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**Title**
ON CONCEPT LATTICE APPROXIMATION (Foundations of Theoretical Computer Science: For New Computational View)

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ON CONCEPT LATTICE APPROXIMATION

LÉONARD KWUIDA

ABSTRACT. In these notes we motivate the need of approximating concept lattices by lattices of small size or by lattices of nicer structure. We also present some approaches towards an approximation theory for concept lattices. The main goal is to support Formal Concept Analysis (FCA) techniques in Knowledge Discovery and Knowledge Management.

1. FCA AND KNOWLEDGE DISCOVERY

1.1. Information systems, contexts and concepts. The elementary way to encode information is to describe, by means of a relation that some objects have some properties. This sets up a binary relation I between the set G of objects and the set M of properties. The triple (G, M, I) is called a formal context. (g, m) ∈ I reads "the object g has the property m"; we also write gi m. Figure 1 (taken from [GS]) shows us the members of the Star Alliance and their flying destinations.

Some interesting patterns are formed by objects sharing the same properties. In Knowledge discovery, many techniques are based on the formalization of such patterns, namely that of concept. A formal concept of a context (G, M, I) is a pair (A, B) such that B is exactly the set of all properties shared by the objects in A (denoted by A′ or A′), and A is the set of all objects that have all the properties in B (denoted by B′ or B′). We called A the extent of the concept (A, B) and B the intent of the concept (A, B). The concept hierarchy states that a concept is more general if its extent is larger or equivalently if its intent is smaller. Formally, A ⊆ C ⇐⇒ (A, B) ≤ (C, D) ⇐⇒ B ⊇ D. This defines an order relation on the set B(G, M, I) of all concepts of (G, M, I).

The structure of this poset is more richer. We call a poset (L, ≤) lattice if min{x, y} and max{x, y} exist for any pair {x, y} ⊆ L. A poset (L, ≤) is a complete lattice if minZ and maxZ (also denoted by \(\wedge\)Z and \(\vee\)Z resp.) exist for every subset Z of L. Equivalently, a lattice is an algebra (L, \(\wedge\), \(\vee\)) of type (2, 2) such that \(\wedge\) and \(\vee\) are idempotent, commutative, associative and satisfy the absorption laws:

\[x \wedge (x \vee y) = x\] and \[x \vee (x \wedge y) = x\].

It holds: \(x \wedge y = \min\{x, y\}\), \(x \vee y = \max\{x, y\}\) and \(x \wedge y = x \iff x \leq y \iff x \vee y = y\).

Theorem 1.1. [Wi82] \((B(G, M, I), \leq)\) is a complete lattice, in which infimum and supremum are given by

\[\bigwedge_{k \in K} (A_k, B_k) = \left(\bigcap_{k \in K} A_k, \left(\bigcup_{k \in K} B_k\right)\right)\] and \[\bigvee_{k \in K} (A_k, B_k) = \left(\left(\bigcup_{k \in K} A_k\right), \bigcap_{k \in K} B_k\right)\].

\(B(G, M, I)\) is called the concept lattice of the context \((G, M, I)\). For \(g \in G\) and \(m \in M\) we set \(g' := \{g\}\) and \(m' := \{m\}'\). We define some special building block concepts: \(\gamma g := (g'', g')\) (object concept) and \(\mu m := (m', m'')\) (attribute

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\(^1\)min\(\{x, y\}\) (also denoted by \(x \wedge y\)) is the greatest element below \(x\) and \(y\). \(\max\{x, y\}\) (also denoted by \(x \vee y\)) is the smallest element above \(x\) and \(y\).
For any concept \((A, B) \in \mathfrak{B}(G, M, I)\) we have \(\{\gamma g | g \in A\} = (A, B) = \{\mu m | m \in B\}\). Thus \(\{\gamma g | g \in G\}\) is \(\vee\)-dense and \(\{\mu m | m \in M\}\) is \(\wedge\)-dense in \(\mathfrak{B}(G, M, I)\). Conversely each complete lattice is (a copy of) a concept lattice of a certain context. In fact,

Theorem 1.2. [Wi82] a complete lattice \(L\) is isomorphic to a concept lattice of a context \((G, M, I)\) iff there are maps \(\alpha : G \rightarrow L\) and \(\beta : M \rightarrow L\) such that \(\alpha(G)\) is \(\vee\)-dense in \(L\), \(\beta(M)\) is \(\wedge\)-dense in \(L\) and \(g1m \iff \alpha(g) \leq \beta(m)\).

Theorem 1.1 and Theorem 1.2 form the basic theorem of Formal Concept Analysis. The Mathematical foundations have been documented in a monograph by Bernhard Ganter and Rudolf Wille [GW99].

1.2. Concept lattices and their diagrams. Finite concept lattices can be represented by labeled Hasse diagrams. Each node represents a concept. The label \(g\) is written underneath of \(\gamma g\) and \(m\) above \(\mu m\). The extent of a concept represented by a node \(a\) is given by all labels in \(G\) from \(a\) downwards, and the intent by all labels in \(M\) from \(a\) upwards. Figure 2 presents the diagram of the concept lattice of the context of Figure 1. Diagrams are valuable tools for visualization of data. However drawing a good diagram is a big challenge. Quite often, the size of the lattice is large and its structure complex. Thus we need tools to “approximate” by reducing the size or by making the structure nicer.

1.3. Galois connections and closure operators.

Definition 1.1. On a poset \((P, \leq)\) a closure operator is a map \(c : P \rightarrow P\) that satisfies \(x \leq c(y) \iff c(x) \leq c(y)\) and a kernel operator a map \(k : P \rightarrow P\) that satisfies \(k(x) \leq y \iff k(x) \leq k(y)\).

2For example we can read on Figure 2 that each member of the Star Alliance who flies to US and Europe also flies to Asia Pacific, or that each member who flies to Mexico and Asia Pacific also flies to Latin America, US, Canada and Europe.
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We often write \( cx, kx, cP \) and \( kP \) for \( c(x), k(x), c(P) \) and \( k(P) \) respectively. A map \( c \) is a closure operator iff \( x \leq cx, ccx = cx \) and \( x \leq y \Rightarrow cx \leq cy \). Dually, a map \( k \) is a kernel operator iff \( x \geq kx, kxk = kx \) and \( x \leq y \Rightarrow kx \leq ky \). The maps \( A \rightarrow A' \) and \( B \rightarrow B'' \) are a closure operator on \( (\mathcal{P}(G), \subseteq) \) and a kernel operator on \( (\mathcal{P}(M), \supseteq) \) respectively. They arise naturally from a Galois connection.

**Definition 1.2.** A Galois connection between \((P, \leq)\) and \((Q, \leq)\) is a pair \((\alpha, \beta)\) of maps \( \alpha : P \rightarrow Q \) and \( \beta : Q \rightarrow P \) such that \( x \leq \beta(y) \iff y \leq \alpha(x) \).

The operations \( A \rightarrow A' \) and \( B \rightarrow B'' \) form a Galois connection between \( \mathcal{P}(G) \) and \( \mathcal{P}(M) \). \( A \rightarrow A'' \) and \( B \rightarrow B'' \) are the corresponding closure operators.

(i) If \((\alpha, \beta)\) is a Galois connection then \( \alpha \circ \beta \) and \( \beta \circ \alpha \) are closure operators.

(ii) If \( c \) is a closure operator on \( P \), then \( \alpha \) and its inclusion map \( \beta : cP \rightarrow P \) form a Galois connection between \( (P, \leq) \) and \( (cP, \supseteq) \) with \( \beta \circ c = c \).

1.4. Concept lattices and implications. A closure system on a set \( M \) is set of subsets of \( M \), closed under intersection. The set of extents (resp. intents) of \((G, M, I)\) is a closure system on \( G \) (resp. \( M \)). Each complete lattice is (a copy of) a closure system, and vice-versa.

**Definition 1.3.** Let \( M \) be a set of properties or attributes. An implication between attributes in \( M \) is a pair \((A, B)\), denoted by \( A \rightarrow B \). \( A \) is the premise and \( B \) the conclusion of \( A \rightarrow B \). An implication \( A \rightarrow B \) holds in a context \((G, M, I)\) if every object having all the attributes in \( A \) also has all the attributes in \( B \). A subset \( T \) of \( M \) respects \( A \rightarrow B \) if \( A \notin T \) or \( B \subseteq T^3 \); we say that \( T \) is a model of \( A \rightarrow B \) and write \( T \models A \rightarrow B \). \( T \) respects a set \( \mathcal{L} \) of implications if \( T \) respects every implication in \( \mathcal{L} \). An implication \( A \rightarrow B \) holds in a family \( T \) if every \( T \in T \) respects \( A \rightarrow B \).

Implications can be read off from the lattice diagram. The rule is given by: \( B \subseteq A' \) iff \((G, M, I) \models A \rightarrow B \) iff \( \mu a \mid a \in A \leq \mu m \) for all \( m \in B \). For example \{Mexico, Asia Pacific\} \rightarrow \{Latin America, US, Canada, Europe\} can be read from the lattice in Figure 2. If \( \mathcal{L} \) is a set of implications in \( M \), then \( \text{Mod} \mathcal{L} := \{T \subseteq M \mid T \models \mathcal{L}\} \) is a closure system on \( M \). The corresponding closure operator, denoted by \( X \mapsto \mathcal{L}(X) \), is obtained by setting \( X^\mathcal{L} := X \).

\[ X^{\mathcal{L}^+} := X^\mathcal{L} \cup \bigcup \{ B \mid A \rightarrow B \in \mathcal{L}, A \subseteq X^{\mathcal{L}^n} \} \text{ and } \mathcal{L}(X) := \bigcup_{n \geq 0} X^{\mathcal{L}^n}. \]

\(^3\text{This is equivalent to } A \subseteq T \Rightarrow B \subseteq T \text{, and can be interpreted as the conclusion } B \text{ is "valid" in } T \text{ whenever the premise } A \text{ is "valid" in } T. \)
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<td>Latin America, Canada, US → Mexico;</td>
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<td>13</td>
<td>Latin America, Europe, Asia Pacific, Africa, Caribbean, US → Canada, Middle East, Mexico.</td>
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**Figure 3.** Duquenne-Guigues implication basis of Star Alliance.

To each arrow, we attach the number of object supporting this implication.

If $\mathcal{L}$ is the set of all implications of $(G, M, I)$ then $\text{Mod}\mathcal{L}$ is the set of all concept intents of $(G, M, I)$. Quite often, the implication list is long and contains trivial implications. So it is desirable to get a minimal list of implications that hold in a context $(G, M, I)$ and that generate all implications valid in $(G, M, I)$.

**Definition 1.4.** An implication $A \rightarrow B$ follows from a set $\mathcal{L}$ of implications in $M$ if each subset of $M$ respecting $\mathcal{L}$ also respects $A \rightarrow B$. We write $\mathcal{L} \vdash A \rightarrow B$. $\mathcal{L}$ is closed if every implication following from $\mathcal{L}$ is in $\mathcal{L}$. $\mathcal{L}$ is non-redundant if no implication in $\mathcal{L}$ follows from other implications of $\mathcal{L}$. A set $\mathcal{L}$ of implications of $(G, M, I)$ is complete if every implication that holds in $(G, M, I)$ follows from $\mathcal{L}$. A set $\mathcal{L}$ of implications of $(G, M, I)$ is sound if every implication of $\mathcal{L}$ holds in $(G, M, I)$. An implication basis of $(G, M, I)$ is a set $\mathcal{L}$ that is sound, complete and non-redundant.

A set $\mathcal{L}$ of implications is closed iff for all $X, Y, Z, W \subseteq M$, $X \rightarrow X \in \mathcal{L}$, $X \rightarrow Y \in \mathcal{L}$ implies $X \cup Z \rightarrow Y \in \mathcal{L}$, and $X \rightarrow Y \in \mathcal{L}$, $Y \cup Z \rightarrow W \in \mathcal{L}$ imply $X \cup Z \rightarrow W \in \mathcal{L}$ (Armstrong rules). In addition $\mathcal{L} \vdash A \rightarrow B$ iff $B \subseteq \mathcal{L}(A)$. For finite contexts implication bases can be computed. Jean Louis Guigues and Vincent Duquenne shown that there is a natural choice [GD86]. Figure 3 gives the Guigues-Duquenne implication basis of the context in Figure 1, with the number of objects really supporting them.

**2. APPROXIMATION**

The need of an approximation theory for concept lattices is motivated by many reasons: given a context $\mathcal{K}$, its concept lattice can be of huge size and have a complex structure; its implications list can long even if restricted only to an implication basis and contains some non “relevant” implications; we might not get some rules, although they are relevant (just because few exceptions violate them). Therefore the approximation problem can be formulated as follow:

*Given a concept lattice $L$, can we replace $L$ with a lattice $\tilde{L}$, that is nicer*

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$4^2M \times 2^M$ is the set of possible implications in $M$.

No object supports implication #13; no member flies to Africa and Caribbean.
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and easy to handle without loosing meaningful information? How can we reduce the number of concepts without loosing meaningful information? How can we express that two lattices carry almost the same information? Three approaches suggest themselves: approximate a given lattice by a lattice of smaller size (using clusters) such that meaningful information are preserved; relax definitions of concepts or implications to get some similar patterns; or approximate a given lattice by some lattices from a well-known and easy to handle class of lattices.

2.1. Approximation via closure and kernel operators.

Lemma 2.1. Let $c$ be a closure operator and $k$ a kernel operator on $(P, \leq)$.

(i) If $(P, \leq)$ is a (complete) lattice then $c(x \vee y) = c(x) \vee c(y)$, and $c(x \wedge y) = c(x) \wedge c(y)$, for all $x, y \in P$, and $(cP, \leq)$ is a (complete) lattice.

(ii) If $(P, \leq)$ is a (complete) lattice then $k(x \vee y) = k(x) \vee k(y)$, and $k(x \wedge y) = k(x) \wedge k(y)$, for all $x, y \in P$, and $(kP, \leq)$ is a (complete) lattice.

Lemma 2.1 states that closure and kernel operators are valuable tools for lattice approximation. They keep lattice sizes smaller. However the structure is not always easy to handle. How can we define interesting closure operators?

2.2. Approximation via association rules.

Definition 2.1. A data mining context is a finite context $(G, M, I)$. The elements of $M$ are called items and its subsets itemsets. Closed itemsets are intents. An association rule is a pair $(B_1, B_2)$ of itemsets, denoted by $B_1 \rightarrow B_2$. Let $\text{minsupp}$, $\text{minconf} \in [0, 1]$, $B$ an itemset and $r := B_1 \rightarrow B_2$ a rule. The support and confidence are defined by:

$$\text{supp}(B) := \frac{|B|}{|G|}, \quad \text{supp}(r) := \frac{|B_1 \cup B_2|}{|G|} \quad \text{and} \quad \text{conf}(r) := \frac{\text{supp}(B_1 \cup B_2)}{\text{supp}(B_1)}.$$ 

$B$ is frequent if $\text{supp}(B) \geq \text{minsupp}$. If $\text{conf}(r) = 1$, $r$ is called an exact rule.

Here we are interested in frequent itemsets and associations between them. For a rule $A \rightarrow B$, $\text{conf}(A \rightarrow B)$ also denoted by $p_A(B)$ or $p(B|A)$ is the probability of $B$ given $A$. The goal is to extract those that are frequent and have a confidence greater than the $\text{minconf}$. The Luxenburger basis [Lu91] of the partial implications of Star Alliance with $\text{minsupp} = 30\%$ and $\text{minconf} = 90\%$ is given by Figure 4 below. We get three new rules: #11, #12 and #13. The implications #09, #11 and #13 of Fig. 3 are not rule anymore, since their support is less than 90%.

2.3. Approximation via pseudocomplementation. $L$ denotes a finite lattice. The pseudocomplement of $x \in L$ (if it exists) is an element $x^*$ such that $x \wedge y = 0 \iff y \leq x^*$. $L$ is pseudocomplemented if $x^*$ exists for every $x \in L$; in this case $x \mapsto x^*$ is a unary operation on $L$, with $(\bigvee_{k \in K} x_k)^* = \bigwedge_{k \in K} x_k^*$. Moreover $c : x \mapsto c(x)$ is a closure operator on $L$ such that $cL$ is a Boolean lattice, called skeleton. For concept lattices the Boolean structure depicts a total independence between (reduced) attributes, meaning that each possible combination is an intent. The structure is also easy to handle. Let $E$ be a finite closure system on $G$ with $A \mapsto A''$ the corresponding closure operator. For simplicity we assume $\emptyset'' = \emptyset$ and $g'' = h'' \implies g = h$. We set $G_{\text{min}} := \{ g \in G \mid g'' = \{g\} \}$, the labels of atomic concepts. Then $E$ is pseudocomplemented iff all $g''$, $g \in G_{\text{min}}$ have pseudocomplements. To

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\[ A \text{ Boolean lattice is distributive} \quad (x \wedge (y \vee z)) = (x \wedge y) \vee (x \wedge z) \]

\[ \text{and complemented lattice} \quad x \vee x^* = 1 \text{ and } x \wedge x^* = 0. \]
express the pseudocomplementation we use a projection $s$ and its inverse $[]$ defined by:

$$s(A) := \bigcup_{g \in A} g'' \cap G_{\text{min}} \quad \text{and} \quad [A] := \{ g \in G \mid s(g) \subseteq s(A) \} \quad \text{with} \quad s(g) := s(\{g\}).$$

**Lemma 2.2.** [GK05] The operator $[]$ defines a closure operator on $G$. An element $A \in \mathcal{E}$ has a pseudocomplement $m$ iff $[G_{\text{min}} \setminus A] \in \mathcal{E}$. $\mathcal{E}$ is a pseudocomplemented closure system iff $[G_{\text{min}} \setminus \{a\}] \in \mathcal{E}$ with for all $a \in G_{\text{min}}$.

Thus if $\mathcal{E}$ is not pseudocomplemented, then $[G_{\text{min}} \setminus \{a\}] \notin \mathcal{E}$ for some $a \in G_{\text{min}}$. We collect these $[G_{\text{min}} \setminus \{a\}]$s and generate a new closure system.

**Theorem 2.3.** [Kw06] Let $\mathcal{E}$ be a closure system on $G$. The closure system $\tilde{\mathcal{E}}$ generated by $\mathcal{E} \cup \{[G_{\text{min}} \setminus \{a\}] \mid a \in G_{\text{min}}\}$ is pseudocomplemented. Meets and existing pseudocomplements in $\mathcal{E}$ are preserved in $\tilde{\mathcal{E}}$. $\tilde{\mathcal{E}}$ is the coarsest pseudocomplemented refinement of $\mathcal{E}$.

**Corollary 2.4.** [Kw06] Each (finite) concept lattice $L$ can be $\land$-embedded into a smallest pseudocomplemented concept lattice $\tilde{L}$.

The process described in Theorem 2.3 can be performed on the context level. We should first check, by means of arrow-relations, whether a given context has a pseudocomplemented concept lattice. The arrow-relations are defined by:

$$g \not\nearrow m : \iff m \notin g' \quad \text{and} \quad g' \not\searrow h' \implies m \in h',$$

$$g \not\nearrow m : \iff g \notin m' \quad \text{and} \quad m' \not\searrow n' \implies g \in n',$$

$$g \not\nearrow m : \iff g \not\nearrow m \quad \text{and} \quad g \not\nearrow m, \text{for } g, h \in G \text{ and } m, n \in M.$$
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Now set $E := Ext(G, M, I)$, the closure system of extents. For $a \in G_{\min}$, if $[G_{\min} \setminus \{a\}] \in E$ then there is $m_a \in M$ such that $m_a' = [G_{\min} \setminus \{a\}]$ ([GK05]). Therefore generating a new closure system with $[G_{\min} \setminus \{a\}, a \in G_{\min}$ is equivalent to adding new attributes $m_a$ in the context whenever $[G_{\min} \setminus \{a\}]$ is not an extent. These attributes have exactly $[G_{\min} \setminus \{a\}]$ as extent. Theorem 2.3 says that the so obtained lattice is pseudocomplemented and has $(B(G, M, I), \wedge)$ as subsemilattice.

The arrow configuration described in Theorem 2.5 is displayed in Figure 5. The subcontext $(G_{\min}, \{m_a \mid a \in G_{\min}\})$ is a copy of $(G_{\min}, G_{\min}, \neq)$, with exactly one double arrow in each row and column and crosses elsewhere. The rows of the atoms $G_{\min}$ contain no empty cells (arrowless non-incidences) and no upward arrows except for the double arrows mentioned. The columns corresponding to the attributes $\{m_a \mid a \in G_{\min}\}$ have no other downward arrows. What Theorem 2.5 expresses is that the configuration displayed in Figure 5 is characteristic for $p$-algebras.

In practice one has to do is to first enter the arrow relations and check if one can obtain the configuration of Figure 5. If this is not the case one should add new attributes $m_a$ for the atoms $a$ whose inverse images are not extents and compute the new concept lattice.

3. What next?

Investigations should be carried out to compare the implication theory of the pcs-completion with that of the initial lattice. This approach should be compared with other, namely the alpha Galois lattices, fault-tolerance patterns, association rules. In a series of papers, V. Ventos and co-authors ([VPS, VST, VS05]) discussed the use of partitions on the set of objects and introduced the so called alpha Galois lattices. More precisely, given a context $(G, M, I)$ and $\alpha \in [0, 1]$, a subset $S$ of $G$ is called an $\alpha$-model of $T \subseteq M$ (denoted by $S \models_{\alpha} T$) if $|T \cap S| \geq \alpha$. For a partition $\pi$ on $G$, we write $g \models_{\pi} T$ to mean that $[g]_\pi \models_\alpha T$, where $[g]_\pi$ denotes the class of $g$ w.r.t. $\pi$. This defines a relation $I^\alpha_\pi \subseteq G \times M$ by $gI^\alpha_\pi m \iff g \models^\alpha_\pi \{m\}$. For $|\pi| = |G|$ and $\alpha = \frac{1}{|G|}$ we have $(G, M, I) = (G, M, I^1_\pi)$. Unfortunately the size of $B(G, M, I^1_\pi)$ is not always smaller as announced. A small example can be found in [MK]. In [PB05] the authors proposed a generalization of concepts to fault-tolerant patterns. In fact concepts are maximal rectangle full of crosses. A fault-tolerant pattern can be interpreted as a concept with some crosses missing. In [Du96] and [Wh96] the authors considered taking the statistics in account to
handle exceptions. As already mentioned closure and kernel operators are approximation means for concept lattices. In [KS08] we gave a correspondence between closure/kernel operators and lower/upper modular valuations. This provides another mean to approximate concept lattices, and will be of great use in bringing together the quantitative and qualitative methods. A general framework for lattice approximation is an urgent need, and will strengthen the use of FCA in huge data.

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