

Sequential Pattern Mining



Examples of Sequence

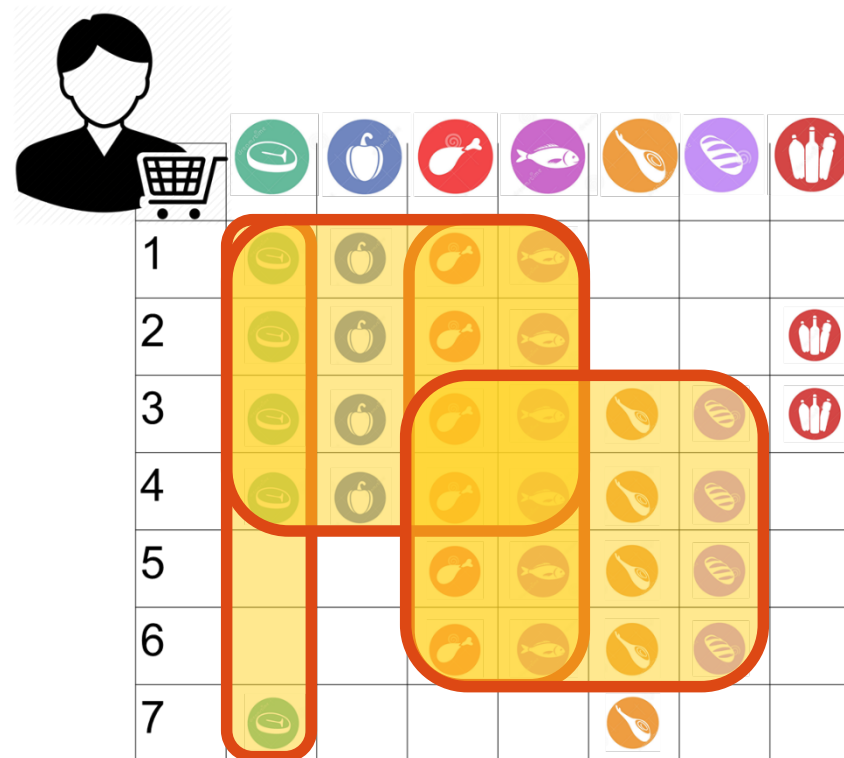
- Sequence of different transactions by a customer at an online store:
< {Digital Camera,iPad} {memory card} {headphone,iPad cover} >
- Sequence of events causing the nuclear accident at 3-mile Island:
(http://stellar-one.com/nuclear/staff_reports/summary_SOE_the_initiating_event.htm)
< {clogged resin} {outlet valve closure} {loss of feedwater}
{condenser polisher outlet valve shut} {booster pumps trip}
{main waterpump trips} {main turbine trips} {reactor pressure increases}>
- Sequence of books checked out at a library:
<{Fellowship of the Ring} {The Two Towers} {Return of the King}>

From Itemsets to Sequences

- Frequent itemsets and association rules focus on transactions and the items that appear there
- Databases of transactions usually have a temporal information
 - Sequential patterns exploit it
- Example data:
 - Market basket transactions
 - Web server logs
 - Tweets
 - Workflow production logs

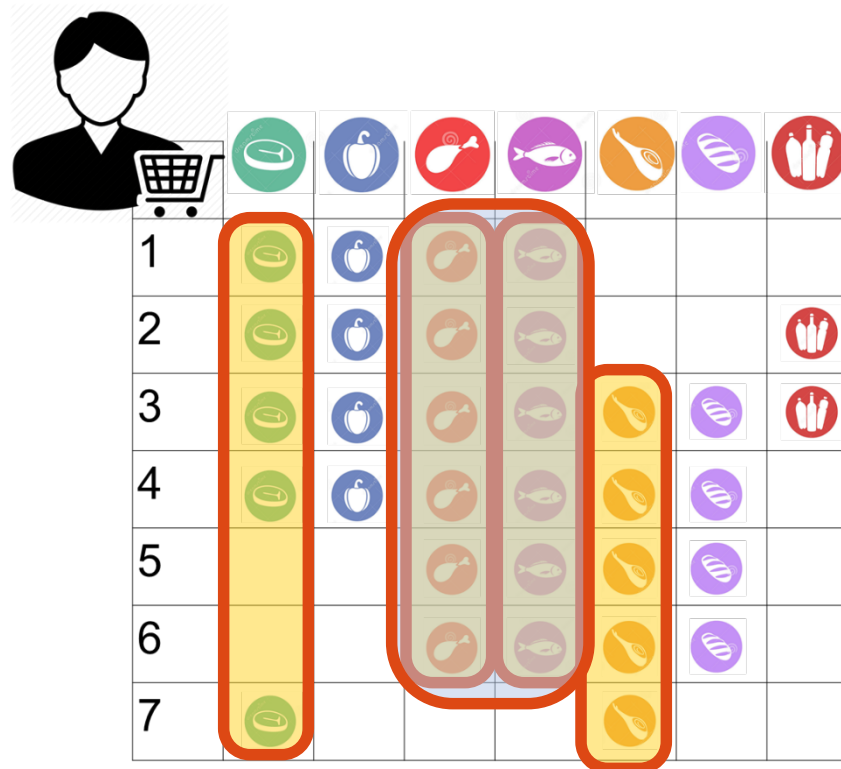
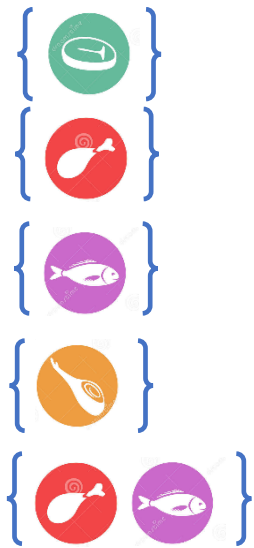
Frequent Patterns

- Events or combinations of events that appear frequently in the data
- E.g. items bought by customers of a supermarket



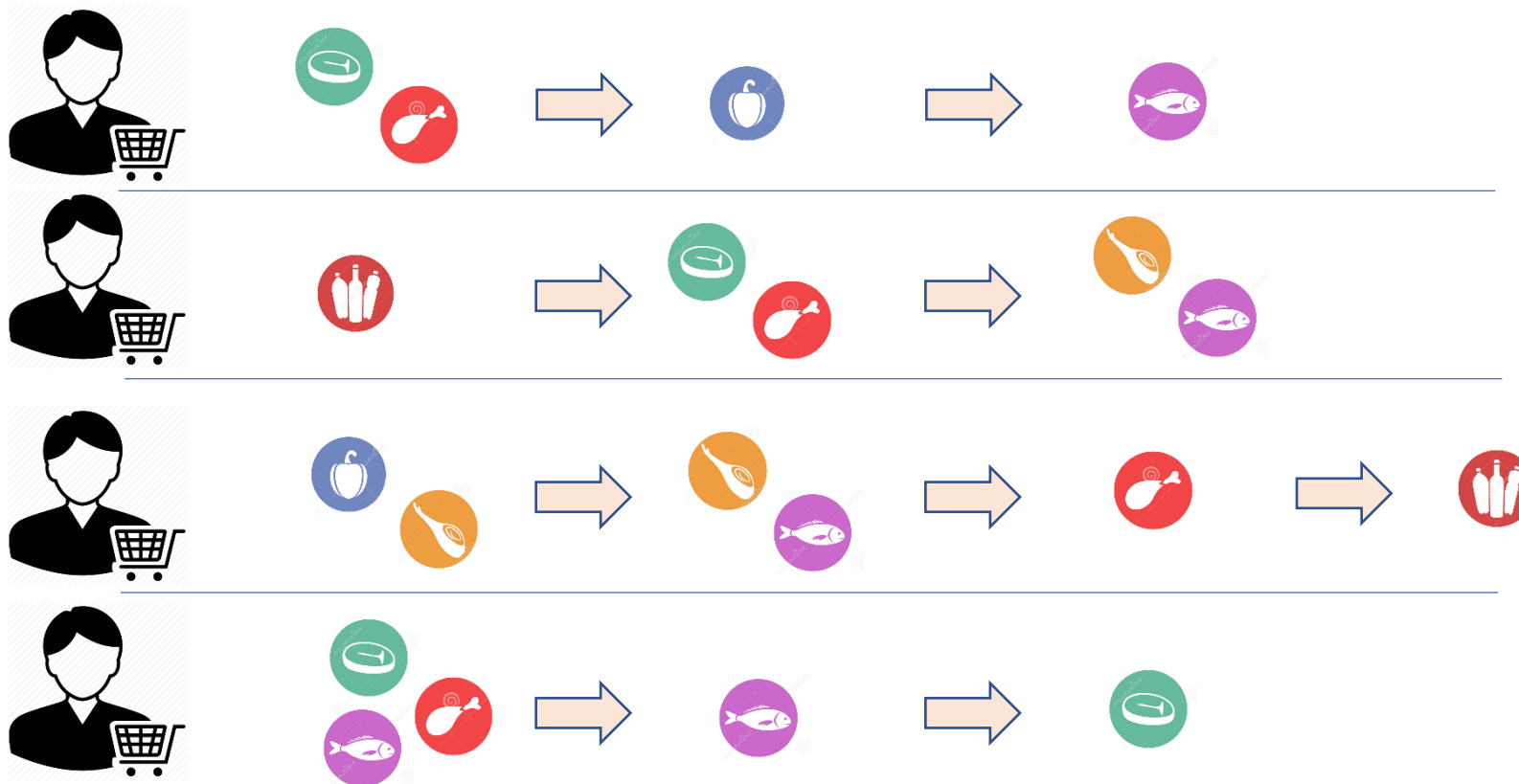
Frequent Patterns

- **Frequent itemsets** w.r.t. minimum threshold
- E.g. with $\text{Min_freq} = 5$



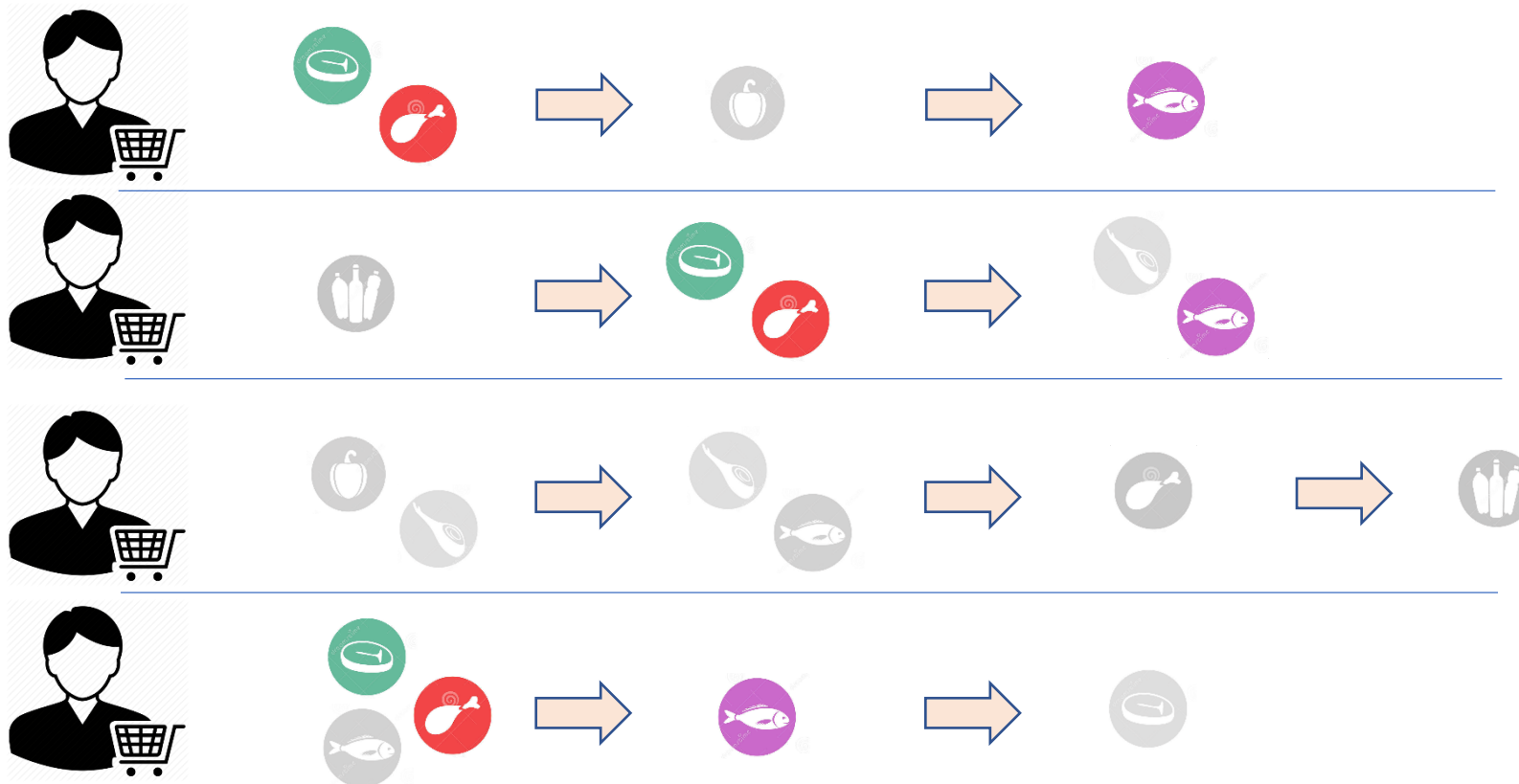
Frequent Patterns in Complex Domains

- Frequent sequences (a.k.a. Sequential patterns)
- Input: sequences of events (or of groups)



Frequent Patterns in Complex Domains

- Objective: identify sequences that occur frequently
 - Sequential pattern: {   } \Rightarrow 

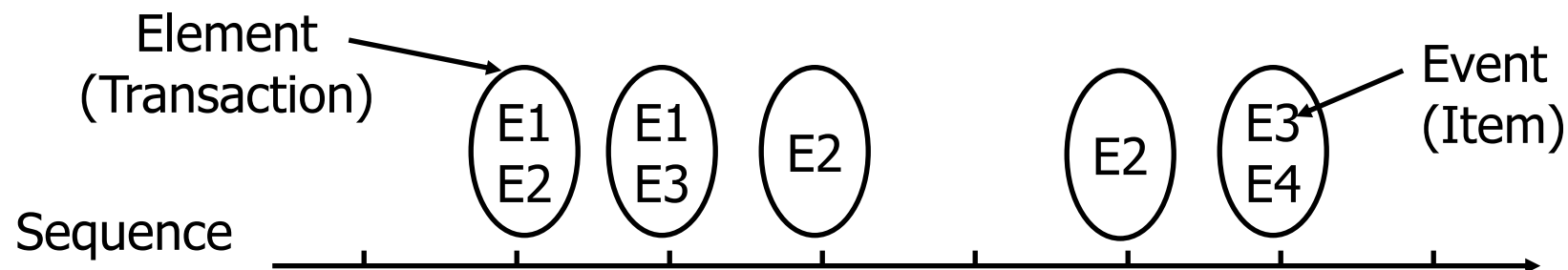


Sequential Pattern Discovery: Examples

- In telecommunications alarm logs,
 - Inverter_Problem:
(Excessive_Line_Current) (Rectifier_Alarm) --> (Fire_Alarm)
- In point-of-sale transaction sequences,
 - Computer Bookstore:
(Intro_To_Visual_C) (C++_Primer) --> (Perl_for_dummies,Tcl_Tk)
 - Athletic Apparel Store:
(Shoes) (Racket, Racketball) --> (Sports_Jacket)

Sequence Data and Terminology

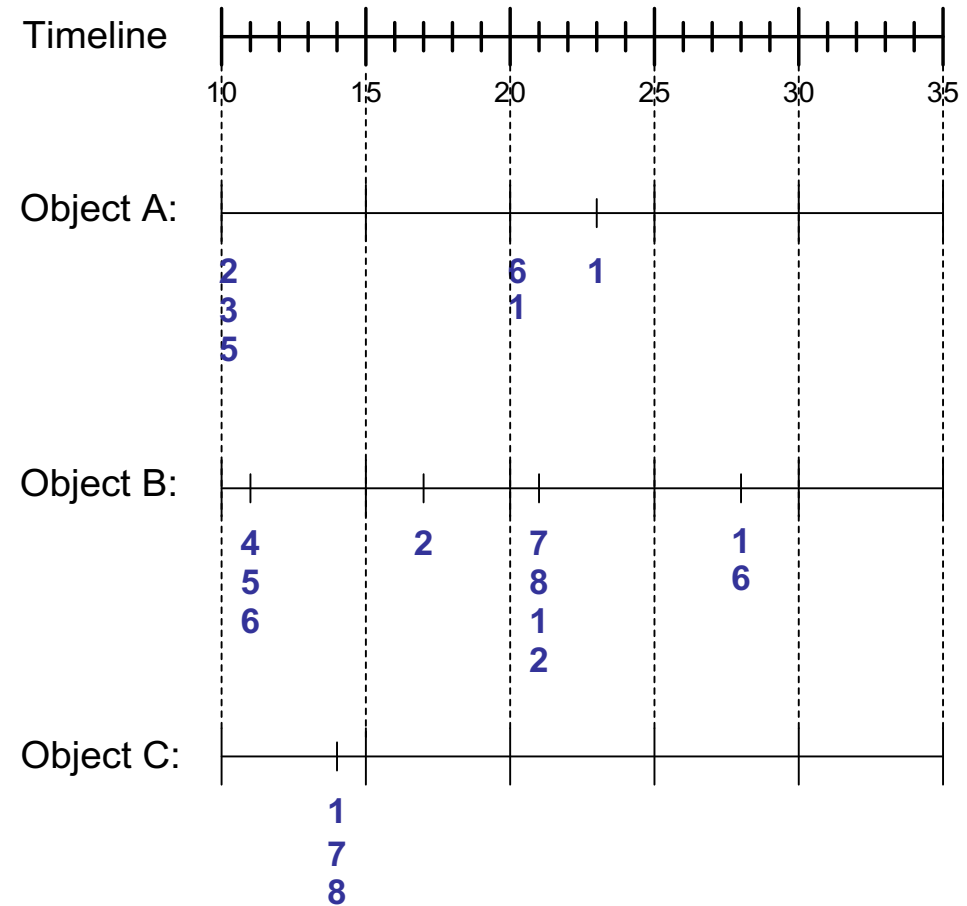
Sequence Database	Sequence	Element (Transaction)	Event (Item)
Customer	Purchase history of a given customer	A set of items bought by a customer at time t	Books, diary products, CDs, etc
Web Data	Browsing activity of a particular Web visitor	A collection of files viewed by a Web visitor after a single mouse click	Home page, index page, contact info, etc
Event data	History of events generated by a given sensor	Events triggered by a sensor at time t	Types of alarms generated by sensors
Genome sequences	DNA sequence of a particular species	An element of the DNA sequence	Bases A,T,G,C



Sequence Data

Sequence Database:

Object	Timestamp	Events
A	10	2, 3, 5
A	20	6, 1
A	23	1
B	11	4, 5, 6
B	17	2
B	21	7, 8, 1, 2
B	28	1, 6
C	14	1, 8, 7



Sequential Pattern Mining

Formal Definition of a Sequence

- A sequence is an ordered list of elements (transactions)

$$s = \langle e_1 e_2 e_3 \dots \rangle$$

- Each element is attributed to a specific time or location
- Each element contains a collection of events (items)

$$e_i = \{i_1, i_2, \dots, i_k\}$$

- Length of a sequence, $|s|$, is given by the number of elements of the sequence
- A k-sequence is a sequence that contains k events (items)

Formal Definition of a Sequence

- Example

$$s = \langle \{A,B\}, \{B,E,F\}, \{A\}, \{E,F,H\} \rangle$$

- Length of s : $|s| = 4$ elements
- s is a 9-sequence
- Times associated to elements:
 - $\{A,B\} \rightarrow \text{time}=0$
 - $\{B,E,F\} \rightarrow \text{time} = 120$
 - $\{A\} \rightarrow \text{time} = 130$
 - $\{E,F,H\} \rightarrow \text{time} = 200$

Sequences without Explicit Time Info

- Default: time of element = position in the sequence
- Example

$S = \langle \{A,C\}, \{E\}, \{A,F\}, \{E,G,H\} \rangle$

- Default times associated to elements:
 - $\{A,C\} \rightarrow \text{time}=0$
 - $\{E\} \rightarrow \text{time} = 1$
 - $\{A,F\} \rightarrow \text{time} = 2$
 - $\{E,G,H\} \rightarrow \text{time} = 3$

Examples of Sequence

- Web sequence:

< {Homepage} {Electronics} {Digital Cameras} {Canon Digital Camera} {Shopping Cart} {Order Confirmation} {Return to Shopping} >

Singleton elements



- Sequence of events causing the nuclear accident at 3-mile Island:

(http://stellar-one.com/nuclear/staff_reports/summary_SOE_the_initiating_event.htm)

< {clogged resin & outlet valve closure} {loss of feedwater}
{condenser polisher outlet valve shut} {booster pumps trip}
{main waterpump trips & main turbine trips & reactor pressure increases}>

Complex elements



- Sequence of books checked out at a library:

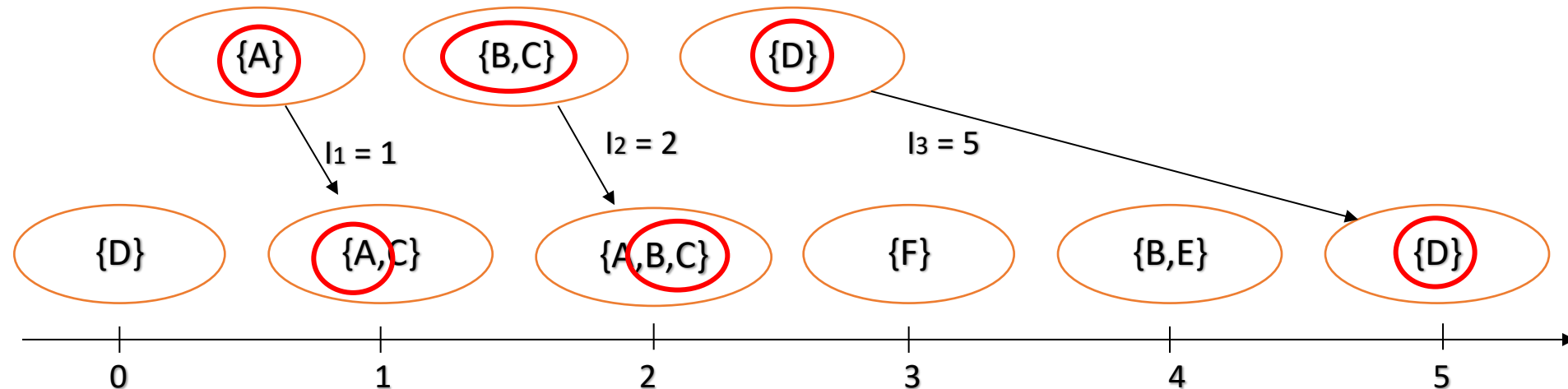
<{Fellowship of the Ring} {The Two Towers} {Return of the King}>

Singleton elements



Formal Definition of a Subsequence

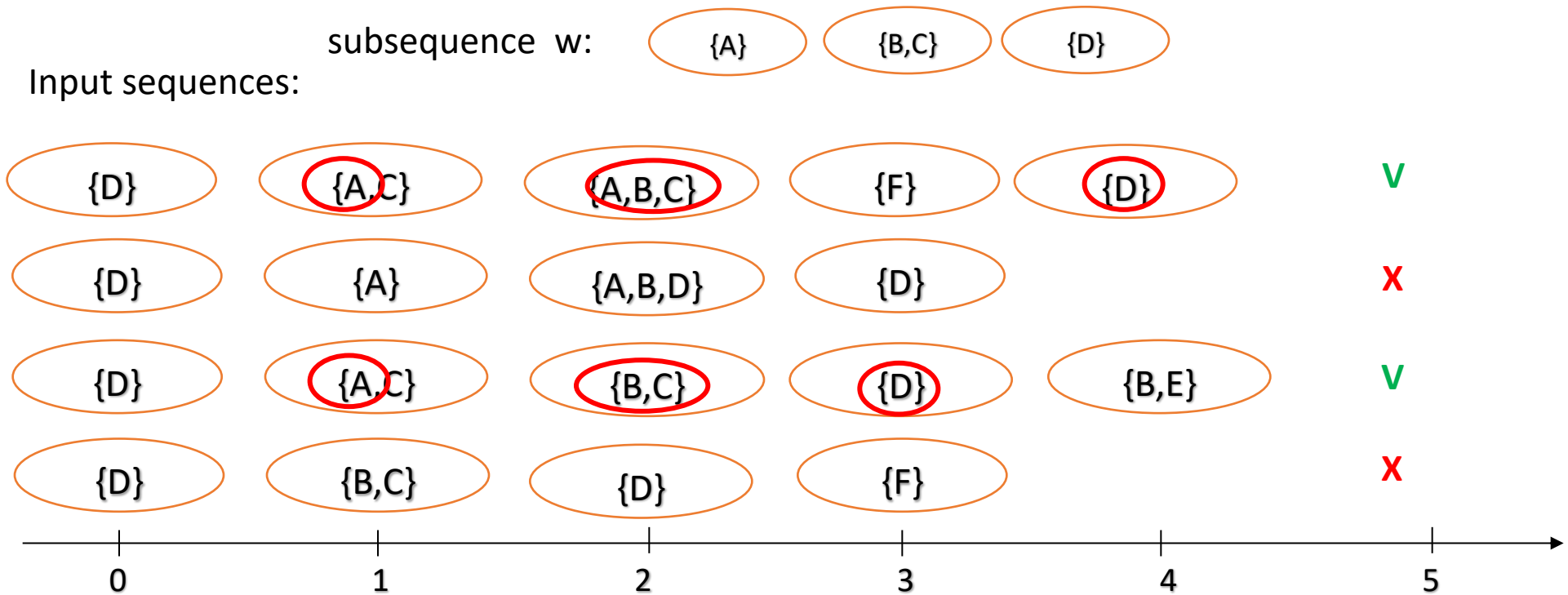
- A sequence $\langle a_1 a_2 \dots a_n \rangle$ is contained in another sequence $\langle b_1 b_2 \dots b_m \rangle$ ($m \geq n$) if there exist integers $i_1 < i_2 < \dots < i_n$ such that $a_1 \subseteq b_{i_1}, a_2 \subseteq b_{i_2}, \dots, a_n \subseteq b_{i_n}$



Data sequence	Subsequence	Contain?
$\langle \{2,4\} \{3,5,6\} \{8\} \rangle$	$\langle \{2\} \{3,5\} \rangle$	
$\langle \{1,2\} \{3,4\} \rangle$	$\langle \{1\} \{2\} \rangle$	
$\langle \{2,4\} \{2,4\} \{2,5\} \rangle$	$\langle \{2\} \{4\} \rangle$	

Formal Definition of Sequential Pattern

- The **support** of a subsequence w is the fraction of data sequences that contain w

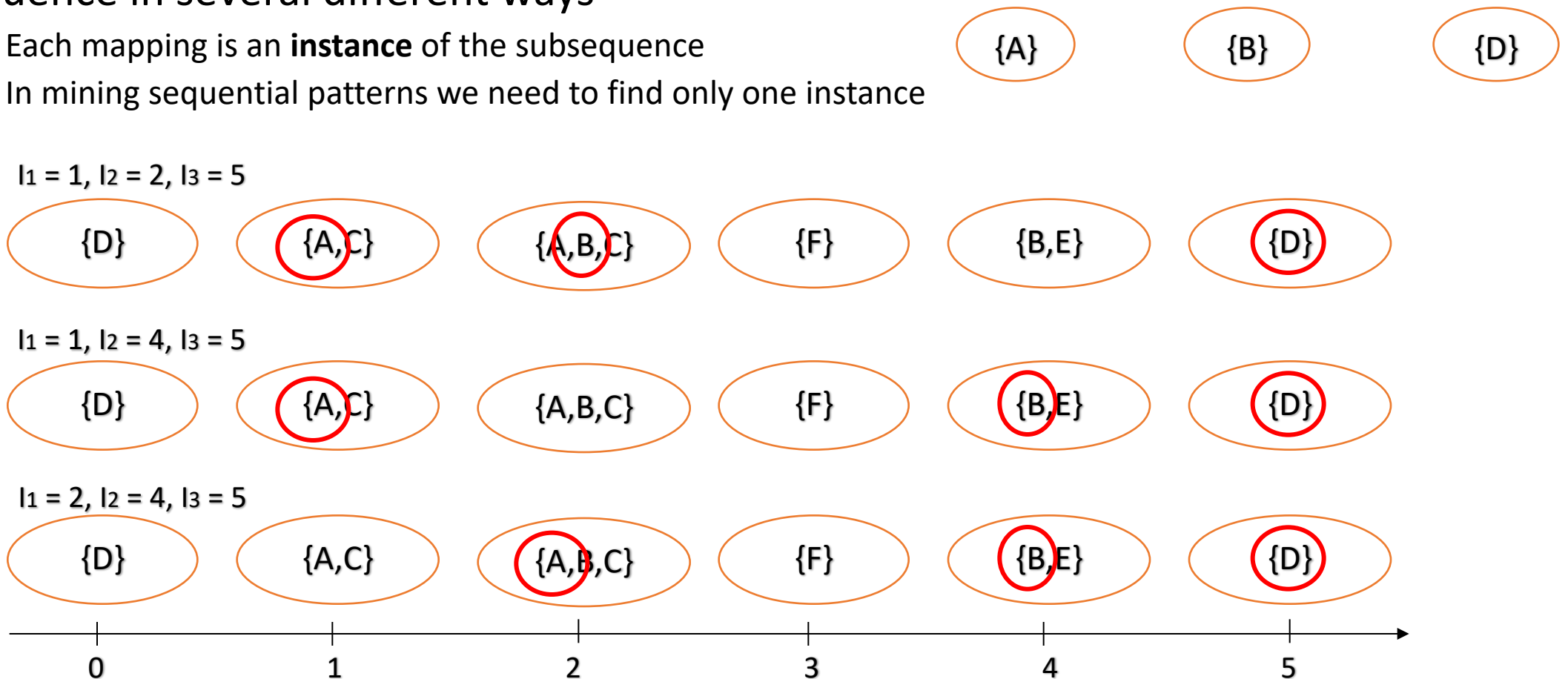


support of w : $2/4 = 0.50$ (50%)

- A **sequential pattern**
 - is a **frequent** subsequence
 - i.e., a subsequence whose support is \geq *minsup*

Formal Definition of Sequential Pattern

- Remark: a subsequence (i.e. a candidate pattern) might be mapped into a sequence in several different ways
 - Each mapping is an **instance** of the subsequence
 - In mining sequential patterns we need to find only one instance



Exercise 1

- find instances/occurrence of the following patterns

$\langle \{C\} \{H\} \{C\} \rangle$

$\langle \{A\} \{F\} \rangle$

$\langle \{A\} \{A\} \{D\} \rangle$

$\langle \{A\} \{A,B\} \{F\} \rangle$

- in the input sequence below

$\langle \begin{array}{cccccccc} \{A,C\} & \{C,D\} & \{F,H\} & \{A,B\} & \{B,C,D\} & \{E\} & \{A,B,D\} & \{F\} \\ t=0 & t=1 & t=2 & t=3 & t=4 & t=5 & t=6 & t=7 \end{array} \rangle$

Exercise 2

- find instances/occurrence of the following patterns

$\langle \{C\} \{H\} \{C\} \rangle$

$\langle \{A\} \{B\} \rangle$

$\langle \{C\} \{C\} \{E\} \rangle$

$\langle \{A\} \{E\} \rangle$

- in the input sequence below

$\langle \begin{array}{ccccccc} \{A,C\} & \{C,D,E\} & \{F\} & \{A,H\} & \{B,C,D\} & \{E\} & \{A,B,D\} \\ t=0 & t=1 & t=2 & t=3 & t=4 & t=5 & t=6 \end{array} \rangle$

Sequential Pattern Mining: Definition

- Given:
 - a database of sequences
 - a user-specified minimum support threshold, *minsup*
- Task:
 - Find all subsequences with support $\geq \textit{minsup}$

Sequential Pattern Mining: Challenge

- Trivial approach: generate all possible k-subsequences, for k=1,2,3,... and compute support
- Combinatorial explosion!
 - With frequent itemsets mining we had:
 - N. of k-subsets = $\binom{n}{k}$ *n = n. of distinct items in the data*
 - With sequential patterns:
 - N. of k-subsequences = n^k
 - The same item can be repeated:
 - $\langle \{A\} \{A\} \{B\} \{A\} \dots \rangle$

Sequential Pattern Mining: Challenge

- Even if we generate them from input sequences

- E.g.: Given a n-sequence: $\langle \{a\} \{b\} \{c\} \{d\} \{e\} \{f\} \{g\} \{h\} \{i\} \rangle$

- Examples of subsequences:

$\langle \{a\} \{c\} \{d\} \{f\} \{g\} \rangle$, $\langle \{c\} \{d\} \{e\} \rangle$, $\langle \{b\} \{g\} \rangle$, etc.

- Number of k-subsequences can be extracted from it

$\langle \{a\} \{b\} \{c\} \{d\} \{e\} \{f\} \{g\} \{h\} \{i\} \rangle \quad n = 9$

k=4: $\begin{array}{cccccccc} \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ Y & _ & _ & Y & Y & _ & _ & _ & Y \\ \langle \{a\} & & \{d\} \{e\} & & & & & \{i\} \rangle \end{array}$

Answer :

$$\binom{n}{k} = \binom{9}{4} = 126$$

Sequential Pattern Mining: Example

Object	Timestamp	Events
A	1	1,2,4
A	2	2,3
A	3	5
B	1	1,2
B	2	2,3,4
C	1	1, 2
C	2	2,3,4
C	3	2,4,5
D	1	2
D	2	3, 4
D	3	4, 5
E	1	1, 3
E	2	2, 4, 5

Minsup = 50%

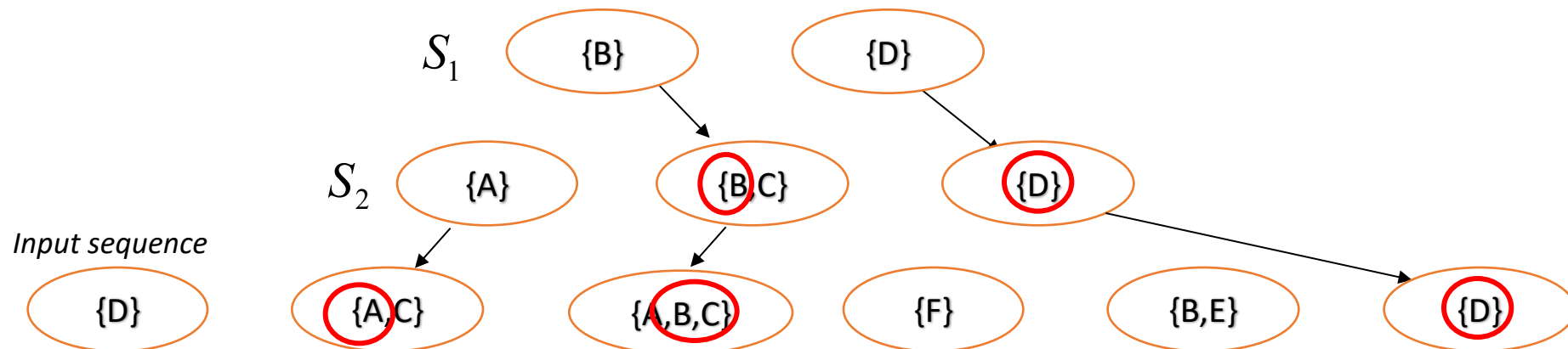
Examples of Frequent Subsequences:

< {1,2} > s=60%
< {2,3} > s=60%
< {2,4}> s=80%
< {3} {5}> s=80%
< {1} {2} > s=80%
< {2} {2} > s=60%
< {1} {2,3} > s=60%
< {2} {2,3} > s=60%
< {1,2} {2,3} > s=60%

Generalized Sequential Pattern

Generalized Sequential Pattern (GSP)

- **Follows the same structure of Apriori**
 - Start from short patterns and find longer ones at each iteration
- **Based on “Apriori principle” or “anti-monotonicity of support”**
 - If one sequence S_1 is contained in sequence S_2 , then the support of S_2 cannot be larger than that of S_1 :
$$S_1 \subseteq S_2 \Rightarrow \text{sup}(S_1) \geq \text{sup}(S_2)$$
- **Intuitive proof**
 - Any input sequence that contains S_2 will also contain S_1



Generalized Sequential Pattern (GSP)

- **Follows the same structure of Apriori**
 - Start from short patterns and find longer ones at each iteration
- **Step 1:**
 - Make the first pass over the sequence database D to yield all the 1-element frequent sequences
- **Step 2:** Repeat until no new frequent sequences are found:
 - **Candidate Generation:**
 - Merge pairs of frequent subsequences found in the $(k-1)th$ pass to generate candidate sequences that contain k items
 - **Candidate Pruning:**
 - Prune candidate k -sequences that contain infrequent $(k-1)$ -subsequences
 - **Support Counting:**
 - Make a new pass over the sequence database D to find the support for these candidate sequences
 - **Candidate Elimination:**
 - Eliminate candidate k -sequences whose actual support is less than *minsup*

Extracting Sequential Patterns

- Given n events: $i_1, i_2, i_3, \dots, i_n$
 - Candidate 1-subsequences:
 $\langle \{i_1\} \rangle, \langle \{i_2\} \rangle, \langle \{i_3\} \rangle, \dots, \langle \{i_n\} \rangle$
 - Candidate 2-subsequences:
 $\langle \{i_1, i_2\} \rangle, \langle \{i_1, i_3\} \rangle, \dots, \langle \{i_1\} \{i_1\} \rangle, \langle \{i_1\} \{i_2\} \rangle, \dots, \langle \{i_{n-1}\} \{i_n\} \rangle$
 - Candidate 3-subsequences:
 $\langle \{i_1, i_2, i_3\} \rangle, \langle \{i_1, i_2, i_4\} \rangle, \dots, \langle \{i_1, i_2\} \{i_1\} \rangle, \langle \{i_1, i_2\} \{i_2\} \rangle, \dots,$
 $\langle \{i_1\} \{i_1, i_2\} \rangle, \langle \{i_1\} \{i_1, i_3\} \rangle, \dots, \langle \{i_1\} \{i_1\} \{i_1\} \rangle, \langle \{i_1\} \{i_1\} \{i_2\} \rangle, \dots$
- Remark: events within an element are ordered
 - YES: $\langle \{i_1, i_2, i_3\} \rangle$ NO: $\langle \{i_3, i_1, i_2\} \rangle$

Candidate Generation

- Base case ($k=2$):
 - Merging two frequent 1-sequences $\langle\{i_1\}\rangle$ and $\langle\{i_2\}\rangle$ will produce two candidate 2-sequences: $\langle\{i_1\}\{i_2\}\rangle$ and $\langle\{i_1\}i_2\rangle$
 - Special case: i_1 can be merged with itself: $\langle\{i_1\}\{i_1\}\rangle$
- General case ($k>2$):
 - A frequent $(k-1)$ -sequence w_1 is merged with another frequent $(k-1)$ -sequence w_2 to produce a candidate k -sequence if the subsequence obtained by removing the **first event in w_1** is the same as the one obtained by removing the **last event in w_2**
 - The resulting candidate after merging is given by the sequence w_1 extended with the last event of w_2 .
 - If last two events in w_2 belong to the same element \Rightarrow last event in w_2 becomes part of the last element in w_1 :
 $\langle\{d\}\{a\}\{b\}\rangle + \langle\{a\}\{b,c\}\rangle = \langle\{d\}\{a\}\{b,c\}\rangle$
 - Otherwise, the last event in w_2 becomes a separate element appended to the end of w_1 :
 $\langle\{a,d\}\{b\}\rangle + \langle\{d\}\{b\}\{c\}\rangle = \langle\{a,d\}\{b\}\{c\}\rangle$
 - Special case: check if w_1 can be merged with itself
 - Works when it contains only one event type: $\langle\{a\}\{a\}\rangle + \langle\{a\}\{a\}\rangle = \langle\{a\}\{a\}\{a\}\rangle$

Candidate Generation Examples

- Merging the sequences
 $w_1 = \langle \{1\} \{2\ 3\} \{4\} \rangle$ and $w_2 = \langle \{2\ 3\} \{4\ 5\} \rangle$
will produce the candidate sequence $\langle \{1\} \{2\ 3\} \{4\ 5\} \rangle$ because the last two events in w_2 (4 and 5) belong to the same element
- Merging the sequences
 $w_1 = \langle \{1\} \{2\ 3\} \{4\} \rangle$ and $w_2 = \langle \{2\ 3\} \{4\} \{5\} \rangle$
will produce the candidate sequence $\langle \{1\} \{2\ 3\} \{4\} \{5\} \rangle$ because the last two events in w_2 (4 and 5) do not belong to the same element
- We **do not have** to merge the sequences
 $w_1 = \langle \{1\} \{2\ 6\} \{4\} \rangle$ and $w_2 = \langle \{1\} \{2\} \{4\ 5\} \rangle$
to produce the candidate $\langle \{1\} \{2\ 6\} \{4\ 5\} \rangle$
 - Notice that if the latter is a viable candidate, it will be obtained by merging w_1 with $\langle \{2\ 6\} \{4\ 5\} \rangle$

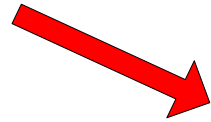
Candidate Pruning

- Based on Apriori principle:
 - If a k -sequence W contains a $(k-1)$ -subsequence that is not frequent, then W is not frequent and can be pruned
- Method:
 - Enumerate all $(k-1)$ -subsequence:
 - $\{a,b\}\{c\}\{d\} \rightarrow \{b\}\{c\}\{d\}, \{a\}\{c\}\{d\}, \{a,b\}\{d\}, \{a,b\}\{c\}$
 - Each subsequence generated by cancelling 1 event in W
 - Number of $(k-1)$ -subsequences = k
 - Remark: candidates are generated by merging two “mother” $(k-1)$ -subsequences that we know to be frequent
 - Correspond to remove the first event or the last one
 - Number of significant $(k-1)$ -subsequences to test = $k - 2$
 - Special cases: at step $k=2$ the pruning has no utility, since the only $(k-1)$ -subsequences are the “mother” ones

GSP Example

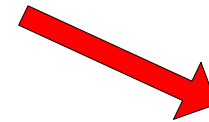
Frequent
3-sequences

< {1} {2} {3} >
< {1} {2 5} >
< {1} {5} {3} >
< {2} {3} {4} >
< {2 5} {3} >
< {3} {4} {5} >
< {5} {3 4} >



Candidate
Generation

< {1} {2} {3} {4} >
< {1} {2 5} {3} >
< {1} {5} {3 4} >
< {2} {3} {4} {5} >
< {2 5} {3 4} >



Candidate
Pruning

< {1} {2 5} {3} >

GSP Exercise

- Given the following dataset of sequences

ID	Sequence
1	a b → a → b
2	b → a → c d
3	a → b
4	a → a → b d

- Generate sequential patterns if min_sup = 35%

GSP Exercise - Solution

ID	Sequence
1	a b → a → b
2	b → a → c d
3	a → b
4	a → a → b d

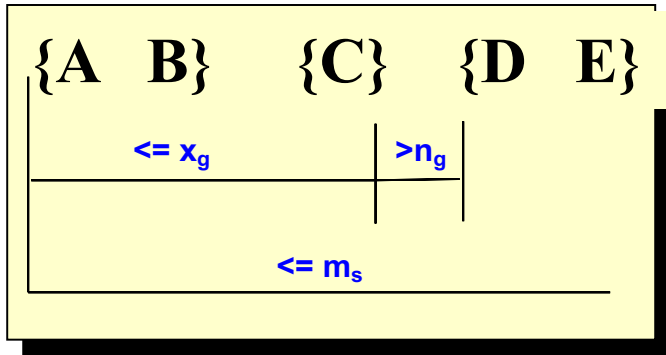
Sequential pattern	Support
a	100 %
b	100 %
d	50 %
a → a	50 %
a → b	75 %
a → d	50 %
b → a	50 %
a → a → b	50 %

Timing Constraints

- Motivation by examples:
- Sequential Pattern {milk} → {cookies}
 - It might suggest that cookies are bought to better enjoy milk
 - Yet, we might obtain it even if all customers buy milk and **after 6 months** buy cookies, in which case our interpretation is wrong
- {cheese A} → {cheese B}
 - Does it mean that buying and eating cheese A induces the customer to try also cheese B (e.g. by the same brand)?
 - Maybe, yet if they are bought within 20 minutes it is like that they were to be bought together (and the customer forgot it)
- {buy PC} → {buy printer} → {ask for repair}
 - Is it a good or bad sign?
 - It depends on how much time the whole process took:
 - Short time => issues, Long time => OK, normal life cycle

Timing Constraints

- Define 3 types of constraint on the instances to consider
 - E.g. ask that the pattern instances last no more than 30 days



x_g : max-gap



Each element of the pattern instance must be **at most** x_g time after the previous one

n_g : min-gap



Each element of the pattern instance must be **at least** n_g time after the previous one

m_s : maximum span



The overall duration of the pattern instance must be at most m_s

$x_g = 2, n_g = 0, m_s = 4$



consecutive elements at most distance 2 & overall duration at most 4 time units

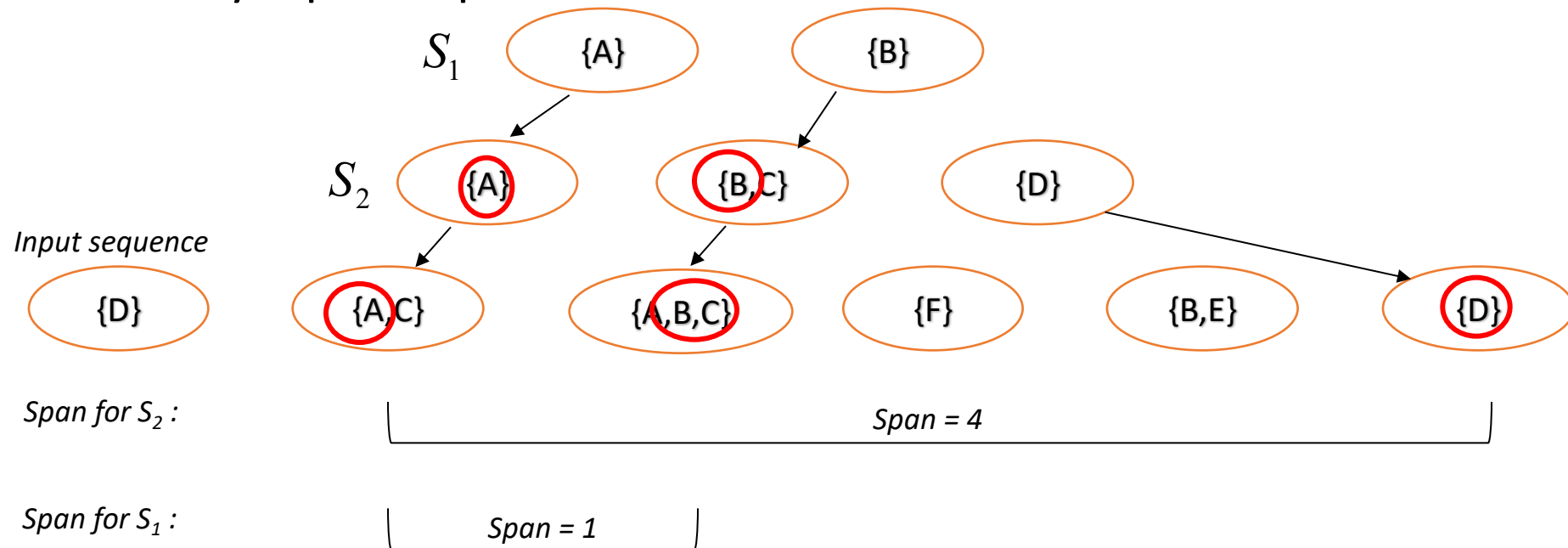
Data sequence	Subsequence	Contain?
$\langle \{2,4\} \{3,5,6\} \{4,7\} \{4,5\} \{8\} \rangle$	$\langle \{6\} \{5\} \rangle$	
$\langle \{1\} \{2\} \{3\} \{4\} \{5\} \rangle$	$\langle \{1\} \{4\} \rangle$	
$\langle \{1\} \{2,3\} \{3,4\} \{4,5\} \rangle$	$\langle \{2\} \{3\} \{5\} \rangle$	
$\langle \{1,2\} \{3\} \{2,3\} \{3,4\} \{2,4\} \{4,5\} \rangle$	$\langle \{1,2\} \{5\} \rangle$	

Mining Sequential Patterns with Timing Constraints

- Approach 1:
 - Mine sequential patterns without timing constraints
 - Postprocess the discovered patterns
 - Dangerous: might generate billions of sequential patterns to obtain only a few time-constrained ones
- Approach 2:
 - Modify GSP to directly prune candidates that violate timing constraints
 - Question:
 - Does Apriori principle still hold?

Apriori Principle with Time Constraints

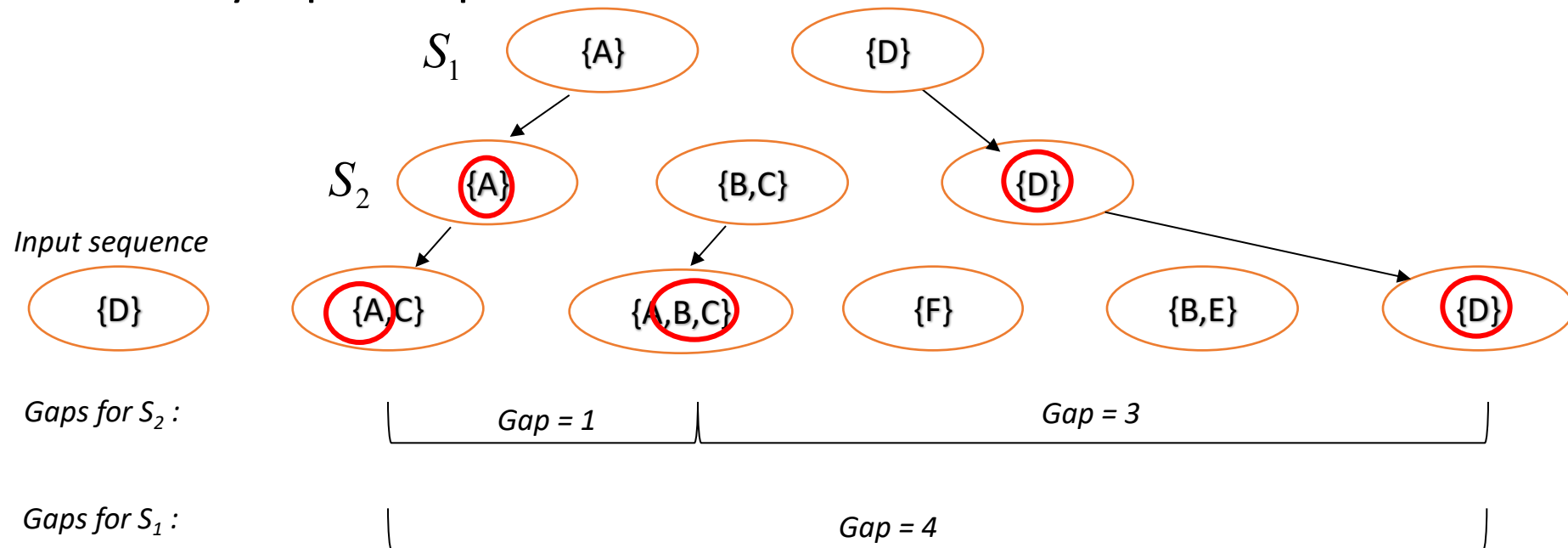
- **Case 1: max-span**
- **Intuitive check**
 - Does any input sequence that contains S2 will also contain S1 ?



- **When S1 has less elements, S1 span can (only) decrease**
 - If S2 span is OK, then also S1 span is OK

Apriori Principle with Time Constraints

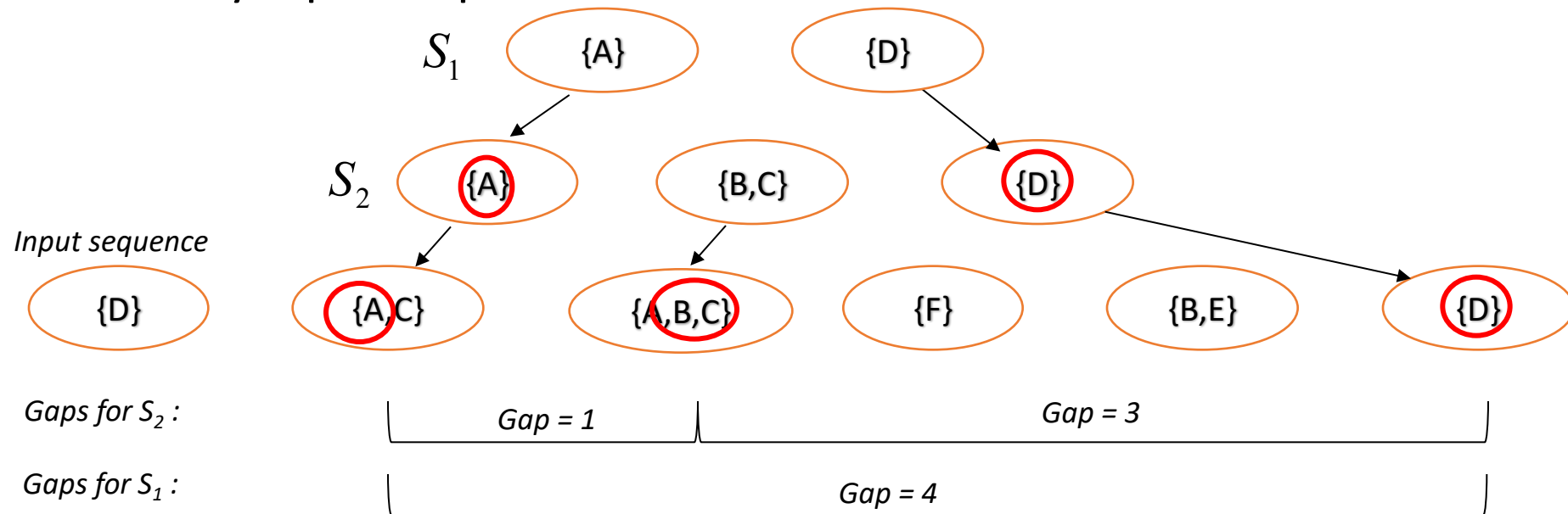
- **Case 2: min-gap**
- **Intuitive check**
 - Does any input sequence that contains S_2 will also contain S_1 ?



- **When S_1 has less elements, gaps for S_1 can (only) increase**
 - If S_2 gaps are OK, they are OK also for S_1

Apriori Principle with Time Constraints

- **Case 3: max-gap**
- **Intuitive check**
 - Does any input sequence that contains S_2 will also contain S_1 ?



- **When S_1 has less elements, gaps for S_1 can (only) increase**
 - Happens when S_1 has lost an internal element w.r.t. S_2
 - Even if S_2 gaps are OK, S_1 gaps might grow too large w.r.t. max-gap

X

Apriori Principle for Sequence Data

Object	Timestamp	Events
A	1	1,2,4
A	2	2,3
A	3	5
B	1	1,2
B	2	2,3,4
C	1	1, 2
C	2	2,3,4
C	3	2,4,5
D	1	2
D	2	3, 4
D	3	4, 5
E	1	1, 3
E	2	2, 4, 5

Suppose:

$x_g = 1$ (max-gap)

$n_g = 0$ (min-gap)

$m_s = 5$ (maximum span)

$minsup = 60\%$

$\langle \{2\} \{5\} \rangle$ support = 40%

but

$\langle \{2\} \{3\} \{5\} \rangle$ support = 60%

Problem exists because of max-gap constraint

No such problem if max-gap is infinite

Contiguous Subsequences

- s is a contiguous subsequence of

$$w = \langle e_1 \rangle \langle e_2 \rangle \dots \langle e_k \rangle$$

if any of the following conditions hold:

1. s is obtained from w by deleting an item from either e_1 or e_k
2. s is obtained from w by deleting an item from any element e_i that contains **at least 2 items**
3. s is a contiguous subsequence of s' and s' is a contiguous subsequence of w (recursive definition)

} *Key point: avoids internal "jumps"*

} *Not interesting for our usage*

- Examples: $s = \langle \{1\} \{2\} \rangle$

- is a contiguous subsequence of $\langle \{1\} \{2\} \{3\} \rangle$, $\langle \{1\} \{2\} \{3\} \{4\} \rangle$, and $\langle \{3\} \{4\} \{1\} \{2\} \{2\} \{3\} \{4\} \rangle$
- is not a contiguous subsequence of $\langle \{1\} \{3\} \{2\} \rangle$ and $\langle \{2\} \{1\} \{3\} \{2\} \rangle$

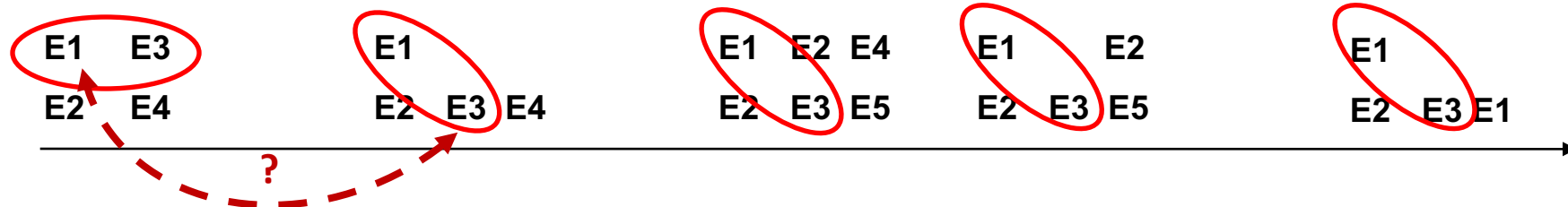
Modified Candidate Pruning Step

- Without maxgap constraint:
 - A candidate k -sequence is pruned if at least one of its $(k-1)$ -subsequences is infrequent
- With maxgap constraint:
 - A candidate k -sequence is pruned if at least one of its **contiguous** $(k-1)$ -subsequences is infrequent
 - Remark: the “pruning power” is now reduced
 - Less subsequences to test for “killing” the candidate

Other kinds of patterns for sequences

- In some domains, we may have only one very long time series
 - Example:
 - monitoring network traffic events for attacks
 - monitoring telecommunication alarm signals
- Goal is to find frequent sequences of events in the time series
 - Now we have to count “instances”, but which ones?
 - This problem is also known as frequent episode mining

Pattern: <E1> <E3>



References

- Sequential Pattern Mining. Chapter 7.
Introduction to Data Mining.

