

Discovery of Frequent Episodes in Event Sequences

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Abstract. Sequences of events describing the behavior and actions of users or systems can be collected in several domains. An episode is a collection of events that occur relatively close to each other in a given partial order. We consider the problem of discovering frequently occurring episodes in a sequence. Once such episodes are known, one can produce rules for describing or predicting the behavior of the sequence. We give efficient algorithms for the discovery of all frequent episodes from a given class of episodes, and present detailed experimental results. The methods are in use in telecommunication alarm management.

Keywords: event sequences, frequent episodes, sequence analysis

1. Introduction

There are important data mining and machine learning application areas where the data to be analyzed consists of a sequence of events. Examples of such data are alarms in a telecommunication network, user interface actions, crimes committed by a person, occurrences of recurrent illnesses, etc. Abstractly, such data can be viewed as a sequence of events, where each event has an associated time of occurrence. An example of an event sequence is represented in figure 1. Here *A*, *B*, *C*, *D*, *E*, and *F* are event types, e.g., different types of alarms from a telecommunication network, or different types of user actions, and they have been marked on a time line. Recently, interest in knowledge discovery from sequential data has increased (see e.g., Agrawal and Srikant, 1995; Bettini et al., 1996; Dousson et al., 1993; Hättönen et al., 1996a; Howe, 1995; Jonassen et al., 1995; Laird, 1993; Mannila et al., 1995; Morris et al., 1994; Oates and Cohen, 1996; Wang et al., 1994).

One basic problem in analyzing event sequences is to find frequent *episodes* (Mannila et al., 1995; Mannila and Toivonen, 1996), i.e., collections of events occurring frequently together. For example, in the sequence of figure 1, the episode “*E* is followed by *F*” occurs several times, even when the sequence is viewed through a narrow window. Episodes, in general, are partially ordered sets of events. From the sequence in the figure one can make, for instance, the observation that whenever *A* and *B* occur, in either order, *C* occurs soon.

Our motivating application was in the telecommunication alarm management, where thousands of alarms accumulate daily; there can be hundreds of different alarm types.

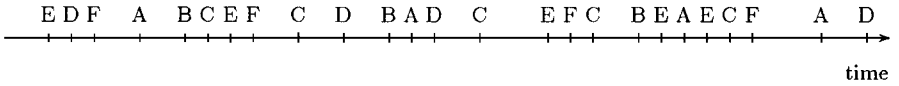


Figure 1. A sequence of events.

When discovering episodes in a telecommunication network alarm log, the goal is to find relationships between alarms. Such relationships can then be used in the on-line analysis of the incoming alarm stream, e.g., to better explain the problems that cause alarms, to suppress redundant alarms, and to predict severe faults.

In this paper we consider the following problem. Given a class of episodes and an input sequence of events, find all episodes that occur frequently in the event sequence. We describe the framework and formalize the discovery task in Section 2. Algorithms for discovering all frequent episodes are given in Section 3. They are based on the idea of first finding small frequent episodes, and then progressively looking for larger frequent episodes. Additionally, the algorithms use some simple pattern matching ideas to speed up the recognition of occurrences of single episodes. Section 4 outlines an alternative way of approaching the problem, based on locating minimal occurrences of episodes. Experimental results using both approaches and with various data sets are presented in Section 5. We discuss extensions and review related work in Section 6. Section 7 is a short conclusion.

2. Event sequences and episodes

Our overall goal is to analyze sequences of events, and to discover recurrent episodes. We first formulate the concept of event sequence, and then look at episodes in more detail.

2.1. Event sequences

We consider the input as a sequence of events, where each event has an associated time of occurrence. Given a set E of *event types*, an *event* is a pair (A, t) , where $A \in E$ is an event type and t is an integer, the (*occurrence*) *time* of the event. The event type can actually contain several attributes; for simplicity we consider here just the case where the event type is a single value.

An *event sequence* s on E is a triple (s, T_s, T_e) , where

$$s = \langle (A_1, t_1), (A_2, t_2), \dots, (A_n, t_n) \rangle$$

is an ordered sequence of events such that $A_i \in E$ for all $i = 1, \dots, n$, and $t_i \leq t_{i+1}$ for all $i = 1, \dots, n - 1$. Further on, T_s and T_e are integers: T_s is called the starting time and T_e the ending time, and $T_s \leq t_i < T_e$ for all $i = 1, \dots, n$.

Example. Figure 2 presents the event sequence $s = (s, 29, 68)$, where

$$s = \langle (E, 31), (D, 32), (F, 33), (A, 35), (B, 37), (C, 38), \dots, (D, 67) \rangle.$$

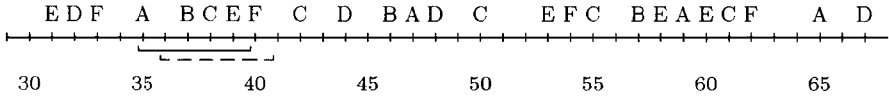


Figure 2. The example event sequence and two windows of width 5.

Observations of the event sequence have been made from time 29 to just before time 68. For each event that occurred in the time interval $[29, 68)$, the event type and the time of occurrence have been recorded.

In the analysis of sequences we are interested in finding all frequent episodes from a class of episodes. To be considered interesting, the events of an episode must occur close enough in time. The user defines how close is close enough by giving the width of the *time window* within which the episode must occur. We define a window as a slice of an event sequence, and we then consider an event sequence as a sequence of partially overlapping windows. In addition to the width of the window, the user specifies in how many windows an episode has to occur to be considered frequent.

Formally, a *window* on an event sequence $s = (s, T_s, T_e)$ is an event sequence $w = (w, t_s, t_e)$, where $t_s < T_e$ and $t_e > T_s$, and w consists of those pairs (A, t) from s where $t_s \leq t < t_e$. The time span $t_e - t_s$ is called the *width* of the window w , and it is denoted $width(w)$. Given an event sequence s and an integer win , we denote by $\mathcal{W}(s, win)$ the set of all windows w on s such that $width(w) = win$.

By the definition the first and last windows on a sequence extend outside the sequence, so that the first window contains only the first time point of the sequence, and the last window contains only the last time point. With this definition an event close to either end of a sequence is observed in equally many windows to an event in the middle of the sequence. Given an event sequence $s = (s, T_s, T_e)$ and a window width win , the number of windows in $\mathcal{W}(s, win)$ is $T_e - T_s + win - 1$.

Example. Figure 2 shows also two windows of width 5 on the sequence s . A window starting at time 35 is shown in solid line, and the immediately following window, starting at time 36, is depicted with a dashed line. The window starting at time 35 is

$$((A, 35), (B, 37), (C, 38), (E, 39), 35, 40).$$

Note that the event $(F, 40)$ that occurred at the ending time is not in the window. The window starting at 36 is similar to this one; the difference is that the first event $(A, 35)$ is missing and there is a new event $(F, 40)$ at the end.

The set of the 43 partially overlapping windows of width 5 constitutes $\mathcal{W}(s, 5)$; the first window is $(\emptyset, 25, 30)$, and the last is $((D, 67), 67, 72)$. Event $(D, 67)$ occurs in 5 windows of width 5, as does, e.g., event $(C, 50)$.

2.2. Episodes

Informally, an episode is a partially ordered collection of events occurring together. Episodes can be described as directed acyclic graphs. Consider, for instance, episodes α , β , and γ

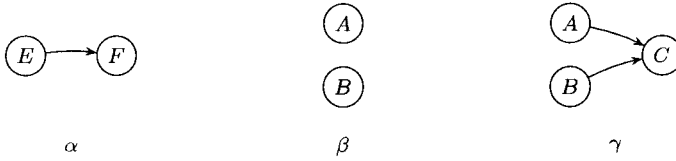


Figure 3. Episodes α , β , and γ .

in figure 3. Episode α is a *serial episode*: it occurs in a sequence only if there are events of types E and F that occur in this order in the sequence. In the sequence there can be other events occurring between these two. The alarm sequence, for instance, is merged from several sources, and therefore it is useful that episodes are insensitive to intervening events. Episode β is a *parallel episode*: no constraints on the relative order of A and B are given. Episode γ is an example of non-serial and non-parallel episode: it occurs in a sequence if there are occurrences of A and B and these precede an occurrence of C ; no constraints on the relative order of A and B are given. We mostly consider the discovery of serial and parallel episodes.

We now define episodes formally. An *episode* α is a triple (V, \leq, g) where V is a set of nodes, \leq is a partial order on V , and $g : V \rightarrow E$ is a mapping associating each node with an event type. The interpretation of an episode is that the events in $g(V)$ have to occur in the order described by \leq . The *size* of α , denoted $|\alpha|$, is $|V|$. Episode α is *parallel* if the partial order \leq is trivial (i.e., $x \not\leq y$ for all $x, y \in V$ such that $x \neq y$). Episode α is *serial* if the relation \leq is a total order (i.e., $x \leq y$ or $y \leq x$ for all $x, y \in V$). Episode α is *injective* if the mapping g is an injection, i.e., no event type occurs twice in the episode.

Example. Consider episode $\alpha = (V, \leq, g)$ in figure 3. The set V contains two nodes; we denote them by x and y . The mapping g labels these nodes with the event types that are seen in the figure: $g(x) = E$ and $g(y) = F$. An event of type E is supposed to occur before an event of type F , i.e., x precedes y , and we have $x \leq y$. Episode α is injective, since it does not contain duplicate event types. In a window where α occurs there may, of course, be multiple events of types E and F , but we only compute the number of windows where α occurs at all, not the number of occurrences per window.

We next define when an episode is a subepisode of another; this relation is used extensively in the algorithms for discovering all frequent episodes. An episode $\beta = (V', \leq', g')$ is a *subepisode* of $\alpha = (V, \leq, g)$, denoted $\beta \preceq \alpha$, if there exists an injective mapping $f : V' \rightarrow V$ such that $g'(v) = g(f(v))$ for all $v \in V'$, and for all $v, w \in V'$ with $v \leq' w$ also $f(v) \leq f(w)$. An episode α is a *superepisode* of β if and only if $\beta \preceq \alpha$. We write $\beta \prec \alpha$ if $\beta \preceq \alpha$ and $\alpha \not\preceq \beta$.

Example. From figure 3 we see that $\beta \preceq \gamma$ since β is a subgraph of γ . In terms of the definition, there is a mapping f that connects the nodes labeled A with each other and the nodes labeled B with each other, i.e., both nodes of β have (disjoint) corresponding nodes in γ . Since the nodes in episode β are not ordered, the corresponding nodes in γ do not need to be ordered, either.

We now consider what it means that an episode occurs in a sequence. Intuitively, the nodes of the episode need to have corresponding events in the sequence such that the event types are the same and the partial order of the episode is respected. Formally, an episode $\alpha = (V, \leq, g)$ occurs in an event sequence

$$\mathbf{s} = ((A_1, t_1), (A_2, t_2), \dots, (A_n, t_n)), T_s, T_e),$$

if there exists an injective mapping $h : V \rightarrow \{1, \dots, n\}$ from nodes of α to events of \mathbf{s} such that $g(x) = A_{h(x)}$ for all $x \in V$, and for all $x, y \in V$ with $x \neq y$ and $x \leq y$ we have $t_{h(x)} < t_{h(y)}$.

Example. The window $(w, 35, 40)$ of figure 2 contains events A, B, C , and E . Episodes β and γ of figure 3 occur in the window, but α does not.

We define the *frequency* of an episode as the fraction of windows in which the episode occurs. That is, given an event sequence \mathbf{s} and a window width win , the frequency of an episode α in \mathbf{s} is

$$fr(\alpha, \mathbf{s}, win) = \frac{|\{\mathbf{w} \in \mathcal{W}(\mathbf{s}, win) \mid \alpha \text{ occurs in } \mathbf{w}\}|}{|\mathcal{W}(\mathbf{s}, win)|}.$$

Given a *frequency threshold* min_fr , α is *frequent* if $fr(\alpha, \mathbf{s}, win) \geq min_fr$. The task we are interested in is to discover all frequent episodes from a given class \mathcal{E} of episodes. The class could be, e.g., all parallel episodes or all serial episodes. We denote the collection of frequent episodes with respect to \mathbf{s} , win and min_fr by $\mathcal{F}(\mathbf{s}, win, min_fr)$.

Once the frequent episodes are known, they can be used to obtain rules that describe connections between events in the given event sequence. For example, if we know that the episode β of figure 3 occurs in 4.2% of the windows and that the superepisode γ occurs in 4.0% of the windows, we can estimate that after seeing a window with A and B , there is a chance of about 0.95 that C follows in the same window. Formally, an *episode rule* is an expression $\beta \Rightarrow \gamma$, where β and γ are episodes such that $\beta \leq \gamma$. The fraction $\frac{fr(\gamma, \mathbf{s}, win)}{fr(\beta, \mathbf{s}, win)}$ is the *confidence* of the episode rule. The confidence can be interpreted as the conditional probability of the whole of γ occurring in a window, given that β occurs in it. Episode rules show the connections between events more clearly than frequent episodes alone.

3. Algorithms

Given all frequent episodes, rule generation is straightforward. Algorithm 1 describes how rules and their confidences can be computed from the frequencies of episodes. Note that indentation is used in the algorithms to specify the extent of loops and conditional statements.

Algorithm 1.

Input: A set E of event types, an event sequence \mathbf{s} over E , a set \mathcal{E} of episodes, a window width win , a frequency threshold min_fr , and a confidence threshold min_conf .

Output: The episode rules that hold in \mathbf{s} with respect to win , min_fr , and min_conf .

Method:

1. /* Find frequent episodes (Algorithm 2): */
2. compute $\mathcal{F}(\mathbf{s}, win, min_fr)$;

3. */* Generate rules: */*
4. *for all $\alpha \in \mathcal{F}(\mathbf{s}, \text{win}, \text{min_fr})$ do*
5. *for all $\beta \prec \alpha$ do*
6. *if $\text{fr}(\alpha)/\text{fr}(\beta) \geq \text{min_conf}$ then*
7. output the rule $\beta \rightarrow \alpha$ and the confidence $\text{fr}(\alpha)/\text{fr}(\beta)$;

We now concentrate on the following discovery task: given an event sequence \mathbf{s} , a set \mathcal{E} of episodes, a window width win , and a frequency threshold min_fr , find $\mathcal{F}(\mathbf{s}, \text{win}, \text{min_fr})$. We give first a specification of the algorithm and then exact methods for its subtasks. We call these methods collectively the WINEPI algorithm. See Section 6 for related work and some methods based on similar ideas.

3.1. Main algorithm

Algorithm 2 computes the collection $\mathcal{F}(\mathbf{s}, \text{win}, \text{min_fr})$ of frequent episodes from a class \mathcal{E} of episodes. The algorithm performs a levelwise (breadth-first) search in the class of episodes following the subepisode relation. The search starts from the most general episodes, i.e., episodes with only one event. On each level the algorithm first computes a collection of candidate episodes, and then checks their frequencies from the event sequence. The crucial point in the candidate generation is given by the following immediate lemma.

Lemma 1. *If an episode α is frequent in an event sequence \mathbf{s} , then all subepisodes $\beta \preceq \alpha$ are frequent.*

The collection of candidates is specified to consist of episodes such that all smaller subepisodes are frequent. This criterion safely prunes from consideration episodes that can not be frequent. More detailed methods for the candidate generation and database pass phases are given in the following subsections.

Algorithm 2.

Input: A set E of event types, an event sequence \mathbf{s} over E , a set \mathcal{E} of episodes, a window width win , and a frequency threshold min_fr

Output: The collection $\mathcal{F}(\mathbf{s}, \text{win}, \text{min_fr})$ of frequent episodes.

Method:

1. $C_1 := \{\alpha \in \mathcal{E} \mid |\alpha| = 1\}$;
2. $l := 1$;
3. *while $C_l \neq \emptyset$ do*
4. */* Database pass (Algorithms 4 and 5): */*
5. compute $\mathcal{F}_l := \{\alpha \in C_l \mid \text{fr}(\alpha, \mathbf{s}, \text{win}) \geq \text{min_fr}\}$;
6. $l := l + 1$;
7. */* Candidate generation (Algorithm 3): */*
8. compute $C_l := \{\alpha \in \mathcal{E} \mid |\alpha| = l \text{ and for all } \beta \in \mathcal{E} \text{ such that } \beta \prec \alpha \text{ and}$
9. $|\beta| < l \text{ we have } \beta \in \mathcal{F}_{|\beta|}\}$;
10. *for all l do output \mathcal{F}_l ;*

3.2. Generation of candidate episodes

We present now a candidate generation method in detail. Algorithm 3 computes candidates for parallel episodes. The method can be easily adapted to deal with the classes of parallel episodes, serial episodes, and injective parallel and serial episodes. In the algorithm, an episode $\alpha = (V, \leq, g)$ is represented as a lexicographically sorted array of event types. The array is denoted by the name of the episode and the items in the array are referred to with the square bracket notation. For example, a parallel episode α with events of types A, C, C , and F is represented as an array α with $\alpha[1] = A, \alpha[2] = C, \alpha[3] = C$, and $\alpha[4] = F$. Collections of episodes are also represented as lexicographically sorted arrays, i.e., the i th episode of a collection \mathcal{F} is denoted by $\mathcal{F}[i]$.

Since the episodes and episode collections are sorted, all episodes that share the same first event types are consecutive in the episode collection. In particular, if episodes $\mathcal{F}_l[i]$ and $\mathcal{F}_l[j]$ of size l share the first $l - 1$ events, then for all k with $i \leq k \leq j$ we have that $\mathcal{F}_l[k]$ shares also the same events. A maximal sequence of consecutive episodes of size l that share the first $l - 1$ events is called a *block*. Potential candidates can be identified by creating all combinations of two episodes in the same block. For the efficient identification of blocks, we store in $\mathcal{F}_l.\text{block_start}[j]$ for each episode $\mathcal{F}_l[j]$ the i such that $\mathcal{F}_l[i]$ is the first episode in the block.

Algorithm 3.

Input: A sorted array \mathcal{F}_l of frequent parallel episodes of size l .

Output: A sorted array of candidate parallel episodes of size $l + 1$.

Method:

1. $\mathcal{C}_{l+1} := \emptyset$;
2. $k := 0$;
3. if $l = 1$ then for $h := 1$ to $|\mathcal{F}_l|$ do $\mathcal{F}_l.\text{block_start}[h] := 1$;
4. for $i := 1$ to $|\mathcal{F}_l|$ do
5. $\text{current_block_start} := k + 1$;
6. for ($j := i$; $\mathcal{F}_l.\text{block_start}[j] = \mathcal{F}_l.\text{block_start}[i]$; $j := j + 1$) do
7. /* $\mathcal{F}_l[i]$ and $\mathcal{F}_l[j]$ have $l - 1$ first event types in common,
8. build a potential candidate α as their combination: */
9. for $x := 1$ to l do $\alpha[x] := \mathcal{F}_l[i][x]$;
10. $\alpha[l + 1] := \mathcal{F}_l[j][l]$;
11. /* Build and test subepisodes β that do not contain $\alpha[y]$: */
12. for $y := 1$ to $l - 1$ do
13. for $x := 1$ to $y - 1$ do $\beta[x] := \alpha[x]$;
14. for $x := y$ to l do $\beta[x] := \alpha[x + 1]$;
15. if β is not in \mathcal{F}_l then continue with the next j at line 6;
16. /* All subepisodes are in \mathcal{F}_l , store α as candidate: */
17. $k := k + 1$;
18. $\mathcal{C}_{l+1}[k] := \alpha$;
19. $\mathcal{C}_{l+1}.\text{block_start}[k] := \text{current_block_start}$;
20. output \mathcal{C}_{l+1} ;

Algorithm 3 can be easily modified to generate candidate serial episodes. Now the events in the array representing an episode are in the order imposed by a total order \leq . For instance, a serial episode β with events of types C , A , F , and C , in that order, is represented as an array β with $\beta[1] = C$, $\beta[2] = A$, $\beta[3] = F$, and $\beta[4] = C$. By replacing line 6 by

6. *for*($j := \mathcal{F}_l.\text{block_start}[i]$; $\mathcal{F}_l.\text{block_start}[j] = \mathcal{F}_l.\text{block_start}[i]$; $j := j + 1$) *do*

Algorithm 3 generates candidates for serial episodes.

There are further options with the algorithm. If the desired episode class consists of parallel or serial injective episodes, i.e., no episode should contain any event type more than once, insert line

6b. *if* $j = i$ *then* continue with the next j at line 6;

after line 6.

The candidate generation method aims at minimizing the number of candidates on each level, in order to reduce the work per database pass. Often it can be useful to combine several candidate generation iterations to one database pass, to cut down the number of expensive database passes. This can be done by first computing candidates for the next level $l + 1$, then computing candidates for the following level $l + 2$ assuming that all candidates of level $l + 1$ are indeed frequent, and so on. This method does not miss any frequent episodes, but the candidate collections can be larger than if generated from the frequent episodes. Such a combination of iterations is useful when the overhead of generating and evaluating the extra candidates is less than the effort of reading the database, as is the case often in the last iterations.

The time complexity of Algorithm 3 is polynomial in the size of the collection of frequent episodes and it is independent of the length of the event sequence.

Theorem 1. *Algorithm 3 (with any of the above variations) has time complexity $\mathcal{O}(l^2 |\mathcal{F}_l|^2 \log |\mathcal{F}_l|)$.*

Proof: The initialization (line 3) takes time $\mathcal{O}(|\mathcal{F}_l|)$. The outer loop (line 4) is iterated $\mathcal{O}(|\mathcal{F}_l|)$ times and the inner loop (line 6) $\mathcal{O}(|\mathcal{F}_l|)$ times. Within the loops, a potential candidate (lines 9 and 10) and $l - 1$ subcandidates (lines 12 to 14) are built in time $\mathcal{O}(l + 1 + (l - 1)l) = \mathcal{O}(l^2)$. More importantly, the $l - 1$ subsets need to be searched for in the collection \mathcal{F}_l (line 15). Since \mathcal{F}_l is sorted, each subcandidate can be located with binary search in time $\mathcal{O}(l \log |\mathcal{F}_l|)$. The total time complexity is thus $\mathcal{O}(|\mathcal{F}_l| + |\mathcal{F}_l| |\mathcal{F}_l| (l^2 + (l - 1)l \log |\mathcal{F}_l|)) = \mathcal{O}(l^2 |\mathcal{F}_l|^2 \log |\mathcal{F}_l|)$. \square

When the number of event types $|E|$ is less than $l |\mathcal{F}_l|$, the following theorem gives a tighter bound.

Theorem 2. *Algorithm 3 (with any of the above variations) has time complexity $\mathcal{O}(l |E| |\mathcal{F}_l| \log |\mathcal{F}_l|)$.*

Proof: The proof is similar to the one above, but we have a useful observation (due to Juha Kärkkäinen) about the total number of subepisode tests over all iterations. Consider the number of failed and successful test separately. First, the number of potential candidates is bounded by $\mathcal{O}(|\mathcal{F}_l| |E|)$, since they are constructed by adding an event to a frequent episode of size l . There can be at most one *failed* test for each potential candidate, since the subcandidate loop is exited at the first failure (line 15). Second, each *successful* test corresponds one-to-one with a frequent episode in \mathcal{F}_l and an event type. The numbers of failed and successful tests are thus both bounded by $\mathcal{O}(|\mathcal{F}_l| |E|)$. Since the work per test is $\mathcal{O}(l \log |\mathcal{F}_l|)$, the total amount of work is $\mathcal{O}(l |E| |\mathcal{F}_l| \log |\mathcal{F}_l|)$. \square

In practice the time complexity is likely to be dominated by $l |\mathcal{F}_l| \log |\mathcal{F}_l|$, since the blocks are typically small with respect to the sizes of both \mathcal{F}_l and E . If the number of episode types is fixed, a subcandidate test can be implemented practically in time $\mathcal{O}(l)$, removing the logarithmic factor from the running time.

3.3. Recognizing episodes in sequences

Let us now consider the implementation of the database pass. We give algorithms which recognize episodes in sequences in an incremental fashion. For two windows $\mathbf{w} = (w, t_s, t_s + \text{win})$ and $\mathbf{w}' = (w', t_s + 1, t_s + \text{win} + 1)$, the sequences w and w' of events are similar to each other. We take advantage of this similarity: after recognizing episodes in \mathbf{w} , we make incremental updates in our data structures to achieve the shift of the window to obtain \mathbf{w}' .

The algorithms start by considering the empty window just before the input sequence, and they end after considering the empty window just after the sequence. This way the incremental methods need no other special actions at the beginning or end. When computing the frequency of episodes, only the windows correctly on the input sequence are, of course, considered.

3.3.1. Parallel episodes. Algorithm 4 recognizes candidate parallel episodes in an event sequence. The main ideas of the algorithm are the following. For each candidate parallel episode α we maintain a counter $\alpha.\text{event_count}$ that indicates how many events of α are present in the window. When $\alpha.\text{event_count}$ becomes equal to $|\alpha|$, indicating that α is entirely included in the window, we save the starting time of the window in $\alpha.\text{inwindow}$. When $\alpha.\text{event_count}$ decreases again, indicating that α is no longer entirely in the window, we increase the field $\alpha.\text{freq_count}$ by the number of windows where α remained entirely in the window. At the end, $\alpha.\text{freq_count}$ contains the total number of windows where α occurs.

To access candidates efficiently, they are indexed by the number of events of each type that they contain: all episodes that contain exactly a events of type A are in the list $\text{contains}(A, a)$. When the window is shifted and the contents of the window change, the episodes that are affected are updated. If, for instance, there is one event of type A in the window and a second one comes in, all episodes in the list $\text{contains}(A, 2)$ are updated with the information that both events of type A they are expecting are now present.

Algorithm 4.

Input: A collection \mathcal{C} of parallel episodes, an event sequence $\mathbf{s} = (s, T_s, T_e)$, a window width win , and a frequency threshold min_fr .

Output: The episodes of \mathcal{C} that are frequent in \mathbf{s} with respect to win and min_fr .

Method:

```

1.  /* Initialization: */
2.  for each  $\alpha$  in  $\mathcal{C}$  do
3.      for each  $A$  in  $\alpha$  do
4.           $A.\text{count} := 0$ ;
5.          for  $i := 1$  to  $|\alpha|$  do  $\text{contains}(A, i) := \emptyset$ ;
6.  for each  $\alpha$  in  $\mathcal{C}$  do
7.      for each  $A$  in  $\alpha$  do
8.           $a :=$  number of events of type  $A$  in  $\alpha$ ;
9.           $\text{contains}(A, a) := \text{contains}(A, a) \cup \{a\}$ ;
10.  $\alpha.\text{event\_count} := 0$ ;
11.  $\alpha.\text{freq\_count} := 0$ ;
12. /* Recognition: */
13. for  $\text{start} := T_s - \text{win} + 1$  to  $T_e$  do
14.     /* Bring in new events to the window: */
15.     for all events  $(A, t)$  in  $\mathbf{s}$  such that  $t = \text{start} + \text{win} - 1$  do
16.          $A.\text{count} := A.\text{count} + 1$ ;
17.         for each  $\alpha \in \text{contains}(A, A.\text{count})$  do
18.              $\alpha.\text{event\_count} := \alpha.\text{event\_count} + A.\text{count}$ ;
19.             if  $\alpha.\text{event\_count} = |\alpha|$  then  $\alpha.\text{inwindow} := \text{start}$ ;
20.     /* Drop out old events from the window: */
21.     for all events  $(A, t)$  in  $\mathbf{s}$  such that  $t = \text{start} - 1$  do
22.         for each  $\alpha \in \text{contains}(A, A.\text{count})$  do
23.             if  $\alpha.\text{event\_count} = |\alpha|$  then
24.                  $\alpha.\text{freq\_count} := \alpha.\text{freq\_count} - \alpha.\text{inwindow} + \text{start}$ ;
25.                  $\alpha.\text{event\_count} := \alpha.\text{event\_count} - A.\text{count}$ ;
26.          $A.\text{count} := A.\text{count} - 1$ ;
27. /* Output: */
28. for all episodes  $\alpha$  in  $\mathcal{C}$  do
29.     if  $\alpha.\text{freq\_count} / (T_e - T_s + \text{win} - 1) \geq \text{min\_fr}$  then output  $\alpha$ ;
```

3.3.2. Serial episodes. Serial candidate episodes are recognized in an event sequence by using state automata that accept the candidate episodes and ignore all other input. The idea is that there is an automaton for each serial episode α , and that there can be several instances of each automaton at the same time, so that the active states reflect the (disjoint) prefixes of α occurring in the window. Algorithm 5 implements this idea.

We initialize a new instance of the automaton for a serial episode α every time the first event of α comes into the window; the automaton is removed when the same event leaves the window. When an automaton for α reaches its accepting state, indicating that α is entirely included in the window, and if there are no other automata for α in the accepting state already,

we save the starting time of the window in $\alpha.inwindow$. When an automaton in the accepting state is removed, and if there are no other automata for α in the accepting state, we increase the field $\alpha.freq_count$ by the number of windows where α remained entirely in the window.

It is useless to have multiple automata in the same state, as they would only make the same transitions and produce the same information. It suffices to maintain the one that reached the common state last since it will be also removed last. There are thus at most $|\alpha|$ automata for an episode α . For each automaton we need to know when it should be removed. We can thus represent all the automata for α with one array of size $|\alpha|$: the value of $\alpha.initialized[i]$ is the latest initialization time of an automaton that has reached its i th state. Recall that α itself is represented by an array containing its events; this array can be used to label the state transitions.

To access and traverse the automata efficiently they are organized in the following way. For each event type $A \in E$, the automata that accept A are linked together to a list $waits(A)$. The list contains entries of the form (α, x) meaning that episode α is waiting for its x th event. When an event (A, t) enters the window during a shift, the list $waits(A)$ is traversed. If an automaton reaches a common state i with another automaton, the earlier entry $\alpha.initialized[i]$ is simply overwritten.

The transitions made during one shift of the window are stored in a list $transitions$. They are represented in the form (α, x, t) meaning that episode α got its x th event, and the latest initialization time of the prefix of length x is t . Updates regarding the old states of the automata are done immediately, but updates for the new states are done only after all transitions have been identified, in order to not overwrite any useful information. For easy removal of automata when they go out of the window, the automata initialized at time t are stored in a list $beginsat(t)$.

Algorithm 5.

Input: A collection \mathcal{C} of serial episodes, an event sequence $s = (s, T_s, T_e)$, a window width win , and a frequency threshold min_fr

Output: The episodes of \mathcal{C} that are frequent in s with respect to win and min_fr

Method:

1. /* Initialization: */
2. for each α in \mathcal{C} do
3. for $i := 1$ to $|\alpha|$ do
4. $\alpha.initialized[i] := 0$;
5. $waits(\alpha[i]) := \emptyset$;
6. for each $\alpha \in \mathcal{C}$ do
7. $waits(\alpha[1]) := waits(\alpha[1]) \cup \{(\alpha, 1)\}$;
8. $\alpha.freq_count := 0$;
9. for $t := T_s - win$ to $T_s - 1$ do $beginsat(t) := \emptyset$;
10. /* Recognition: */
11. for $start := T_s - win + 1$ to T_e do
12. /* Bring in new events to the window: */
13. $beginsat(start + win - 1) := \emptyset$;
14. $transitions := \emptyset$;

```

15.   for all events  $(A, t)$  in  $s$  such that  $t = \text{start} + \text{win} - 1$  do
16.       for all  $(\alpha, j) \in \text{waits}(A)$  do
17.           if  $j = |\alpha|$  and  $\alpha.\text{initialized}[j] = 0$  then  $\alpha.\text{inwindow} := \text{start}$ ;
18.           if  $j = 1$  then
19.                $\text{transitions} := \text{transitions} \cup \{(\alpha, 1, \text{start} + \text{win} - 1)\}$ ;
20.           else
21.                $\text{transitions} := \text{transitions} \cup \{(\alpha, j, \alpha.\text{initialized}[j - 1])\}$ ;
22.                $\text{beginsat}(\alpha.\text{initialized}[j - 1]) :=$ 
23.                    $\text{beginsat}(\alpha.\text{initialized}[j - 1] \setminus \{(\alpha, j - 1)\})$ ;
24.                $\alpha.\text{initialized}[j - 1] := 0$ ;
25.                $\text{waits}(A) := \text{waits}(A) \setminus \{(\alpha, j)\}$ ;
26.   for all  $(\alpha, j, t) \in \text{transitions}$  do
27.        $\alpha.\text{initialized}[j] := t$ ;
28.        $\text{beginsat}(t) := \text{beginsat}(t) \cup \{(\alpha, j)\}$ ;
29.       if  $j < |\alpha|$  then  $\text{waits}(\alpha[j + 1]) := \text{waits}(\alpha[j + 1]) \cup \{(\alpha, j + 1)\}$ ;
30.   /* Drop out old events from the window: */
31.   for all  $(\alpha, l) \in \text{beginsat}(\text{start} - 1)$  do
32.       if  $l = |\alpha|$  then  $\alpha.\text{freq\_count} := \alpha.\text{freq\_count} - \alpha.\text{inwindow} + \text{start}$ ;
33.       else  $\text{waits}(\alpha[l + 1]) := \text{waits}(\alpha[l + 1]) \setminus \{(\alpha, l + 1)\}$ ;
34.        $\alpha.\text{initialized}[l] := 0$ ;
35.   /* Output: */
36.   for all episodes  $\alpha$  in  $\mathcal{C}$  do
37.       if  $\alpha.\text{freq\_count} / (T_e - T_s + \text{win} - 1) \geq \text{min\_fr}$  then output  $\alpha$ ;

```

3.3.3. Analysis of time complexity For simplicity, suppose that the class of event types E is fixed, and assume that exactly one event takes place every time unit. Assume candidate episodes are all of size l , and let n be the length of the sequence.

Theorem 3. *The time complexity of Algorithm 4 is $\mathcal{O}((n + l^2) |\mathcal{C}|)$.*

Proof: Initialization takes time $\mathcal{O}(|\mathcal{C}| l^2)$. Consider now the number of operations in the innermost loops, i.e., increments and decrements of $\alpha.\text{event_count}$ on lines 18 and 25. In the recognition phase there are $\mathcal{O}(n)$ shifts of the window. In each shift, one new event comes into the window, and one old event leaves the window. Thus, for any episode α , $\alpha.\text{event_count}$ is accessed at most twice during one shift. The cost of the recognition phase is thus $\mathcal{O}(n |\mathcal{C}|)$. \square

In practice the size l of episodes is very small with respect to the size n of the sequence, and the time required for the initialization can be safely neglected. For injective episodes we have the following tighter result.

Theorem 4. *The time complexity of recognizing injective parallel episodes in Algorithm 4 (excluding initialization) is $\mathcal{O}(\frac{n}{\text{win}} |\mathcal{C}| l + n)$.*

Proof: Consider win successive shifts of one time unit. During such sequence of shifts, each of the $|\mathcal{C}|$ candidate episodes α can undergo at most $2l$ changes: any event type A can

have $A.count$ increased to 1 and decreased to 0 at most once. This is due to the fact that after an event of type A has come into the window, $A.count \geq 1$ for the next win time units. Reading the input takes time n . \square

This time bound can be contrasted with the time usage of a trivial non-incremental method where the sequence is pre-processed into windows, and then frequent sets are searched for. The time requirement for recognizing $|\mathcal{C}|$ candidate sets in n windows, plus the time required to read in n windows of size win , is $\mathcal{O}(n |\mathcal{C}| l + n \cdot win)$, i.e., larger by a factor of win .

Theorem 5. *The time complexity of Algorithm 5 is $\mathcal{O}(n |\mathcal{C}| l)$.*

Proof: The initialization takes time $\mathcal{O}(|\mathcal{C}| l + win)$. In the recognition phase, again, there are $\mathcal{O}(n)$ shifts, and in each shift one event comes into the window and one event leaves the window. In one shift, the effort per an episode α depends on the number of automata accessed; there are a maximum of l automata for each episode. The worst-case time complexity is thus $\mathcal{O}(|\mathcal{C}| l + win + n |\mathcal{C}| l) = \mathcal{O}(n |\mathcal{C}| l)$ (note that win is $\mathcal{O}(n)$). \square

In the worst case for Algorithm 5 the input sequence consists of events of only one event type, and the candidate serial episodes consist only of events of that particular type. Every shift of the window results now in an update in every automaton. This worst-case complexity is close to the complexity of the trivial non-incremental method $\mathcal{O}(n |\mathcal{C}| l + n \cdot win)$. In practical situations, however, the time requirement of Algorithm 5 is considerably smaller, and we approach the savings obtained in the case of injective parallel episodes.

Theorem 6. *The time complexity of recognizing injective serial episodes in Algorithm 5 (excluding initialization) is $\mathcal{O}(n |\mathcal{C}|)$.*

Proof: Each of the $\mathcal{O}(n)$ shifts can now affect at most two automata for each episode: when an event comes into the window there can be a state transition in at most one automaton, and at most one automaton can be removed because the initializing event goes out of the window. \square

3.4. General partial orders

So far we have only discussed serial and parallel episodes. We next discuss briefly the use of other partial orders in episodes. The recognition of an arbitrary episode can be reduced to the recognition of a hierarchical combination of serial and parallel episodes. For example, episode γ in figure 4 is a serial combination of two episodes: a parallel episode δ' consisting



Figure 4. Recursive composition of a complex episode.

of A and B , and an episode δ'' consisting of C alone. The occurrence of an episode in a window can be tested using such hierarchical structure: to see whether episode γ occurs in a window one checks (using a method for serial episodes) whether the subepisodes δ' and δ'' occur in this order; to check the occurrence of δ' one uses a method for parallel episodes to verify whether A and B occur.

There are, however, some complications one has to take into account. First, it is sometimes necessary to duplicate an event node to obtain a decomposition to serial and parallel episodes. Duplication works easily with injective episodes, but non-injective episodes need more complex methods. Another important aspect is that composite events have a duration, unlike the elementary events in E .

A practical alternative to the recognition of general episodes is to handle all episodes basically like parallel episodes, and to check the correct partial ordering only when all events are in the window. Parallel episodes can be located efficiently; after they have been found, checking the correct partial ordering is relatively fast.

4. An alternative approach to episode discovery: minimal occurrences

4.1. Outline of the approach

In this section we describe an alternative approach to the discovery of episodes. Instead of looking at the windows and only considering whether an episode occurs in a window or not, we now look at the exact occurrences of episodes and the relationships between those occurrences. One of the advantages of this approach is that focusing on the occurrences of episodes allows us to more easily find rules with two window widths, one for the left-hand side and one for the whole rule, such as “if A and B occur within 15 seconds, then C follows within 30 seconds”.

The approach is based on minimal occurrences of episodes. Besides the new rule formulation, the use of minimal occurrences gives raise to the following new method, called MINEPI, for the recognition of episodes in the input sequence. For each frequent episode we store information about the locations of its minimal occurrences. In the recognition phase we can then compute the locations of minimal occurrences of a candidate episode α as a temporal join of the minimal occurrences of two subepisodes of α . This is simple and efficient, and the confidences and frequencies of rules with a large number of different window widths can be obtained quickly, i.e., there is no need to rerun the analysis if one only wants to modify the window widths. In the case of complicated episodes, the time needed for recognizing the occurrence of an episode can be significant; the use of stored minimal occurrences of episodes eliminates unnecessary repetition of the recognition effort.

We identify minimal occurrences with their time intervals in the following way. Given an episode α and an event sequence \mathbf{s} , we say that the interval $[t_s, t_e]$ is a *minimal occurrence* of α in \mathbf{s} , if (1) α occurs in the window $\mathbf{w} = (w, t_s, t_e)$ on \mathbf{s} , and if (2) α does not occur in any proper subwindow on \mathbf{w} , i.e., α does not occur in any window $\mathbf{w}' = (w', t'_s, t'_e)$ on \mathbf{s} such that $t_s \leq t'_s$, $t'_e \leq t_e$, and $\text{width}(\mathbf{w}') < \text{width}(\mathbf{w})$. The set of (intervals of) *minimal occurrences* of an episode α in a given event sequence is denoted by $mo(\alpha) = \{[t_s, t_e] \mid [t_s, t_e] \text{ is a minimal occurrence of } \alpha\}$.

Example. Consider the event sequence \mathbf{s} in figure 2 and the episodes in figure 3. The parallel episode β consisting of event types A and B has four minimal occurrences in \mathbf{s} : $mo(\beta) = \{[35, 38], [46, 48], [47, 58], [57, 60]\}$. The partially ordered episode γ has the following three minimal occurrences: $[35, 39], [46, 51], [57, 62]$.

An *episode rule (with two time bounds)* is an expression $\beta[win_1] \Rightarrow \alpha[win_2]$, where β and α are episodes such that $\beta \preceq \alpha$, and win_1 and win_2 are integers. The informal interpretation of the rule is that if episode β has a minimal occurrence at interval $[t_s, t_e]$ with $t_e - t_s \leq win_1$, then episode α occurs at interval $[t_s, t'_e]$ for some t'_e such that $t'_e - t_s \leq win_2$. Formally this can be expressed in the following way. Given win_1 and β , denote $mo_{win_1}(\beta) = \{[t_s, t_e] \in mo(\beta) \mid t_e - t_s \leq win_1\}$. Further, given α and an interval $[u_s, u_e]$, define $occ(\alpha, [u_s, u_e]) = \text{true}$ if and only if there exists a minimal occurrence $[u'_s, u'_e] \in mo(\alpha)$ such that $u_s \leq u'_s$ and $u'_e \leq u_e$. The confidence of an episode rule $\beta[win_1] \Rightarrow \alpha[win_2]$ is now

$$\frac{|\{[t_s, t_e] \in mo_{win_1}(\beta) \mid occ(\alpha, [t_s, t_s + win_2])\}|}{|mo_{win_1}(\beta)|}.$$

Example. Continuing the previous example, we have, e.g., the following rules and confidences. For the rule $\beta[3] \Rightarrow \gamma[4]$ we have $|\{[35, 38], [46, 48], [57, 60]\}|$ in the denominator and $|\{[35, 38]\}|$ in the numerator, so the confidence is $1/3$. For the rule $\beta[3] \Rightarrow \gamma[5]$ the confidence is 1.

There exists a variety of possibilities for the temporal relationships in episode rules with two time bounds. For example, the partial order of events can be such that the left-hand side events follow or surround the unseen events in the right-hand side. Such relationships are specified in the rules since the rule right-hand side α is a superepisode of the left-hand side β , and thus α contains the partial order of each event in the rule. Alternatively, rules that point backwards in time can be defined by specifying that the rule $\beta[win_1] \Rightarrow \alpha[win_2]$ describes the case where episode β has a minimal occurrence at an interval $[t_s, t_e]$ with $t_e - t_s \leq win_1$, and episode α occurs at interval $[t'_s, t_e]$ for some t'_s such that $t_e - t'_s \leq win_2$. For brevity, we do not consider any alternative definitions.

In Section 2 we defined the frequency of an episode as the fraction of windows that contain the episode. While frequency has a nice interpretation as the probability that a randomly chosen window contains the episode, the concept is not very useful with minimal occurrences: (1) there is no fixed window size, and (2) a window may contain several minimal occurrences of an episode. Instead of frequency, we use the concept of *support*, the number of minimal occurrences of an episode: the support of an episode α in a given event sequence \mathbf{s} is $|mo(\alpha)|$. Similarly to a frequency threshold, we now use a threshold for the support: given a support threshold min_sup , an episode α is frequent if $|mo(\alpha)| \geq min_sup$.

The current episode rule discovery task can be stated as follows. Given an event sequence \mathbf{s} , a class \mathcal{E} of episodes, and a set W of time bounds, find all frequent episode rules of the form $\beta[win_1] \Rightarrow \alpha[win_2]$, where $\beta, \alpha \in \mathcal{E}$, $\beta \preceq \alpha$, and $win_1, win_2 \in W$.

4.2. Finding minimal occurrences of episodes

In this section we describe informally the collection MINEPI of algorithms that locate the minimal occurrences of frequent serial and parallel episodes. Let us start with some observations about the basic properties of episodes. Lemma 1 still holds: the subepisodes of a frequent episode are frequent. Thus we can use the main algorithm (Algorithm 2) and the candidate generation (Algorithm 3) also for MINEPI. We have the following results about the minimal occurrences of an episode also containing minimal occurrences of its subepisodes.

Lemma 2. *Assume α is an episode and $\beta \preceq \alpha$ is its subepisode. If $[t_s, t_e] \in mo(\alpha)$, then β occurs in $[t_s, t_e]$ and hence there is an interval $[u_s, u_e] \in mo(\beta)$ such that $t_s \leq u_s \leq u_e \leq t_e$.*

Lemma 3. *Let α be a serial episode of size l , and let $[t_s, t_e] \in mo(\alpha)$. Then there are subepisodes α_1 and α_2 of α of size $l - 1$ such that for some $t_e^1 < t_e$ and $t_s^2 > t_s$ we have $[t_s, t_e^1] \in mo(\alpha_1)$ and $[t_s^2, t_e] \in mo(\alpha_2)$.*

Lemma 4. *Let α be a parallel episode of size l , and let $[t_s, t_e] \in mo(\alpha)$. Then there are subepisodes α_1 and α_2 of α of size $l - 1$ such that $[t_s^1, t_e^1] \in mo(\alpha_1)$ and $[t_s^2, t_e^2] \in mo(\alpha_2)$ for some $t_s^1, t_e^1, t_s^2, t_e^2 \in [t_s, t_e]$, and furthermore $t_s = \min\{t_s^1, t_s^2\}$ and $t_e = \max\{t_e^1, t_e^2\}$.*

The minimal occurrences of a candidate episode α are located in the following way. In the first iteration of the main algorithm, $mo(\alpha)$ is computed from the input sequence for all episodes α of size 1. In the rest of the iterations, the minimal occurrences of a candidate α are located by first selecting two suitable subepisodes α_1 and α_2 of α , and then computing a temporal join between the minimal occurrences of α_1 and α_2 , in the spirit of Lemmas 3 and 4.

To be more specific, for serial episodes the two subepisodes are selected so that α_1 contains all events except the last one and α_2 in turn contains all except the first one. The minimal occurrences of α are then found with the following specification:

$$mo(\alpha) = \{[t_s, u_e] \mid \text{there are } [t_s, t_e] \in mo(\alpha_1) \text{ and } [u_s, u_e] \in mo(\alpha_2) \\ \text{such that } t_s < u_s, t_e < u_e, \text{ and } [t_s, u_e] \text{ is minimal}\}.$$

For parallel episodes, the subepisodes α_1 and α_2 contain all events except one; the omitted events must be different. See Lemma 4 for the idea of how to compute the minimal occurrences of α .

The minimal occurrences of a candidate episode α can be found in a linear pass over the minimal occurrences of the selected subepisodes α_1 and α_2 . The time required for one candidate is thus $\mathcal{O}(|mo(\alpha_1)| + |mo(\alpha_2)| + |mo(\alpha)|)$, which is $\mathcal{O}(n)$, where n is the length of the event sequence. To optimize the running time, α_1 and α_2 can be selected so that $|mo(\alpha_1)| + |mo(\alpha_2)|$ is minimized.

The space requirement of the algorithm can be expressed as $\sum_i \sum_{\alpha \in \mathcal{F}_i} |mo(\alpha)|$, assuming the minimal occurrences of all frequent episodes are stored, or alternatively as $\max_i (\sum_{\alpha \in \mathcal{F}_i \cup \mathcal{F}_{i+1}} |mo(\alpha)|)$, if only the current and next levels of minimal occurrences are

stored. The size of $\sum_{\alpha \in \mathcal{F}_1} |mo(\alpha)|$ is bounded by n , the number of events in the input sequence, as each event in the sequence is a minimal occurrence of an episode of size 1. In the second iteration, an event in the input sequence can start at most $|\mathcal{F}_1|$ minimal occurrences of episodes of size 2. The space complexity of the second iteration is thus $\mathcal{O}(|\mathcal{F}_1|n)$.

While minimal occurrences of episodes can be located quite efficiently, the size of the data structures can be even larger than the original database, especially in the first couple of iterations. A practical solution is to use in the beginning other pattern matching methods, e.g., similar to the ones given for WINEPI in Section 3, to locate the minimal occurrences.

Finally, note that MINEPI can be used to solve the task of WINEPI. Namely, a window contains an occurrence of an episode exactly when it contains a minimal occurrence. The frequency of an episode α can thus be computed from $mo(\alpha)$.

4.3. Finding confidences of rules

We now show how the information about minimal occurrences of frequent episodes can be used to obtain confidences of episode rules with two time bounds without looking at the data again.

Recall that we defined an episode rule with two time bounds as an expression $\beta[win_1] \Rightarrow \alpha[win_2]$, where β and α are episodes such that $\beta \leq \alpha$, and win_1 and win_2 are integers. To find such rules, first note that for the rule to be frequent, the episode α has to be frequent. Rules of the above form can thus be enumerated by looking at all frequent episodes α , and then looking at all subepisodes β of α . The evaluation of the confidence of the rule $\beta[win_1] \Rightarrow \alpha[win_2]$ can be done in one pass through the structures $mo(\beta)$ and $mo(\alpha)$, as follows. For each $[t_s, t_e] \in mo(\beta)$ with $t_e - t_s \leq win_1$, locate the minimal occurrence $[u_s, u_e]$ of α such that $t_s \leq u_s$ and $[u_s, u_e]$ is the first interval in $mo(\alpha)$ with this property. Then check whether $u_e - t_s \leq win_2$.

The time complexity of the confidence computation for given episodes β and α and given time bounds win_1 and win_2 is $\mathcal{O}(|mo(\beta)| + |mo(\alpha)|)$. The confidences for all win_1, win_2 in the set W of time bounds can be found, using a table of size $|W|^2$, in time $\mathcal{O}(|mo(\beta)| + |mo(\alpha)| + |W|^2)$. For reasons of brevity we omit the details.

The set W of time bounds can be used to restrict the initial search of minimal occurrences of episodes. Given W , denote the maximum time bound by $win_{\max} = \max(W)$. In episode rules with two time bounds, only occurrences of at most win_{\max} time units can be used; longer episode occurrences can thus be ignored already in the search of frequent episodes. We consider the support, too, to be computed with respect to a given win_{\max} .

5. Experiments

We have run a series of experiments using WINEPI and MINEPI. The general performance of the methods, the effect of the various parameters, and the scalability of the methods are considered in this section. Consideration is also given to the applicability of the methods to various types of data sets. At the end of the section we briefly summarize our experiences in the analysis of telecommunication alarm sequences in co-operation with telecommunication companies.

The experiments have been run on a PC with 166 MHz Pentium processor and 32 MB main memory, under the Linux operating system. The sequences resided in a flat text file.

5.1. Performance overview

For an experimental overview we discovered episodes and rules in a telecommunication network fault management database. The database is a sequence of 73679 alarms covering a time period of 7 weeks. There are 287 different types of alarms with very diverse frequencies and distributions. On the average there is an alarm every minute. However, the alarms tend to occur in bursts: in the extreme cases over 40 alarms occurred in a period of one second.

We start by looking at the performance of the WINEPI method described in Section 3. There are several performance characteristics that can be used to evaluate the method. The time required by the method and the number of episodes and rules found by the method, with respect to the frequency threshold or the window width, are possible performance measures. We present results for two cases: serial episodes and injective parallel episodes.

Tables 1 and 2 represent performance statistics for finding frequent episodes in the alarm database with various frequency thresholds. The number of frequent episodes decreases rapidly as the frequency threshold increases, and so does the processing time.

Table 1. Performance characteristics for serial episodes with WINEPI; alarm database, window width 60 s.

Frequency threshold	Candidates	Frequent episodes	Iterations	Total time (s)
0.001	4528	359	45	680
0.002	2222	151	44	646
0.005	800	48	10	147
0.010	463	22	7	110
0.020	338	10	4	62
0.050	288	1	2	22
0.100	287	0	1	16

Table 2. Performance characteristics for injective parallel episodes with WINEPI; alarm database, window width 60 s.

Frequency threshold	Candidates	Frequent episodes	Iterations	Total time (s)
0.001	2122	185	5	49
0.002	1193	93	4	48
0.005	520	32	4	34
0.010	366	17	4	34
0.020	308	9	3	19
0.050	287	1	2	15
0.100	287	0	1	14

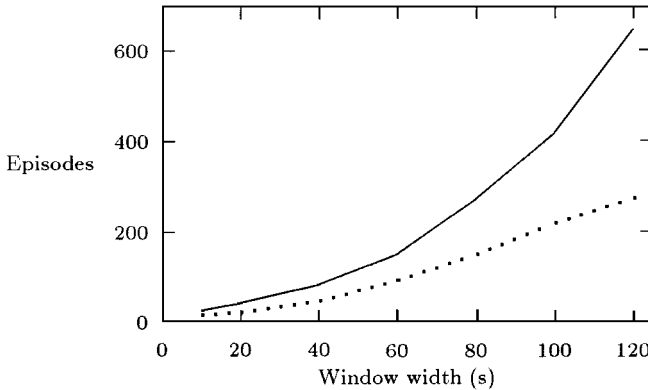


Figure 5. Number of frequent serial (solid line) and injective parallel (dotted line) episodes as a function of the window width; WINEPI, alarm database, frequency threshold 0.002.

With a given frequency threshold, the numbers of serial and injective parallel episodes may be fairly similar, e.g., a frequency threshold of 0.002 results in 151 serial episodes or 93 parallel episodes. The actual episodes are, however, very different, as can be seen from the number of iterations: recall that the l th iteration produces episodes of size l . For the frequency threshold of 0.002, the longest frequent serial episode consists of 43 events (all candidates of the last iteration were infrequent), while the longest frequent injective parallel episodes have three events. The long frequent serial episodes are not injective. The number of iterations in the table equals the number of candidate generation phases. The number of database passes made equals the number of iterations, or is smaller by one when there were no candidates in the last iteration.

The time requirement is much smaller for parallel episodes than for serial episodes with the same threshold. There are two reasons for this. The parallel episodes are considerably shorter and hence, fewer database passes are needed. The complexity of recognizing injective parallel episodes is also smaller.

The effect of the window width on the number of frequent episodes is represented in figure 5. For each window width, there are considerably fewer frequent injective parallel episodes than frequent serial episodes. With the alarm data, the increase in the number of episodes is fairly even throughout the window widths that we considered. However, we show later that this is not the case for all types of data.

5.2. Quality of candidate generation

We now take a closer look at the candidates considered and frequent episodes found during the iterations of the algorithm. As an example, let us look at what happens during the first iterations when searching for serial episodes. Statistics of the first ten iterations of a run with a frequency threshold of 0.001 and a window width of 60 s is shown in Table 3.

The three first iterations dominate the behavior of the method. During these phases, the number of candidates is large, and only a small fraction (less than 20 per cent) of the

Table 3. Number of candidate and frequent serial episodes during the first ten iterations with WINEPI; alarm database, frequency threshold 0.001, window width 60 s.

Episode size	Possible episodes	Candidates	Frequent episodes	Match
1	287	287	58	20%
2	82369	3364	137	4%
3	$2 \cdot 10^7$	719	46	6%
4	$7 \cdot 10^9$	37	24	64%
5	$2 \cdot 10^{12}$	24	17	71%
6	$6 \cdot 10^{14}$	18	12	67%
7	$2 \cdot 10^{17}$	13	12	92%
8	$5 \cdot 10^{19}$	13	8	62%
9	$1 \cdot 10^{22}$	8	3	38%
10	$4 \cdot 10^{24}$	3	2	67%

candidates turns out to be frequent. After the third iteration the candidate generation is efficient, few of the candidates are found infrequent, and although the total number of iterations is 45, the last 35 iterations involve only 1–3 candidates each. Thus we could safely combine several of the later iteration steps, to reduce the number of database passes.

If we take a closer look at the frequent episodes, we observe that all frequent episodes longer than 7 events consist of repeating occurrences of two very frequent alarms. Each of these two alarms occurs in the database more than 12000 times (16 per cent of the events each).

5.3. Comparison of algorithms WINEPI and MINEPI

Tables 4 and 5 represent performance statistics for finding frequent episodes with MINEPI, the method using minimal occurrences. Compared to the corresponding figures for WINEPI

Table 4. Performance characteristics for serial episodes with MINEPI; alarm database, maximum time bound 60 s.

Support threshold	Candidates	Frequent episodes	Iterations	Total time (s)
50	12732	2735	83	28
100	5893	826	71	16
250	2140	298	54	16
500	813	138	49	14
1000	589	92	48	14
2000	405	64	47	13
4000	352	53	46	12

Table 5. Performance characteristics for parallel episodes with MINEPI; alarm database, maximum time bound 60 s.

Support threshold	Candidates	Frequent episodes	Iterations	Total time (s)
50	10041	4856	89	30
100	4376	1755	71	20
250	1599	484	54	14
500	633	138	49	13
1000	480	89	48	12
2000	378	66	47	12
4000	346	53	46	12

in Tables 1 and 2, we observe the same general tendency for a rapidly decreasing number of candidates and episodes, as the support threshold increases.

The episodes found by WINEPI and MINEPI are not necessarily the same. If we compare the cases in Tables 1 and 4 with approximately the same number of frequent episodes, e.g., 151 serial episodes for WINEPI and 138 for MINEPI, we notice that they do not correspond to the same episodes. The sizes of the longest frequent episodes are somewhat different (43 for WINEPI vs. 48 for MINEPI). The frequency threshold 0.002 for WINEPI corresponds to about 150 instances of the episode, at the minimum, while the support threshold used for MINEPI is 500. The difference between the methods is very clear for small episodes. Consider an episode α consisting of just one event A . WINEPI considers a single event A to occur in 60 windows of width 60 s, while MINEPI sees only one minimal occurrence. On the other hand, two successive events of type A result in α occurring in 61 windows, but the number of minimal occurrences is doubled from 1 to 2.

Figure 6 shows the time requirement for finding frequent episodes with MINEPI, as a function of the support threshold. The processing time for MINEPI reaches a plateau when

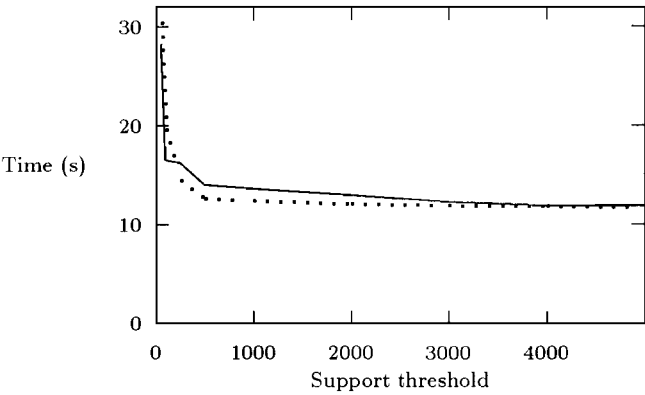


Figure 6. Processing time for serial (solid line) and parallel (dotted line) episodes with MINEPI; alarm database, maximum time bound 60 s.

the size of the maximal episodes no longer changes (in this case, at support threshold 500). The behavior is similar for serial and parallel episodes. The time requirements of MINEPI should not be directly compared to WINEPI: the episodes discovered are different, and our implementation of MINEPI works entirely in the main memory. With very large databases this might not be possible during the first iterations; either the minimal occurrences need to be stored on the disk, or other methods (e.g., variants of Algorithms 4 and 5) must be used.

5.4. Episode rules

The methods can easily produce large amounts of rules with varying confidences. Recall that rules are constructed by considering all frequent episodes α as the right-hand side and all subepisodes $\beta \preceq \alpha$ as the left-hand side of the rule. Additionally, MINEPI considers variations of these rules with all the time bounds in the given set W .

Table 6 represents results with serial episodes. The initial episode generation with MINEPI took around 14 s, and the total number of frequent episodes was 92. The table shows the number of rules with two time bounds obtained by MINEPI with confidence threshold 0 and with maximum time bound 60 s. On the left, we have varied the support threshold. Rules that differ only in their time bounds are excluded from the figures; the rule generation time is, however, obtained by generating rules with four different time bounds.

The minimal occurrence method is particularly useful if we are interested in finding rules with several different time bounds. The right side of Table 6 represents performance results with a varying number of time bounds. The time requirement increases slowly as more time bounds are used, and slower than the number of rules.

Rules with a high confidence are often the most interesting and useful ones, especially if they are used for prediction. Figure 7 shows how the number of distinct rules varies as a function of the confidence threshold for MINEPI. Of the over 10000 rules generated, 2000 have a confidence of exactly 1. For many applications it is reasonable to use a fairly low

Table 6. Number of rules and rule generation time with MINEPI; alarm database, serial episodes, support threshold 1000, maximum time bound 60 s, confidence threshold 0.

Varying support threshold, four time bounds			Varying number of time bounds, support threshold 1000		
Support threshold	Distinct rules	Rule gen. time (s)	Number of time bounds	All rules	Rule gen. time (s)
50	50470	149	1	1221	13
100	10809	29	2	2488	13
250	4041	20	4	5250	15
500	1697	16	10	11808	18
1000	1221	15	20	28136	22
2000	1082	14	30	42228	27
4000	1005	14	60	79055	43

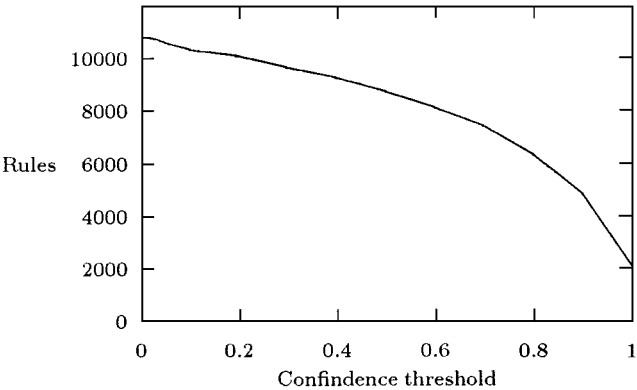


Figure 7. Total number of distinct rules found by MINEPI with various confidence thresholds; alarm database, maximum time bound 60 s, support threshold 100.

confidence threshold in order to point out the interesting connections, as is discussed in the following subsection.

The amount of almost 80000 rules, obtained with 60 time bounds, may seem unnecessarily large and unjustified. Remember, however, that when ignoring the time bounds, there are only 1221 distinct rules. The rest of the rules present different combinations of time bounds, in this case down to the granularity of one second. For the cost of 43 s we thus obtain very fine-grained rules from the frequent episodes. Different criteria, such as a confidence threshold or the deviation from an expected confidence, can then be used to select the most interesting rules from these.

5.5. Results with different data sets

In addition to the experiments on the alarm database, we have run MINEPI on a variety of different data collections to get a better view of the usefulness of the method. The data collections that were used and some results with typical parameter values are presented in Table 7.

Table 7. Characteristic parameter values for each of the data sets and the number of episodes and rules found by MINEPI.

Data set name	Events	Event types	Support threshold	Max time bound	Confidence threshold	Frequent episodes	Rules
alarms	73679	287	100	60	0.8	826	6303
WWW	116308	7634	250	120	0.2	454	316
text1	5417	1102	20	20	0.2	127	19
text2	2871	905	20	20	0.2	34	4
protein	4941	22	7	10	n/a	21234	n/a

The WWW data is part of the WWW server log from the Department of Computer Science at the University of Helsinki. The log contains requests to WWW pages at the department's server made by WWW browsers in the Internet. We consider the WWW page fetched as the event type. The total number of events in the data set is 116308, covering three weeks in February and March, 1996. In total, 7634 different pages are referred to. Requests for images have been excluded from consideration.

Suitable support thresholds vary a lot, depending on the number of events and the distribution of event types. A suitable maximum time bound for the device-generated alarm data is one minute, while the slower pace of a human user requires using a larger time bound (two minutes or more) for the WWW log. By using a relatively small time bound we reduce the probability of unrelated requests contributing to the support. A low confidence threshold for the WWW log is justified since we are interested in all fairly usual patterns of usage. In the WWW server log we found, e.g., long paths of pages from the home page of the department to the pages of individual courses. Such behavior suggests that rather than using a bookmark directly to the home page of a course, many users quickly navigate there from the departmental home page.

The two text data collections are modifications of the same English text. Each word is considered an event, and the words are indexed consecutively to give a "time" for each event. The end of each sentence causes a gap in the indexing scheme, to correspond to a longer distance between words in different sentences. We used text from GNU man pages (the gnu awk manual). The size of the original text (text1) is 5417 words, and the size of the condensed text file (text2), where non-informative words such as articles, prepositions, and conjunctions, have been stripped off, is 2871 words. The number of different words in the original text is 1102 and in the condensed text 905.

For text analysis, there is no point in using large "time" bounds, since it is unlikely that there is any connection between words that are not fairly close to each other. This can be clearly seen in figure 8 which represents the number of episodes found with various window widths using WINEPI. This figure reveals behavior that is distinctively different

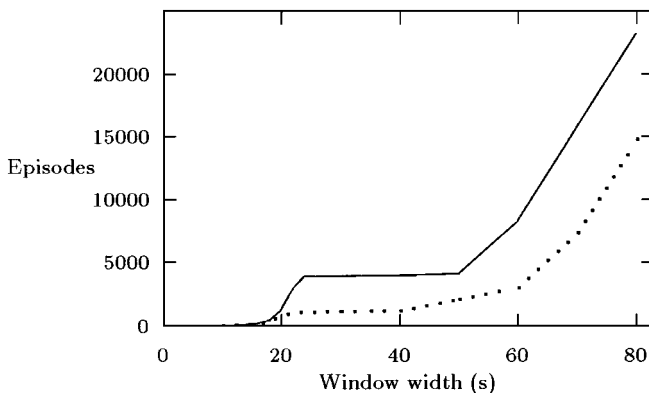


Figure 8. Number of serial (solid line) and injective parallel (dotted line) episodes as a function of the window width; WINEPI, compressed text data (text2), frequency threshold 0.02.

from the corresponding figure 5 for the alarm database. We observe that for the text data, the window widths from 24 to 50 produce practically the same amount of serial episodes. The number of episodes will only increase with considerably larger window widths. For this data, the interesting frequent episodes are smaller than 24, while the episodes found with much larger window widths are noise. The same phenomenon can be observed for parallel episodes. The best window width to use depends on the domain, and cannot be easily adjusted automatically.

Only few rules can be found in text using a simple analysis like this. The strongest rules in the original text involve either the word *gawk*, or common phrases such as

the, value [2] \Rightarrow of [3] (confidence 0.90)

meaning that in 90% of the cases where the words *the* *value* are consecutive, they are immediately followed by the preposition *of*. These rules were not found in the condensed text since all prepositions and articles have been stripped off. The few rules in the condensed text contain multiple occurrences of the word *gawk*, or combinations of words occurring in the header of each main page, such as *free software*.

We performed scale-up tests with 5, 10, and 20 fold multiples of the compressed text file, i.e., sequences of approximately 2900 to 58000 events. The results in figure 9 show that the time requirement is roughly linear with respect to the length of the input sequence, as could be expected.

Finally, we experimented with protein sequences. We used data in the PROSITE database (Bairoch et al., 1995) of the ExPASy WWW molecular biology server of the Geneva University Hospital and the University of Geneva (ExPASy). PROSITE contains biologically significant DNA and protein patterns that help to identify to which family of protein (if any) a new sequence belongs. The purpose of our experiment is to evaluate our algorithm against an external data collection and patterns that are known to exist, not to find patterns previously unknown to the biologists. We selected as our target a family of 7 sequences ("DNA mismatch repair proteins 1", PROSITE entry PS00058). The sequences in the family

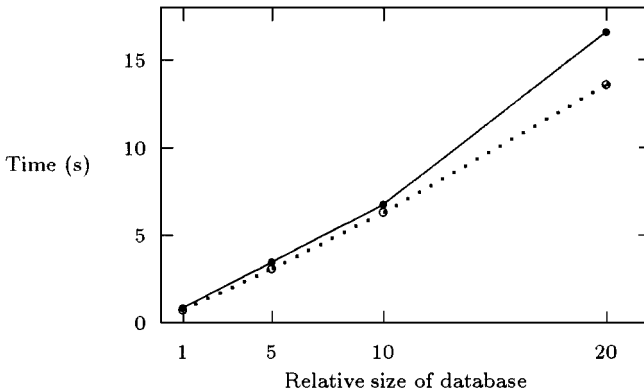


Figure 9. Scale-up results for serial (solid line) and injective parallel (dotted line) episodes with MINEPI; compressed text data, maximum time bound 60, support threshold 10 for the smallest file (n -fold for the larger files).

are known to contain the string GFRGEAL of seven consecutive symbols. The methods can be easily modified to take several separate sequences as input, and to compute the support of an episode α , e.g., as the number of input sequences that contain a (minimal) occurrence of α of length at most the maximum time bound. For simplicity, we transformed the data in a manner similar to the English text: symbols are indexed consecutively, and between the protein sequences we placed a gap. The total length of this data set is 4941 events, with an alphabet of 22 event types.

The parameter values for the protein database are chosen on purpose to reveal the pattern that is known to be present in the database. The window width was selected to be 10, i.e., slightly larger than the length of the pattern that we were looking for, and the support threshold was set to 7, for the seven individual sequences in the original data. With this data, we are only interested in the longest episodes (of length 7 or longer). Of the more than 20000 episodes found, 17 episodes are of length 7 or 8. As expected, these contain the sequence GFRGEAL that was known to be in the database. The longer episodes are variants of this pattern with an eighth symbol fairly near, but not necessarily immediately subsequent to the pattern (e.g., GFRGEAL*S). These types of patterns belong to the pattern class used in PROSITE but, to our surprise, these longer patterns are not reported in the PROSITE database.

5.6. *Experiences in alarm analysis*

Our algorithms for finding episodes have been applied to the analysis of telecommunication alarms. We briefly describe the application and summarize our experiences; see Hätönen et al. (1996a, 1996b) for more details.

Telecommunication networks are growing fast in size and complexity, and at the same time their management is becoming more difficult. The task of identifying and correcting faults in telecommunication networks is, in particular, a critical task of network management. Network elements produce large amounts of alarms about the faults in a network, but fully employing this valuable data is difficult due to the high volume and the fragmented nature of the information. Moreover, changes in equipment, software, and network load mean that the characteristics of the alarm data change.

Episodes can be used in building systems for alarm correlation, a central technique in fault identification. In alarm correlation, a management center automatically analyzes the stream of alarms it receives from a telecommunication network. Alarm correlation is typically based on looking at the active alarms within a time window, and interpreting them as a group. This interpretation can result in filtering of redundant alarms, identification of faults, and in suggestions for corrective actions. See, e.g., Jakobson and Weissman (1993) for a description of a representative correlation system; similar approaches have been used successfully also in process control tasks (Milne et al., 1994). While the use of alarm correlation systems is quite popular and methods for specifying the correlations are maturing, acquiring all the knowledge necessary for constructing an alarm correlation system for a network and its elements is difficult.

Our view to alarm correlation involves three phases. (1) A large database of alarms is analyzed off-line, and frequent episodes are discovered. (2) The network management

specialists use discovered episodes as drafts for correlation rules, when building or updating a correlation system. (3) The correlation system is applied in real-time alarm processing. The methodology for the first step and a supporting system, TASA, have been described in Hätönen et al. (1996a).

Knowledge about different aspects of alarms can be discovered by specifying the event types in alternative ways. If only the alarm type is considered as the event type, then episodes reveal connections between types of alarms without respect to the network elements that sent the alarms. Alternatively, e.g., the pair (sender, alarm type) can be considered to constitute the event type, thus making it explicit that the input is merged from alarms from several senders in the network. An episode rule found in events like this shows connections between alarms from particular network elements. Events consisting of the (sender type, alarm type) pair have actually proved to be one of the most useful forms: episode rules between problems in different types of devices seem to describe the network behavior in a reasonable level of abstraction.

Episode algorithms have been in prototype use in four telecommunication companies since the beginning of 1995. Beginning from the first tests, discovered episodes have been applied in alarm correlation systems. Unexpected but useful dependencies have been found, e.g., between network elements which are not immediately connected in the network topology. The fault management experts in the telecommunication companies have found episodes useful in three tasks: (1) finding long-term, rather frequently occurring dependencies, (2) creating an overview of a short-term alarm sequence, and (3) evaluating the alarm database consistency and correctness. Although the algorithms are not directly applicable for on-line analysis, they have turned out to be useful in network surveillance. Especially when supplemented with browsing tools, such as in the TASA system, episodes can provide useful views to the collection of recent alarms.

6. Related work

The work most closely related to ours is perhaps (Agrawal and Srikant, 1995; Srikant and Agrawal, 1996). There multiple sequences are searched for patterns that are similar to serial episodes with some extra restrictions and an event taxonomy. Our methods can be extended with a taxonomy by a direct application of the similar extensions to association rules (Han and Fu, 1995; Holsheimer et al., 1995; Srikant and Agrawal, 1995). Also, our methods can be applied on analyzing several sequences; there is actually a variety of choices for the definition of frequency (or support) of an episode in a set of sequences.

Patterns over multiple, synchronized sequences are searched for in Oates and Cohen (1996). The patterns are similar to but more rigid than episodes. For instance, the insertion of unrelated events into the sequences is problematic. The use of multiple sequences corresponds here to searching episodes from a sequence of (sender, alarm type) pairs.

First order temporal logic has been proposed as a means of both expressing and discovering temporal patterns (Padmanabhan and Tuzhilin, 1996). The formalism is strong and allows expressing more complex patterns than episodes; it is unclear what the complexity of different discovery tasks is. There are also some interesting similarities between the

discovery of frequent episodes and the work done on inductive logic programming (see, e.g., Muggleton, 1992); a noticeable difference is caused by the sequentiality of the underlying data model, and the emphasis on time-limited occurrences. Similarly, the problem of looking for one occurrence of an episode can also be viewed as a constraint satisfaction problem.

For a survey on patterns in sequential data, see Laird (1993). Another knowledge discovery method for telecommunication alarm data has been presented in Goodman et al. (1995).

The task of discovering frequent parallel episodes can be stated as a task of discovering all frequent sets, a central phase of discovering association rules (Agrawal et al., 1993). The rule generation methods are essentially the same for association rules and WINEPI. The levelwise main algorithm has also been used successfully in the search of frequent sets (Agrawal et al., 1996); a generic levelwise algorithm and its analysis has been presented in Mannila and Toivonen (1997).

Technical problems related to the recognition of episodes have been researched in several fields. Taking advantage of the slowly changing contents of the group of recent events has been studied, e.g., in artificial intelligence, where a similar problem in spirit is the many pattern/many object pattern match problem in production system interpreters (Forgy, 1982). Also, comparable strategies using a sliding window have been used, e.g., to study the locality of reference in virtual memory (Denning, 1968). Our setting differs from these in that our window is a queue with the special property that we know in advance when an event will leave the window; this knowledge is used by WINEPI in the recognition of serial episodes. In MINEPI, we take advantage of the fact that we know where subepisodes of candidates have occurred.

The methods for matching sets of episodes against a sequence have some similarities to the algorithms used in string matching (e.g., Grossi and Luccio, 1989). In particular, recognizing serial episodes in a sequence can be seen as locating all occurrences of subsequences, or matches of patterns with variable length do not care symbols, where the length of the occurrences is limited by the window width. Learning from a set of sequences has received considerable interest in the field of bioinformatics, where an interesting problem is the discovery of patterns common to a set of related protein or amino acid sequences. The classes of patterns differ from ours; they can be, e.g., substrings with fixed length do not care symbols (Jonassen et al., 1995). Closer to our patterns are those considered in Wang et al. (1994). The described algorithm finds patterns that are similar to serial episodes; however, the patterns have a given minimum length, and the occurrences can be within a given edit distance. Recent results on the pattern matching aspects of recognizing episodes can be found in Das et al. (1997).

The recent work on sequence data in databases (see Seshadri et al., 1996) provides interesting openings towards the use of database techniques in the processing of queries on sequences. A problem similar to the computation of frequencies occurs also in the area of active databases. There triggers can be specified as composite events, somewhat similar to episodes. In Gehani et al. (1992) it is shown how finite automata can be constructed from composite events to recognize when a trigger should be fired. This method is not practical for episodes since the deterministic automata could be very large.

In stochastics, event sequence data is often called a marked point process (Kalbfleisch and Prentice, 1980). It should be noted that traditional methods for analyzing marked point processes are ill-suited for the cases where the number of event types is large. However, there is a promising combination of techniques: frequent episodes could be discovered first, and then the phenomena they describe are analyzed in more detail with methods for marked point processes.

7. Conclusions

We presented a framework for discovering frequent episodes in sequential data. The framework consists of defining episodes as partially ordered sets of events, and looking at windows on the sequence. We described an algorithm, WINEPI, for finding all episodes from a given class of episodes that are frequent enough. The algorithm was based on the discovery of episodes by only considering an episode when all its subepisodes are frequent, and on an incremental checking of whether an episode occurs in a window. The implementation shows that the method is efficient. We have applied the method in the analysis of the alarm flow from telecommunication networks, and discovered episodes have been embedded in alarm handling software.

We also presented an alternative approach, MINEPI, to the discovery of frequent episodes, based on minimal occurrences of episodes. This approach supplies more power for representing connections between events, as it produces rules with two time bounds.

The rule formalisms of the two methods both have their advantages. While the rules of MINEPI are often more informative, the frequencies and confidences of the rules of WINEPI have nice interpretations as probabilities concerning randomly chosen windows. For a large part the algorithms are similar, there are significant differences only in the computation of the frequency or support. Roughly, a general tendency in the performance is that WINEPI can be more efficient in the first phases of the discovery, mostly due to smaller space requirement. In the later iterations, MINEPI is likely to outperform WINEPI clearly. The methods can be modified for cross-use, i.e., WINEPI for finding minimal occurrences and MINEPI for counting windows, and for some large problems—whether the rule type of WINEPI or MINEPI—a mixture of the two methods could give better performance than either alone.

The classes of patterns discovered can be easily modified in several directions. Different windowing strategies could be used, e.g., considering only windows starting every win' time units for some win' , or windows starting from every event. Other types of patterns could also be searched for with similar methods, e.g., substrings with fixed length do not care symbols; searching for episodes in several sequences is no problem. A more general framework for episode discovery has been presented in Mannila and Toivonen (1996). There episodes are defined as combinations of events satisfying certain user specified unary or binary conditions.

Interesting extensions to the work presented here are facilities for rule querying and compilation, i.e., methods by which the user could specify the episode class in a high-level language and the definition would automatically be compiled into a specialization of the algorithm that would take advantage of the restrictions on the episode class. Other open problems include the combination of episode techniques with marked point processes and intensity models.

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