects for $m \geq 2$, so the smallest number of objects in such a context is 49. Here we propose simpler contexts with sizes of the stem base exponential in the relation size.

Consider a context $K_e = (G, M, I)$ given by the cross table in Figure 1, where $G = G_1 \cup G_2$, $M = M_1 \cup M_2 \cup \{m_0\}$, $I = I_1 \cup I_2 \cup I_3 \cup \{m_0\} \times G_2$ and subcontexts $K_1 = (G_1, M_1, I_1)$, $K_2 = (G_1, M_2, I_2)$, $K_3 = (G_2, M_1 \cup M_2, I_3)$ are of the form $(A, A, \neq)$. More formally, objects and attributes are $G_1 = \{g_1, \ldots, g_n\}$, $G_2 = \{g_{n+1}, \ldots, g_{3n}\}$, $M_1 = \{m_1, \ldots, m_n\}$, $M_2 = \{m_{n+1}, \ldots, m_{2n}\}$. The relations I_1, I_2, and I_3 are defined as follows: $g_i I_1 m_j$ iff $i \neq j$, $g_i I_2 m_j$ iff $i \neq j - n$, $g_i I_3 m_j$ iff $i \neq j + n$ for g_i and m_j from corresponding sets of objects and attributes. For m_0 and $g \in G$ one has $m_0 I g$ iff $g \in G_2$.

[1] I am grateful to Lhouari Nourine for attracting my attention to this fact.

$G \setminus M$	m_0	$m_1, \ldots, m_n$	$m_{n+1}, \ldots, m_{2n}$
g_1			
$\vdots$			
$\vdots$		I_1	I_2
$\vdots$			
g_n			
g_{n+1}	$\times$		
$\vdots$	$\vdots$		
$\vdots$	$\vdots$		
$\vdots$	$\vdots$	I_3	
$\vdots$	$\vdots$		
g_{3n}	$\times$		

Figure 1

Theorem 1. *The number of pseudo-intents of the context K_e is 2^n.*

Proof. First note that the set of attributes $\{m_1, \ldots, m_n\}$ is a pseudo-intent. In fact, for a subset

$$B = \{m_{j_1}, \ldots, m_{j_k}\} \subset \{m_1, \ldots, m_n\} = M_1$$

we have

$$B' = (G_1 \setminus \{g_{j_1}, \ldots, g_{j_k}\}) \cup (G_2 \setminus \{g_{n+j_1}, \ldots, g_{n+j_k}\})$$

and $B'' = B$, i.e., the set B is closed. The set $\{m_1, \ldots, m_n\}$ is not closed, since $\{m_1, \ldots, m_n\}'' = \{m_0, m_1, \ldots, m_n\}$. If a set is not closed and all its subsets are closed, then it is a pseudo-intent by definition. Since the set $\{m_1, \ldots, m_n\}$ is a pseudo-intent, if we replace $m_i \in \{m_1, \ldots, m_n\}$ with m_{n+i}, then the resulting set

$$\{m_1, \ldots, m_{i-1}, m_{i+n}, m_{i+1}, \ldots, m_n\}$$

is still a pseudo-intent, because it is not closed:

$$\{m_1, \ldots, m_{i-1}, m_{i+n}, m_{i+1}, \ldots, m_n\}'' =$$

$$\{m_0, m_1, \ldots, m_{i-1}, m_{i+n}, m_{i+1}, \ldots, m_n\}$$

and every subset

$$C \subset \{m_1, \ldots, m_{i-1}, m_{i+n}, m_{i+1}, \ldots, m_n\}$$

is closed by the same arguments as for $B \subset M_1$. We can replace each m_i with m_{n+i} obtaining another pseudo-intent. Since the replacement of m_i for m_{n+i} can be done independently for each i, we have 2^n pseudo-intents. $\diamond$

Note that in our example pseudo-intents are at the same time proper premises (see, e.g., [Ganter and Wille 1999]), which make the so-called direct base: all implications are deduced from this base by single application of Armstrong rules. Moreover, here all pseudointents are so-called minimal positive hypotheses (see, e.g., [Ganter and Kuznetsov 2000]) w.r.t. the target attribute m_0.

Besides the exponential boundary of the size of the stem base, the problem of counting pseudo-intents is also intractable by the following

Theorem 2. *The problem*

INPUT A formal context $K = (G, M, I)$

OUTPUT The number of pseudointents of K

is #P-hard.

Proof. Consider an abitrary graph (V, E) and three sets $M = \{m_1, \ldots, m_{|V|}\}$, $G_1 = \{g_1, \ldots, g_{|E|}\}$, and $G_2 = \{g_{|E|+1}, \ldots, g_{|E|+|V|}\}$ such that the elements of the set M are in one-to-one correpondence with the set of vertices V (so one can write, e.g., $v(m)$), the elements of the set G_1 are in one-to-one correspondence with the edges from E (so one can write, e.g., $e(g)$), the elements of the set G_2 are in one-to-one correspondence with vertices from V (so one can write, e.g., $v(g)$).

Now consider a context $K = (G_1 \cup G_2, M \cup \{m_0\}, I)$, where I is defined as follows: for $m \in M$ and $g \in G_1$ one has mIg iff $v(m) \notin e(g)$ (i.e., the vertex $v(m)$ is not incident to the edge $e(g)$). For $m \in M$ and $g \in G_2$ one has mIg iff $v(m) \neq v(g)$. For m_0 one has m_0Ig iff $g \in G_2$.

In terms of FCA, the context K is the subposition of two contexts, which can be reprsented by the cross table in Fig. 2. Here $\not I$ is the complement of the vertex-edge incidence relation of the graph (V, E): $v \not I e$ iff v is not incident to e (or $v \notin e$), $\neq$ denotes the "zero-diagonal" relation (only the diagonal pairs do not belong to it).

Recall that in a graph (V, E) a subset $W \subseteq V$ is a vertex cover if every edge $e \in E$ is incident to some $w \in W$. A cover is minimal if no proper subset of it is a cover. The problem of counting all minimal covers was proved to be $\#P$-complete in [Valiant 1979]. We show that for a graph (V, E) pseudo-intents of the context in Fig. 2 are in one-to-one correspondence with minimal vertex covers of (V, E).

Indeed, if a subset $W \subseteq V$ of vertices is a minimal cover, then by definition of $\not I$, for each $g_i \in G_1$ there is an attribute $m_i \in W$ such that $g_j \not I m_i$ does not hold. Thus, the set W' will not contain any object from G_1. Hence, W'' will contain m_0 and, thus W is not closed ($W'' \neq W$). However, for any subset $Q \subset W$ we have $Q'' = Q$ (because Q' contains an object from G_1). Thus, by definition, W is a pseudo-intent.

In the opposite direction, for each $m_i \in M$ consider $W\!: m \notin W$. Since $m_i \notin \{g_{|E|+i}\}'$, the implication $W \to \{m_i\}$ does not hold and there is no nontrivial implications with m_i in the right-hand side. The only possible nontrivial implications are of the form $W \to \{m_0\}$. Hence, if W is a pseudo-intent of the context, then W' should not contain any object from G_1. Thus, by the definition of $\not I$, the set W is a vertex cover. This cover is minimal, since otherwise there had existed a subset $Q \subset W$ which is not closed, $Q'' = Q \cup \{m_0\}$, which contradicts the fact that W is a pseudo-intent such that $W'' = W \cup \{m_0\}$.

$G \setminus M$	m_0	$m_1, \ldots\ldots\ldots\ldots, m_{\vert V\vert}$
g_1 ⋮ ⋮ ⋮ $g_{\vert E\vert}$		$\not I$
$g_{\vert E\vert+1}$ ⋮ ⋮ ⋮ $g_{\vert E\vert+\vert V\vert}$	× ⋮ ⋮ ⋮ ×	$\neq$

Figure 2

Thus, we reduced the decision problem of finding a minimal vertex cover to the problem of finding a pseudo-intent. The reduction is obviously polynomial. $\diamond$

To show that the problem of counting pseudo-intents belongs to the class $\#P$ (and, thus is $\#P$-complete), one should prove that the following decision problem

INSTANCE A context $K = (G, M, I)$, $Q \subseteq M$
QUESTION Is Q a pseudo-intent?

is solvable in polynomial time. Note that the decision problem

INSTANCE A context $K = (G, M, I)$, a natural number $k \leq |M|$.
QUESTION Is there a pseudo-intent of the context K of size not greater than k?

is proved to be NP-hard with the same reduction as in the proof of Theorem 2 from the NP-complete problem of deciding the existence of a vertex cover of size no greater than k.

At the same time the problem

INSTANCE A context $K = (G, M, I)$
QUESTION Is there a pseudo-intent of the context K?

is solvable in polynomial time: The only situation when a context (G, M, I) does not have a pseudo-intent is the case where it has a "diagonal" subcontext of the form $(A, A, \neq)$. For an arbitrary context (G, M, I) one can test whether it has a diagonal subcontext in $(|G| \cdot |M|)$ time (by scanning once all rows of the cross-table of the context K).

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