An Incrementally Maintainable Index for Approximate Lookups in Hierarchical Data

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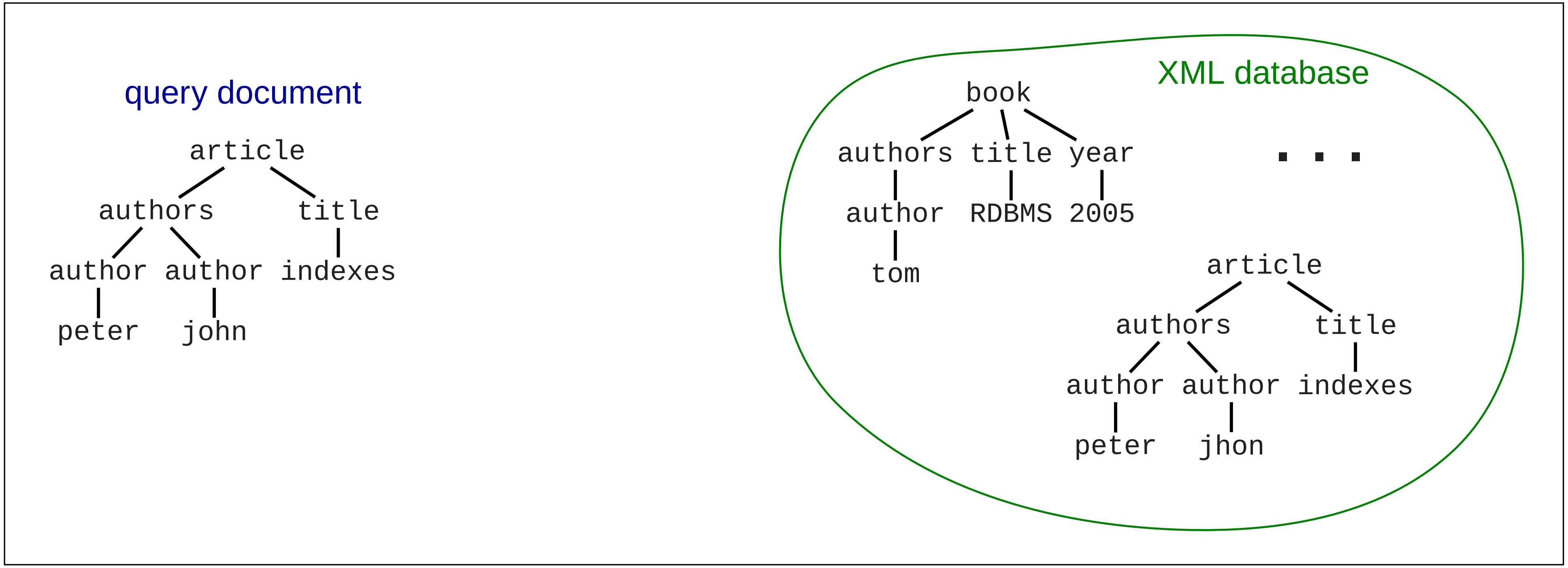
www.inf.unibz.it

[a] Supported by the Municipality of Bozen-Bolzano.

Approximate Lookups in XML Database



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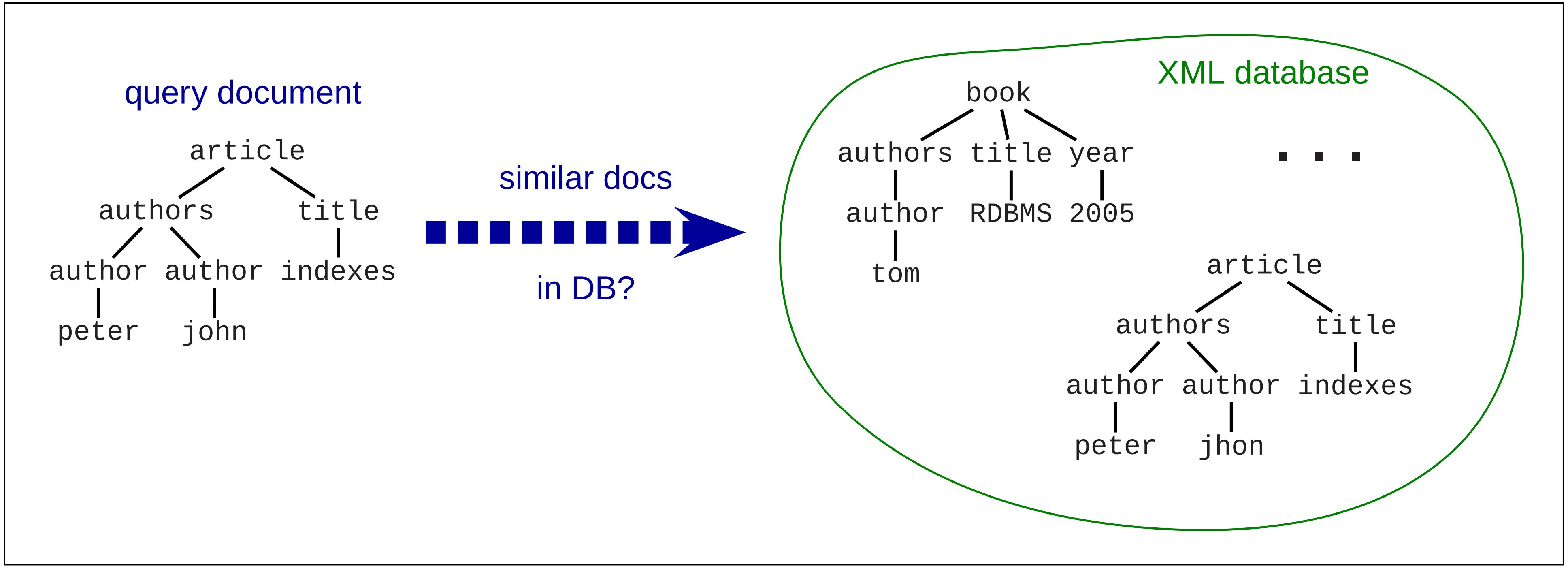

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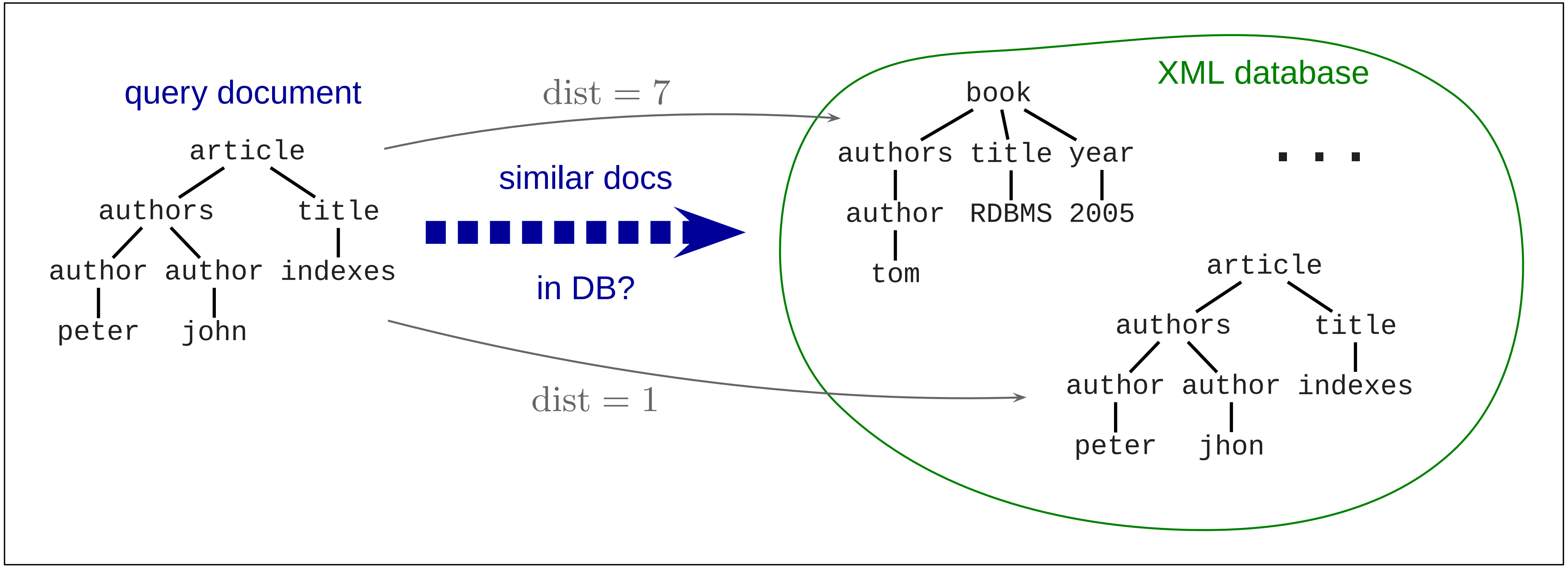

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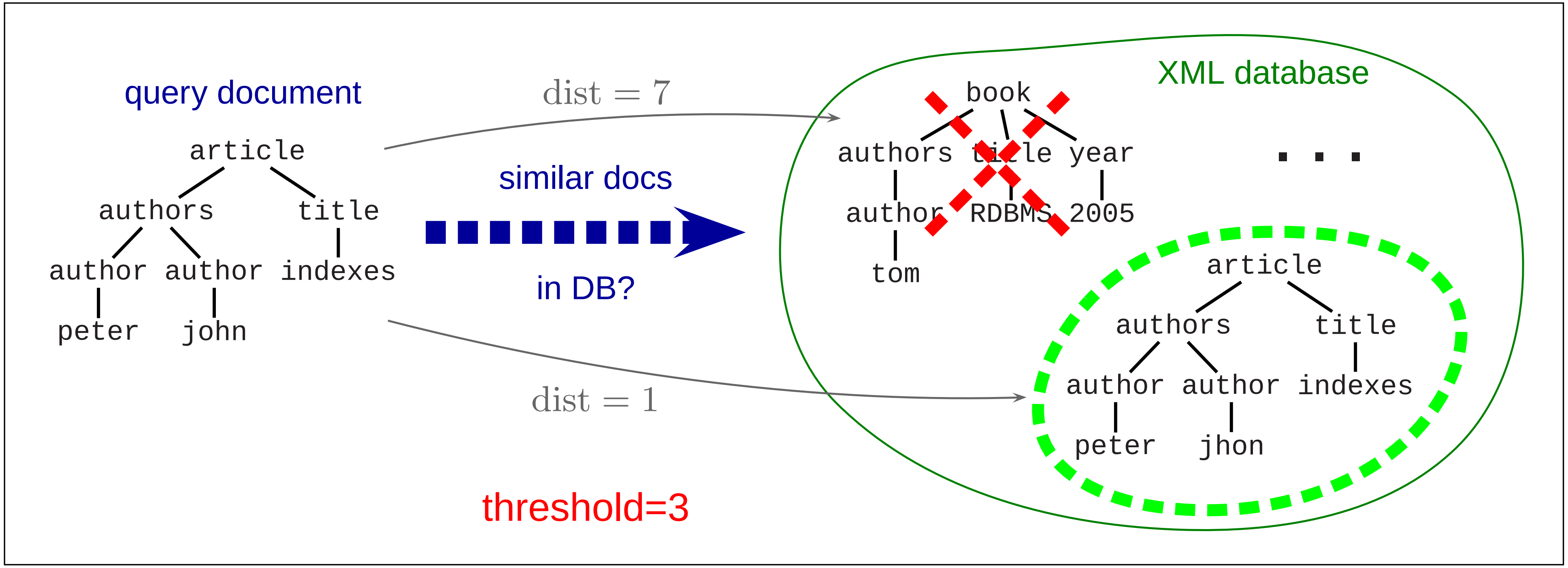

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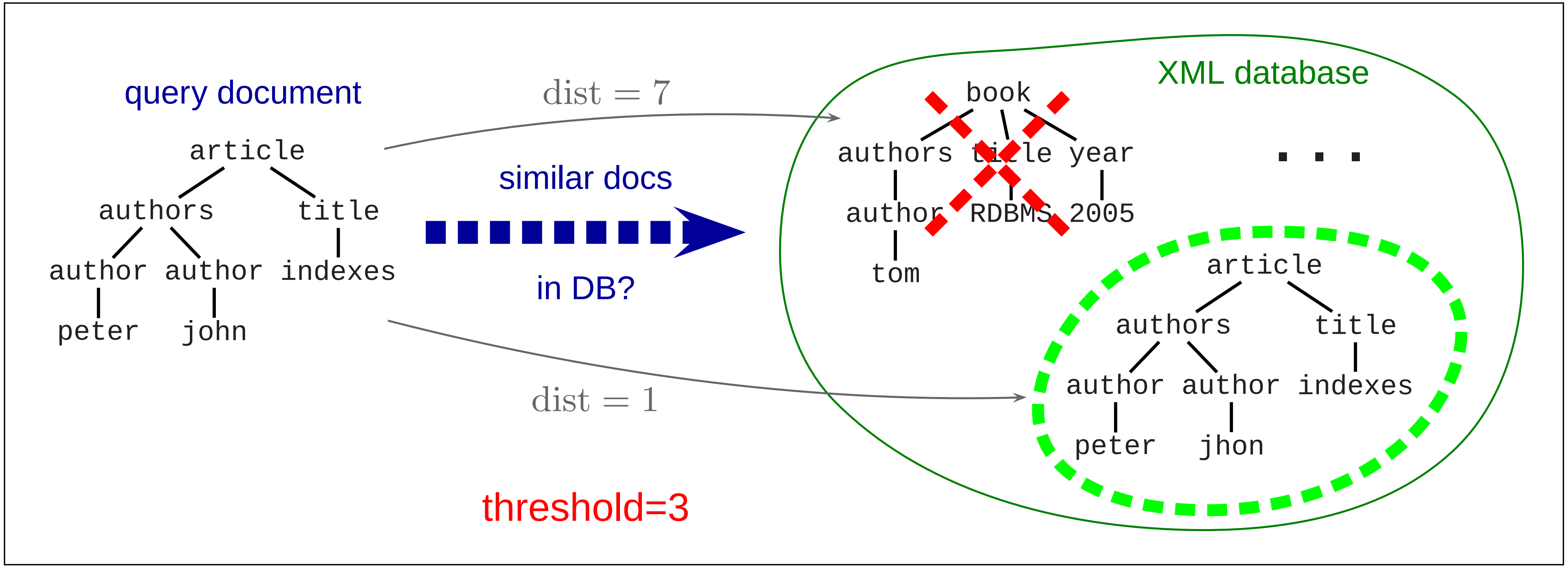

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- scan whole DB
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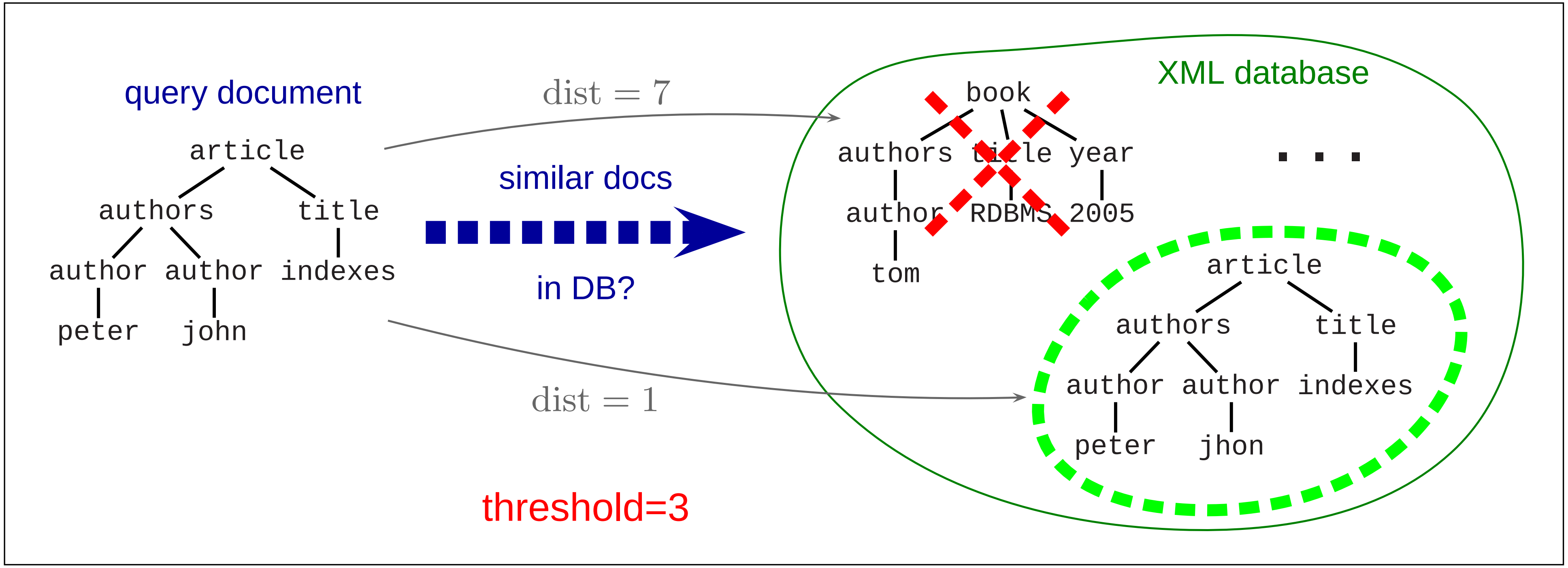

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  1. compute **distance** between the query document and each document in DB
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- Very **expensive**
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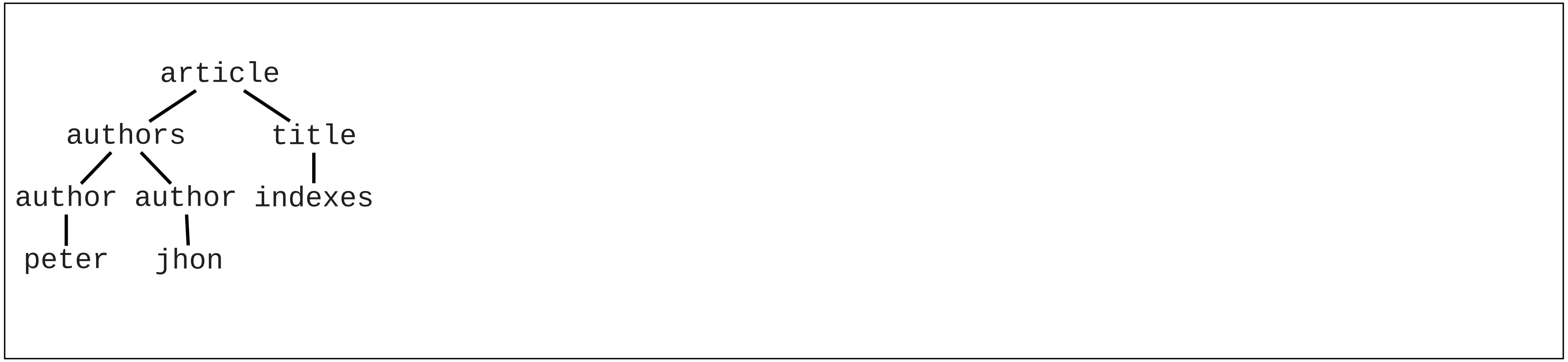
- **Index** for approximate lookups

Need for Incremental Updates

- ☞ **Documents** in database **change**



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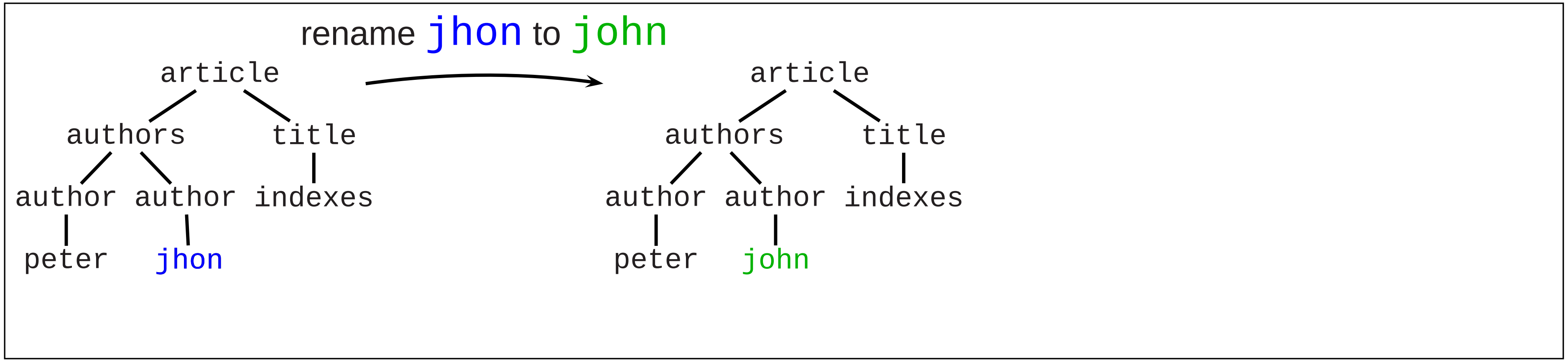

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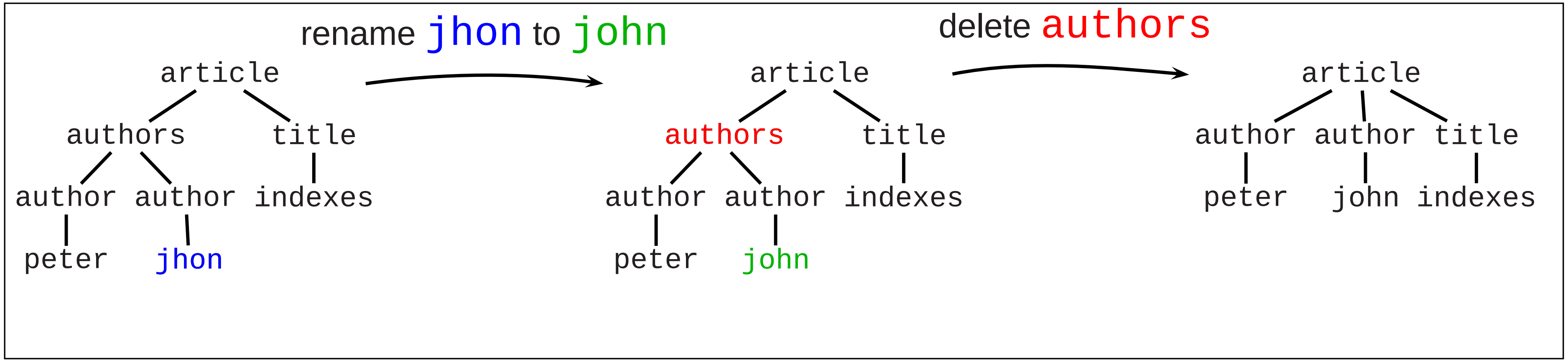

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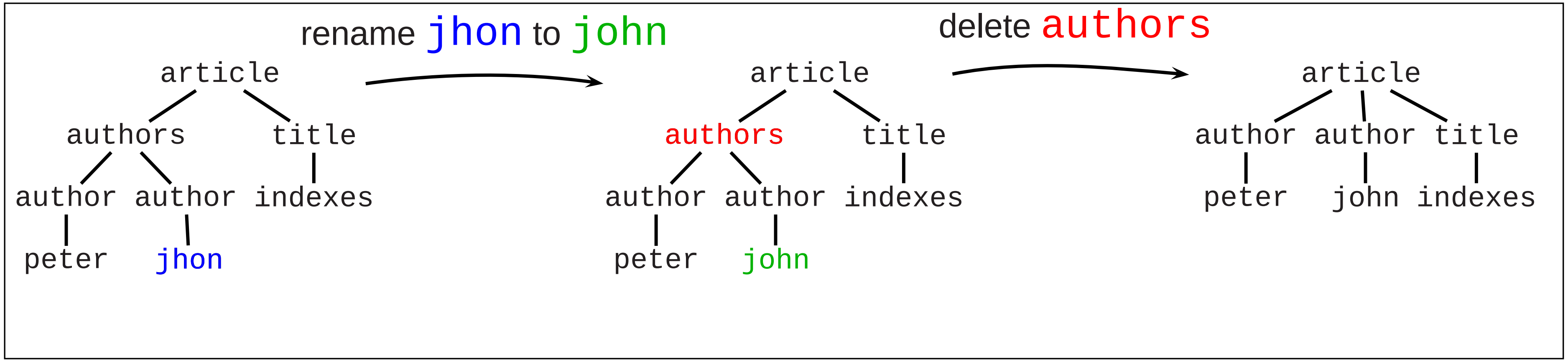

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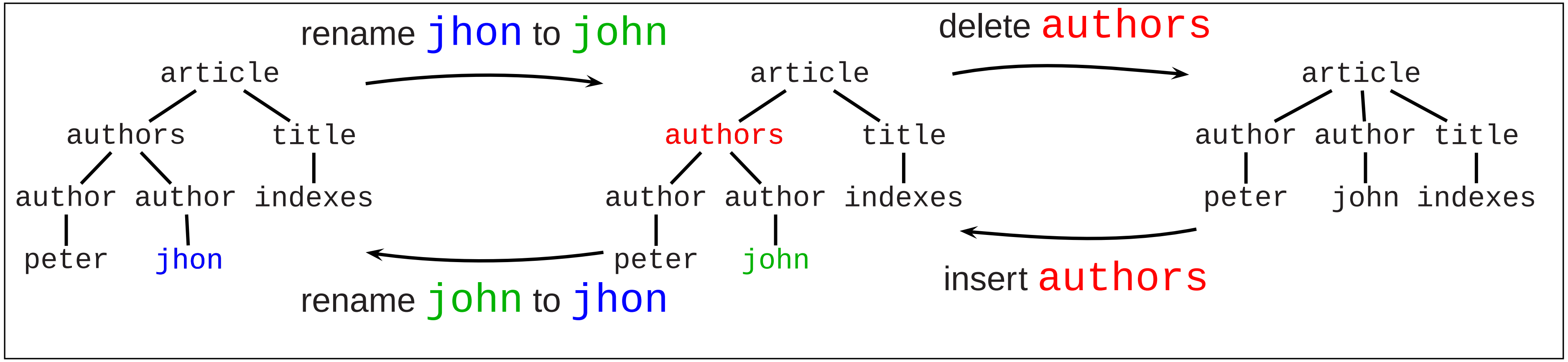

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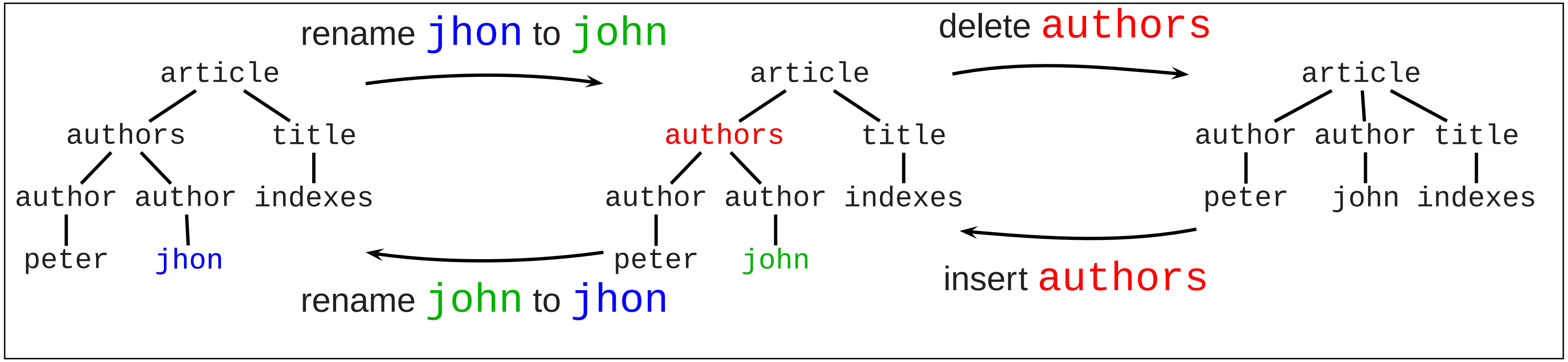

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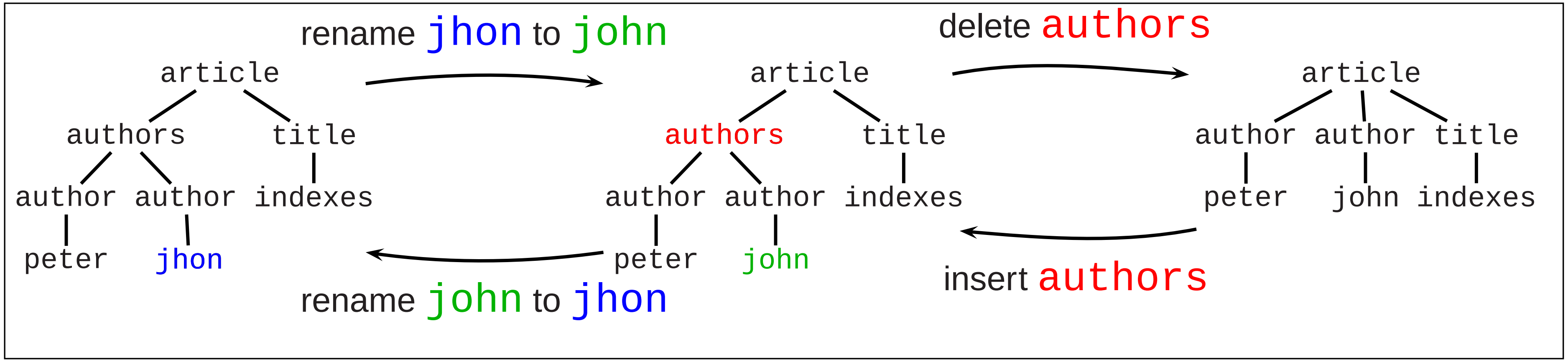

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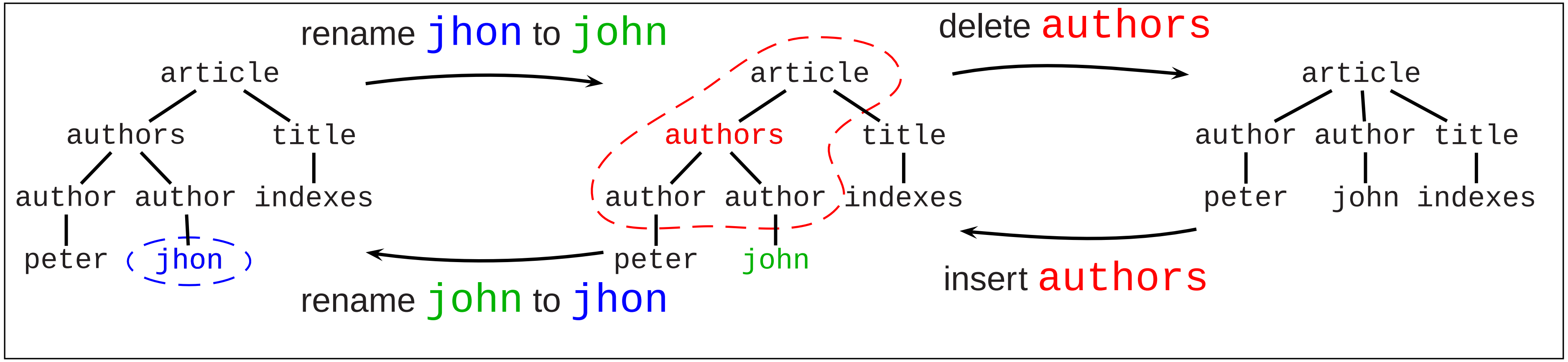

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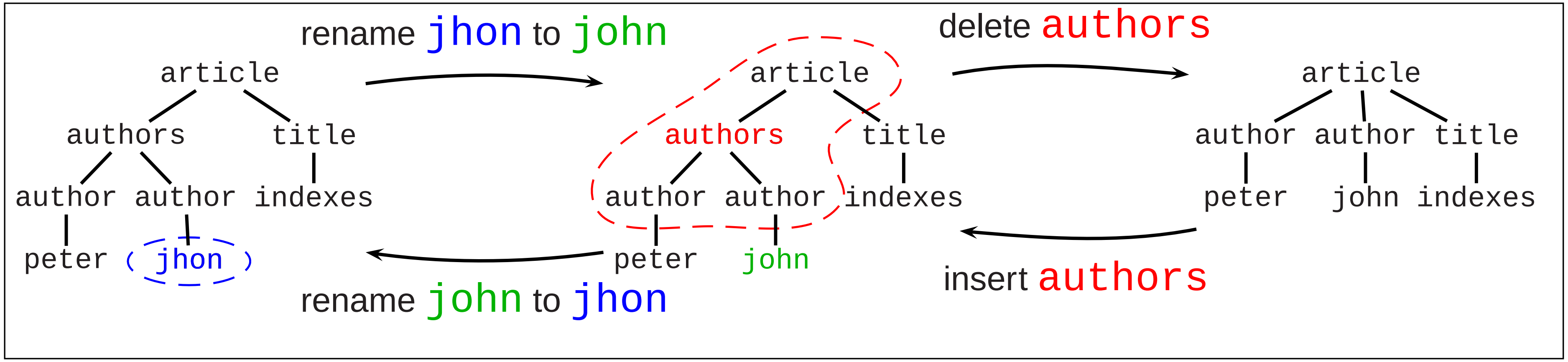

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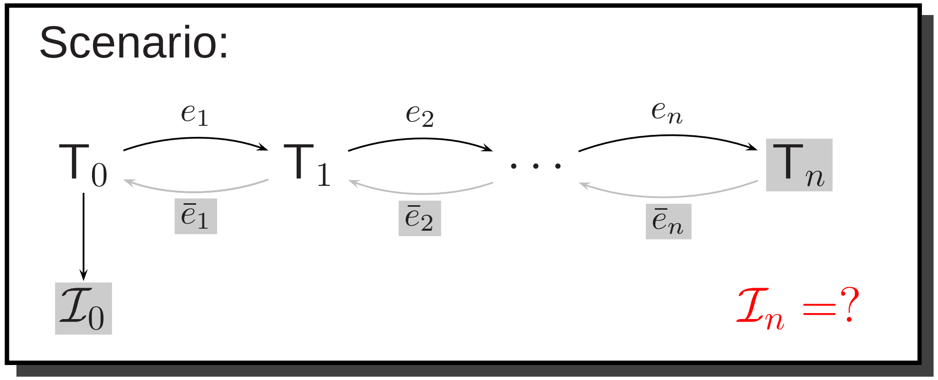
- Only **small subtrees change...**
- **Solution:** incrementally **update changing parts** in index

Problem Definition



- **Update index** based on
  - old index $\mathcal{I}_0$
  - log of inverse edit operations $(\bar{e}_1, \ldots, \bar{e}_n)$
  - resulting tree T_n
- Do **not** compute $\mathcal{I}_n$ **from scratch**.
- Do **not** compute **intermediate trees**.

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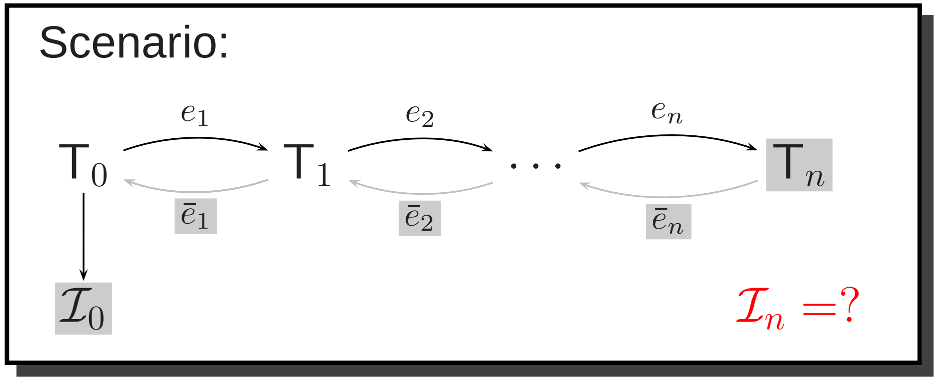

- Example:
  - index for DBLP
  - 1000 updates
  - incrementally update index!

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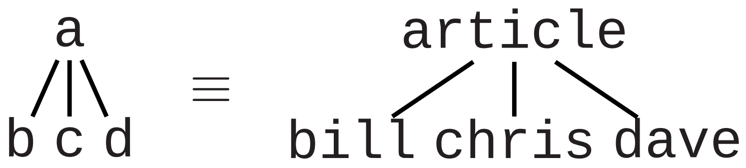
Running Example

Example tree:



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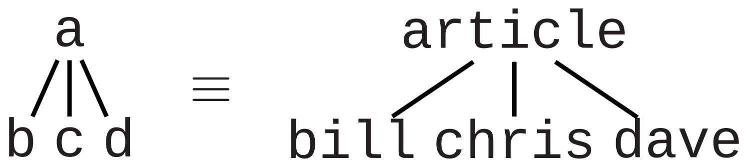
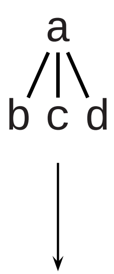


Example Scenario:

T_0



$\mathcal{I}_0$

0103, 0132,
0124, 0140
1300, 1200,
1400

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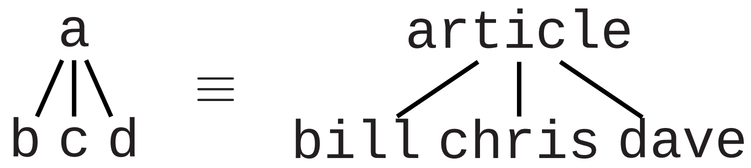

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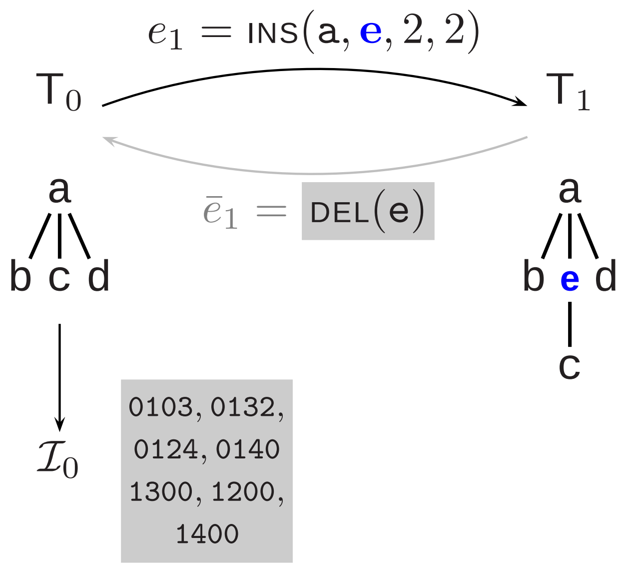

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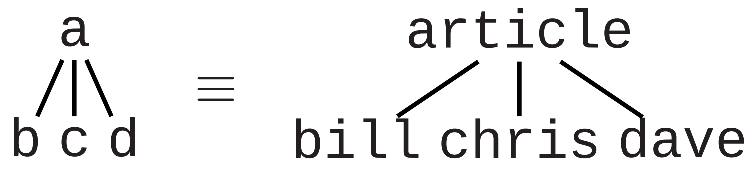

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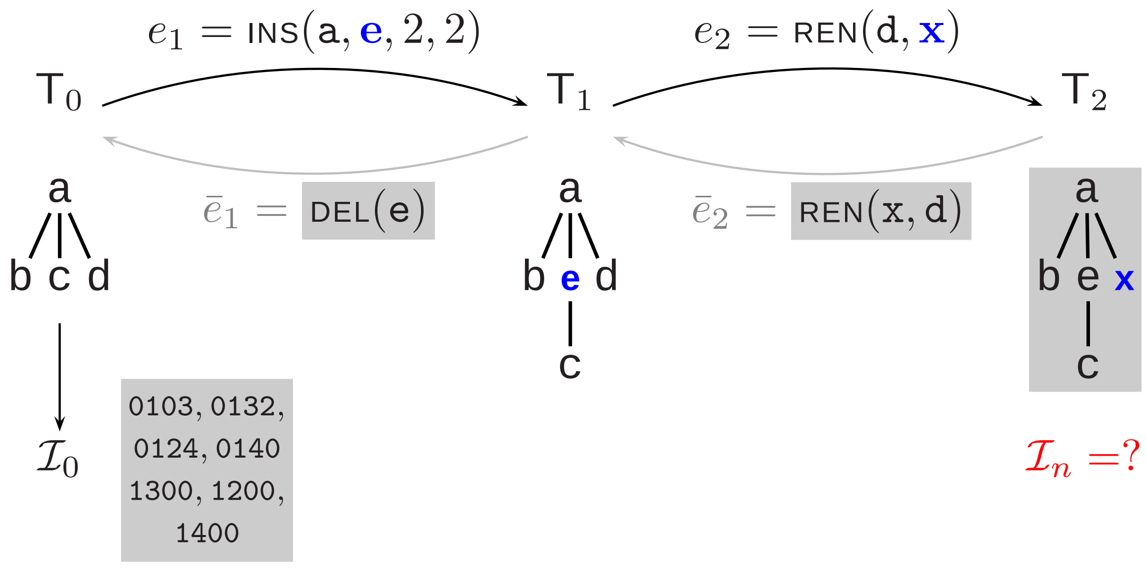
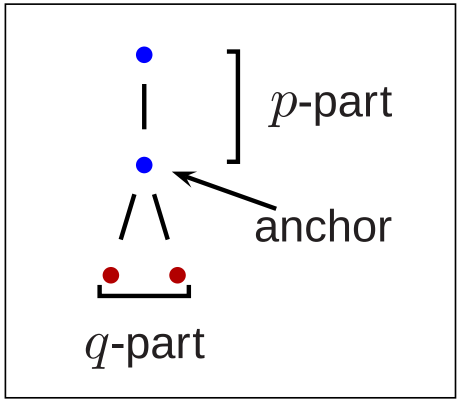


Splitting Tree into pq-Grams

☞ pq-Gram pattern:



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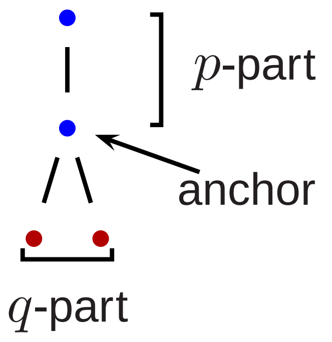
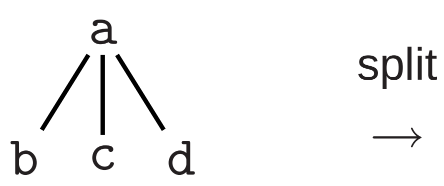


(1) Splitting the tree into 2,2-grams:

Tree T

Profile **P**



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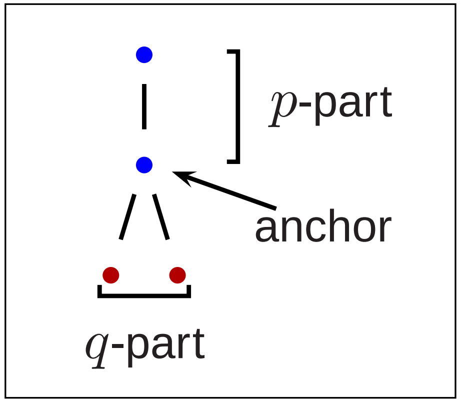

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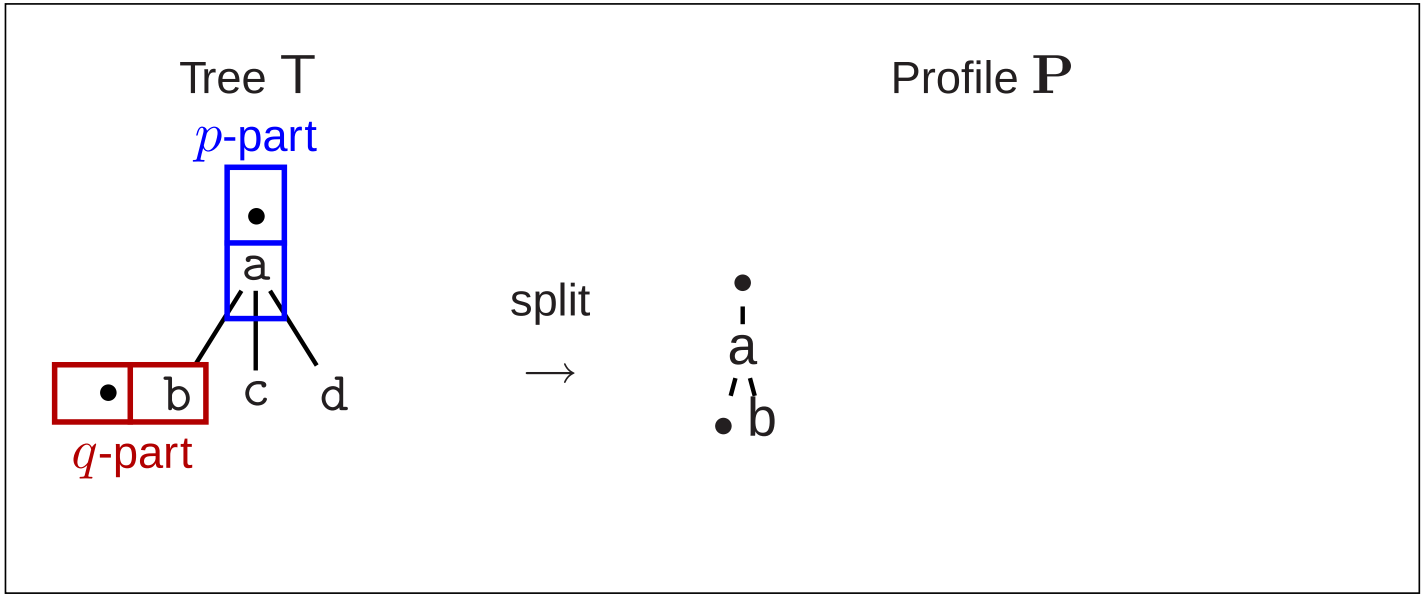

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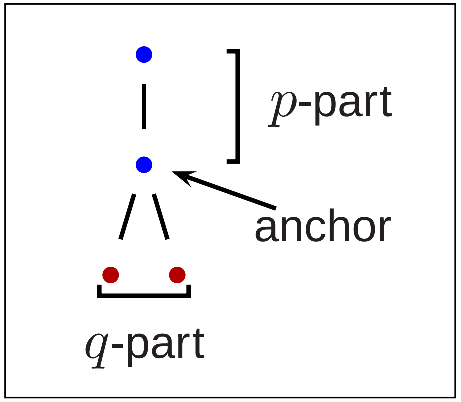

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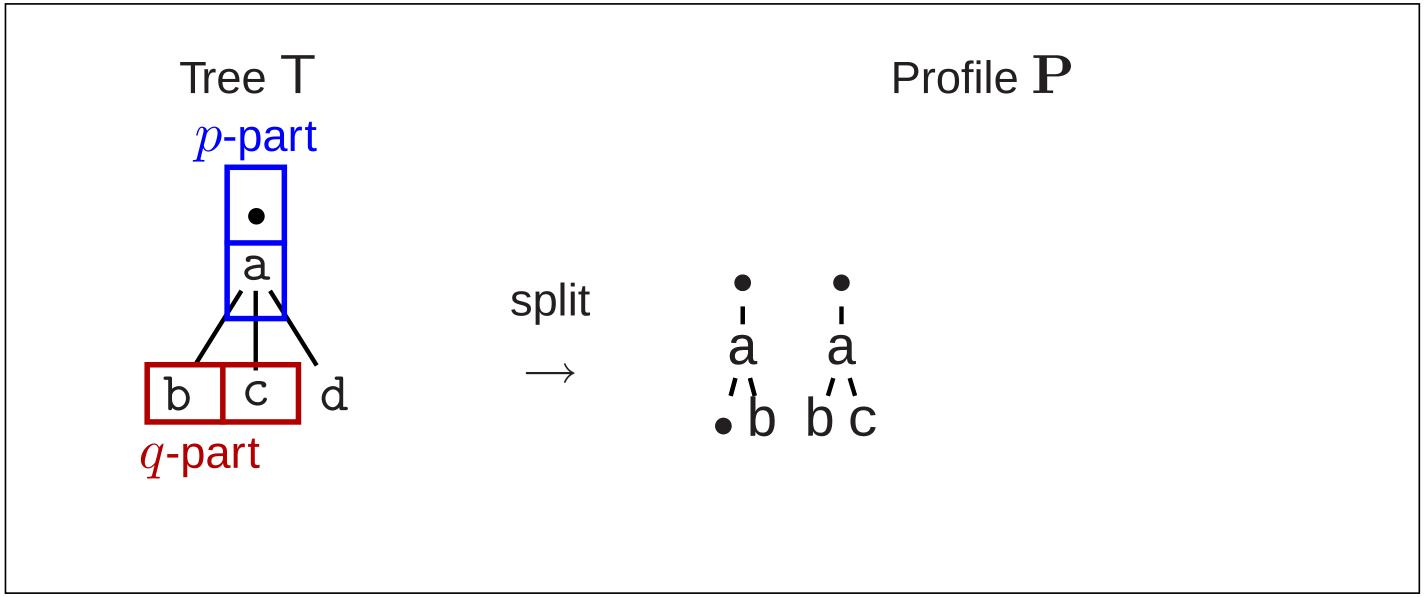

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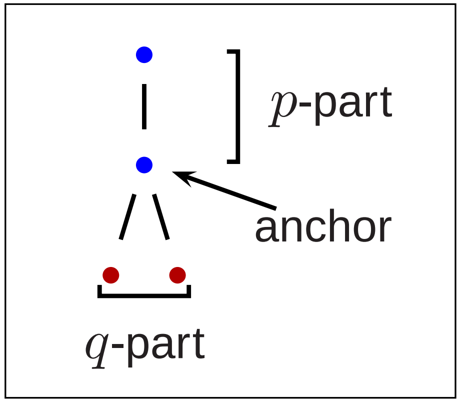

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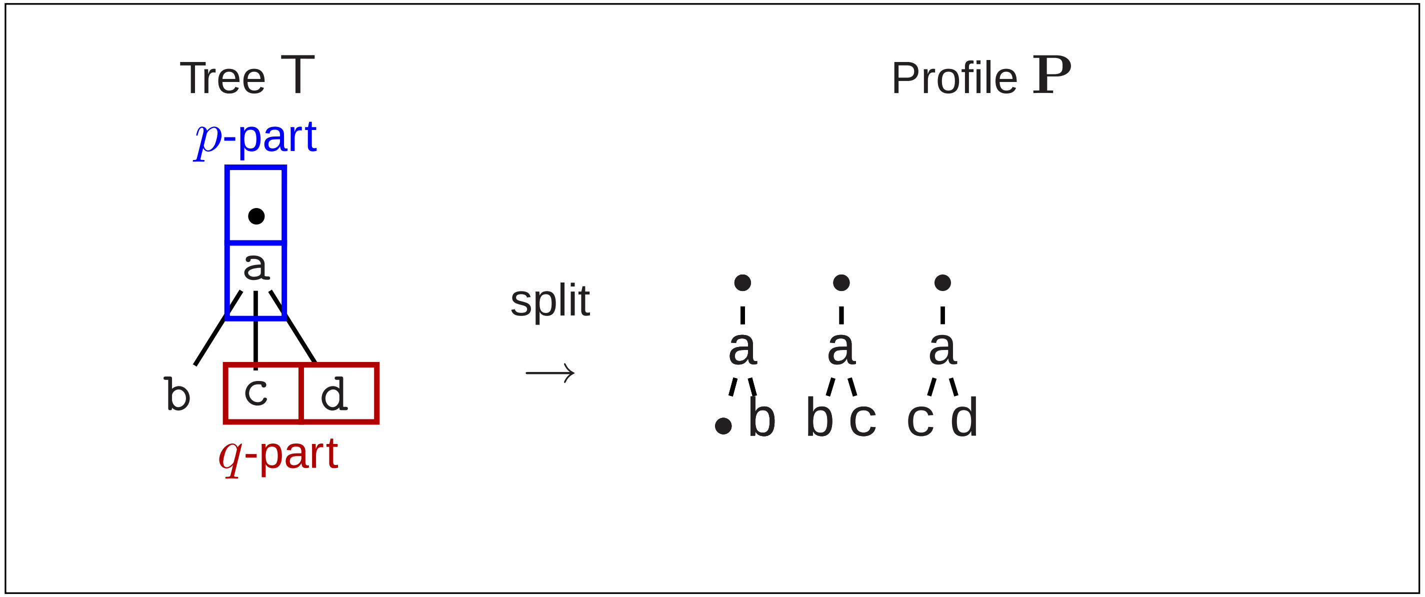

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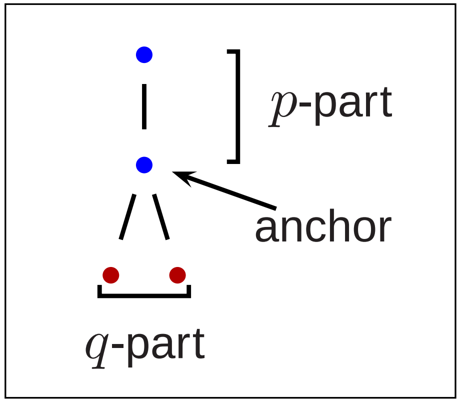

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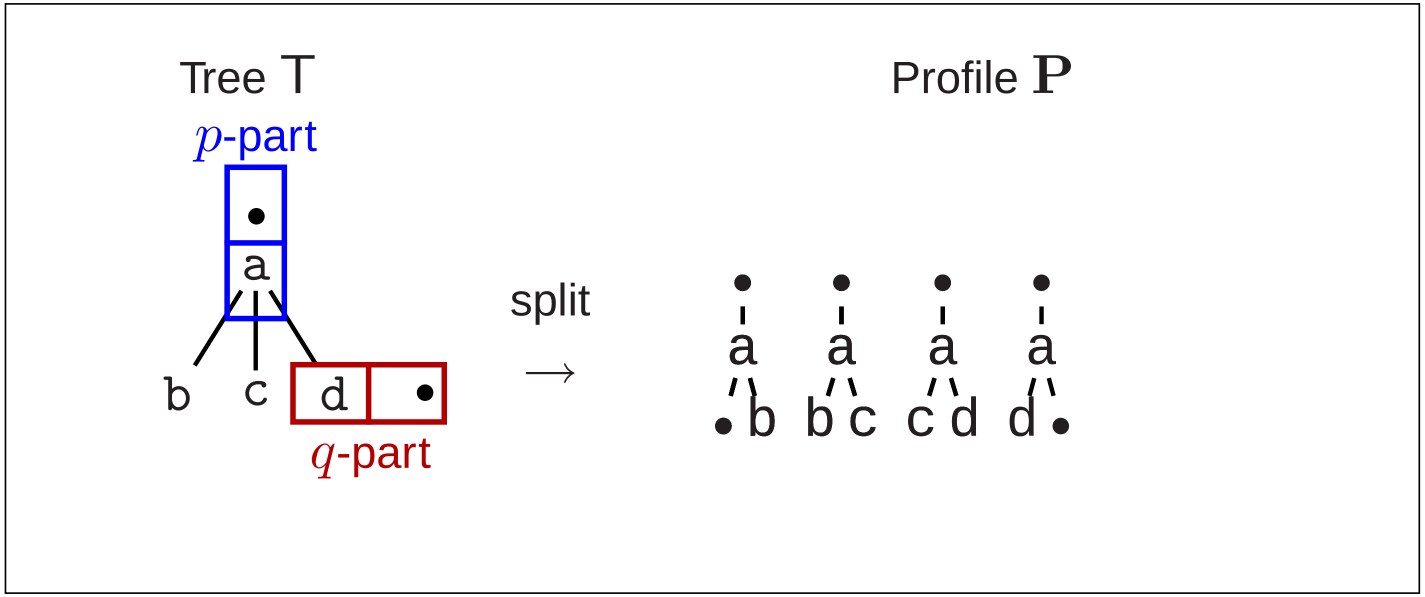

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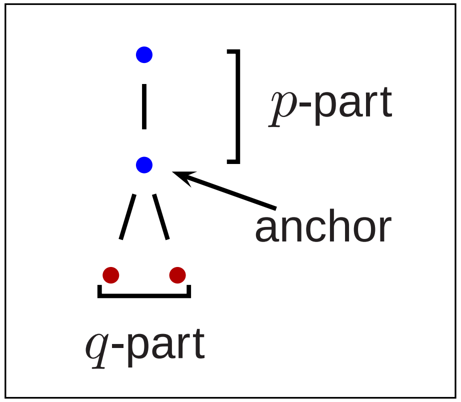

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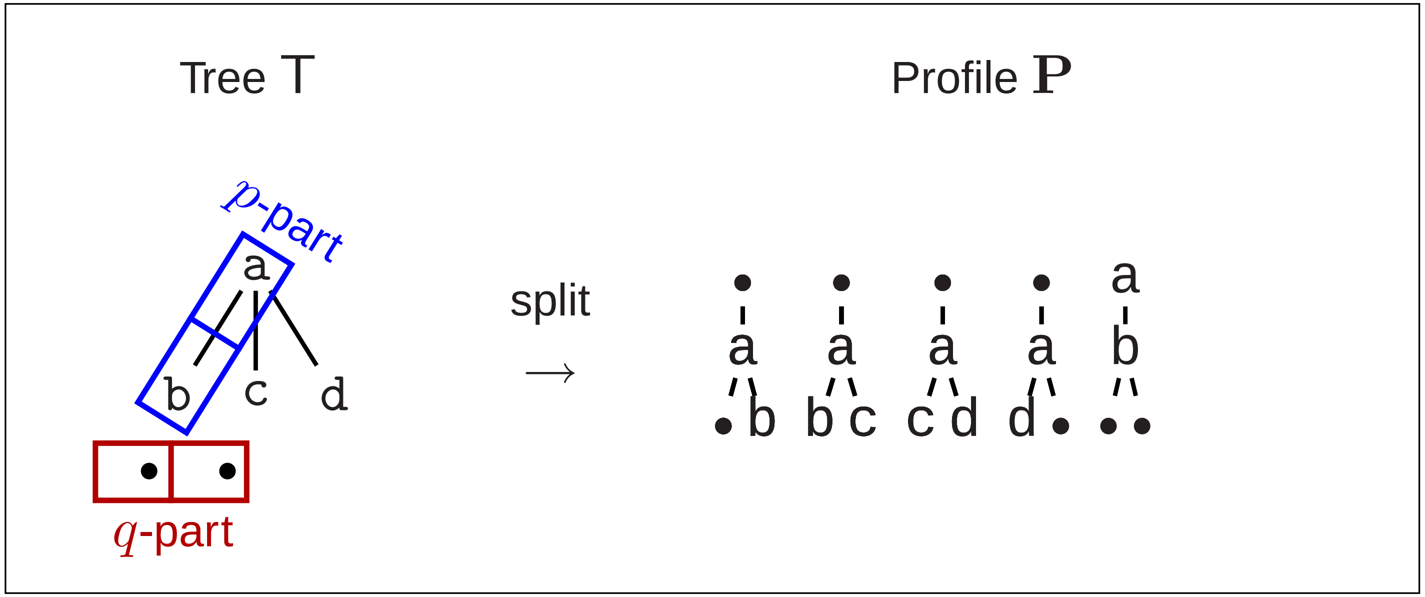

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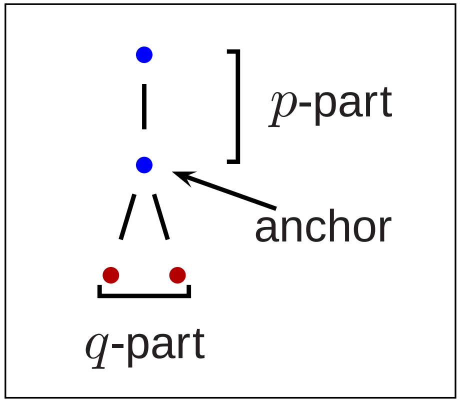

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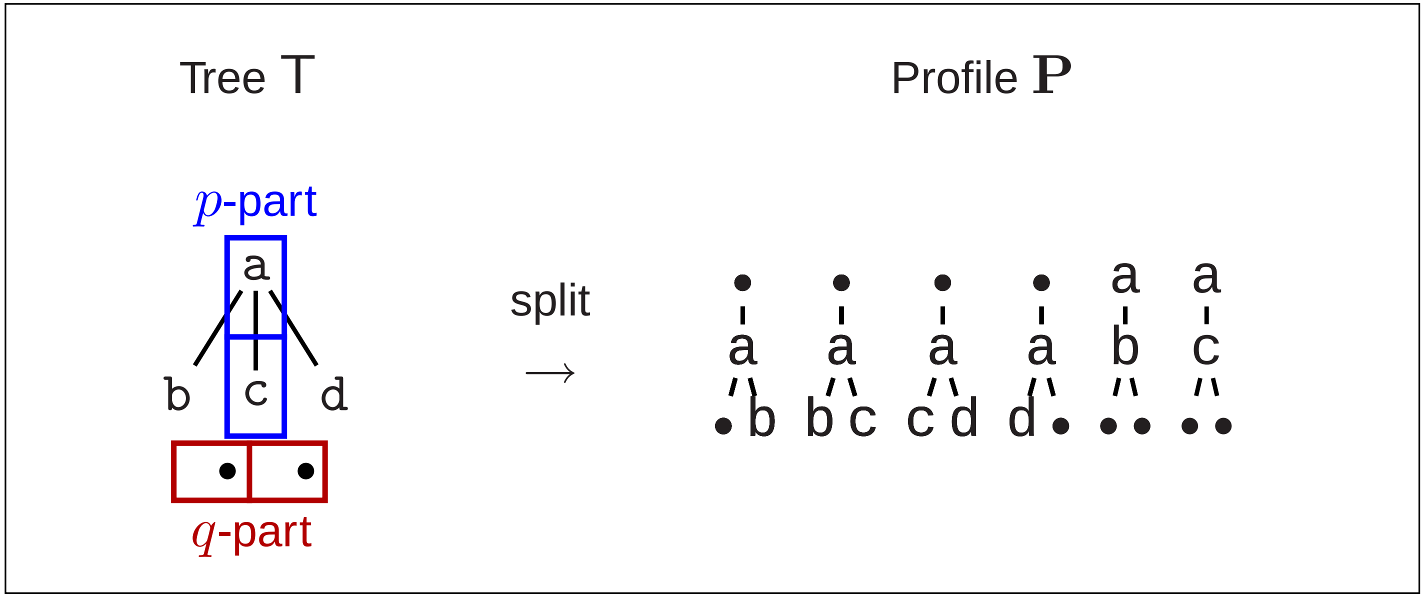

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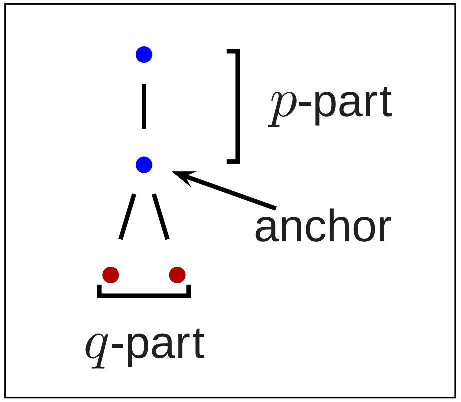

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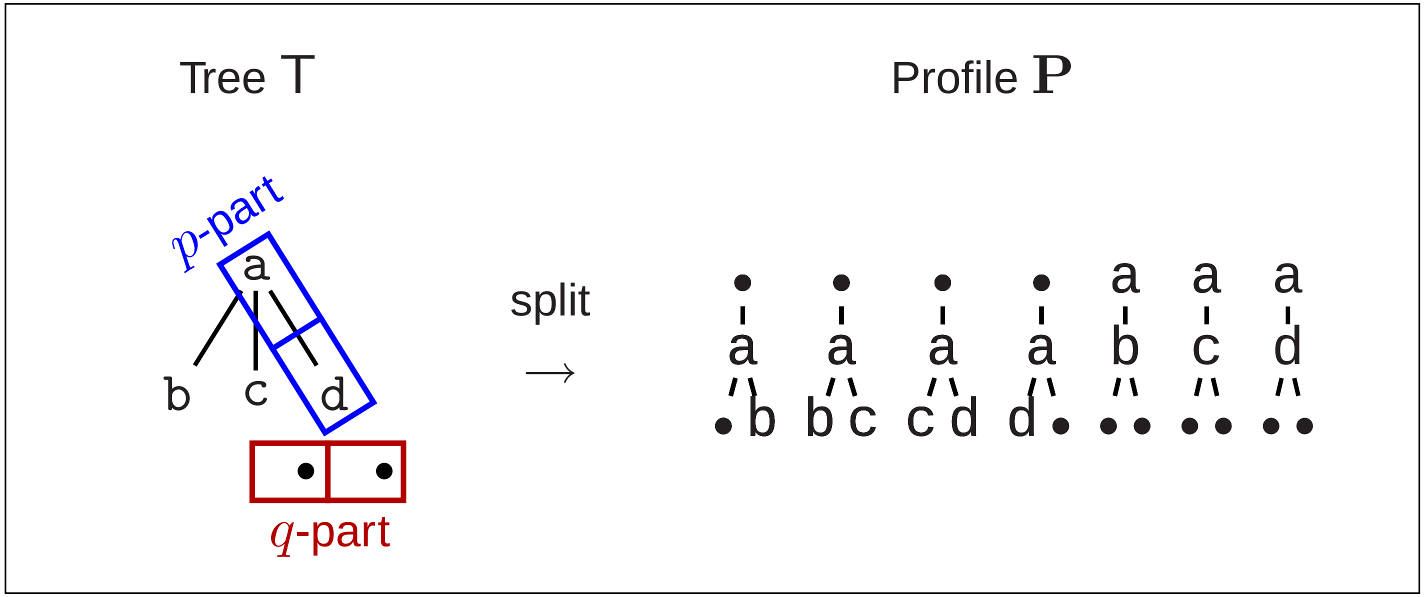

Serialization and Hashing

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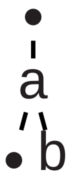

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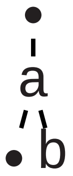

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Hash Function $\lambda()$:

node n	λ(n)
•	0
a	1
b	3
c	2
d	4

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☞ Note: •a•b stands for (•, `article`, •, `bill`)

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$(\bullet,$ `article`$, \bullet,$ `bill`$)$ $\longrightarrow$ 0103

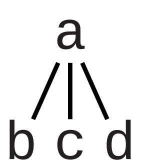
$(\bullet,$ `article`, `bill`, `chris`$)$ $\longrightarrow$ 0132

...

Overview

Overview

Tree T



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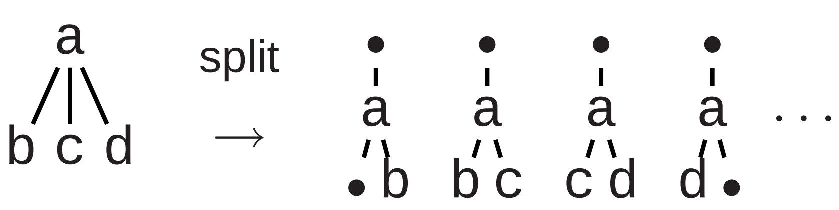
Tree T

Profile $\mathbf{P}$



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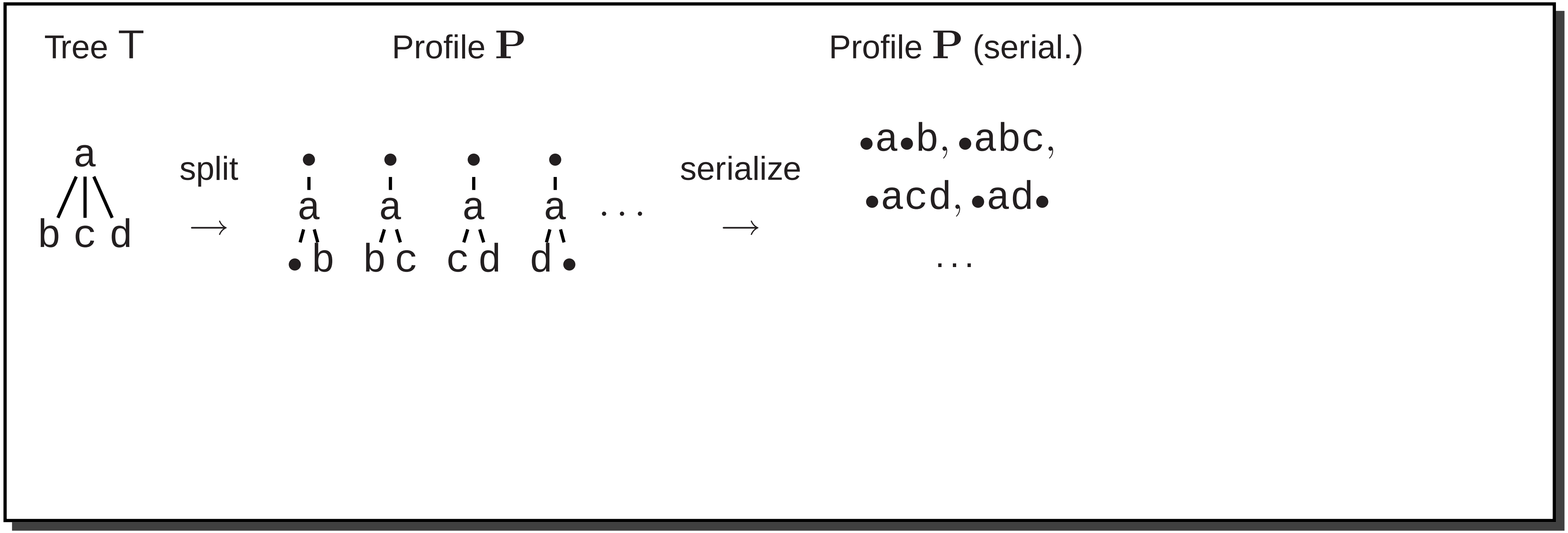
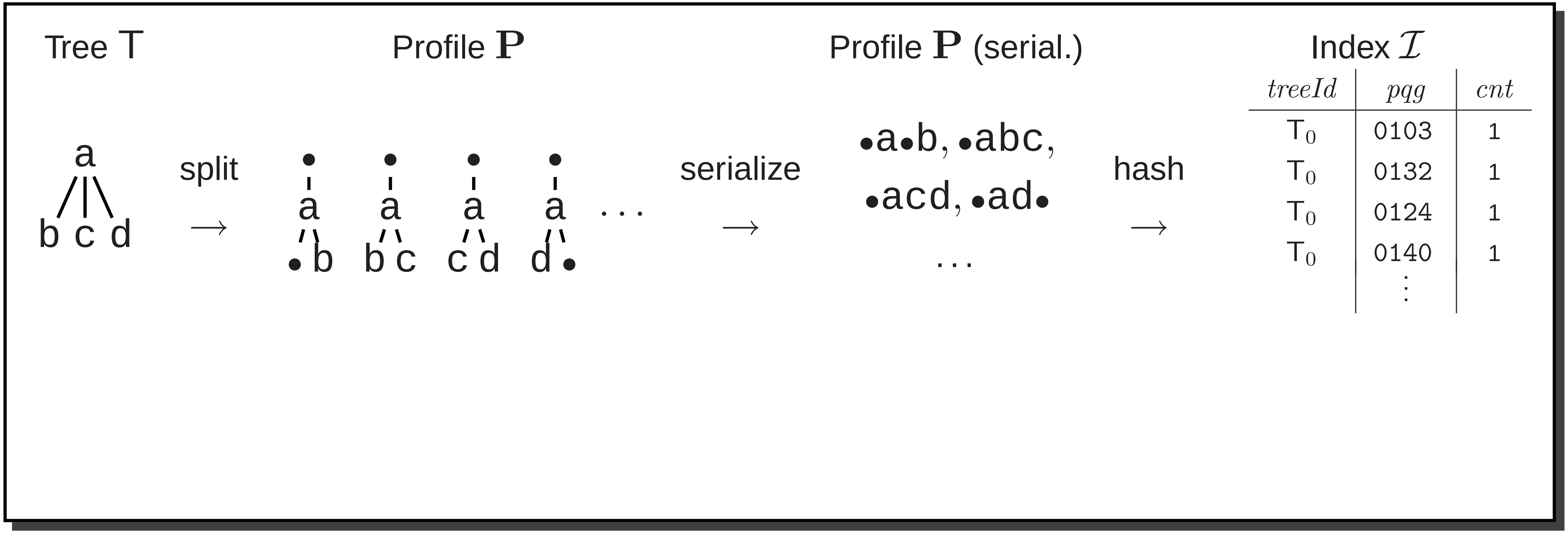


Tree T
Profile P
Profile P (serial.)
a
b c d
split
→
•
a
• b
b c
c d
d •
. . .
serialize
→
•a•b, •abc,
•acd, •ad•
. . .

Overview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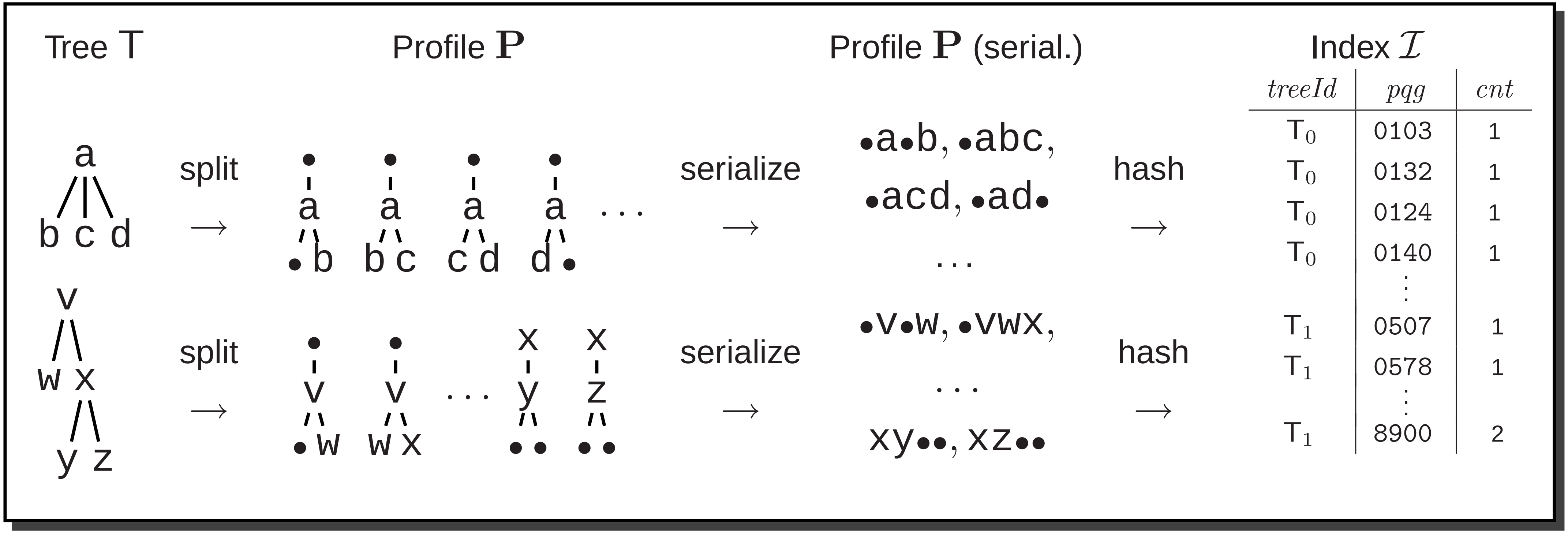
Profile P (serial.)
Index $\mathcal{I}$
a
b c d
split
→
• a • b
a b c
a c d
a d •
. . .
serialize
→
•a•b, •abc,
•acd, •ad•
. . .
hash
→
treeId pqg cnt
T0 0103 1
T0 0132 1
T0 0124 1
T0 0140 1
⋮

Overview


Tree T
Profile P
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Index I
split
serialize
hash
split
serialize
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•a•b, •abc,
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...
•v•w, •vwx,
...
xy••, xz••
treeId
pqg
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T0 0103 1
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T1 0507 1
T1 0578 1
T1 8900 2

Single Edit Step

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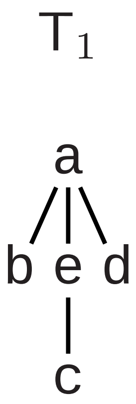

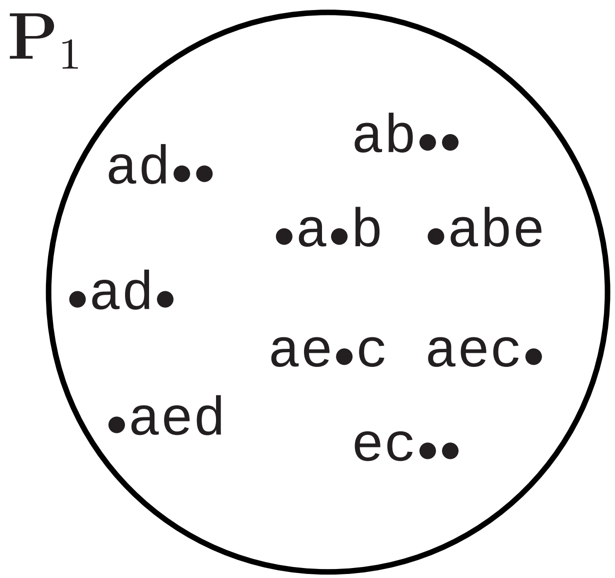

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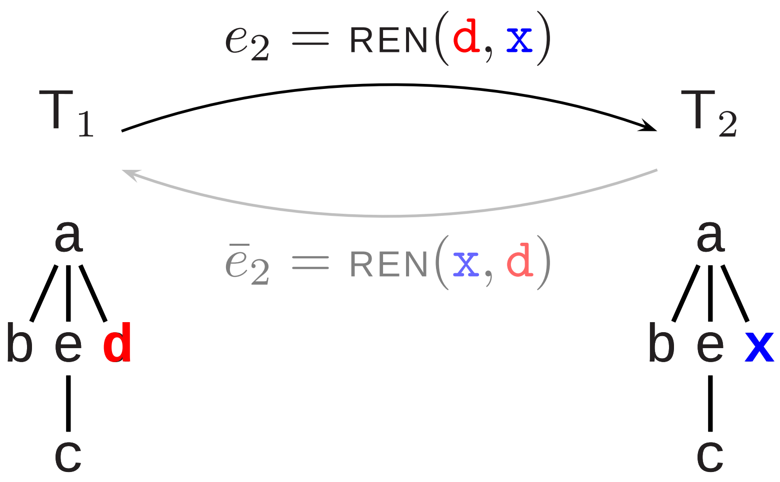
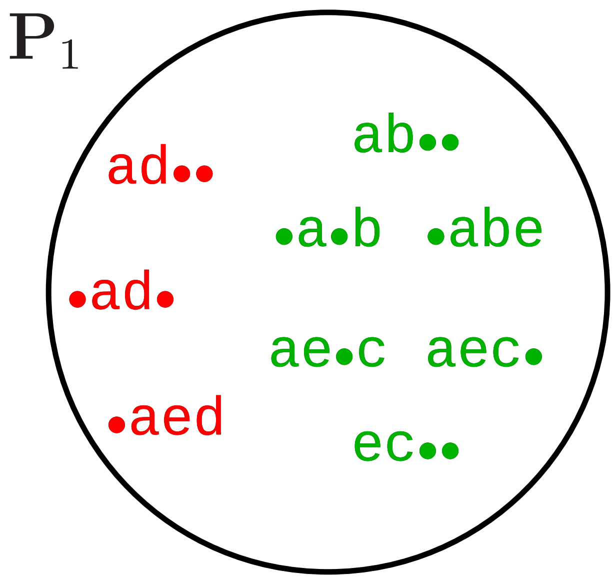
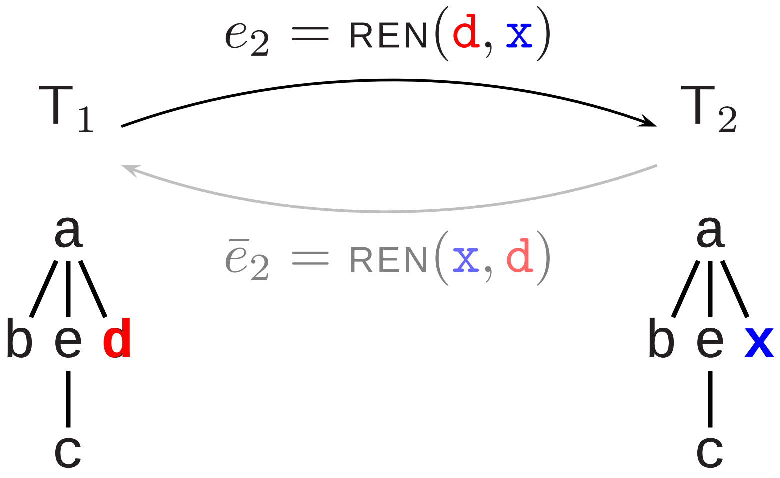
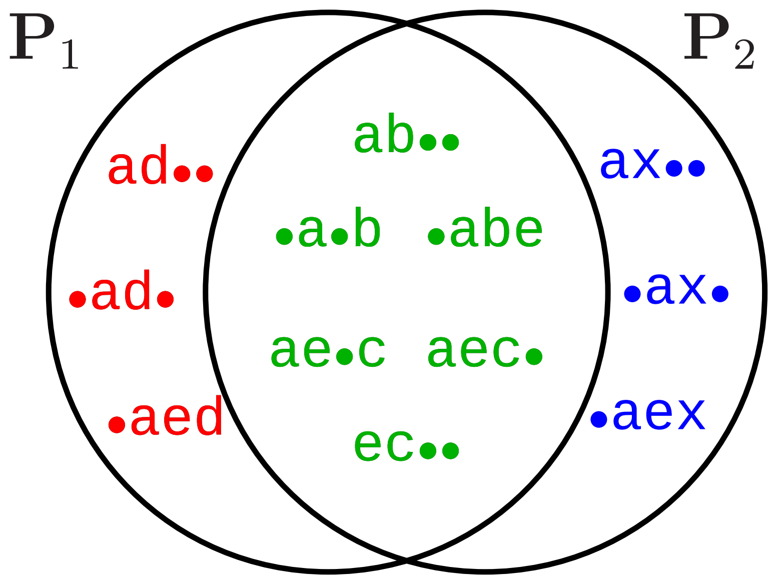


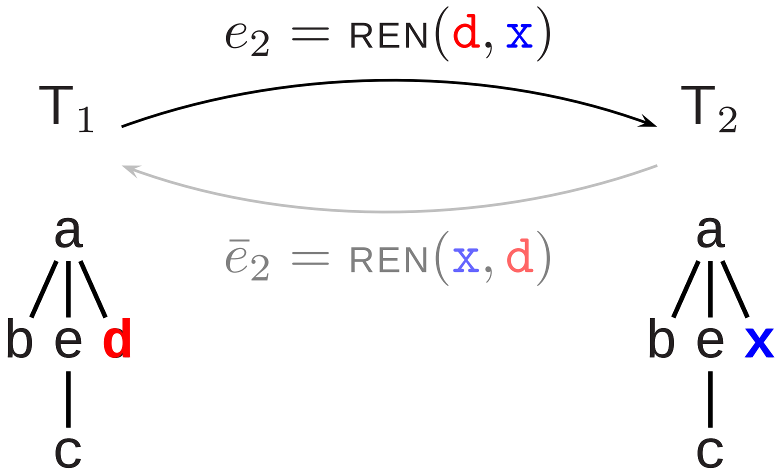


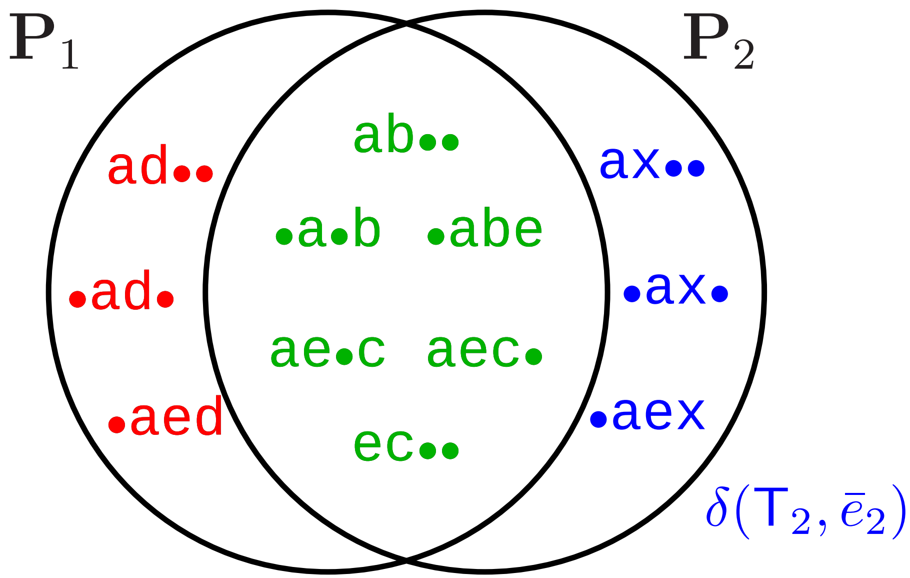
Single Edit Step





Single Edit Step

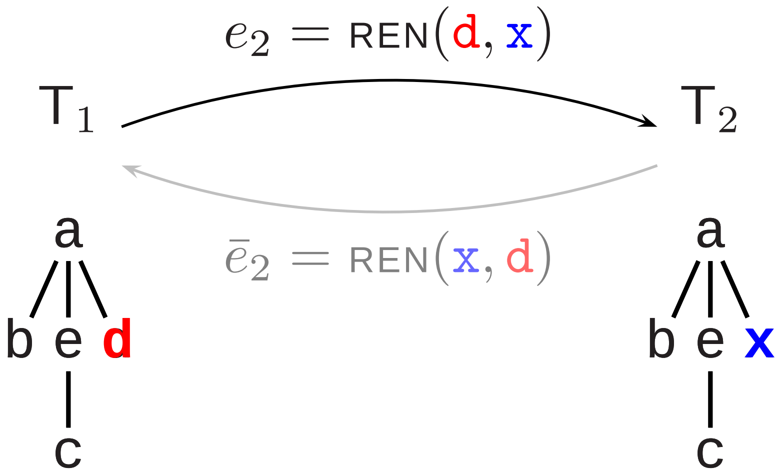


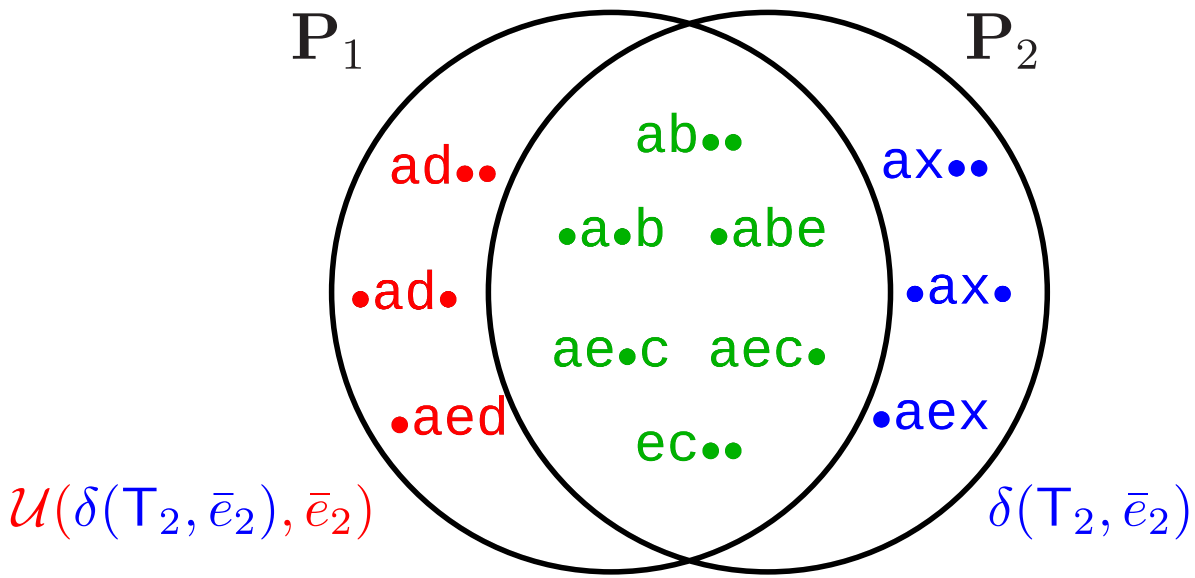


Delta Function (new pq-grams)

$$\delta(T_2, \bar{e}_2) = \begin{cases} \mathbf{P}_2 \setminus \mathbf{P}_1 & \text{if } \bar{e}_2 \text{ is defined on } T_2 \\ \emptyset & \text{otherwise} \end{cases}$$

Single Edit Step





Profile Update Function (old pq-grams)

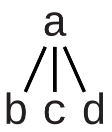
$$\mathcal{U}(\delta(T_2, \bar{e}_2), \bar{e}_2) = \mathbf{P}_1 \setminus \mathbf{P}_2$$

Delta Function (new pq-grams)

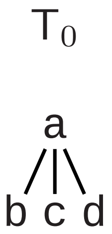
$$\delta(T_2, \bar{e}_2) = \begin{cases} \mathbf{P}_2 \setminus \mathbf{P}_1 & \text{if } \bar{e}_2 \text{ is defined on } T_2 \\ \emptyset & \text{otherwise} \end{cases}$$

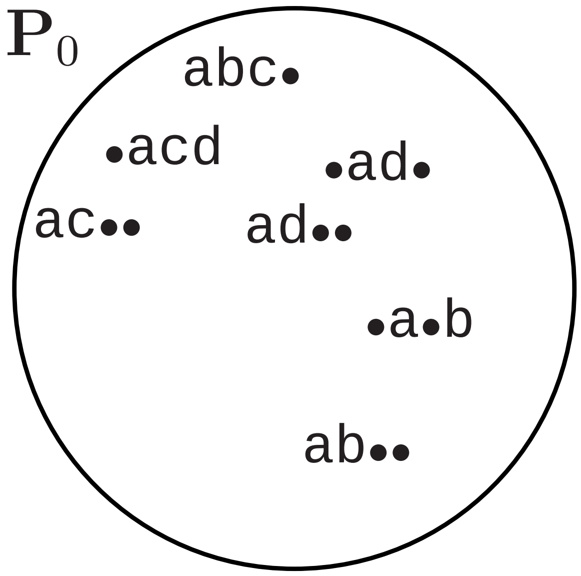
Multiple Edit Steps

T_0

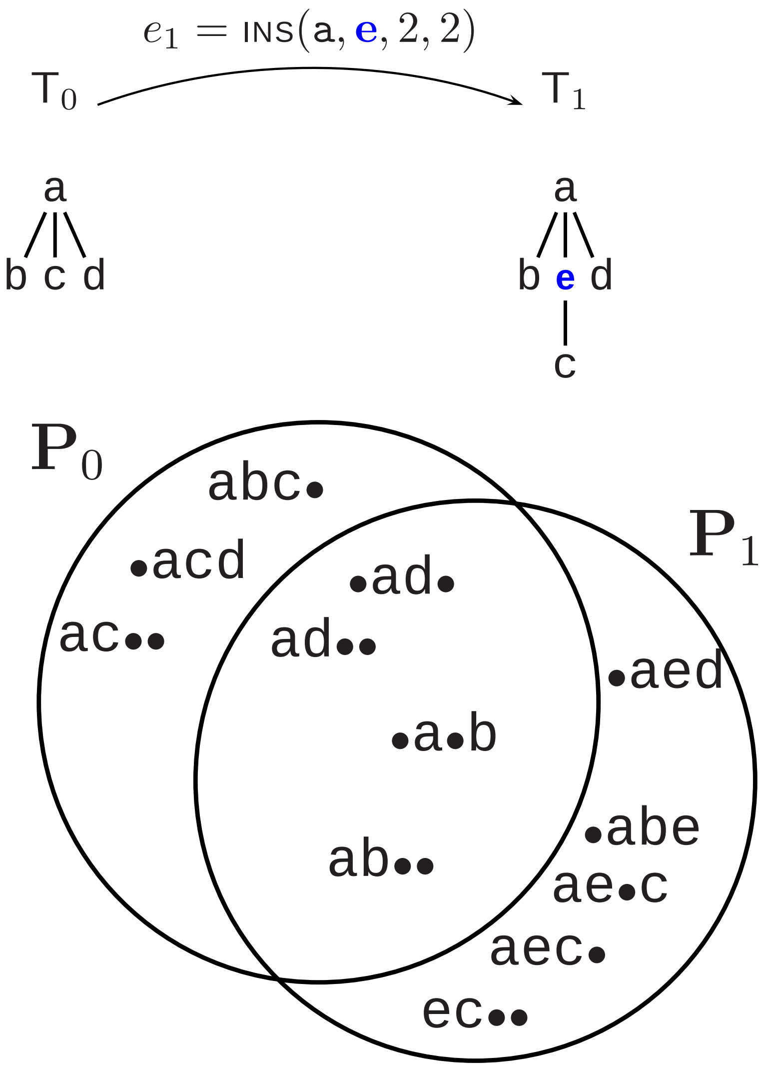


Multiple Edit Steps

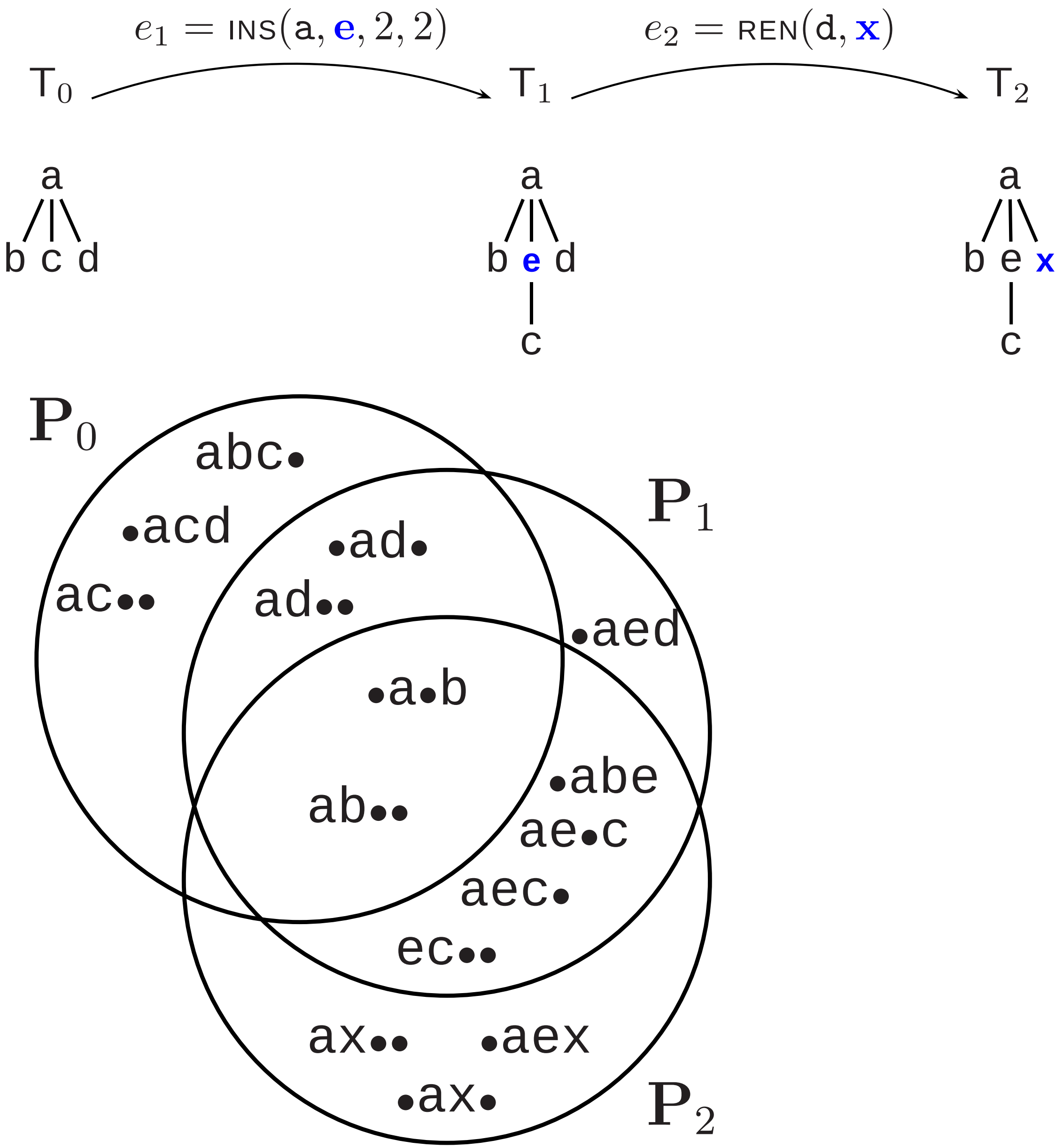




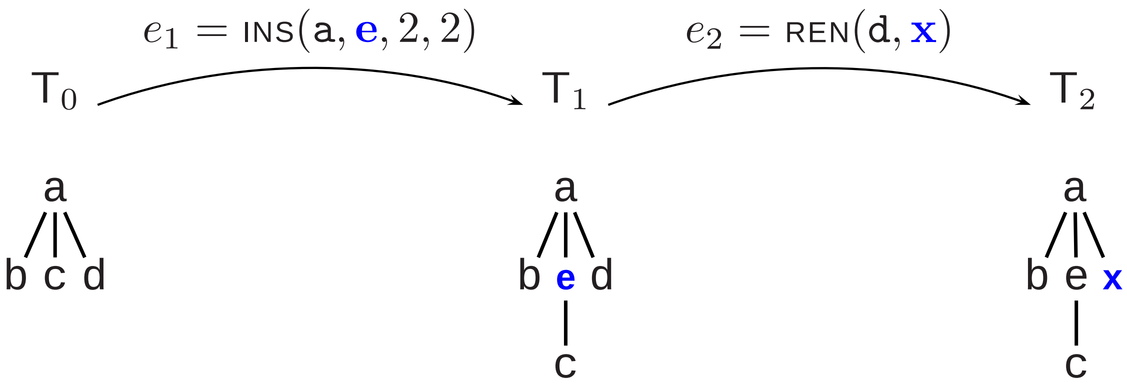
Multiple Edit Steps

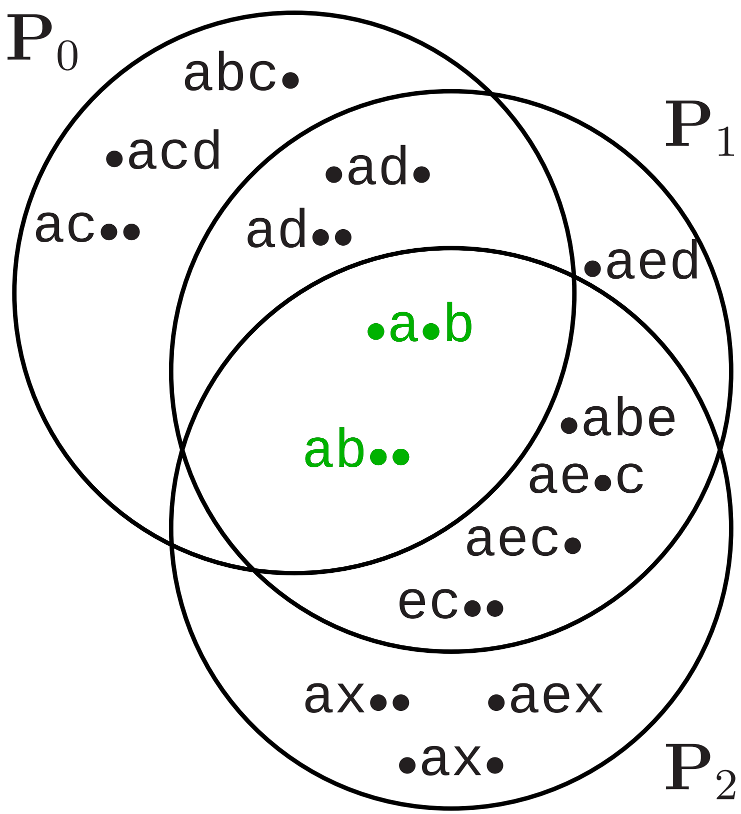


Multiple Edit Steps



Multiple Edit Steps

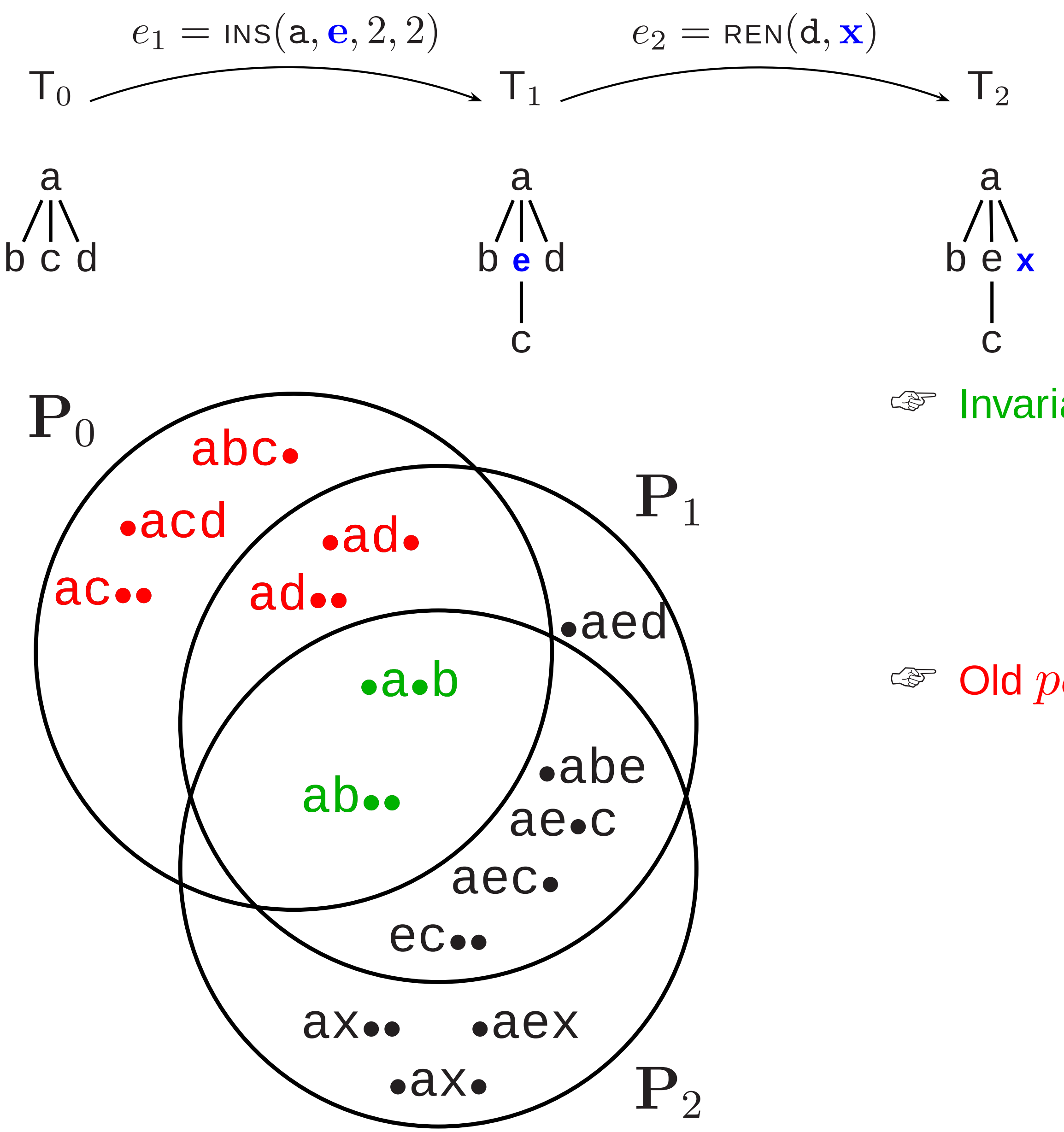




☞ Invariant pq-Grams (no need for update)

$$\mathbf{C}_n = \mathbf{P}_0 \cap \cdots \cap \mathbf{P}_n$$

Multiple Edit Steps



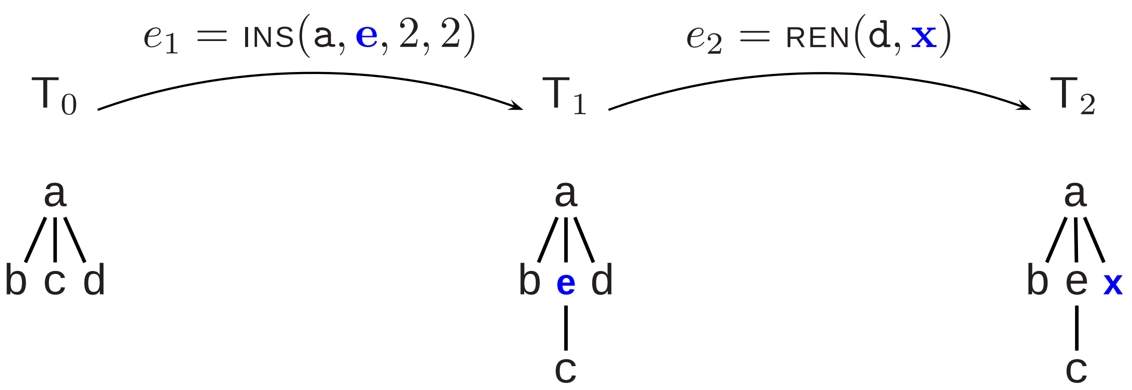
☞ Invariant pq-Grams (no need for update)

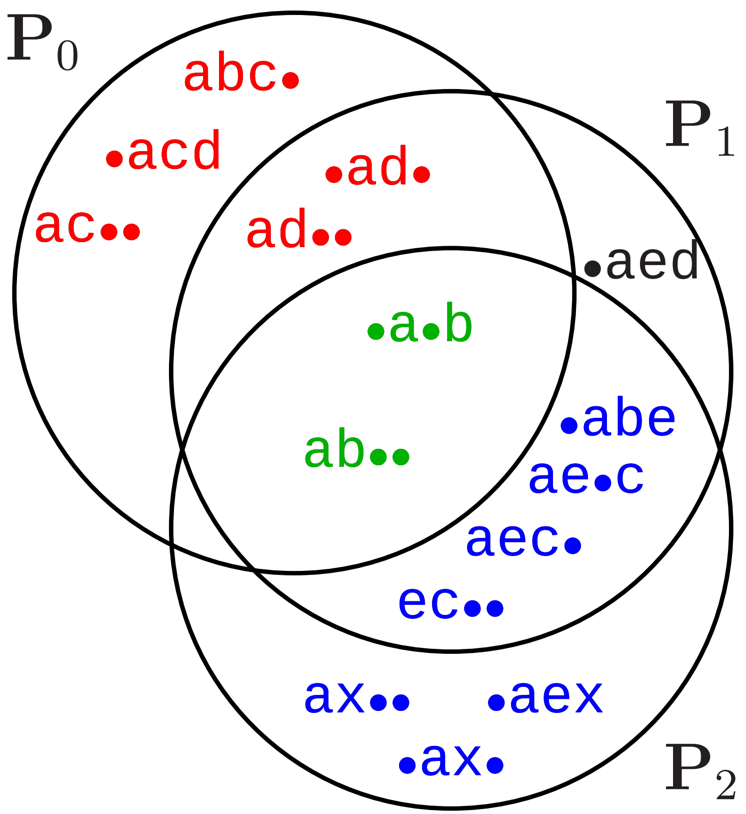
$$\mathbf{C}_n = \mathbf{P}_0 \cap \cdots \cap \mathbf{P}_n$$

☞ Old pq-Grams (deleted from old index $\mathcal{I}_0$)

$$\Delta_n^- = \mathbf{P}_0 \setminus \mathbf{C}_n$$

Multiple Edit Steps





☞ Invariant pq-Grams (no need for update)

$$\mathbf{C}_n = \mathbf{P}_0 \cap \cdots \cap \mathbf{P}_n$$

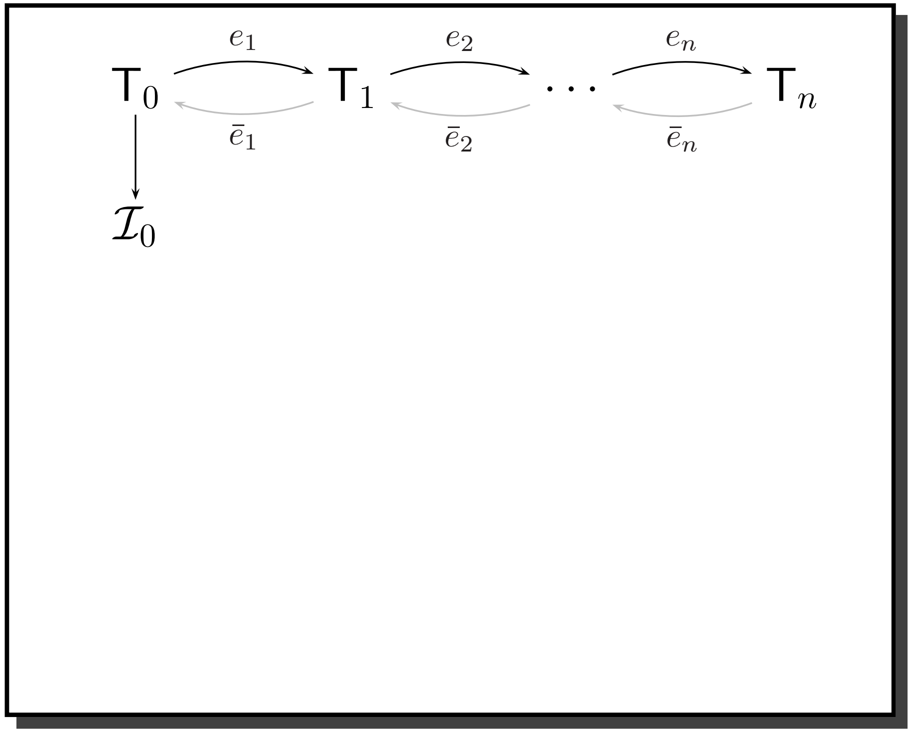
☞ Old pq-Grams (deleted from old index $\mathcal{I}_0$)

$$\Delta_n^- = \mathbf{P}_0 \setminus \mathbf{C}_n$$

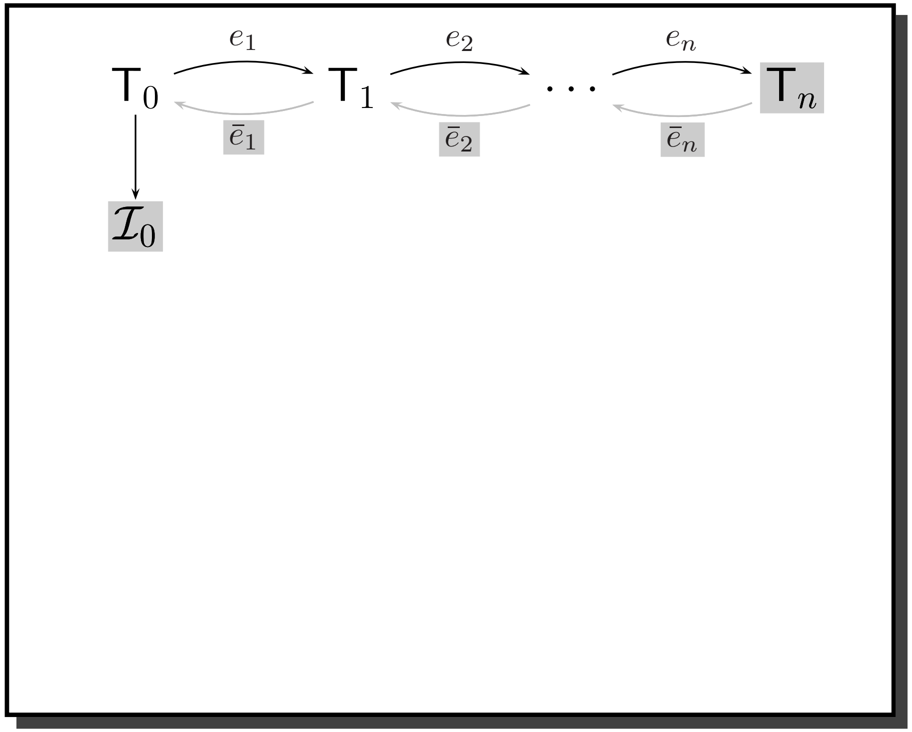
☞ New pq-Grams (inserted into new index $\mathcal{I}_n$)

$$\Delta_n^+ = \mathbf{P}_n \setminus \mathbf{C}_n$$

Solution (Overview)



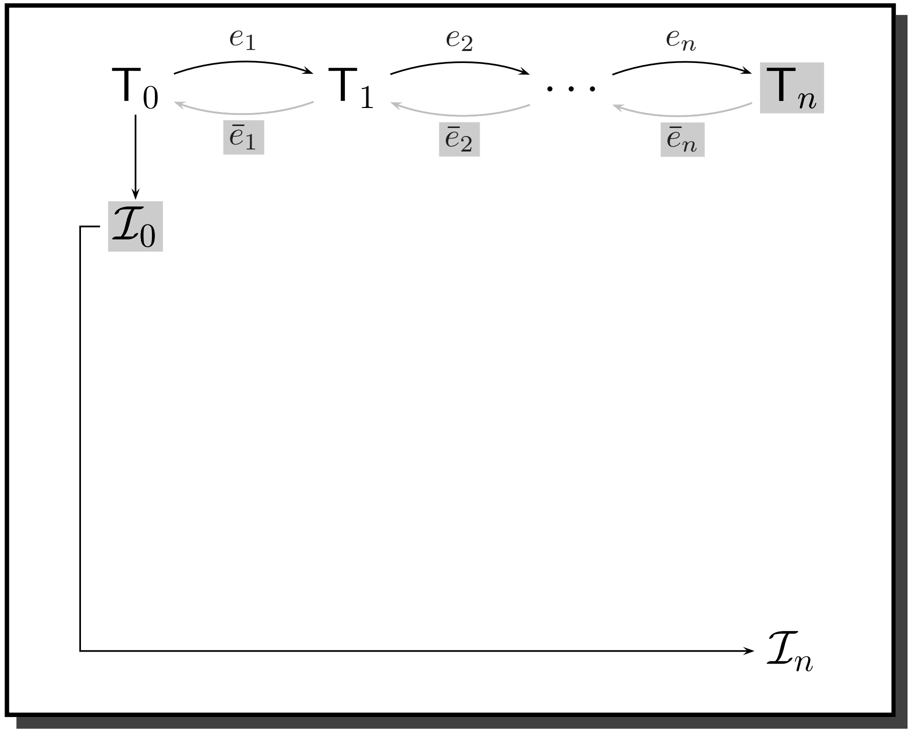
Solution (Overview)



☞ **Input:**

1. old index $\mathcal{I}_0$
2. log of inverse edit operations $(\bar{e}_n, \ldots, \bar{e}_1)$
3. resulting tree T_n

Solution (Overview)



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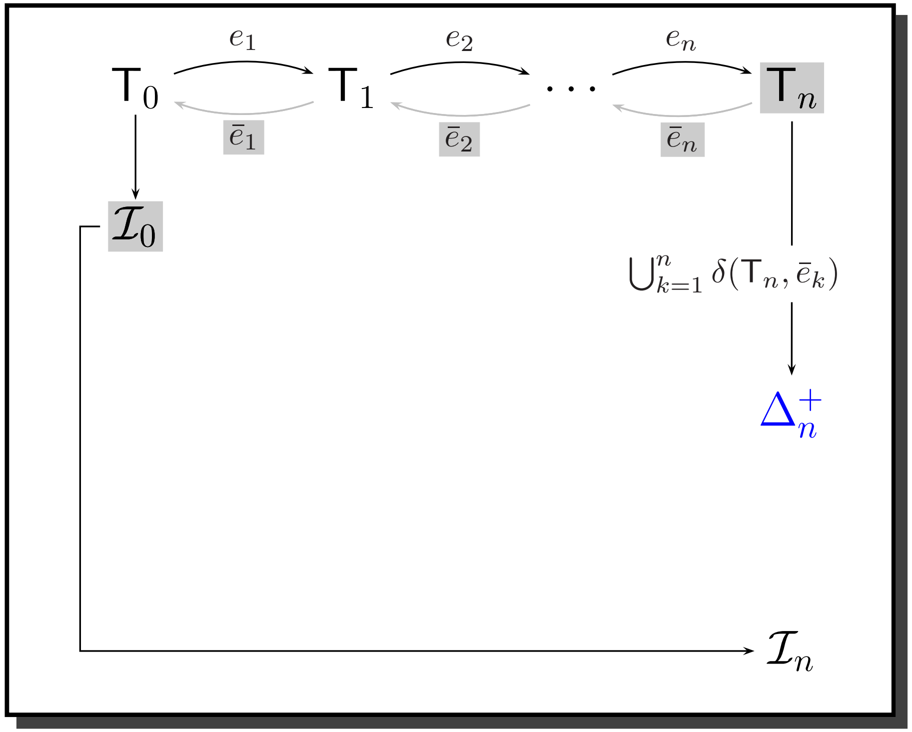
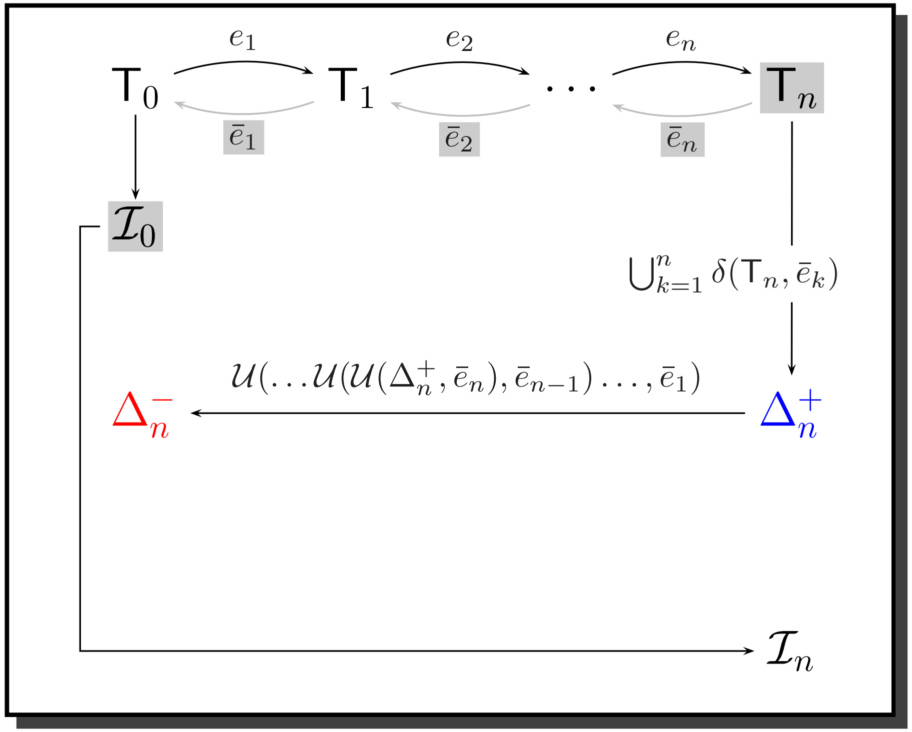
- **Output:** new index $\mathcal{I}_n$

Solution (Overview)



- **Input:**
  1. old index $\mathcal{I}_0$
  2. log of inverse edit operations $(\bar{e}_n, \ldots, \bar{e}_1)$
  3. resulting tree T_n
- **Output:** new index $\mathcal{I}_n$
- **Solution:** 3 Steps
  1. compute **new pq-grams**:
     $\Delta_n^+ = \delta(\mathsf{T}_n, \bar{e}_1) \cup \cdots \cup \delta(\mathsf{T}_n, \bar{e}_n)$

Solution (Overview)



- **Input:**
  1. old index $\mathcal{I}_0$
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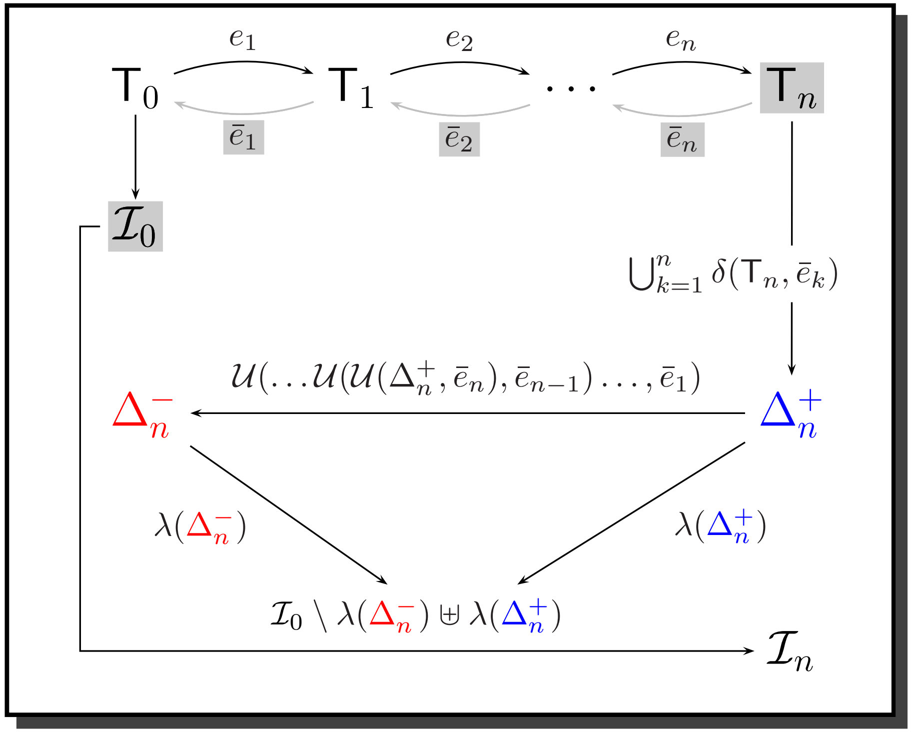
     $\Delta_n^- = \mathcal{U}(\ldots\mathcal{U}(\mathcal{U}(\Delta_n^+, \bar{e}_n), \bar{e}_{n-1})\ldots, \bar{e}_1)$

Solution (Overview)



- **Input:**
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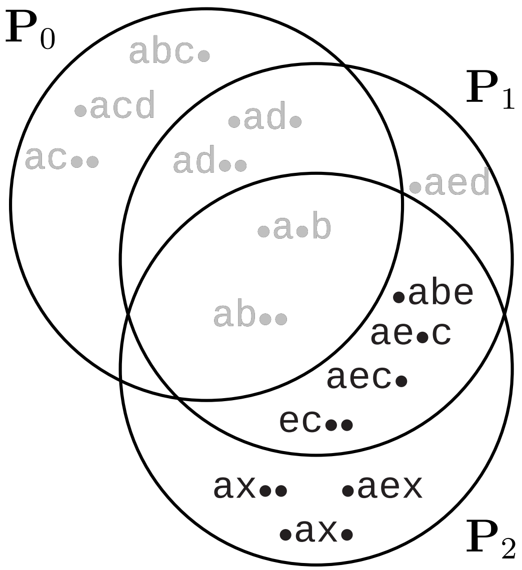
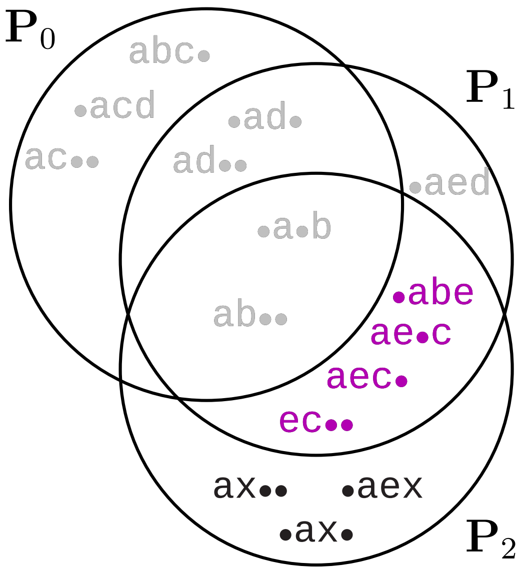
  2. compute **old pq-grams**:
     $\Delta_n^- = \mathcal{U}(\ldots\mathcal{U}(\mathcal{U}(\Delta_n^+, \bar{e}_n), \bar{e}_{n-1})\ldots, \bar{e}_1)$
  3. **update index**:
     $\mathcal{I}_n = \mathcal{I}_0 \setminus \lambda(\Delta_n^-) \uplus \lambda(\Delta_n^+)$

Example of Δ^+ Computation



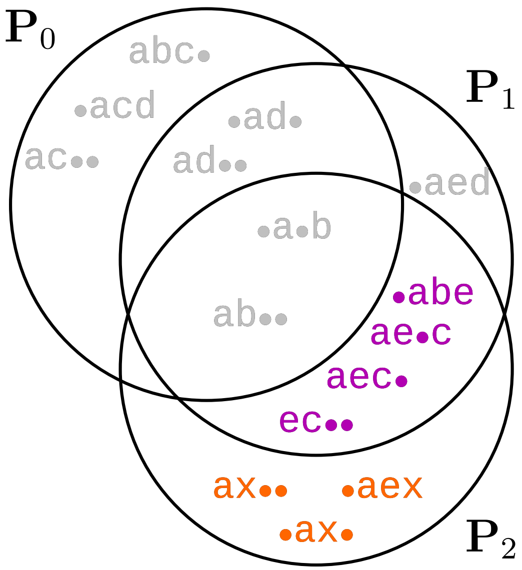
$\Delta_2^+ =$

Example of Δ^+ Computation



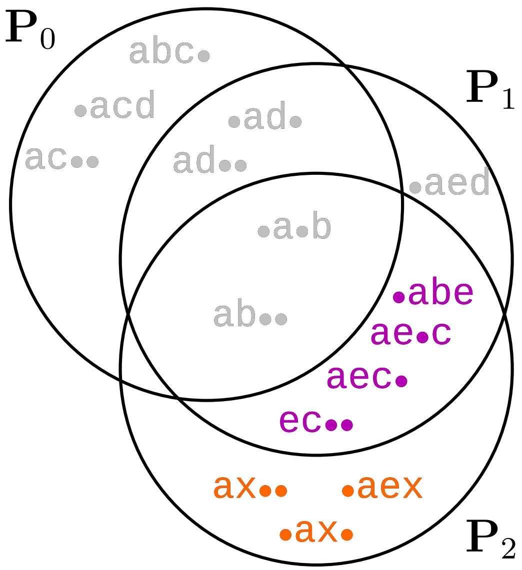
$$\Delta_2^+ = [\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2]$$

Example of Δ^+ Computation



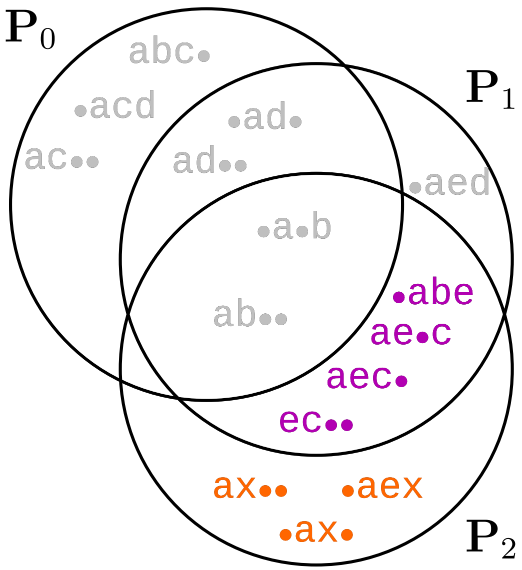
$$\Delta_2^+ = [\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2] \cup \delta(\mathsf{T}_2, \bar{e}_2)$$

Example of Δ^+ Computation



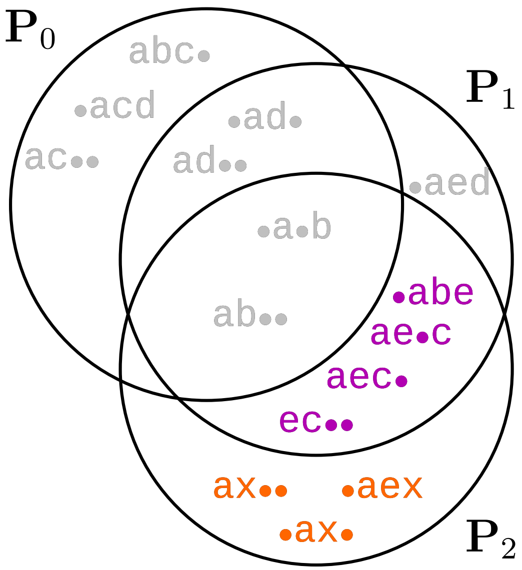
$$\Delta_2^+ = [\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2] \cup \underbrace{\delta(\mathsf{T}_2, \bar{e}_2)}_{\text{OK}}$$

Example of Δ^+ Computation



$$\Delta_2^+ = \underbrace{[\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2]}_{\mathsf{T}_1 \text{ not given!}} \cup \underbrace{\delta(\mathsf{T}_2, \bar{e}_2)}_{\text{OK}}$$

Example of Δ^+ Computation

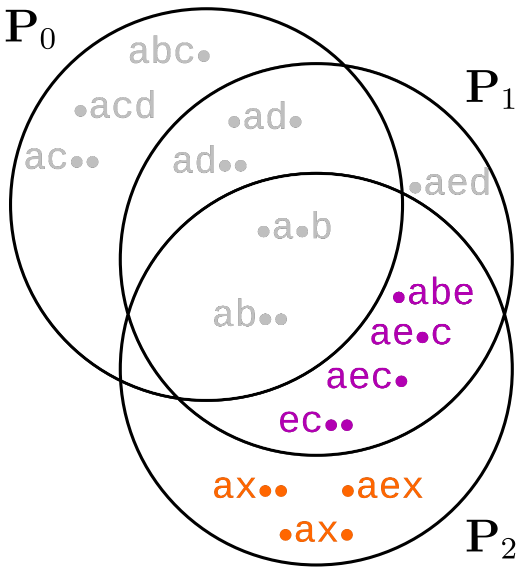


$$\Delta_2^+ = [\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2] \cup \delta(\mathsf{T}_2, \bar{e}_2)$$

T_1 not given! — OK

☞ **Compute δ on wrong tree** (T_2) and fix it

Example of Δ^+ Computation



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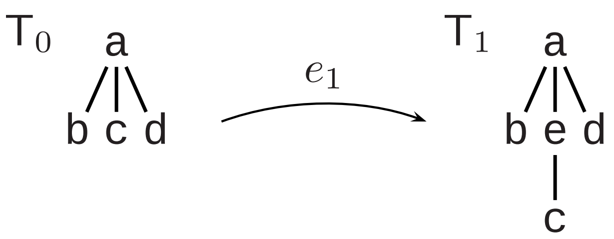
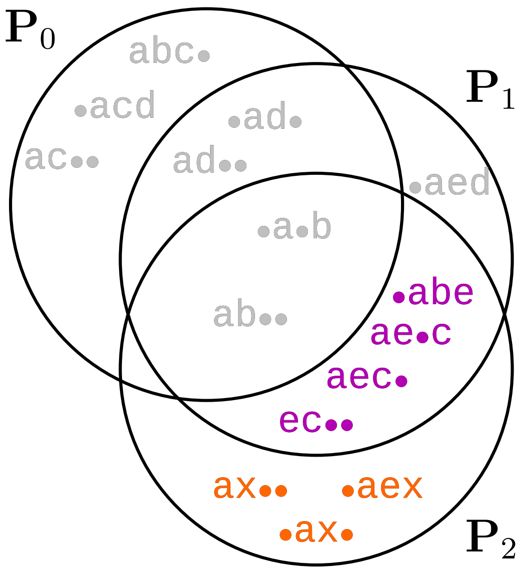
Reality:



Example of Δ^+ Computation



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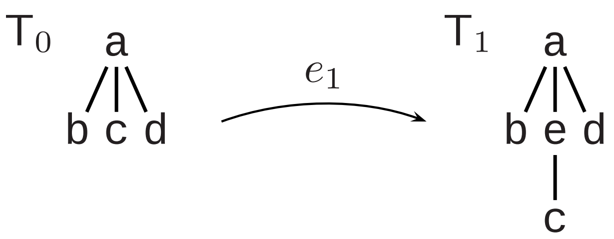
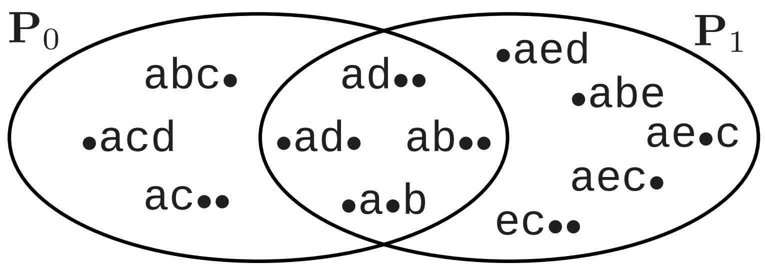
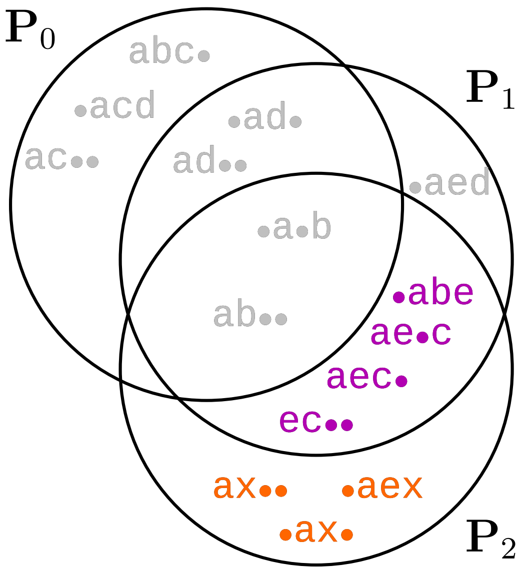




Example of Δ^+ Computation



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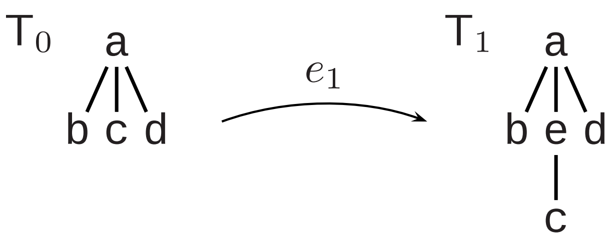
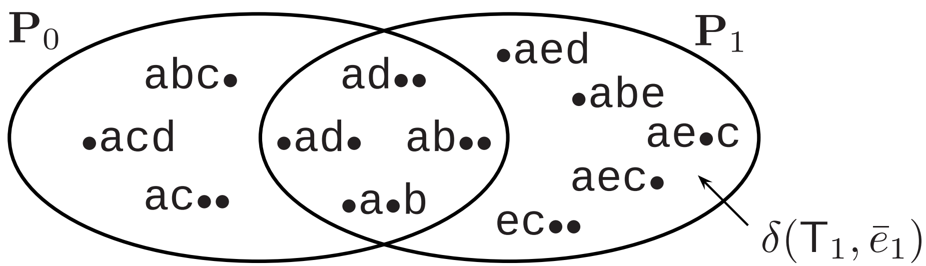
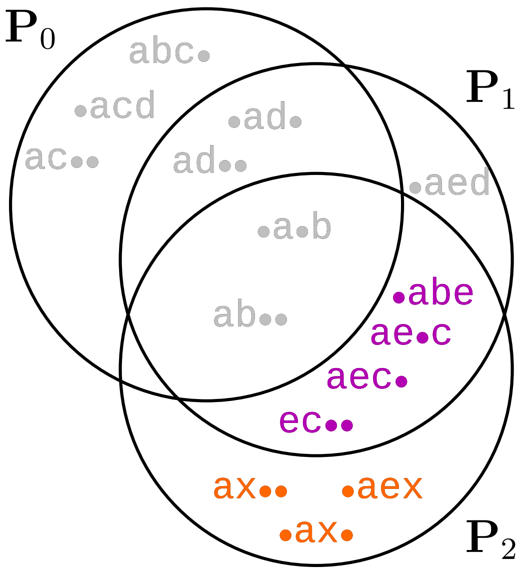




Example of Δ^+ Computation



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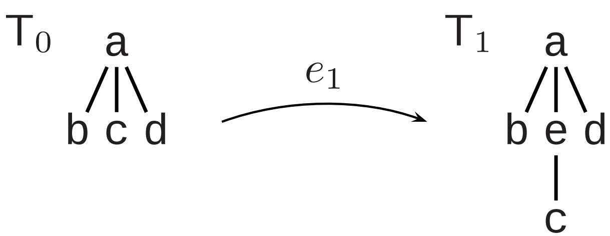
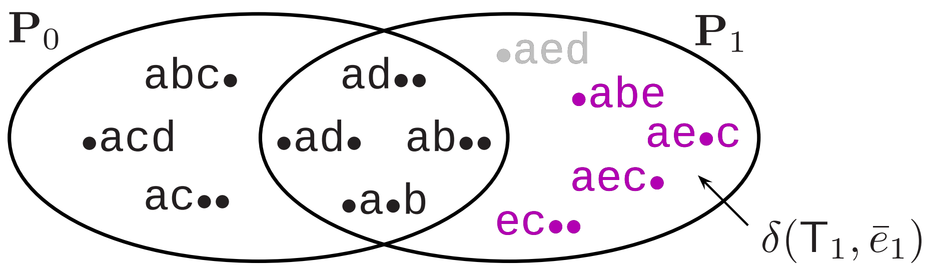
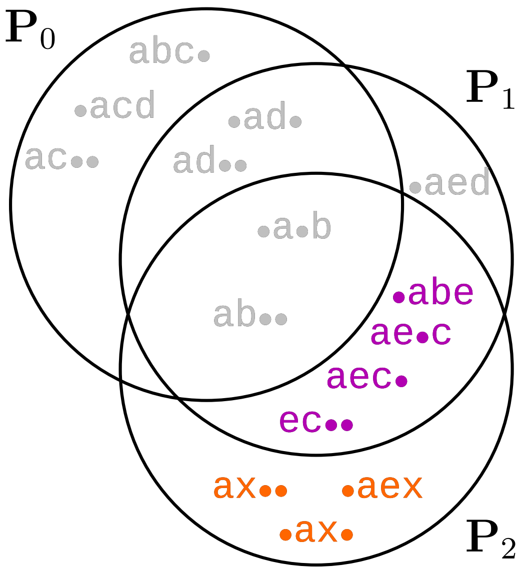
Reality:





Example of Δ^+ Computation



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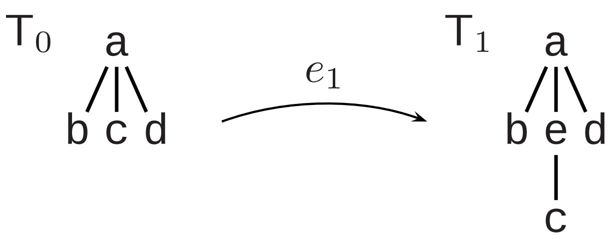
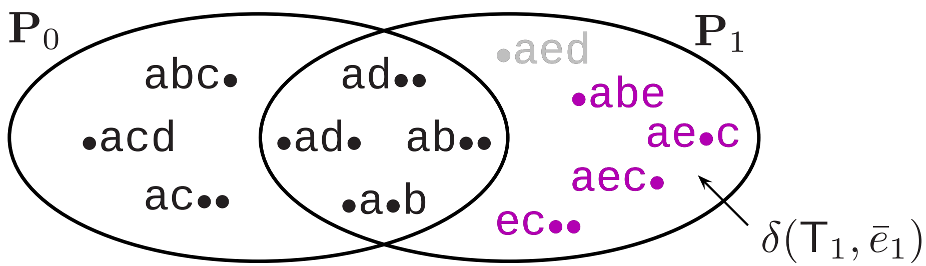
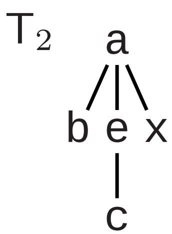
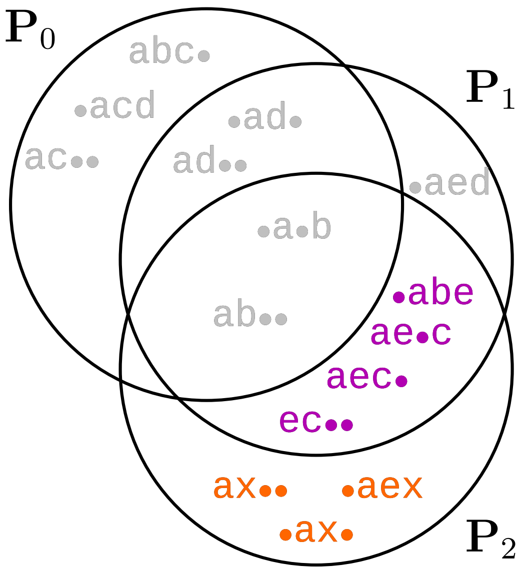




Computation:



Example of Δ^+ Computation



$$\Delta_2^+ = \underbrace{[\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2]}_{\mathsf{T}_1 \text{ not given!}} \cup \underbrace{\delta(\mathsf{T}_2, \bar{e}_2)}_{\text{OK}}$$

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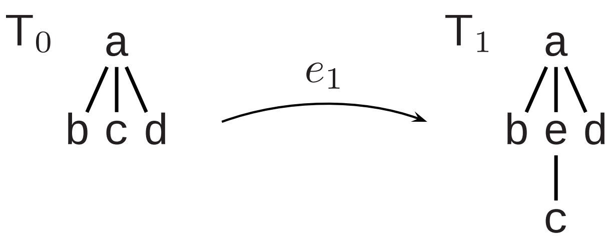
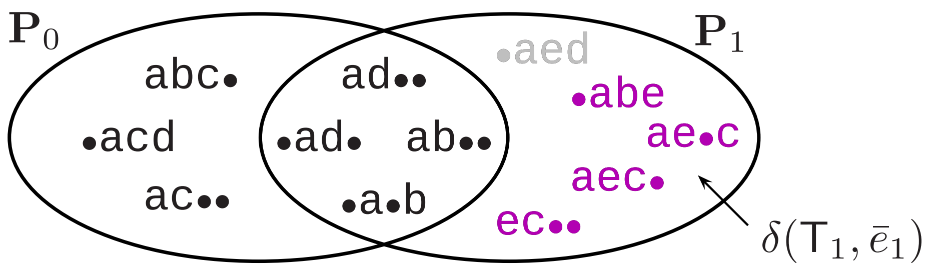
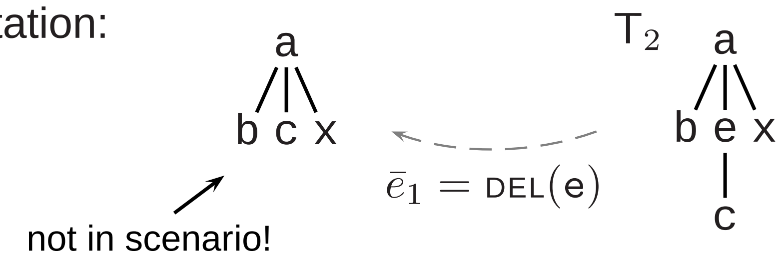
Reality:

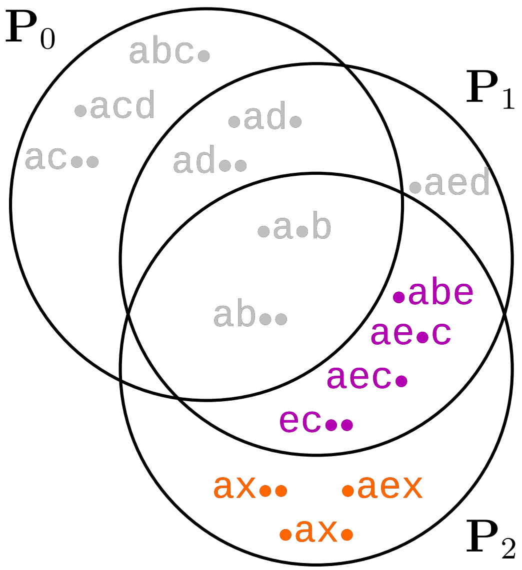




Computation:



Example of Δ^+ Computation



$$\Delta_2^+ = [\delta(T_1, \bar{e}_1) \cap \mathbf{P}_2] \cup \delta(T_2, \bar{e}_2)$$

T_1 not given! | OK

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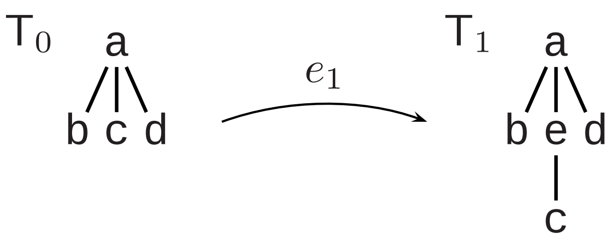
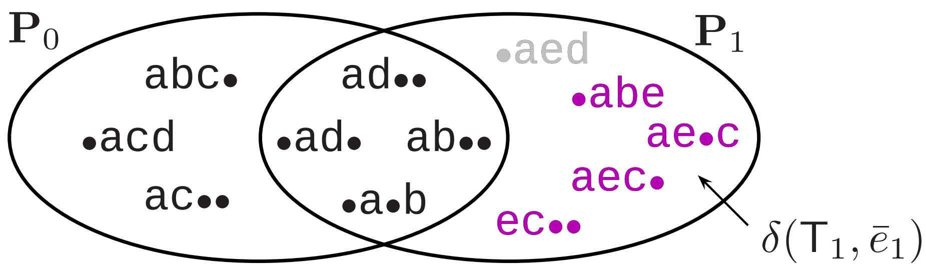
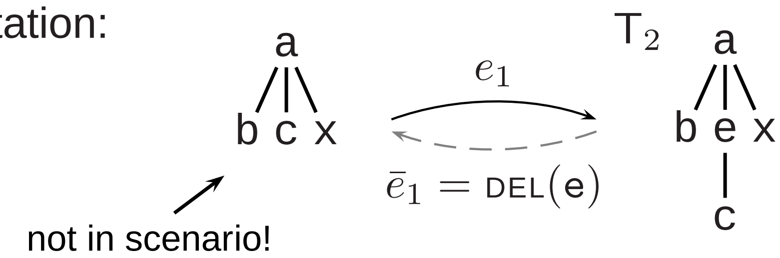
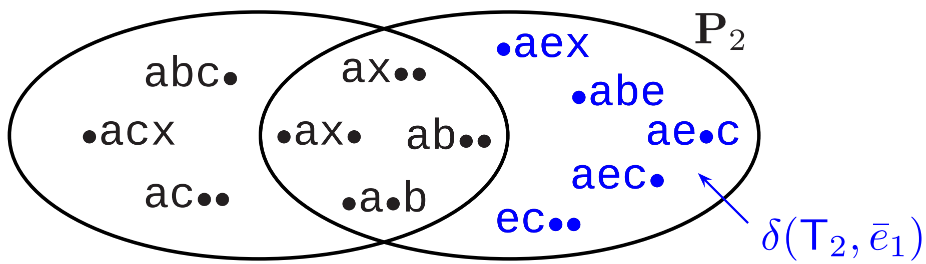
Reality:



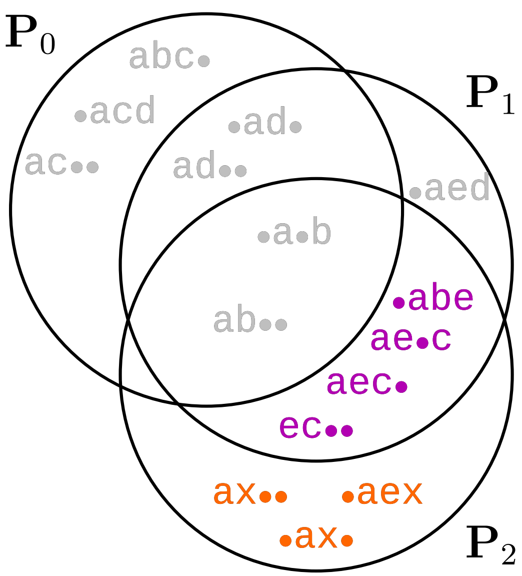


Computation:





Example of Δ^+ Computation



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T_1 not given! — OK

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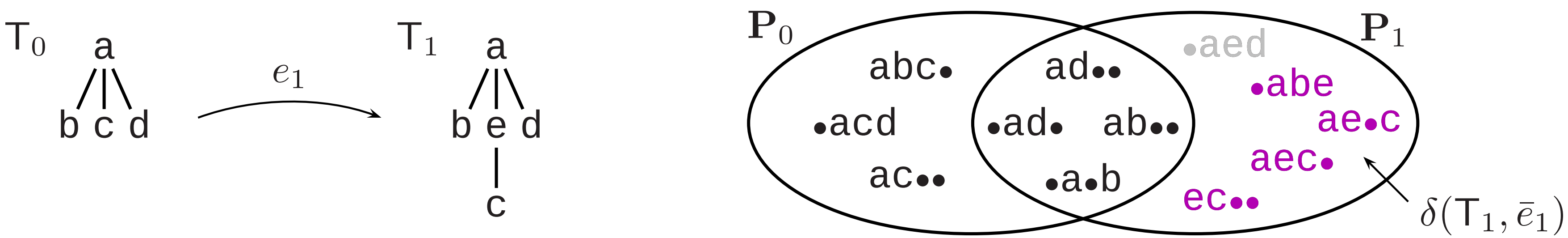
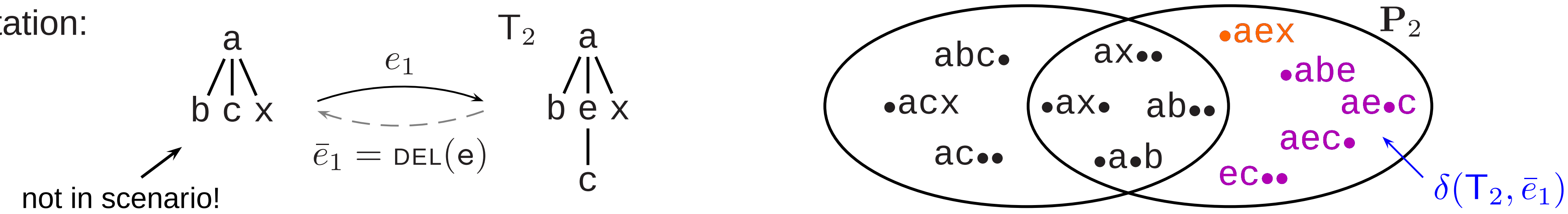
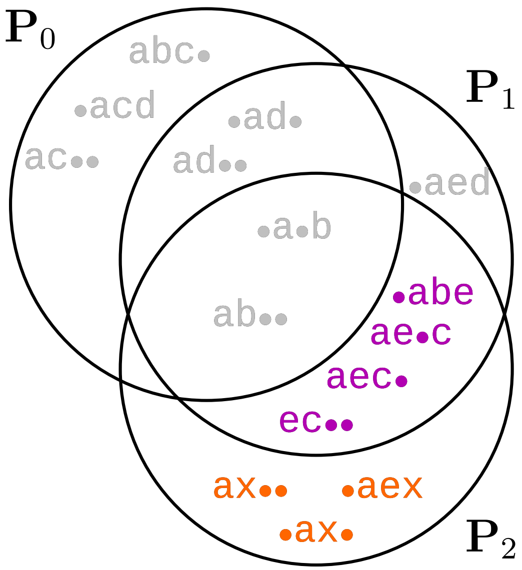
Reality:



Computation:



Example of Δ^+ Computation



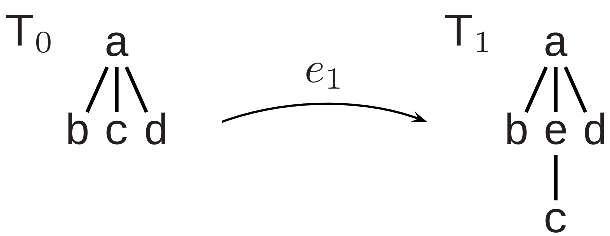
$$\Delta_2^+ = [\delta(T_1, \bar{e}_1) \cap \mathbf{P}_2] \cup \delta(T_2, \bar{e}_2)$$

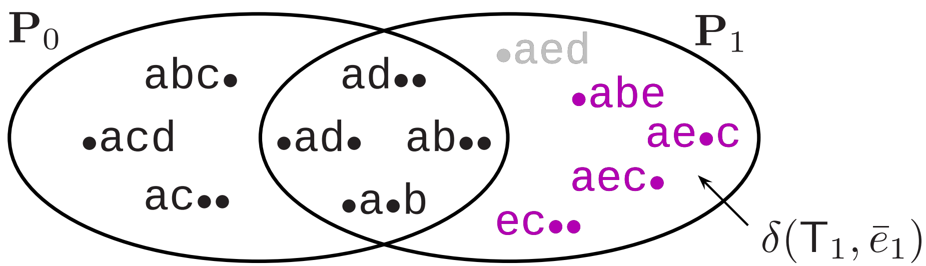
T_1 not given! — OK

☞ **Compute δ on wrong tree** (T_2) and fix it

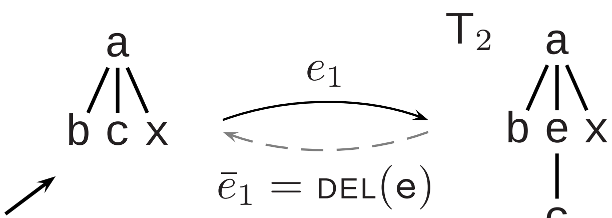
$$\delta(T_1, \bar{e}_1) \cap \mathbf{P}_2 = \delta(T_2, \bar{e}_1) \setminus \delta(T_2, \bar{e}_2)$$

Reality:

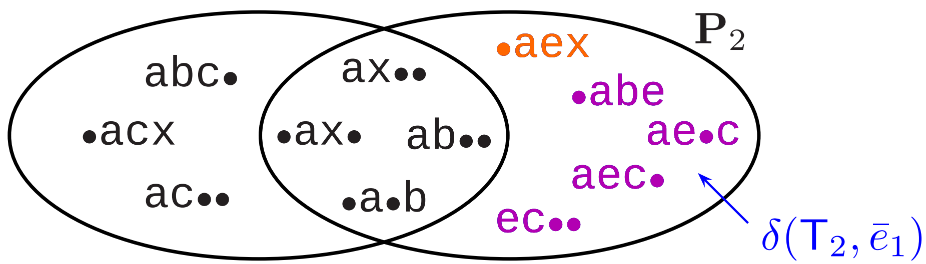




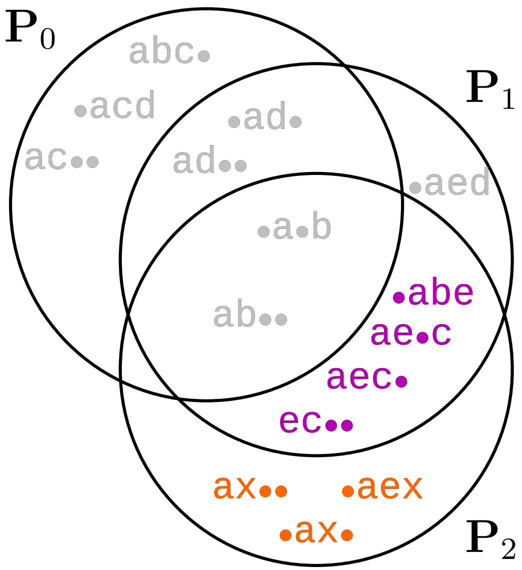
Computation:



not in scenario!



Example of Δ^+ Computation



$$\Delta_2^+ = \underbrace{[\delta(\mathsf{T}_1, \bar{e}_1) \cap \mathbf{P}_2]}_{\mathsf{T}_1 \text{ not given!}} \cup \underbrace{\delta(\mathsf{T}_2, \bar{e}_2)}_{\text{OK}}$$

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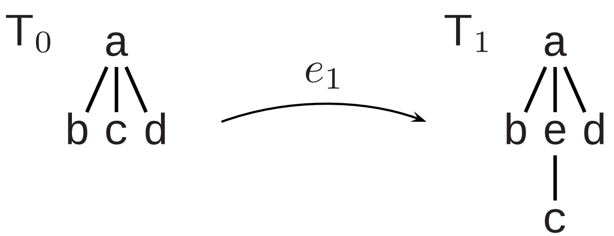

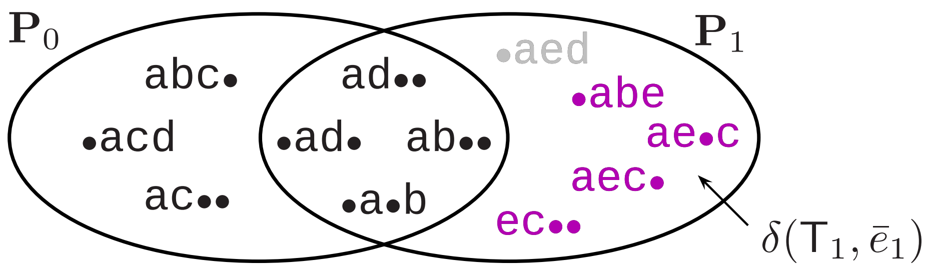

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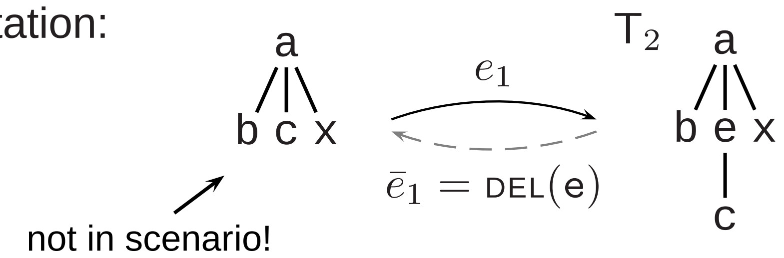

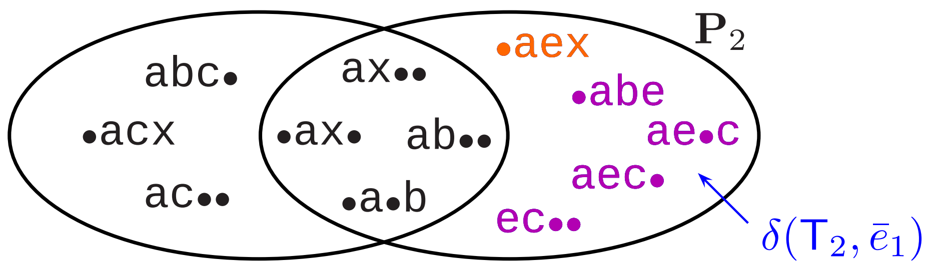

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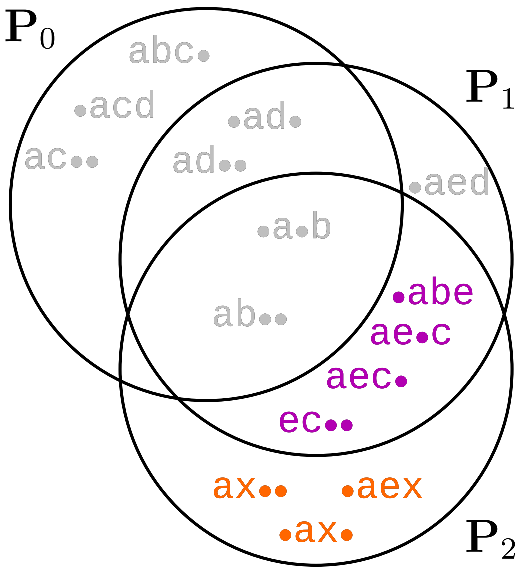

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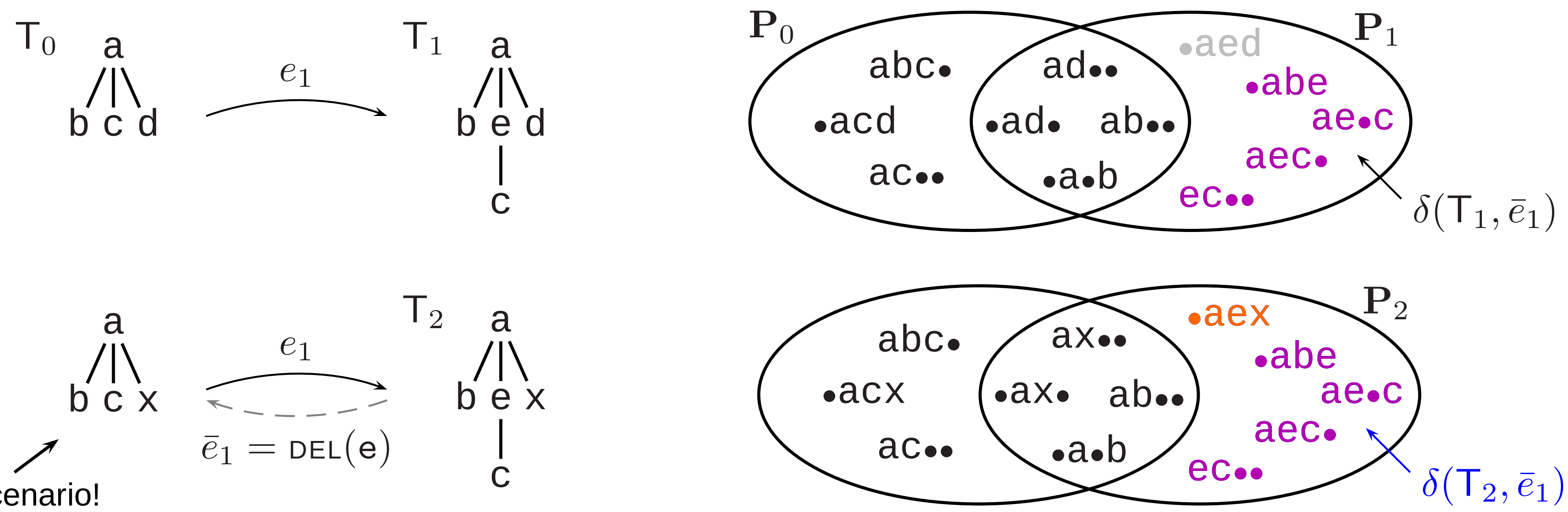
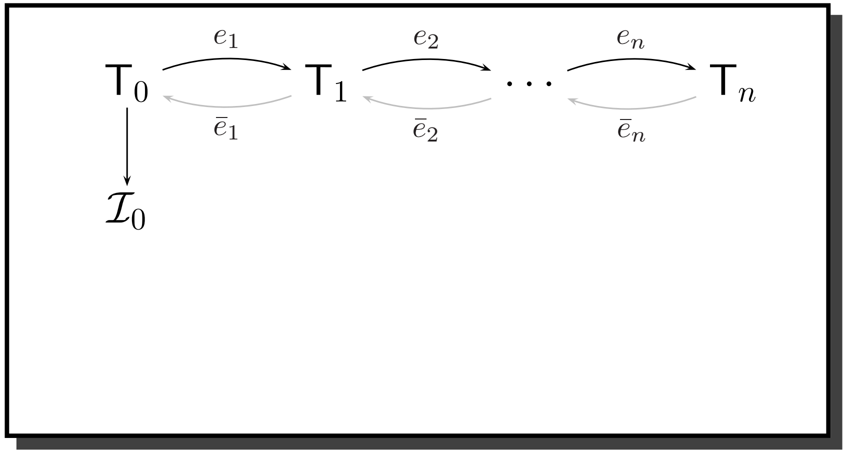
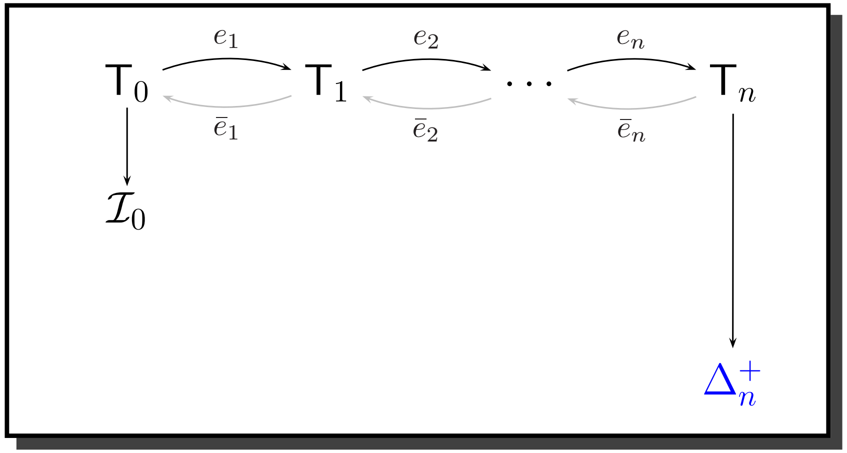
Computation:



Computing Δ^+

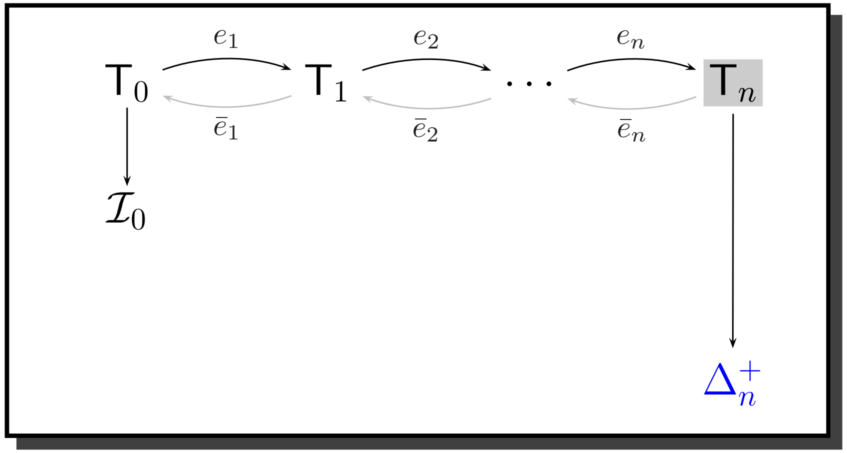


Computing Δ^+



☞ new pq-grams can be computed using:

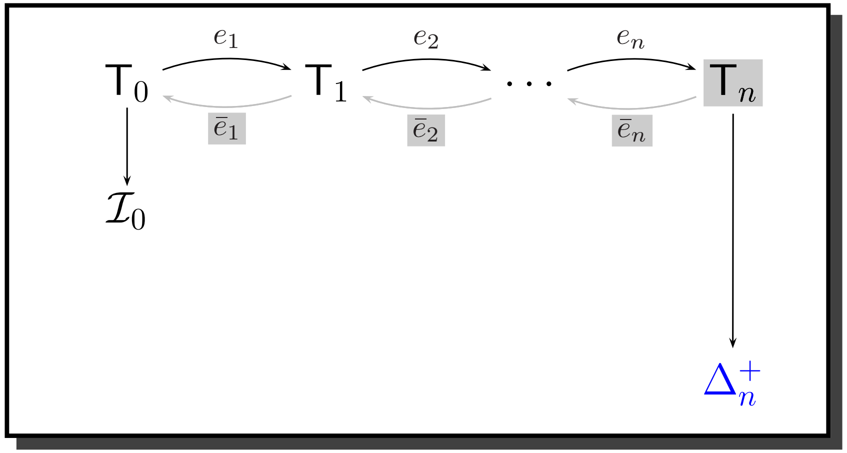
Computing Δ^+



☞ new pq-grams can be computed using:

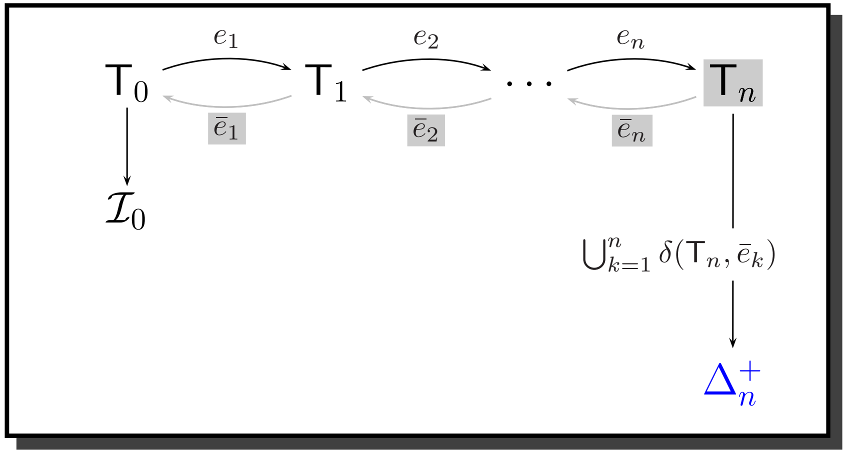
➾ the resulting tree T_n

Computing Δ^+



- new pq-grams can be computed using:
  - the resulting tree T_n
  - the log $(\bar{e}_1, \dots, \bar{e}_n)$

Computing Δ^+



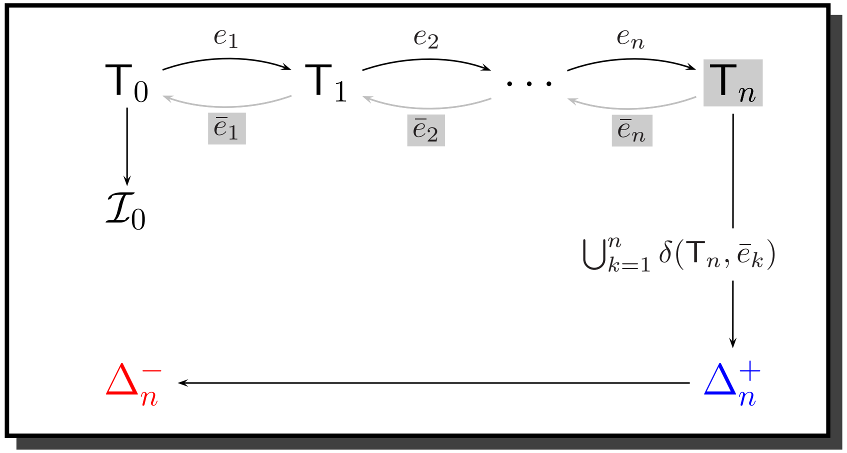
☞ new pq-grams can be computed using:

- the resulting tree T_n
- the log $(\bar{e}_1, \ldots, \bar{e}_n)$

Theorem 1 *The set of new pq-grams can be computed on T_n as*

$$\Delta_n^+ = \bigcup_{k=1}^{n} \delta(\mathsf{T}_n, \bar{e}_k)$$

Computing Δ^+



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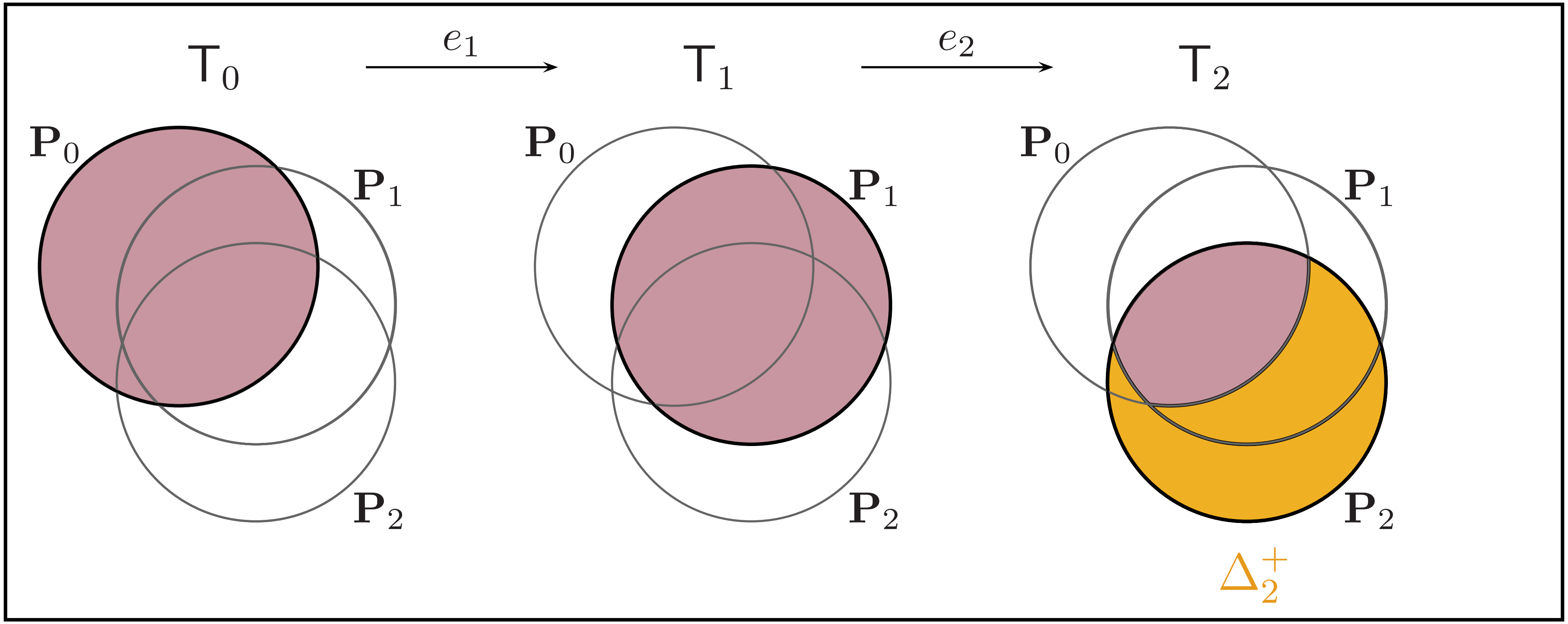
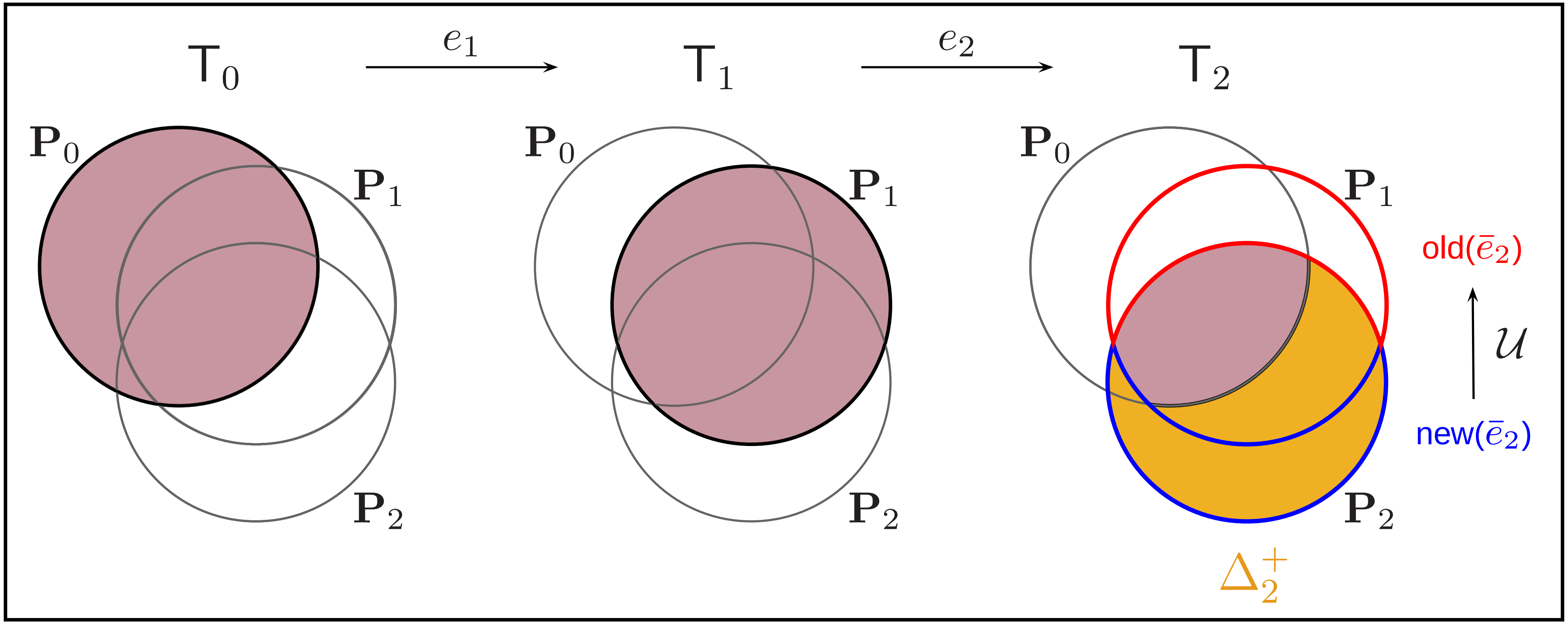
- **Next step:** compute old pq-grams Δ_n^-

Example of Δ^- Computation

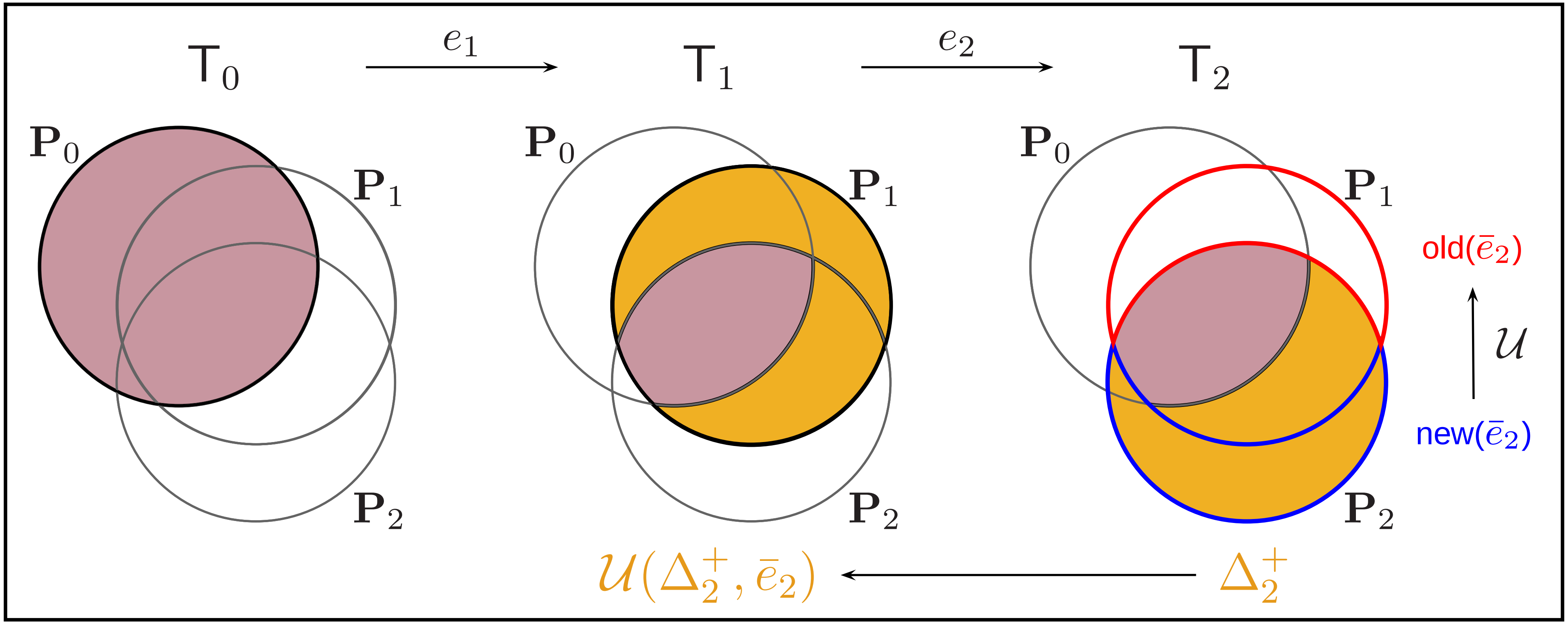


Example of Δ^- Computation



☞ **Profile update function $\mathcal{U}$:** transforms new pq-grams into old pq-grams.

Example of Δ^- Computation



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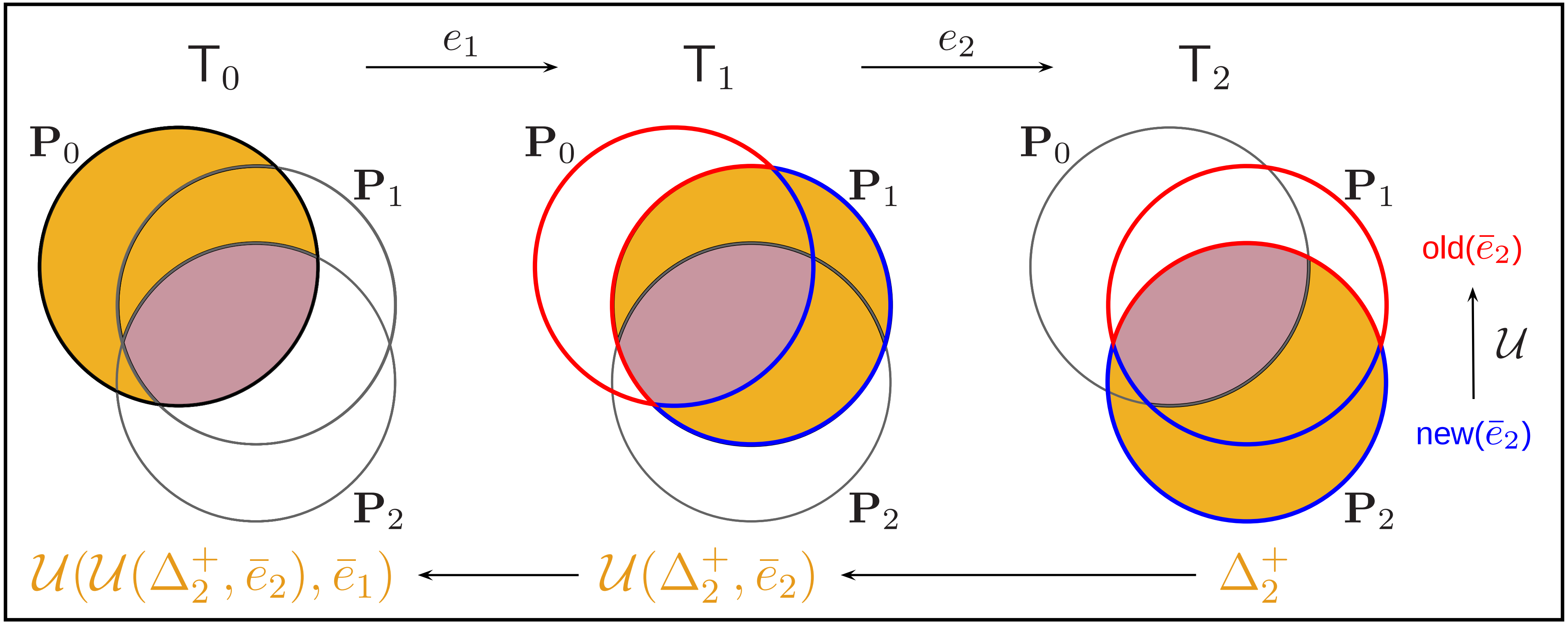
Example of Δ^- Computation



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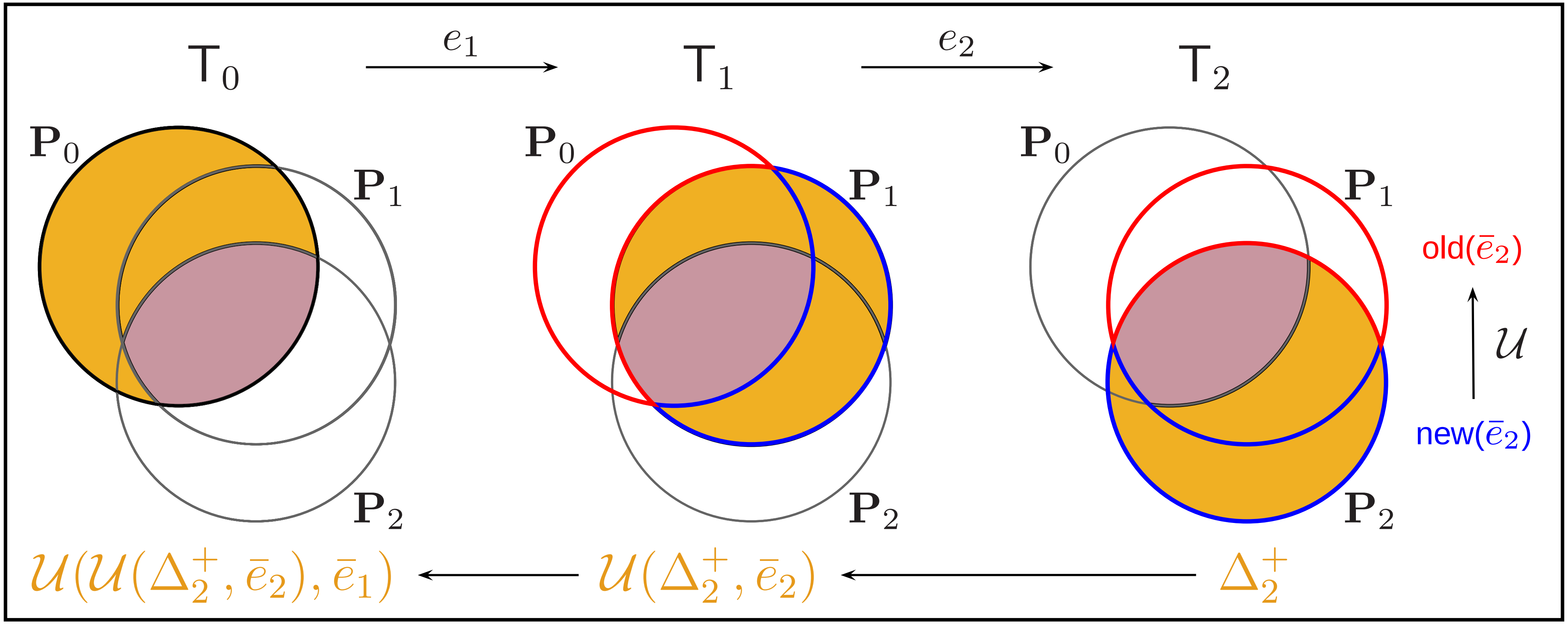


☞ **Profile update function $\mathcal{U}$:** transforms new pq-grams into old pq-grams.

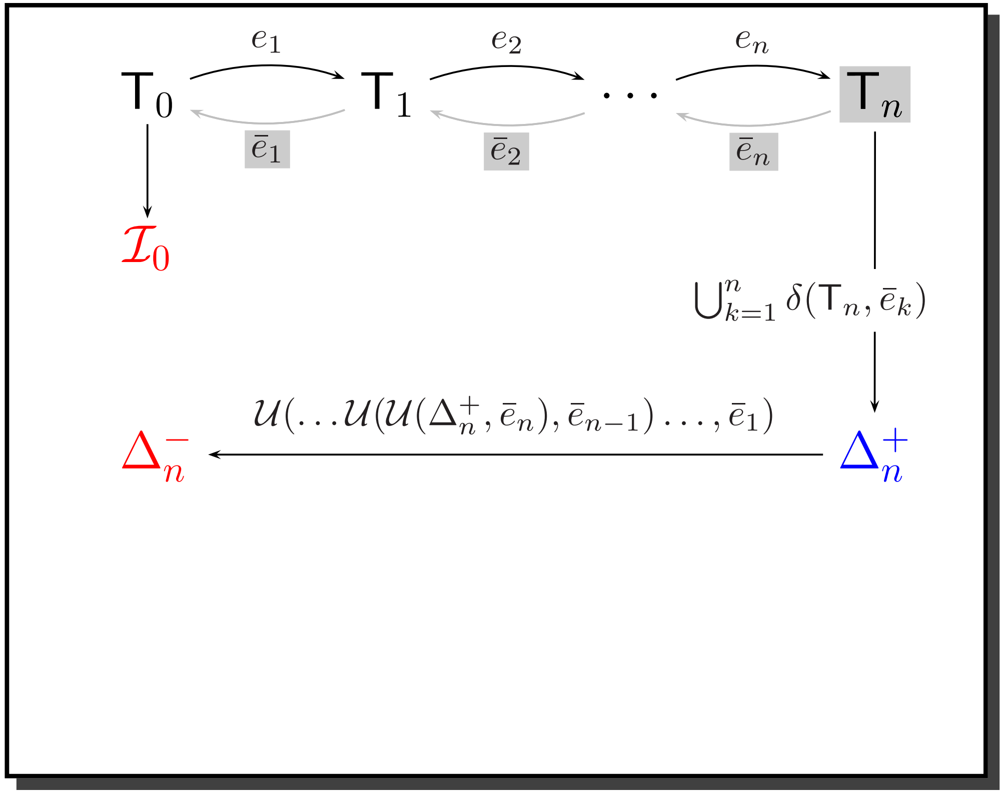
$$\mathcal{U}(\mathcal{U}(\Delta_2^+, \bar{e}_2), \bar{e}_1) = \mathbf{\Delta_2^-}$$

Computing Δ^{-}

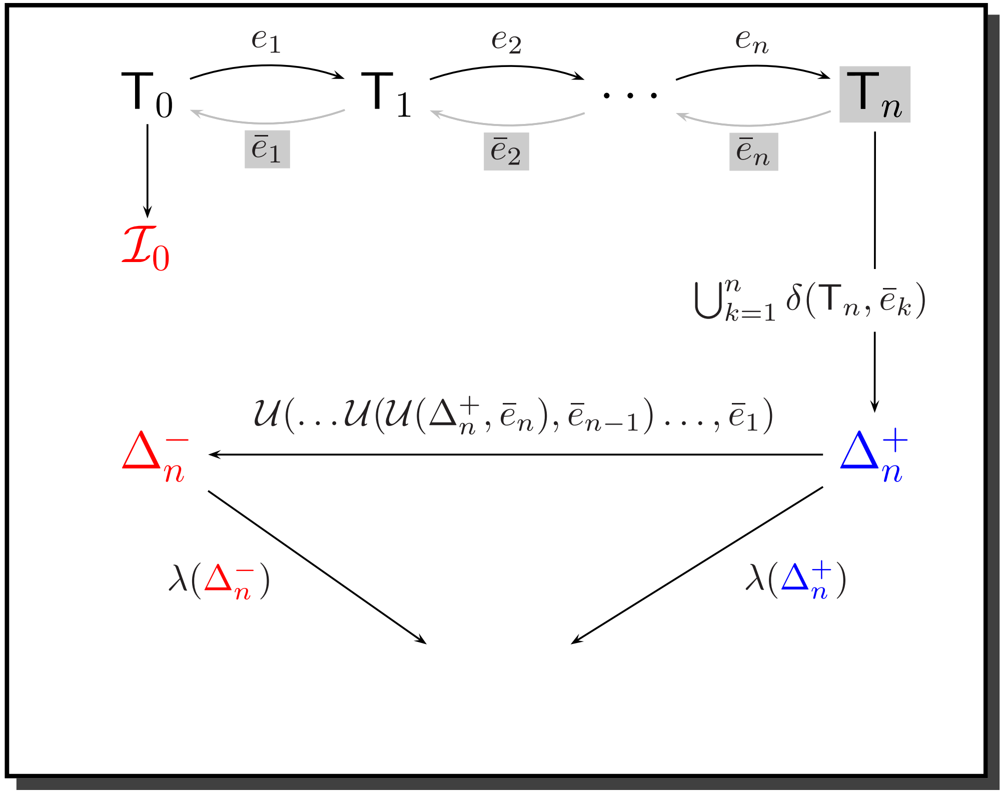
Theorem 2 *The old pq-grams Δ_n^{-} are computed by recursively applying the **update function** $\mathcal{U}$ to the new pq-grams Δ_n^{+}:*

$$\Delta_n^{-} = \mathcal{U}(\ldots\mathcal{U}(\mathcal{U}(\Delta_n^{+}, \bar{e}_n), \bar{e}_{n-1})\ldots, \bar{e}_1).$$

Hash pq-Grams and Update Old Index

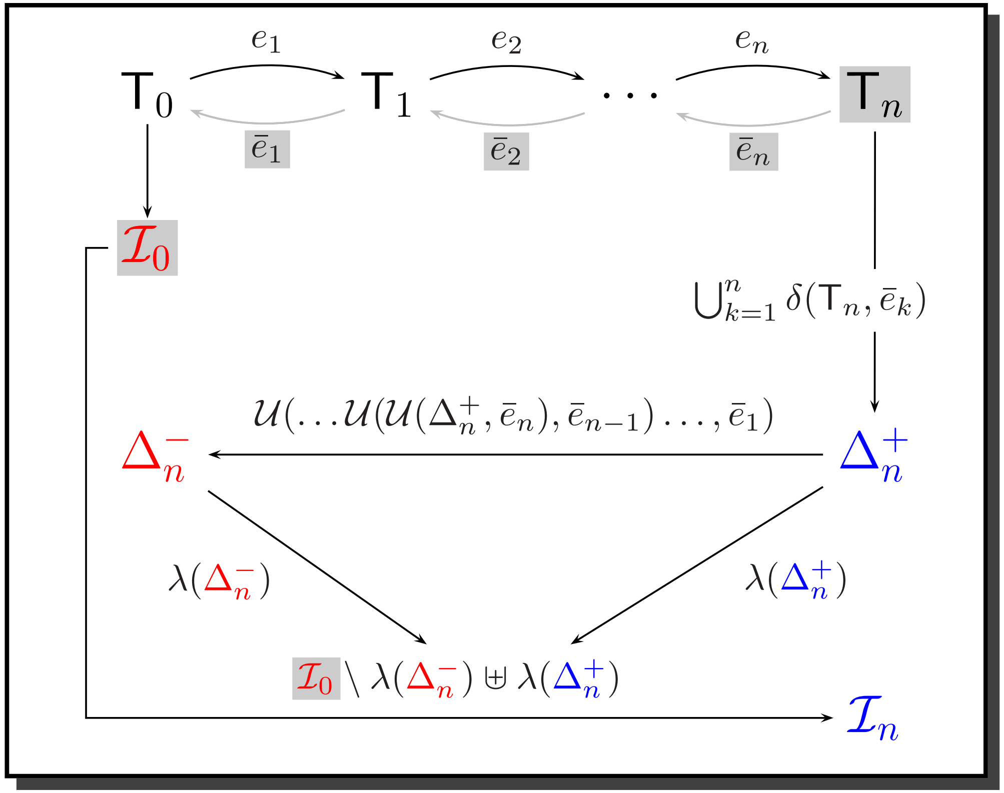


Hash pq-Grams and Update Old Index



☞ **Hash** old (Δ_n^+) and new (Δ_n^-) pq-grams

Hash pq-Grams and Update Old Index



- ☞ **Hash** old (Δ_n^+) and new (Δ_n^-) pq-grams
- ☞ **Update** old index $\mathcal{I}_0$

Algorithm

Algorithm 1: `updateIndex`$(\texttt{I}_0, \texttt{T}_n, log)$

Algorithm

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1 $\Delta_n^+ = \emptyset$;

2 **foreach** $\bar{e}_i \in log$ **do** $\Delta_n^+ \leftarrow \Delta_n^+ \cup \delta(\mathsf{T}_n, \bar{e}_i)$;

Algorithm

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$\Delta_n^- \leftarrow \Delta_n^+$;

for $\bar{e}_i \leftarrow \bar{e}_n$ **downto** $\bar{e}_1$ **do** $\Delta_n^- \leftarrow \mathcal{U}(\Delta_n^-, \bar{e}_i)$;

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$\mathtt{I}^+ \leftarrow \lambda(\Delta_n^+)$;
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$\texttt{I}_n \leftarrow \texttt{I}_0 \setminus \texttt{I}^- \cup \texttt{I}^+$;

return $\texttt{I}_n$;

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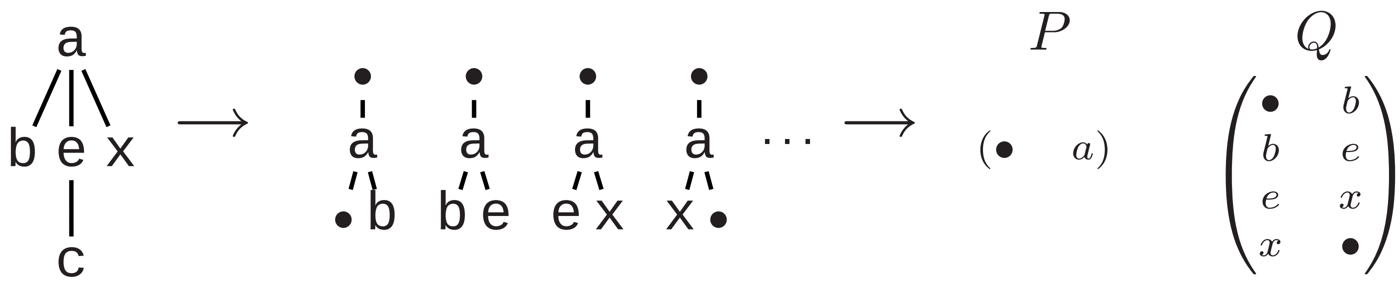
Implementation

☞ Store p-part and q-part in tables P and Q



Formulas for Updating Δ_n^-

Insert node n as the k-th child of node v: INS$(\mathsf{n}, \mathsf{v}, k, m)$

$$\delta(\mathsf{T}_j, \bar{e}) = P(\mathsf{v}) \circ Q^{k..m}(\mathsf{v}) \cup P(\mathsf{x}) \circ Q(\mathsf{x}) \qquad \forall \mathsf{x} \in \mathrm{desc}_{p-2}(\mathsf{c}_k, \ldots, \mathsf{c}_m)$$

$$\mathcal{U}(\delta(\mathsf{T}_j, \bar{e}), \bar{e}) = P(\mathsf{v}) \circ [Q^{k..m}(\mathsf{v}) /\!\!/ D(\mathsf{n})] \cup P^{+\mathsf{n},0}(\mathsf{v}) \circ [D(\bullet) /\!\!/ Q^{k..m}(\mathsf{v})] \cup P^{+\mathsf{n},d}(\mathsf{x}) \circ Q(\mathsf{x}) \qquad \forall \mathsf{x} \in \mathrm{desc}_{p-2}(\mathsf{c}_k, \ldots, \mathsf{c}_m),\ d = \mathrm{dist}(\mathsf{c}_i, \mathsf{x}) + 1$$

c_i : i-th child of v

Delete node n, DEL(n):

$$\delta(\mathsf{T}_j, \bar{e}) = P(\mathsf{v}) \circ Q^{k..k}(\mathsf{v}) \cup P(\mathsf{x}) \circ Q(\mathsf{x}) \qquad \forall \mathsf{x} \in \mathrm{desc}_{p-1}(\mathsf{n})$$

$$\mathcal{U}(\delta(\mathsf{T}_j, \bar{e}), \bar{e}) = P(\mathsf{v}) \circ [Q^{k..k}(\mathsf{v}) /\!\!/ Q(\mathsf{n})] \cup P^{-\mathsf{n}}(\mathsf{x}) \circ Q(\mathsf{x}) \qquad \forall \mathsf{x} \in \mathrm{desc}_{p-1}(\mathsf{n}) \setminus \{\mathsf{n}\}$$

v : n is the k-th child of v

Rename node n to l': REN$(\mathsf{n}, \mathtt{l}')$

$$\delta(\mathsf{T}_j, \bar{e}) = P(\mathsf{v}) \circ Q^{k..k}(\mathsf{v}) \cup P(\mathsf{x}) \circ Q(\mathsf{x}) \qquad \forall \mathsf{x} \in \mathrm{desc}_{p-1}(\mathsf{n})$$

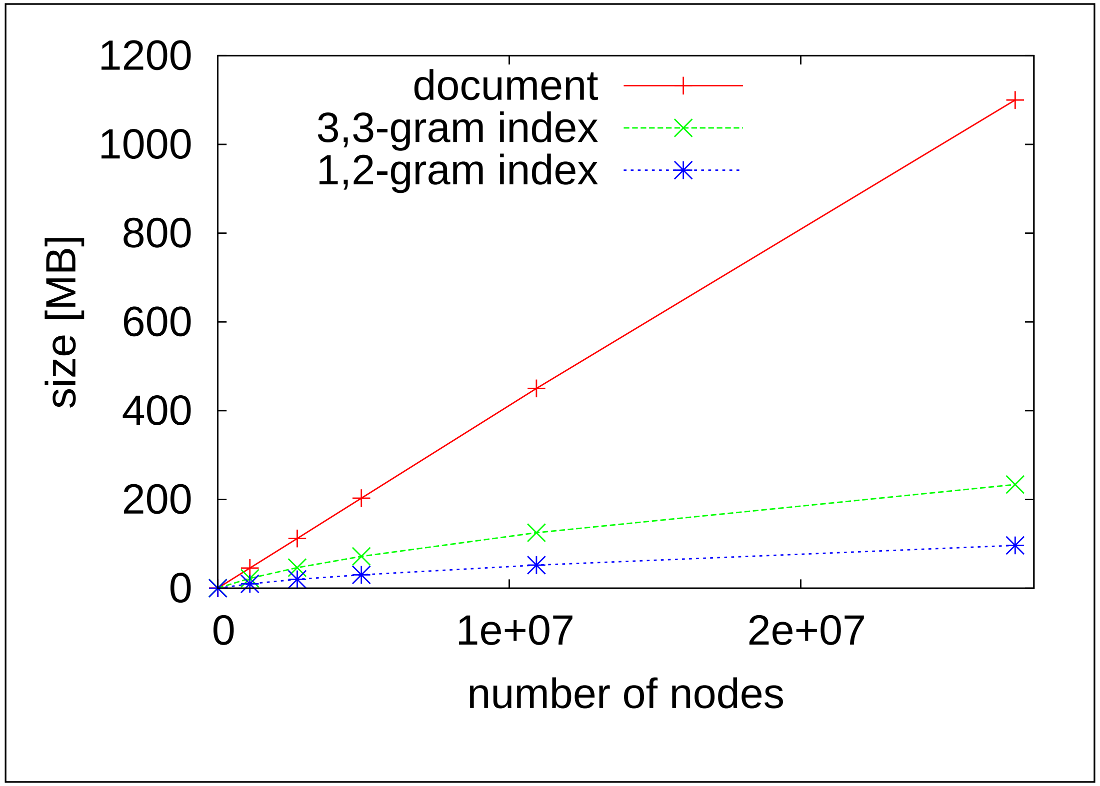
$$\mathcal{U}(\delta(\mathsf{T}_j, \bar{e}), \bar{e}) = P(\mathsf{v}) \circ [Q^{k..k}(\mathsf{v}) /\!\!/ D(\mathsf{m})] \cup P^{\mathsf{n}/\mathsf{m}}(\mathsf{x}) \circ Q(\mathsf{x}) \qquad \forall \mathsf{x} \in \mathrm{desc}_{p-1}(\mathsf{n})$$

$\mathsf{m} = (\mathrm{id}(\mathsf{n}), l')$ v : n is the k-th child of v

Index Size

Index Size

Index size linear in tree size

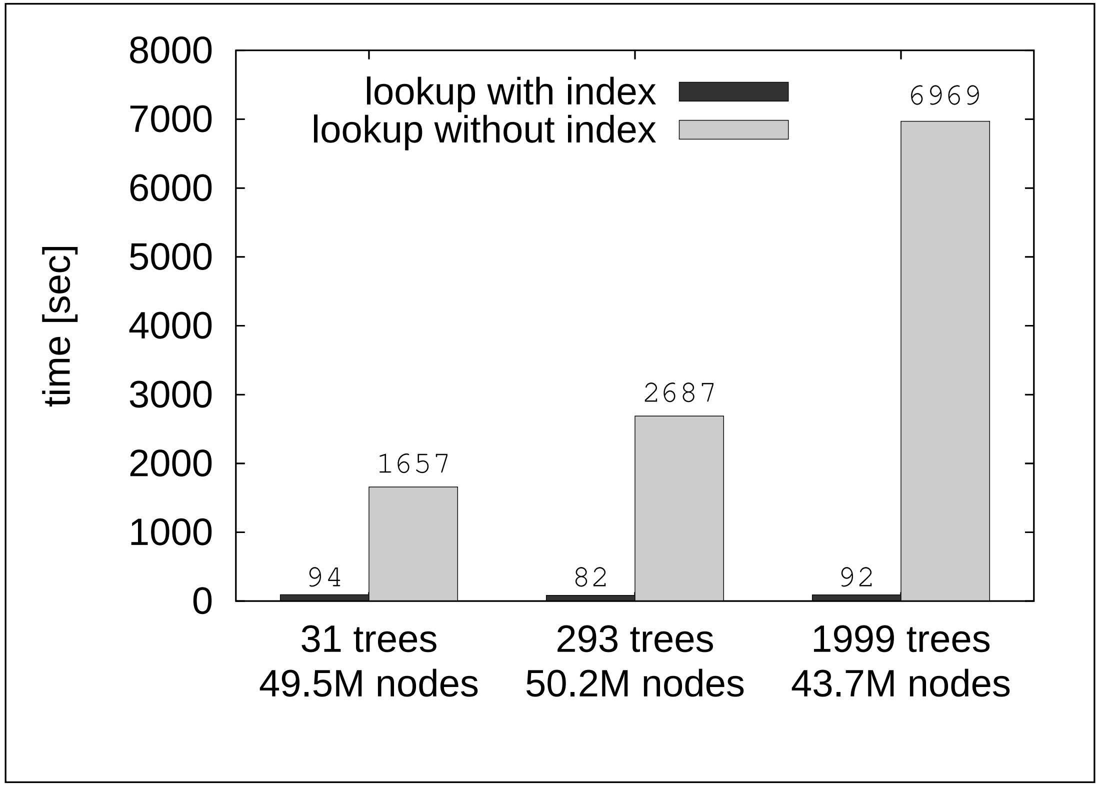


- Experiment: **synthetic** data (XMark)
  - vary document size
  - compute index
  - compare index size with tree size

Lookup Efficiency

Lookup Efficiency

Index greatly increases efficiency for lookup

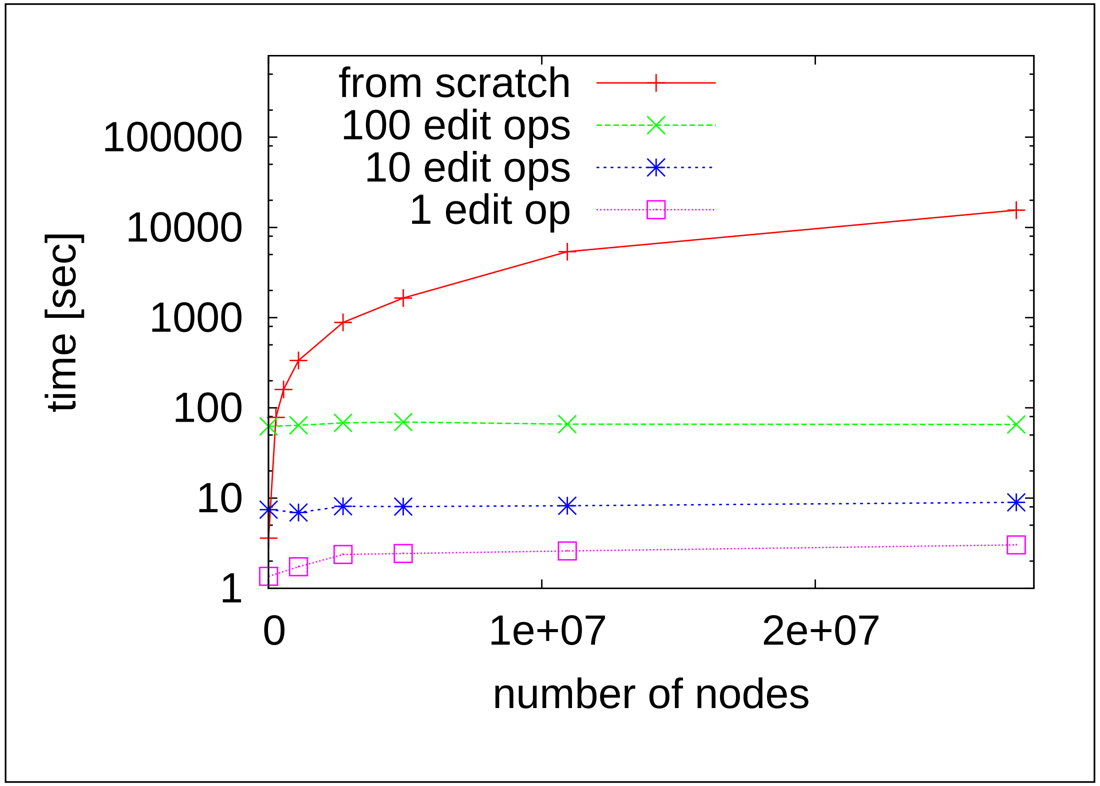


- Experiment: **synthetic** data (XMark)
  - lookup with/without index
  - different document sets of similar size
  - measure wall clock time

Incremental Update vs. Recomputation

Incremental Update vs. Recomputation

Update independent of tree size

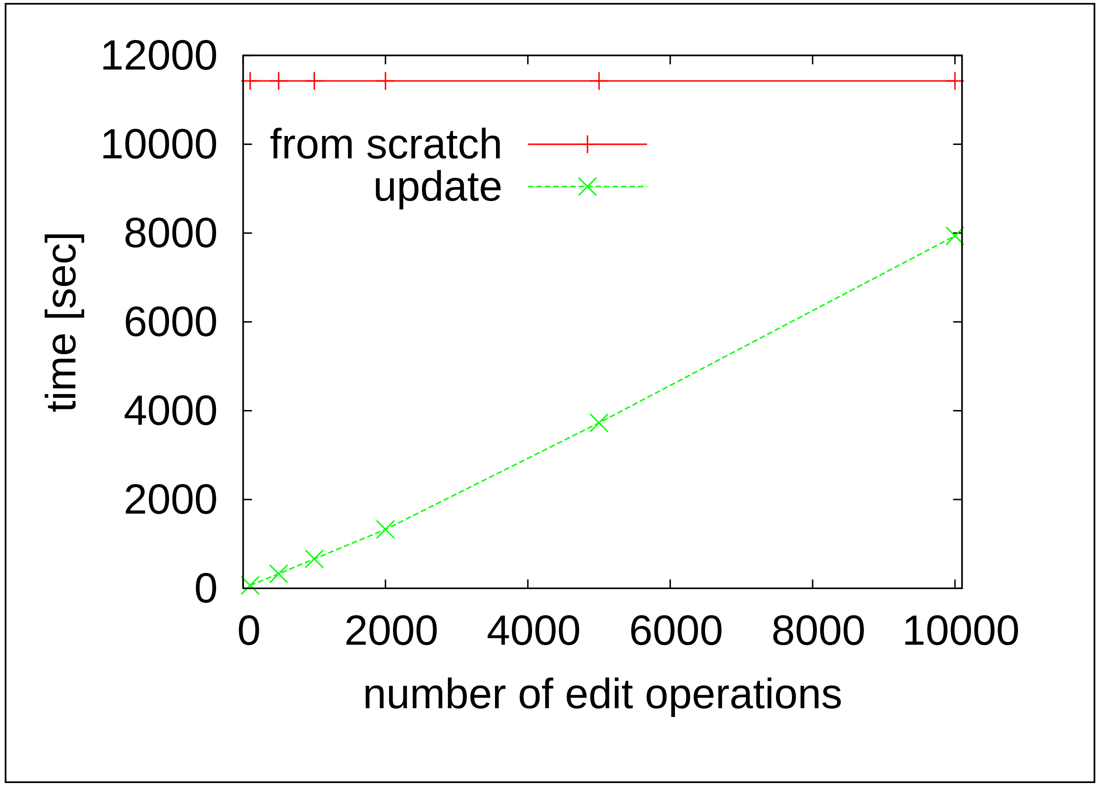


- Experiment: **synthetic** data (XMark)
  - vary tree size (up to 27M nodes)
  - compute incremental update
  - compute index from scratch
  - measure wall clock time

Incremental Update Scalability

Incremental Update Scalability

Update linear in **log size**



- Experiment: **DBLP** (211MB, 11M nodes)
  - vary number of edit operations
  - compute incremental update
  - compute index from scratch
  - measure wall clock time

Breakdown of Update Time

Breakdown of Update Time

Action	Number of edit operations			
	1	10	100	1000
Δ_n^+	0.642s	3.903s	37.533s	391.513s
$\mathtt{I}^+ = \lambda(\Delta_n^+)$	0.184s	0.199s	0.287s	0.443s
Δ_n^-	0.196s	2.836s	27.967s	295.104s
$\mathtt{I}^- = \lambda(\Delta_n^-)$	0.177s	0.191s	0.185s	0.383s
$\mathtt{I}_0 \setminus \mathtt{I}^- \cup \mathtt{I}^+$	2.206s	2.770s	6.475s	19.780s
total	3.405s	9.900s	72.448s	707.224s

- Experiment: **DBLP** (211MB, 11M nodes)
  - vary number of edit operations
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  - wall clock time for each steps

Breakdown of Update Time

Δ^+, Δ^-: main share

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Breakdown of Update Time

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Hashing very cheap

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Breakdown of Update Time

Δ^+, Δ^-: main share

Hashing very cheap

$\mathcal{I}_n = \mathcal{I}_0 \setminus \mathcal{I}^- \cup \mathcal{I}^+$: **sublinear** in **log size**

Action	Number of edit operations			
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Related Work

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- pq-**Gram distance** (Augsten et al., VLDB 2005)
  - edit distance approximation
  - properties analyzed in (Augsten et al., VLDB 2005)

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  - (Yang et al., SIGMOD 2005): *lower bound* for edit distance
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  - (Weis and Naumann, SIGMOD 2005): XML *duplicate detection*
  - (Cobéna et al., ICDE 2002), (Lee et al., TKDE 2004): XML *change detection*
- **Approximate XML join** by (Guha et al., SIGMOD 2002), **index** by (Guha et al., ICDE 2003)
  - optimize join based on tree edit distance using reference sets
  - updates of reference sets not addressed

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- **Future work**
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  - subtree edit operations (e.g. subtree move)
  - compute updates for edit ops in parallel