

Similarity Search

Token-Based Tree Distances

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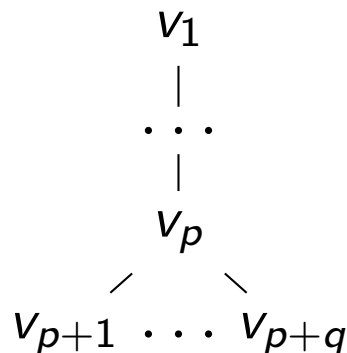
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Outline

- 1 Token-based Tree Distances
- 2 Binary Branches
- 3 pq-Grams
- 4 Conclusion

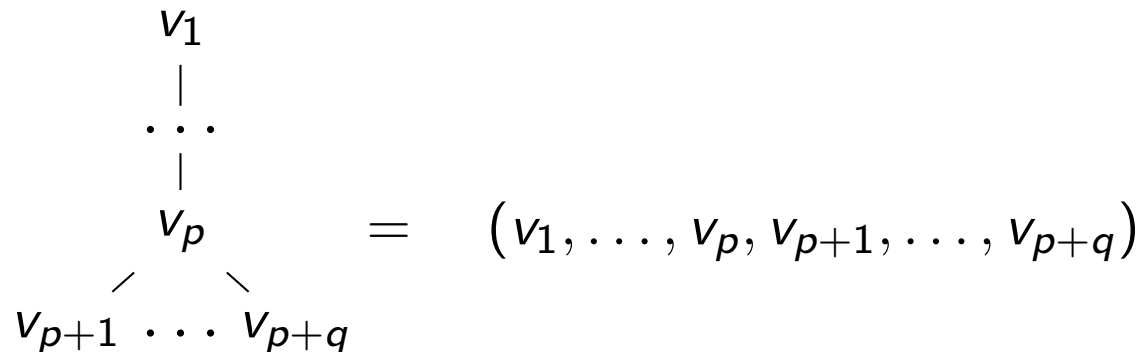
Tokens for Trees – Intuition

- q -Grams for strings:
 - split string into substrings (q -grams) of length q
 - strings with many common substrings are similar
- Tokens for trees:
 - split tree into small subunits (tokens) of the same shape
 - tokens may be individual nodes, subtrees, or subgraphs
 - trees with many common tokens are similar
- **Example:** the so-called pq -gram tokens are besom-shaped subtrees with $p + q$ nodes



Token Profile and Label Tuples

- Token profile $P(T)$: set of all tokens of tree T
 - a token may be a subtree or a subgraph of the tree
 - the token profile $P(T)$ of a tree T is the set of all its tokens
- A linear encoding of a token traverses all its nodes in preorder:



- Label tuple $\lambda(t)$: tuple of the nodes labels $\lambda(v_i)$ of token $t = (v_1, v_2, \dots, v_k)$ in preorder:

$$\lambda(t) = (\lambda(v_1), \lambda(v_2), \dots, \lambda(v_k))$$

Token Index

Definition (Token Index)

Let $P(T)$ be a token profile of tree T . The **token index**, $\mathcal{I}$, of tree T is the **bag of all label tuples** of T ,

$$\mathcal{I}(T) = \bigcup_{g \in P_T} \lambda(g)$$

- **Note:**

- tokens consist of nodes and are unique within a tree
- but: different tokens may yield identical label tuples
- thus the token index may contain duplicates

Token-Based Distance

Definition (Token-Based Distance)

The token-based distance between two trees, T and T' , with token indexes $\mathcal{I}(T)$ and $\mathcal{I}(T')$, respectively, is defined as

$$\delta(T, T') = |\mathcal{I}(T) \uplus \mathcal{I}(T')| - 2|\mathcal{I}(T) \cap \mathcal{I}(T')|$$

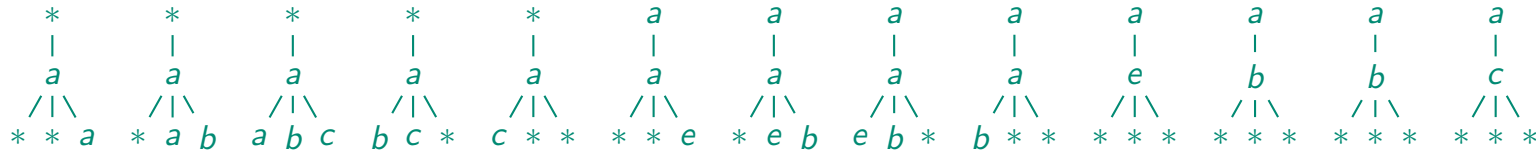
- **Metric normalization** to $[0..1]$: $\delta'_g(T, T') = \frac{\delta_g(T, T')}{|\mathcal{I}(T) \uplus \mathcal{I}(T')| - |\mathcal{I}(T) \cap \mathcal{I}(T')|}$
- **Pseudo-metric** properties hold for normalization [ABG10]:
 - ✓ **self-identity**: $x = y \not\Rightarrow \delta_g(x, y) = 0$
 - ✓ **symmetry**: $\delta_g(x, y) = \delta_g(y, x)$
 - ✓ **triangle inequality**: $\delta_g(x, z) \leq \delta_g(x, y) + \delta_g(y, z)$
- Different trees may have identical indexes.

Storing the Token Index Efficiently

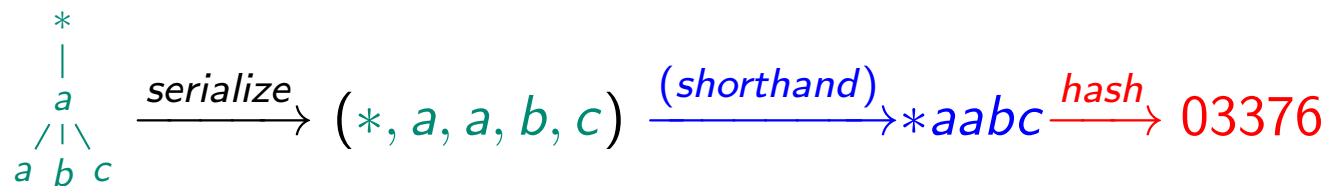
- **Problem:** How to store node labels efficiently?
 - **Long labels:** large storage overhead
 - **Varying label length:** in a relational database, the inefficient VARCHAR type must be used instead of the efficient CHAR type
- **Solution:** Hashing
 - compute fingerprint hash for labels
 - store concatenation of the hashed labels
- **Fingerprint hash function** (e.g., Karp-Rabin [KR87]):
 - maps a string s to a hash value $h(s)$
 - $h(s)$ is of fixed length
 - $h(s)$ is unique with high probability
(for two different strings $s_1 \neq s_2$, $h(s_1) \neq h(s_2)$ with high probability)

Overview: Token Index

- **Token profile:** (so-called pq -grams in the example, $p = 2, q = 3$)



- **Hashing:** map tokens to integers:



label l	h(l)
*	0
a	3
b	7
c	6
e	4

Note: labels may be strings of arbitrary length!

- **Token index:** bag of hashed tokens

$$\mathcal{I}(T) = \{03003, 03037, 03376, 03760, 03600, 33004, 33047, 33470, 33700, 37000, 36000, 34000, 37000\}$$

Intuition: similar trees have similar token indexes.

Binary Tree

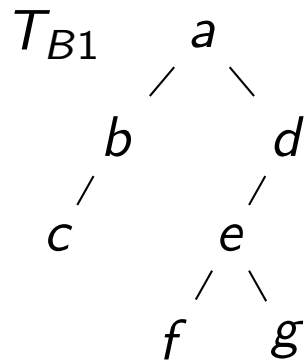
- In a **binary tree**
 - each node has **at most two children**;
 - **left child** and **right child** are distinguished:
a node can have a right child without having a left child;
- **Notation:** $T_B = (N, E_l, E_r)$
 - T_B denotes a binary tree
 - N are the nodes of the binary tree
 - E_l and E_r are the edges to the left and right children, respectively
- **Full binary tree:**
 - binary tree
 - each node has exactly zero or two children.

Example: Binary Tree

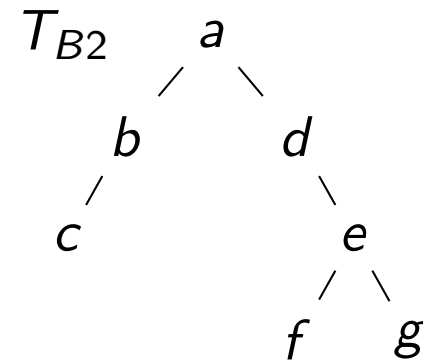
- Two different binary trees: $T_B = (N, E_l, E_r)$

$$T_{B1} = (\{a, b, c, d, e, f, g\}, \{(a, b), (b, c), (d, e), (e, f)\}, \{(a, d), (e, g)\})$$

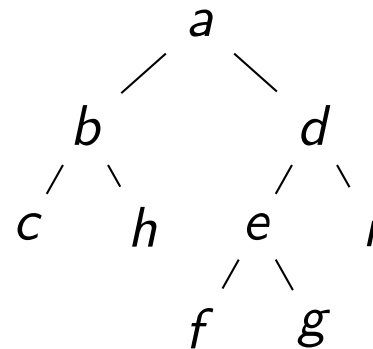
$$T_{B2} = (\{a, b, c, d, e, f, g\}, \{(a, b), (b, c), (e, f)\}, \{(a, d), (d, e), (e, g)\})$$



$\neq$



- A full binary tree:

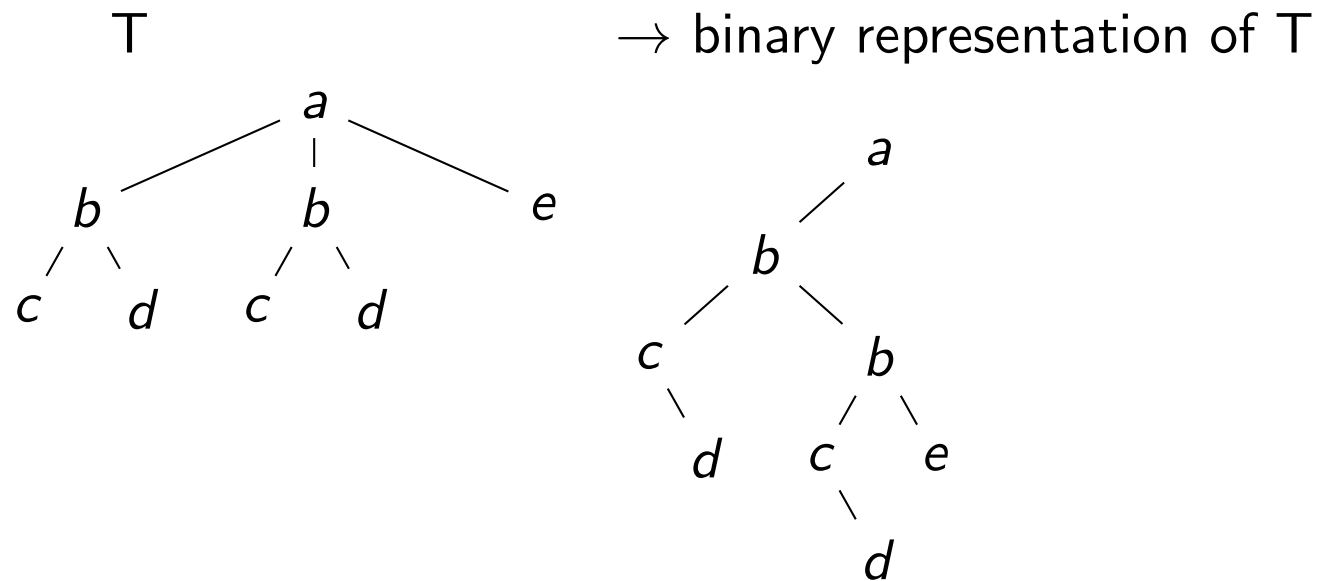


Binary Representation of a Tree

- Binary tree transformation:
 - (i) link all neighboring siblings in a tree with edges
 - (ii) delete all parent-child edges except the edge to the first child
- Transformation **maintains**
 - **label** information
 - **structure** information
- Original tree can be **reconstructed** from the binary tree:
 - a **left edge** represents a **parent-child** relationships in the original tree
 - a **right edge** represents a **right-sibling** relationship in the original tree

Example: Binary Tree Transformation

- Represent tree T as a binary tree:



Normalized Binary Tree Representation

- We extend the binary tree with **null nodes ϵ** as follows:
 - a null node for each **missing left child** of a non-null node
 - a null node for each **missing right child** of a non-null node
- **Note:** Leaf nodes get two null-children.
- The resulting **normalized binary representation**
 - is a **full binary tree**
 - all non-null nodes have two children
 - all leaves are null nodes (and all null nodes are leaves)

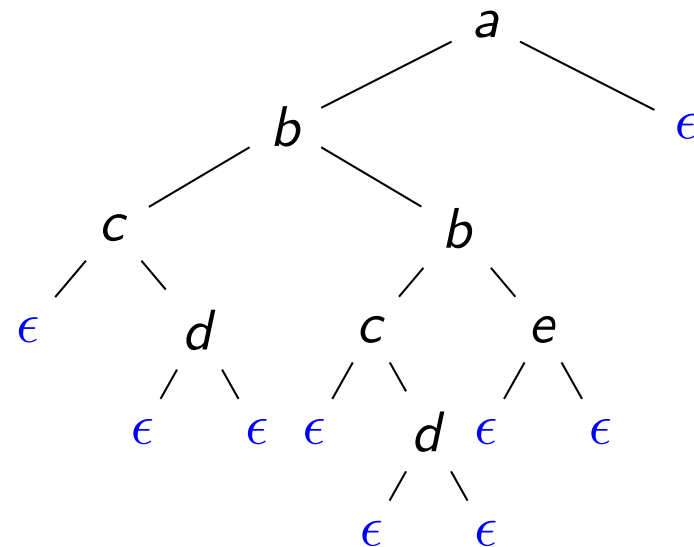
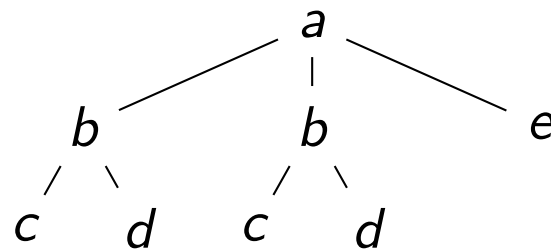
Example: Normalized Binary Tree

- Transforming T to the normalized binary tree $B(T)$:

T

$\rightarrow$

$B(T)$

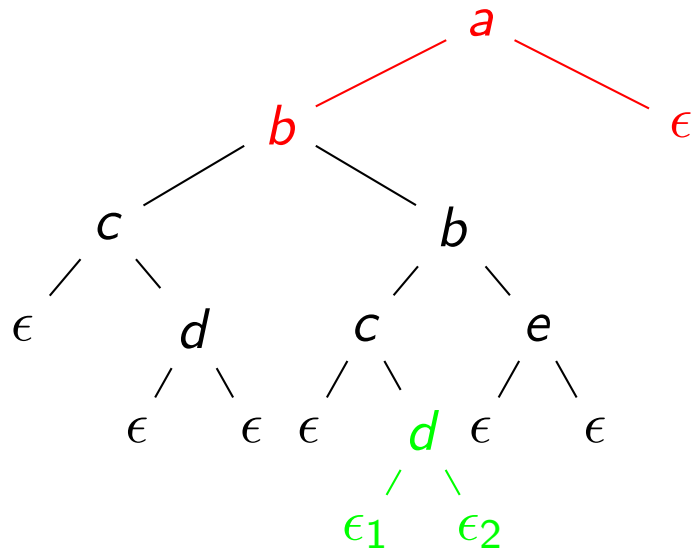


Binary Branch

- A binary branch $BiB(v)$ is
 - a subtree of the normalized binary tree $B(T)$
 - consisting of a non-null node v and its two children
- Example:

$$BiB(a) = (\{a, b, \epsilon\}, \{(a, b)\}, \{(a, \epsilon)\})$$

$$BiB(d) = (\{d, \epsilon_1, \epsilon_2\}, \{(d, \epsilon_1)\}, \{(d, \epsilon_2)\})^1$$



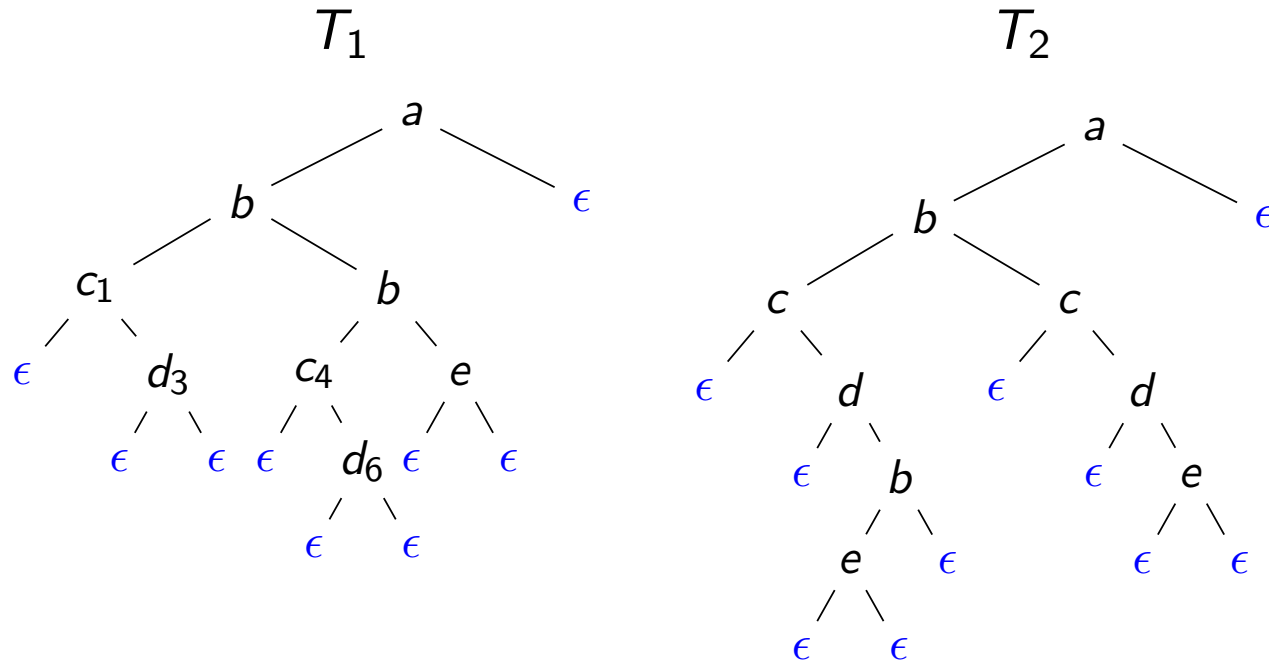
¹Although the two null nodes have identical labels (ϵ), they are different nodes. We emphasize this by showing their IDs in subscript.

Binary Branches of Trees and Datasets

- Binary branches can be **serialized** as label tuples:
 - $BiB(v) = (\{v, a, b\}, \{(v, a)\}, \{(v, b)\}) \rightarrow \lambda(v) \circ \lambda(a) \circ \lambda(b)$
- **Binary branch profile and index:**
 - $P_{bb}(T)$ is the set of all binary branches of T
 - $\mathcal{I}_{bb}(T)$ is the multiset of all binary branch label tuples of T
- **Note:**
 - nodes are unique in the tree, thus binary branches are unique
 - labels are *not* unique, thus the label tuples are *not* unique
- **Binary branch distance:** The binary branch distance between two trees T_1 and T_2 is defined as:

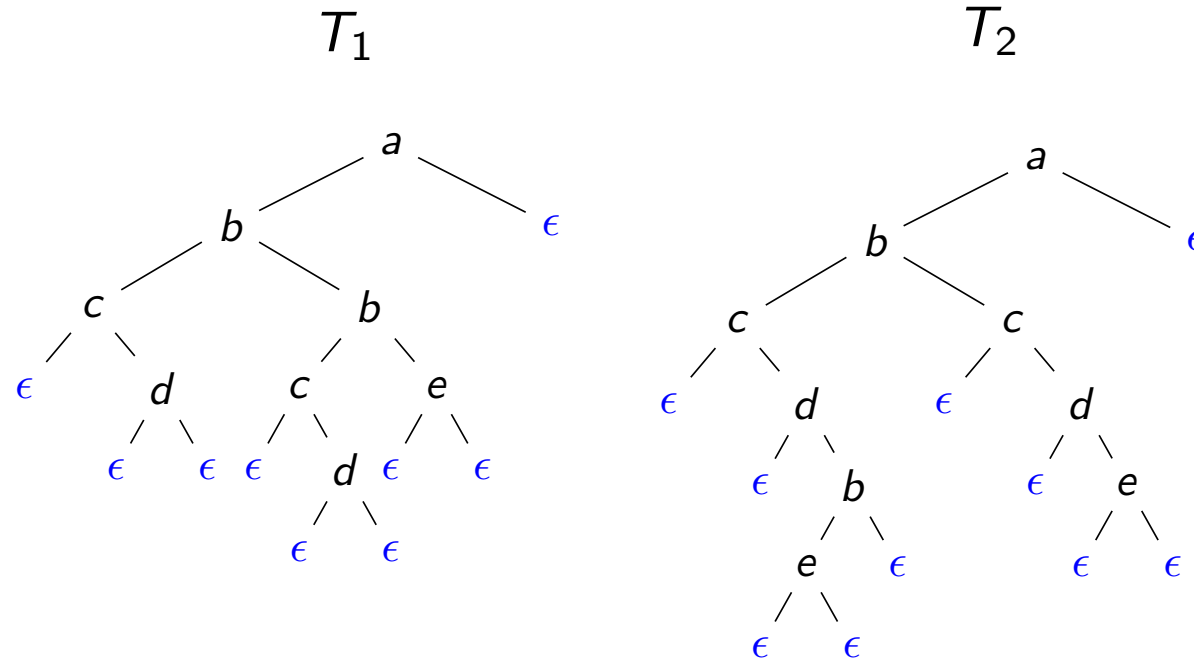
$$\delta_{bb}(T_1, T_2) = |\mathcal{I}_{bb}(T_1) \uplus \mathcal{I}_{bb}(T_2)| - 2|\mathcal{I}_{bb}(T_1) \cap \mathcal{I}_{bb}(T_2)|$$

Example: Binary Branches and Label Tuples



- $BiB(c_1) \neq BiB(c_4)$:
 - $BiB(c_1) = (\{c_1, \epsilon_2, d_3\}, \{(c_1, \epsilon_2)\}, \{(c_1, d_3)\})$
 - $BiB(c_4) = (\{c_4, \epsilon_5, d_6\}, \{(c_4, \epsilon_5)\}, \{(c_4, d_6)\})$
- Serialization of both, $BiB(c_1)$ and $BiB(c_2)$, is identical: 'ced'

Example: Binary Branch Distance



$$\mathcal{I}_{bb}(T_1) = \{ab\epsilon, bcb, c\epsilon d, d\epsilon\epsilon, bce, c\epsilon d, d\epsilon\epsilon, e\epsilon\epsilon\}$$

$$\mathcal{I}_{bb}(T_2) = \{ab\epsilon, bcc, c\epsilon d, d\epsilon b, be\epsilon, e\epsilon\epsilon, c\epsilon d, d\epsilon e, e\epsilon\epsilon\}$$

$$\delta_{bb}(T_1, T_2) = 17 - 2 \cdot 4 = 9$$

Lower Bound Theorem

Theorem (Lower Bound)

Let T_1 and T_2 be two trees. If the tree edit distance between T_1 and T_2 is $\delta_t(T_1, T_2)$, then the binary branch distance between them satisfies

$$\delta_{bb}(T_1, T_2) \leq 5 \times \delta_t(T_1, T_2).$$

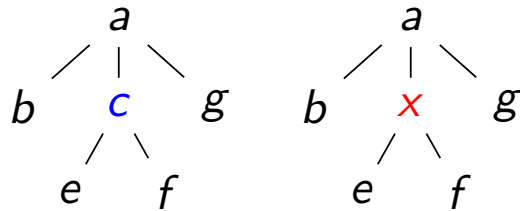
Proof (Sketch — Full Proof in [YKT05]).

- Each node v appears in at most two binary branches.
- *Rename*: Renaming a node causes at most two binary branches in each tree to mismatch. The sum is 4.
- Similar rational for *insert* and its complementary operation *delete* (at most 5 binary branches mismatch).

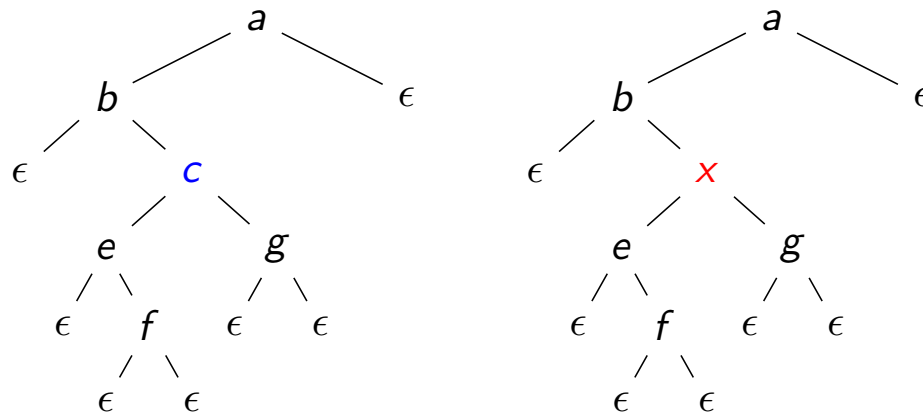


Proof Sketch: Illustration for Rename

- transform T_1 to T_2 : $ren(c, x)$



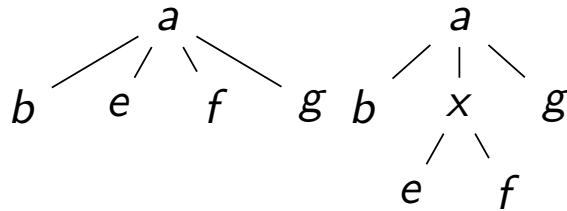
- binary trees $B(T_1)$ and $B(T_2)$



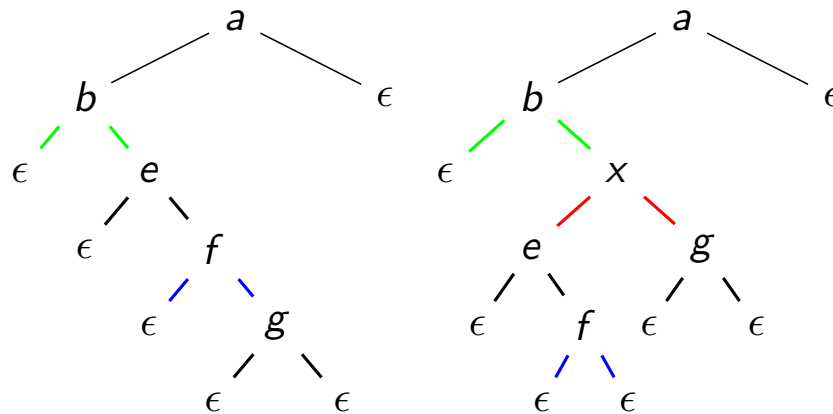
- Two binary branches ($b\epsilon c$, $c e g$) exist only in $B(T_1)$
- Two binary branches ($b\epsilon x$, $x e g$) exist only in $B(T_2)$
- $\delta_t(T_1, T_2) = 1$ (1 rename)
- $\delta_{bb}(T_1, T_2) = 4$ (4 binary branches different)

Proof Sketch: Illustration for Insert

- transform T_1 to T_2 : $ins(x, a, 2, 2)$



- binary trees $B(T_1)$ and $B(T_2)$



- Two binary branches ($b\epsilon e$, $f\epsilon g$) exist only in $B(T_1)$
- Tree binary branches ($b\epsilon x$, $f\epsilon\epsilon$, xeg) exist only in $B(T_2)$
- $\delta_t(T_1, T_2) = 1$ (1 insertion)
- $\delta_{bb}(T_1, T_2) = 5$ (5 binary branches different)

Proof Sketch

- In general it can be shown that
 - **Rename** changes *at most* 4 binary branches
 - **Insert** changes *at most* 5 binary branches
 - **Delete** changes *at most* 5 binary branches
- Each edit operation changes at most 5 binary branches, thus

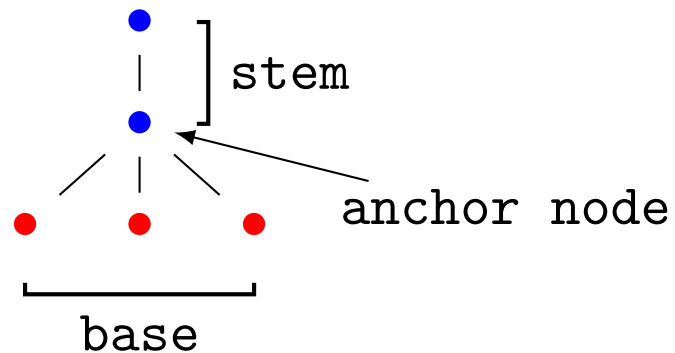
$$\delta_{bb}(T_1, T_2) \leq 5 \times \delta_t(T_1, T_2).$$

Complexity: Binary Branch Distance

- **Generating the binary branches:** $O(n)$ time and space
($n = \max\{|T_1|, |T_2|\}$)
 - the binary branches are formed in a single traversal of the tree
 - for each node of a tree a single binary branch is formed
- **Computing the distance:** $O(n \log n)$ time and $O(n)$ space
 - sort binary branch indexes to compute intersection: $O(n \log n)$
 - alternative: **average case** $O(n)$ runtime complexity
 1. build hash map for index $\mathcal{I}_{bb}(T_2)$
 2. probe label tuples of $\mathcal{I}_{bb}(T_1)$ to compute size of intersection

pq-Grams

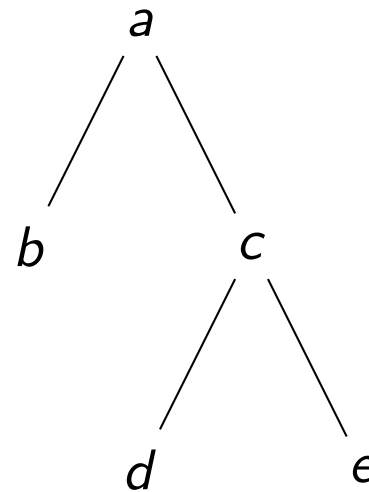
- The shape of a pq -gram ($p=2, q=3$):



- p nodes (anchor node and $p-1$ ancestors) form the **stem**
- q nodes (q consecutive children of the anchor node) form the **base**

pq-Extended Tree

- **Problem:** How can we split the following tree T into 2, 3-grams?

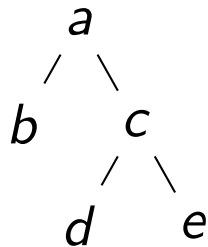


- **Solution:** Extend tree T with dummy nodes ($\bullet$):
 - $p-1$ ancestors to the root node
 - $q-1$ children before the first and after the last child of each non-leaf
 - q children for each leaf
- The result is the **pq-extended tree** T^{pq} .

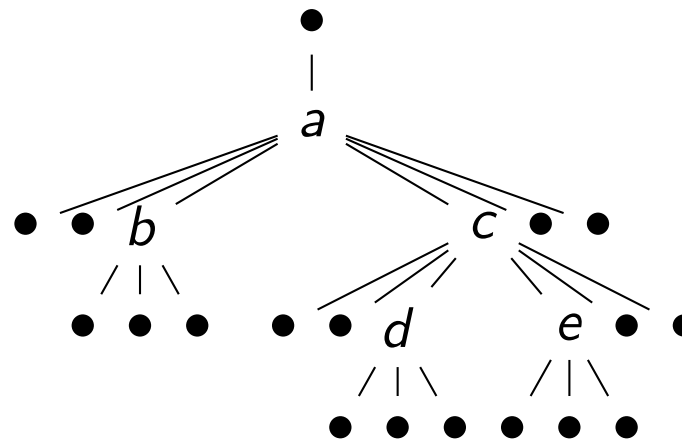
Example: Extended Tree

- An example tree T and its extended tree T^{pq} ($p=2, q=3$):

T



2, 3-extended tree $T^{2,3}$



Definition: *pq*-Gram [ABG05]

Definition (*pq*-Gram)

Let T be a tree, $T^{p,q}$ the respective extended tree, $p > 0$, $q > 0$. A subtree of $T^{p,q}$ is a *pq-gram* g of T iff

- (a) g has q leaf nodes and p non-leaf nodes,
- (b) all leaf nodes of g are children of a single node $a \in N(g)$ with fanout q , called the *anchor node*,
- (c) the leaf nodes of g are consecutive siblings in $T^{p,q}$.

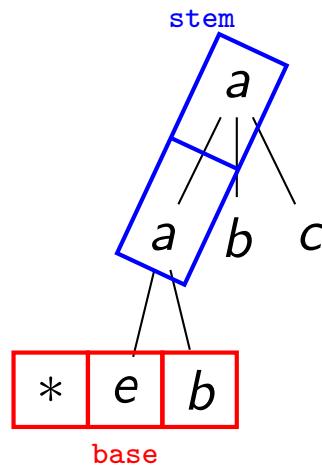
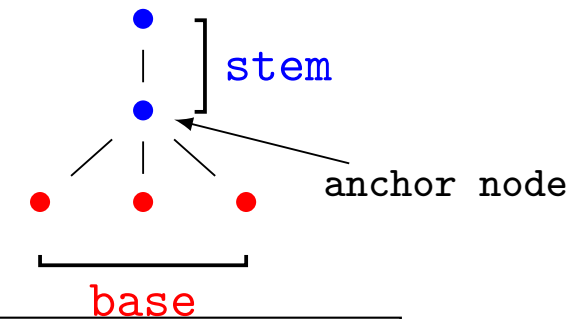
- *Stem*: anchor node and its ancestors in the *pq*-gram.
- *Base*: children of the anchor node in the *pq*-gram.

Definition (*pq*-Gram Profile)

The *pq*-gram profile, P_T , of a tree T is the set of all its *pq*-grams.

Example: Systematically Split Tree

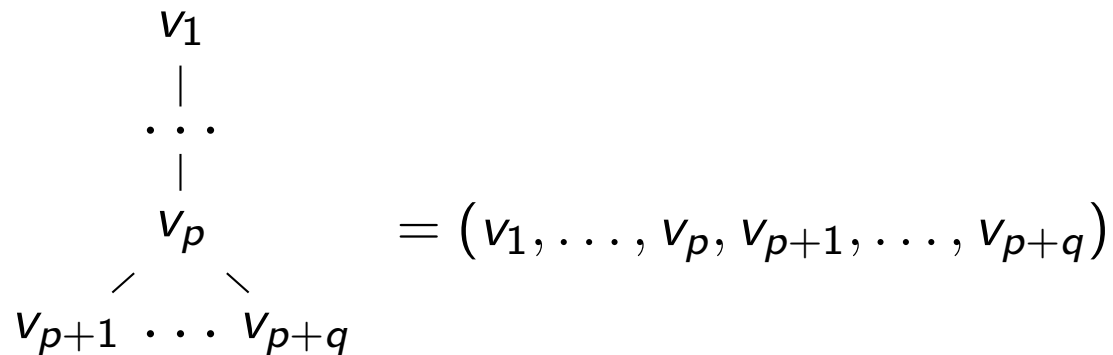
- *pq*-Gram: small subtree with **stem** and **base**
Example: $p = 2$, $q = 3$
- Systematically split tree into *pq*-grams
- *pq*-Gram profile: set of all *pq*-grams of a tree.



*	*	*	*	*
a	a	a	a	a
/ \	/ \	/ \	/ \	/ \
* * a	* a b	a b c	b c *	c * *
a	a	a	a	a
a	a	a	a	e
/ \	/ \	/ \	/ \	/ \
* * e	* e b	e b *	b * *	* * *
a	a	a		
b	b	c		
/ \	/ \	/ \		
* * *	* * *	* * *		

Label Tuples

- **Linear encoding** of a pq -gram g with anchor node v_p :
(traverse pq -gram in preorder)



- **Label tuple**: tuple of the pq -gram's node labels

$$\lambda(g) = (\lambda(v_1), \dots, \lambda(v_{p+q}))$$

for the pq -gram $g = (v_1, \dots, v_{p+q})$.

pq-Gram Index

Definition (pq-Gram Index)

Let T be a tree with profile P_T , $p > 0$, $q > 0$. The pq -gram index, $\mathcal{I}$, of tree T is the **bag of all label tuples** of T ,

$$\mathcal{I}(T) = \bigcup_{g \in P_T} \lambda(g)$$

- Note:
 - pq -grams are unique within a tree
 - but: different pq -grams may yield identical label tuples
 - thus the pq -gram index may contain duplicates

Size of the pq -Gram Index

Theorem (Size of the pq -Gram Index)

Let T be a tree of size $n = l + i$ with l leaves and i non-leaves. The size of the pq -gram index of T is linear in the tree size:

$$|\mathcal{I}^{pq}(T)| = 2l + qi - 1 = O(n)$$

Proof.

1. We **count** all pq -grams whose leftmost leaf is a **dummy node**: Each leaf is the anchor node of exactly one pq -gram whose leftmost leaf is a dummy node, giving l pq -grams. Each non-leaf is the anchor of $q - 1$ pq -grams whose leftmost leaf is a dummy, giving $i(q - 1)$ pq -grams.
2. We **count** all pq -grams whose leftmost leaf is **not a dummy node**: Each node of the tree except the root is the leftmost leaf of exactly one pq -gram, giving $l + i - 1$ pq -grams.

Overall number of pq -grams: $l + i(q - 1) + (l + i - 1) = 2l + qi - 1$. $\square$

The pq -Gram Distance

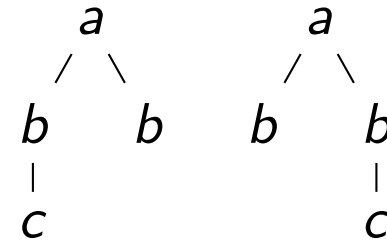
Definition (pq -Gram Distance)

The pq -gram distance between two trees, T and T' , is defined as

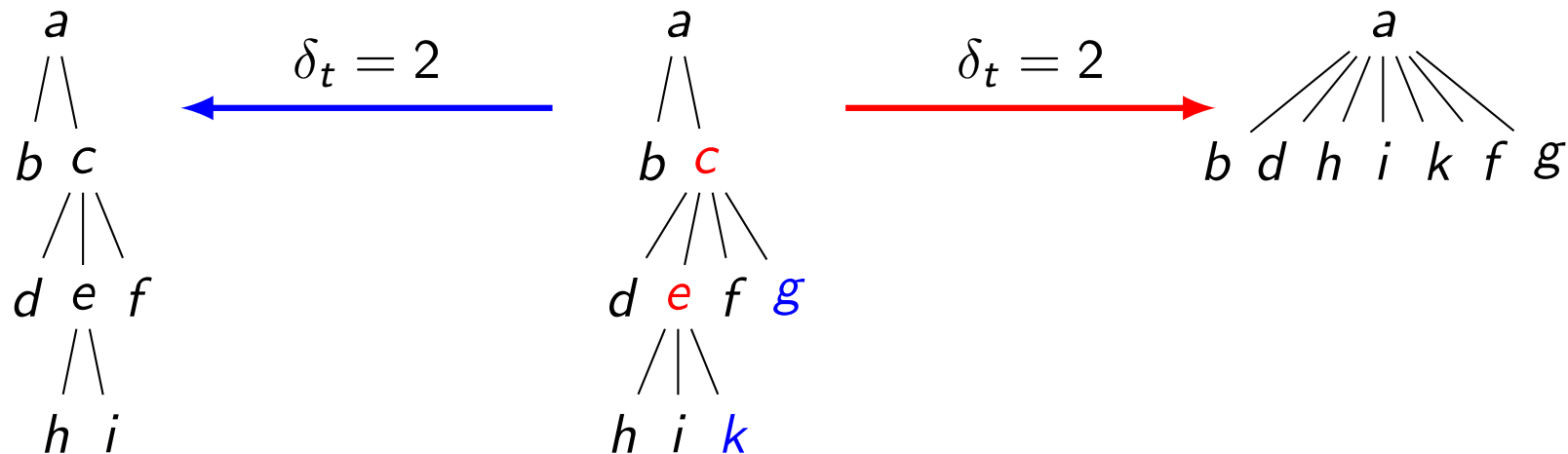
$$\delta_g(T, T') = |\mathcal{I}(T) \uplus \mathcal{I}(T')| - 2|\mathcal{I}(T) \cap \mathcal{I}(T')|$$

- **Metric normalization** to $[0..1]$: $\delta'_g(T, T') = \frac{\delta_g(T, T')}{|\mathcal{I}(T) \uplus \mathcal{I}(T')| - |\mathcal{I}(T) \cap \mathcal{I}(T')|}$
- **Pseudo-metric** properties hold for normalization [ABG10]:
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 - ✓ **symmetry**: $\delta_g(x, y) = \delta_g(y, x)$
 - ✓ **triangle inequality**: $\delta_g(x, z) \leq \delta_g(x, y) + \delta_g(y, z)$

- Different trees may have identical indexes:



Motivation: Unit Cost Model Not Always Intuitive



- Unit cost edit distance:
 - no difference between leaves and non-leaves
 - may lead to non-intuitive results
- **Conclusion:** Non-leaves should have more weight than leaves.

Fanout Weighted Tree Edit Distance

Definition (Fanout Weighted Tree Edit Distance)

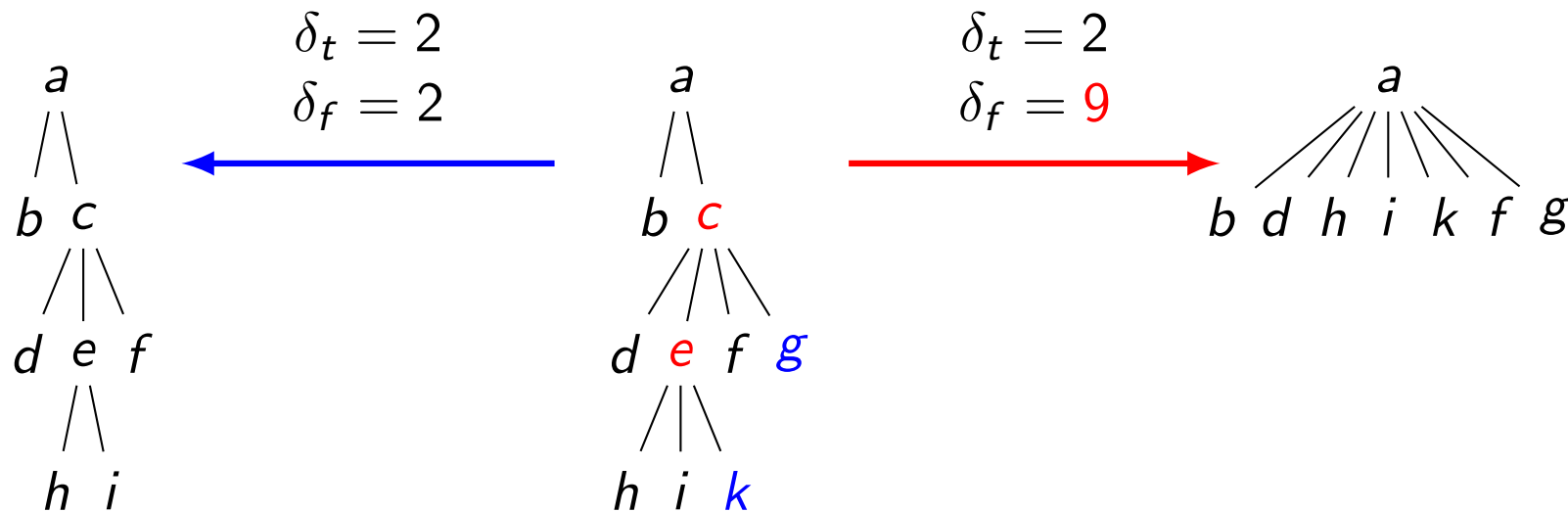
Let T and T' be two trees, $w \in N(T)$ a node with fanout f , $w' \in N(T')$ a node with fanout f' , $c > 0$ a constant. The **fanout weighted tree edit distance**, $\delta_f = (T, T')$, between T and T' is defined as the tree edit distance with the following costs for the edit operations:

- Delete: $\alpha(w \rightarrow \epsilon) = f + c$
 - Insert: $\alpha(\epsilon \rightarrow w') = f' + c$
 - Rename: $\alpha(w \rightarrow w') = (f + f')/2 + c$
-
- **Cost** of changing a **non-leaf** node: proportional to its fanout.
 - **Cost** of changing a **leaf** node: constant c .

Example: Fanout-Weighted Tree Edit Distance

- Fanout-Weighted Tree Edit Distance:

- leaf changes have small cost ($c = 1$ in the example)
- non-leaf changes cost proportional to the node fanout



pq-Gram Distance Lower Bound

Theorem

Let $p = 1$ and $c \geq \max(2q - 1, 2)$ be the cost of changing a leaf node. The pq-gram distance provides a lower bound for the fanout weighted tree edit distance, i.e., for any two trees, T and T' ,

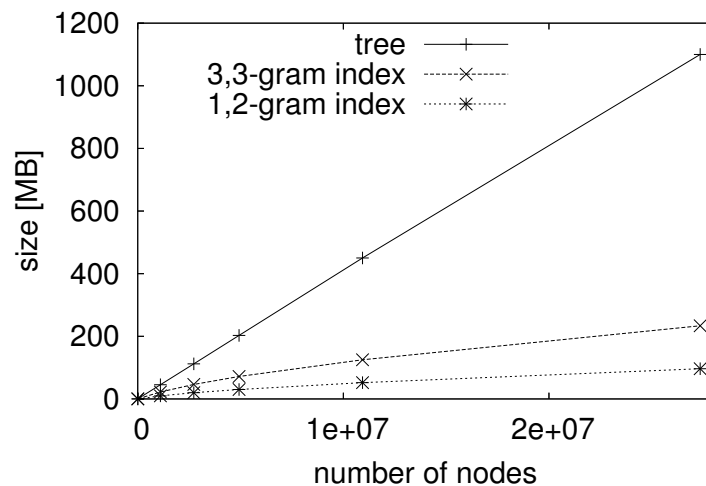
$$\frac{\delta_g(T, T')}{2} \leq \delta_f(T, T').$$

Proof.

See [ABG10] (ACM Transactions on Database Systems). □

Size of the *pq*-Gram Index

- *pq*-Gram index size: linear in the tree size
- Experiment:
 - compute *pq*-gram index for trees with different number of nodes
 - compare tree and index size



[Trees created with `xmlgen`.]

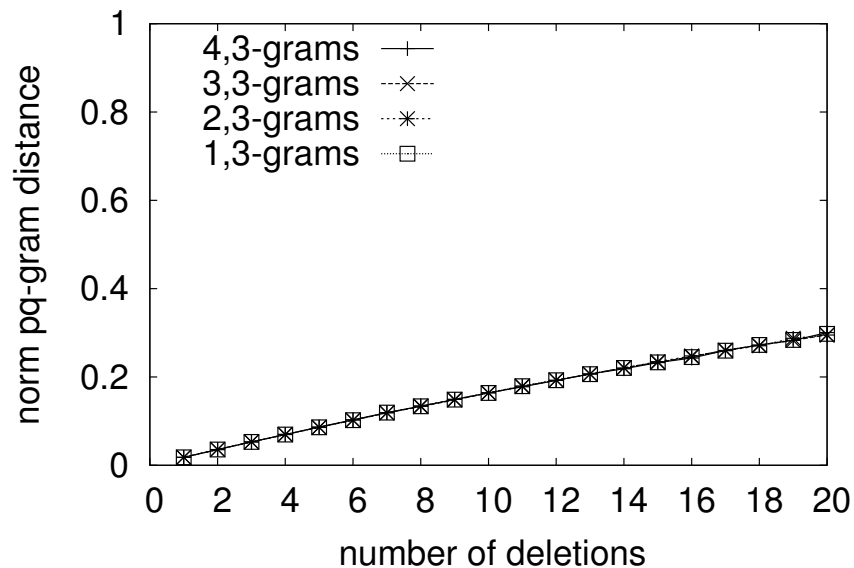
Why is the *pq*-gram index smaller than the tree?

- hash values are smaller than labels
- duplicate *pq*-grams of a tree are stored only once

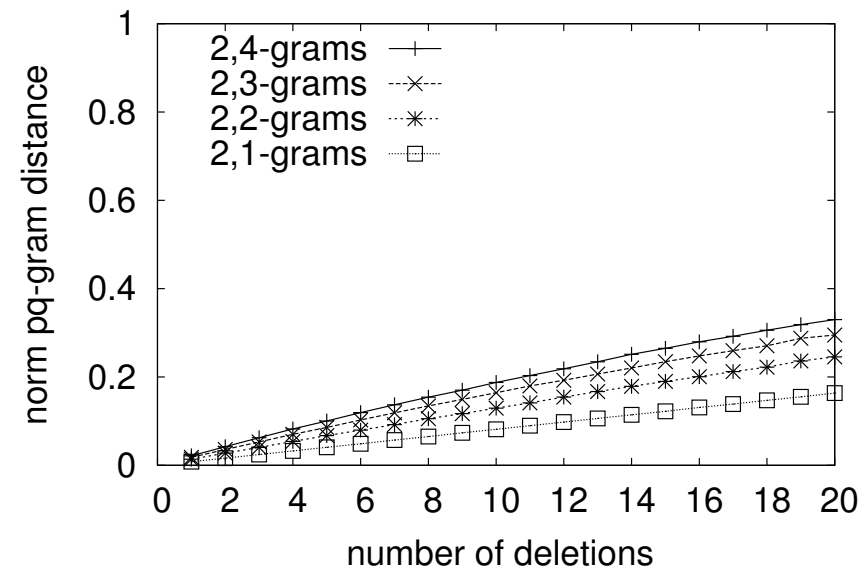
Sensitivity to Structure Change — Leaf

- Cost of **leaf change** $\rightarrow$ depends only on q
- Experiment:
 - delete leaf nodes
 - measure normalized pq -gram distance

vary p



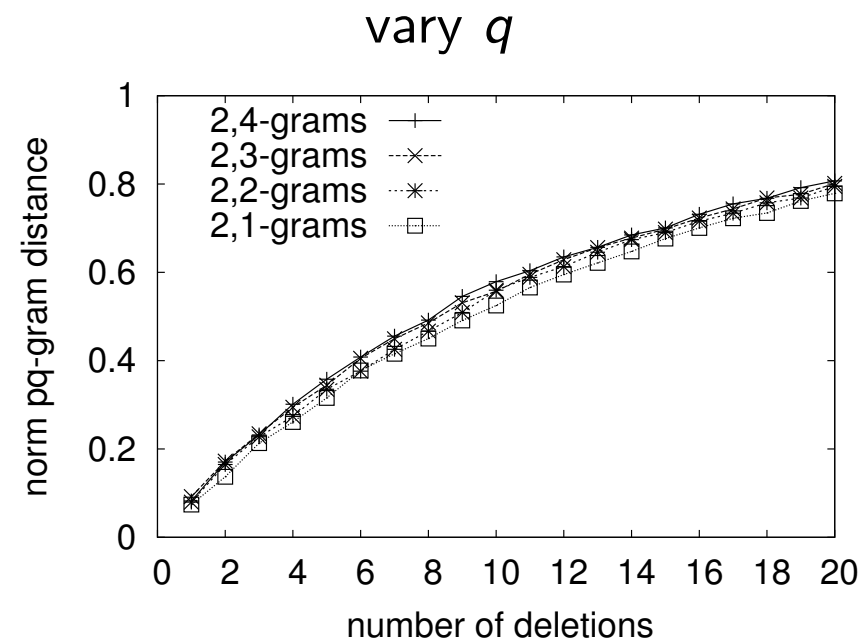
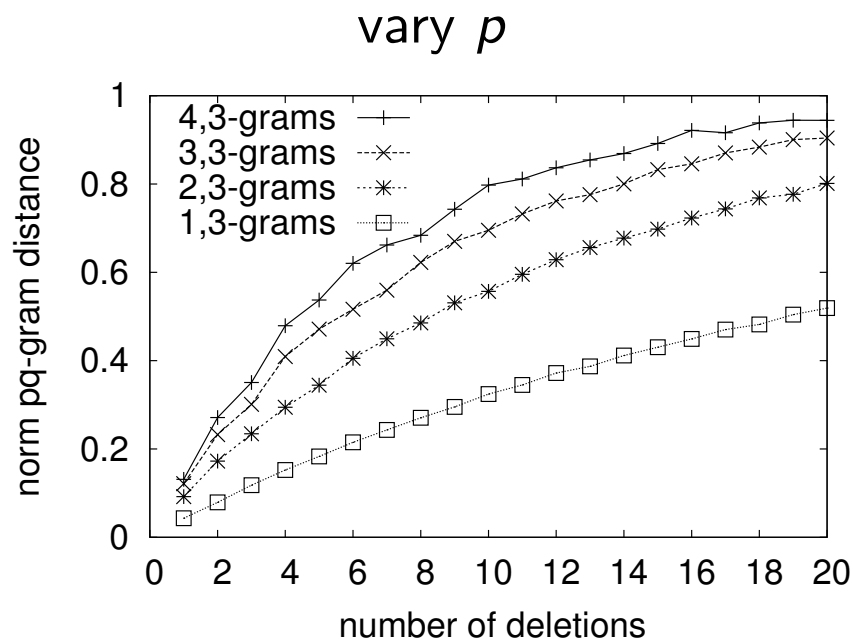
vary q



(Artificial tree with 144 nodes, 102 leaves, fanout 2–6 and depth 6. Average over 100 runs.)

Sensitivity to Structure Change — Non-Leaf

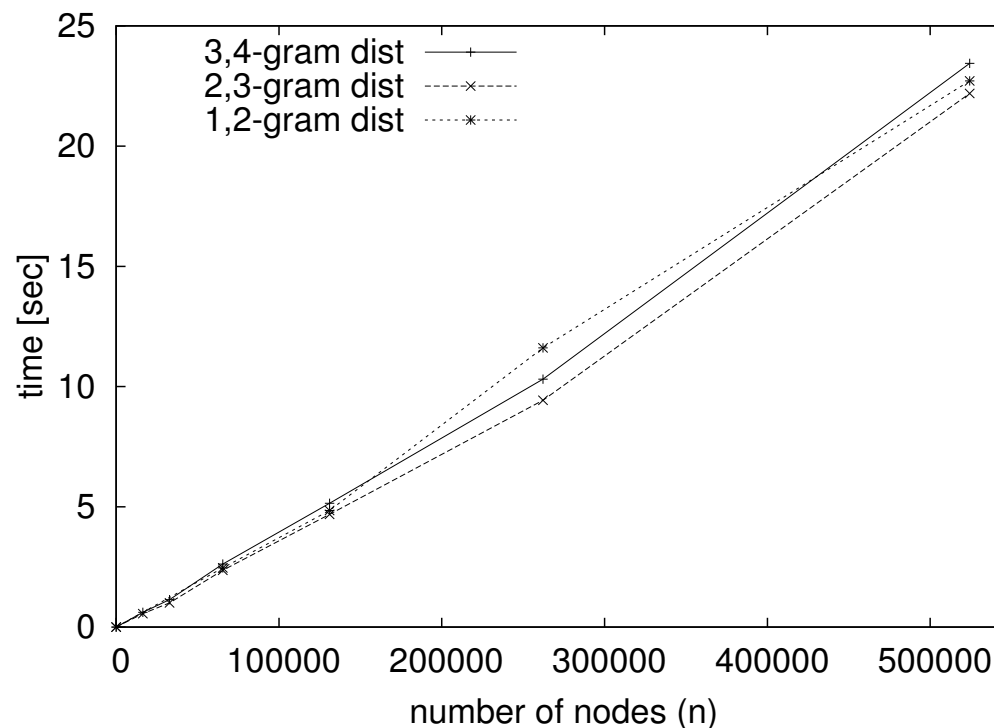
- Cost for **non-leaf change** $\rightarrow$ controlled by p
- **Experiment:**
 - delete non-leaf nodes
 - measure normalized pq -gram distance



(Artificial tree with 144 nodes, 102 leaves, fanout 2–6 and depth 6. Average over 100 runs.)

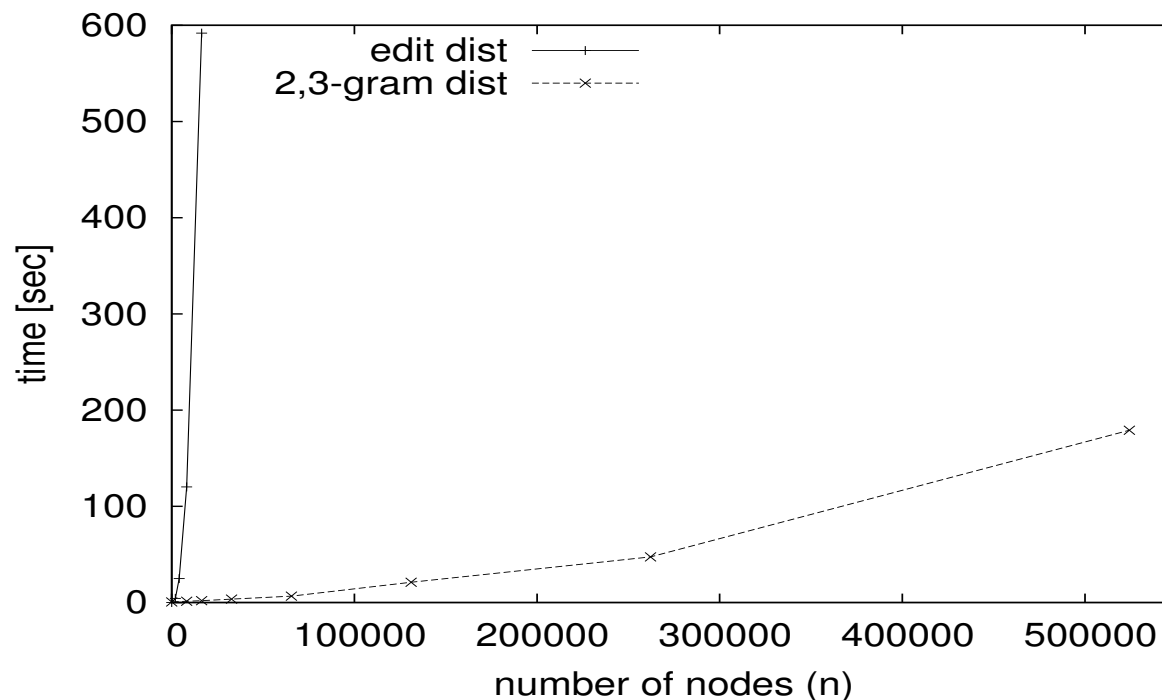
Influence of p and q on Scalability

- Scalability (almost) independent of p and q .
- **Experiment:** For pair of trees
 - compute pq -gram distance for varying p and q
 - vary tree size: up to 10^6 nodes
 - measure wall clock time



Scalability to Large Trees

- *pq*-gram distance → **scalable** to large trees
- compare with edit distance
- **Experiment:** For pair of trees
 - compute tree edit distance and *pq*-gram distance
 - vary tree size: up to 5×10^5 nodes
 - measure wall clock time



pq-Grams vs. other Edit Distance Approximations

Effectiveness: *pq*-grams outperform all other approximations

Experiment: two sets of *address trees* (299 and 302 trees)

- compute distances between all tree pairs
- find matches (symmetric nearest neighbor)

Distance	Correct	Recall	Precision	f-Measure	Runtime
fanout edit dist	259	86.6%	98.5%	0.922	19 min
unit edit dist	247	82.6%	96.5%	0.890	14 min
node intersection	197	65.9%	93.8%	0.774	4.3s
p,q-grams	236	78.9%	98.7%	0.877	8.1s
tree-embedding	206	68.9%	96.3%	0.803	7.1s
binary branch	193	64.5%	93.2%	0.763	7.4s
bottom-up	148	49.6%	92.5%	0.645	67.0s

Summary

- Binary Branch Distance

- lower bound of the **unit cost** tree edit distance
- trees are split into binary branches (small subgraphs)
- similar trees have many common binary branches
- complexity $O(n \log n)$ time and (n) space

- *pq*-Gram Distance

- lower bound for the **fanout weighted** tree edit distance
- trees are split into *pq*-grams (small subtrees)
- similar trees have many common *pq*-grams
- complexity $O(n \log n)$ time and $O(n)$ space



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