Part XVII

Staircase Join—Tree-Aware Relational (X)Query Processing

Outline of this part

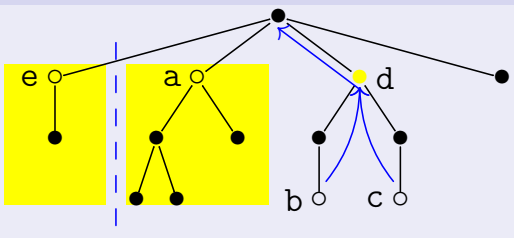
1. XPath Accelerator—Tree aware relational XML representation
   - Enhancing Tree Awareness
2. Staircase Join
   - Tree Awareness
   - Context Sequence Pruning
   - Staircases
3. Injecting 🪜 into PostgreSQL
4. Outlook: More on Performance Tuning in MonetDB/XQuery

Enhancing tree awareness

- We now know that the XPath Accelerator is a true **isomorphism** with respect to the XML skeleton **tree structure.**
  - Witnessed by our discussion of **shredder** ($\mathcal{E}$) and **serializer** ($\mathcal{E}^{-1}$).
- We will now see how the database kernel can benefit from a more elaborate **tree awareness** (beyond document order and semantics of the four major XPath axes).
- This will lead to the design of **staircase join** ⟓, the core of MonetDB/XQuery's XPath engine.
  - We will also discuss issues of how to tune ⟓ to get the most out of modern CPUs and memory architectures.

Tree awareness?

Document order and XPath semantics aside, what are further **tree properties** of value to a relational XML processor?



1. The **size of the subtree** rooted in node a is 5
2. The leaf-to-root **paths** of nodes b, c **meet** in node d
3. The **subtrees** rooted in e and a are necessarily **disjoint**

Tree awareness ①: Subtree size

We have seen that tree property **subtree size** (① on previous slide) is implicitly present in a *pre*/*post*-based tree encoding:

$$post(v) - pre(v) = size(v) - level(v)$$

- To exploit property subtree size, we were able to find a means on the **SQL language level**, *i.e.*, **outside the database kernel.**

⇒ This led to *window shrink-wrapping* for the XPath `descendant` axis.

Tree awareness on the SQL level

Shrink-wrapping for the `descendant` axis

$$Q \equiv (c)/\texttt{following::node()/descendant::node()}$$

path(Q)

```
SELECT   DISTINCT v2.pre
  FROM   accel v1, accel v2
 WHERE   v1.pre > c.pre
   AND   v1.pre < v2.pre
   AND   v1.post > c.post
   AND   v1.post > v2.post
   AND   v2.pre <= v1.post + h AND v2.post >= v1.pre + h
ORDER BY v2.pre
```

Tree awareness ②: Meeting `ancestor` paths

- Evaluation of axis `ancestor` can clearly benefit from knowledge about the exact element node where several given **node-to-root paths meet.**
  - For example:
    For context nodes $c_1, \ldots, c_n$, determine their lowest common ancestor $v = lca(c_1, \ldots, c_n)$.
    $\Rightarrow$ Above v, produce result nodes once only.

    (This still produces duplicate nodes below v.)
- This knowledge *is* present in the encoding but is **not as easily expressed on the level of commonly available relational query languages** (such as, SQL or relational algebra).

Flashback: XPath: Ensuring order is not for free

The strict XPath requirement to construct a result in document order may imply **sorting effort** depending on the actual XPath implementation strategy used by the processor.

```
(<x>
  <x><y id="0"/></x>                          ⇒   (<y id="0"/>,
  <y id="1"/>                                      <y id="1"/>)
 </x>)/descendant-or-self::x/child::y
```

- In many implementations, the `descendant-or-self::x` step will yield the context node sequence (`<x>···</x>`,`<x>···</x>`) for the `child::y` step.
- Such implementations thus will typically extract `<y id="1"/>` before `<y id="0"/>` from the input document.

Flashback: `(e,f)/descendant::node()`

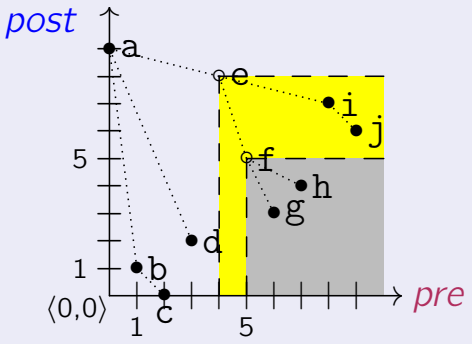
Context & frag. encodings

context

pre	*post*	···
5	5	
4	8	

accel

pre	*post*	···
0	9	
1	1	
2	0	
3	2	
4	8	
5	5	
6	3	
7	4	
8	7	
9	6	



SQL query with expanded *window*() predicate

```
SELECT    DISTINCT v1.*
FROM      context v, accel v1
WHERE     v1.pre > v.pre AND v1.post < v.post
ORDER BY  v1.pre
```


Tree awareness ③: Disjoint subtrees

- An XPath location step cs/α is evaluated for a context node **sequence** cs.
  - This "*set-at-a-time*" processing mode is key to the efficient evaluation of queries against bulk data. We want to map this into **set-oriented operations** on the RDBMS.
    (Remember: location step is translated into **join** between context node sequence and document encoding table *accel*.)
- But: If two context nodes $c_{i,j} \in cs$ are in α-relationship, **duplicates** and **out-of-order** results may occur.
  - Need efficient way to identify the $c_i \in cs$ which are *not* in α-relationship with any other c_j
    (for $\alpha =$ `descendant`: "$c_{i,j}$ in disjoint subtrees?").

Staircase Join: An injection of tree awareness

Since we fail to explain tree properties ② and ③ at the relational language level interface, we opt to **invade the database kernel** in a controlled fashion.[46]

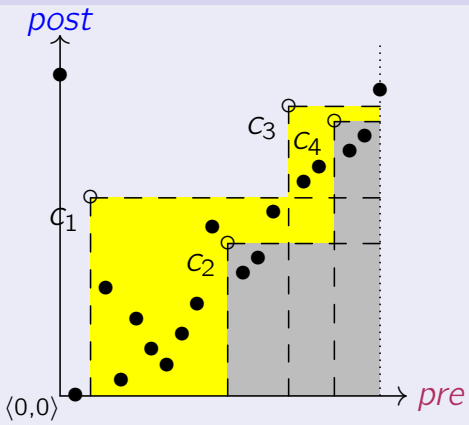
- Inject a new relational operator, **staircase join** ⟓, into the relational query engine.
- Query translation and optimization in the presence of ⟓ continues to work like before (*e.g.*, selection pushdown).
- The ⟓ algorithm encapsulates the necessary tree knowledge. ⟓ is a **local change** to the database kernel.

[46] Remember: All of this is optional. XPath Accelerator is a purely relational XML document encoding, working on top of *any* RDBMS.

Tree awareness: Window overlap, coverage

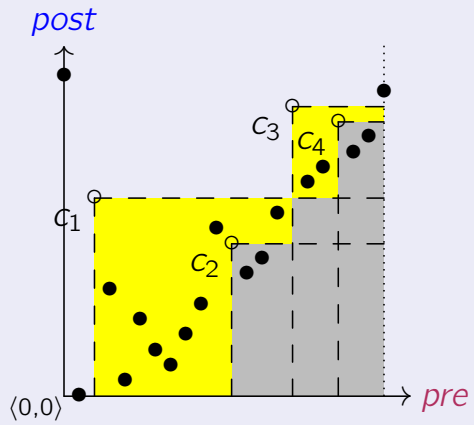
Location step (c_1, c_2, c_3, c_4)/`descendant::node()`. The pairs (c_1, c_2) and (c_3, c_4) are in `descendant`-relationship:

Window overlap and coverage (`descendant` axis)

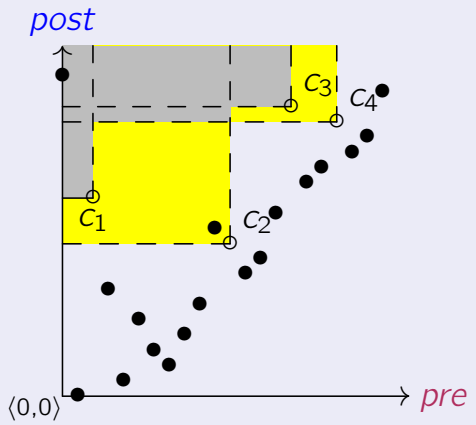


Tree awareness: Window overlap, coverage

Axis window overlap (`descendant` axis)

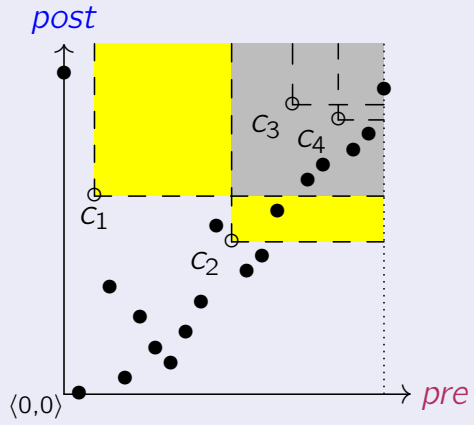


Axis window overlap (`ancestor` axis)

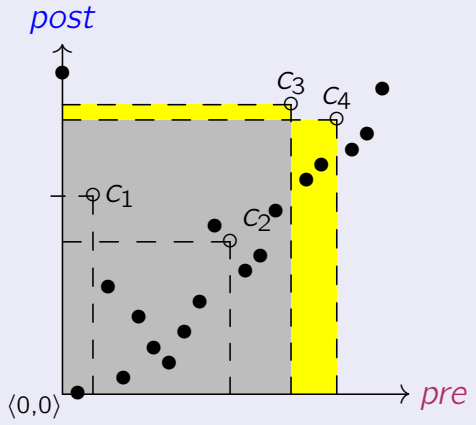


Tree awareness: Window overlap, coverage

Axis window overlap (`following` axis)



Axis window overlap (`preceding` axis)



Context node sequence pruning

We can turn these observations about axis window overlap and coverage into a simple strategy to **prune the initial context node sequence** for an XPath location step.

Context node sequence pruning

Given cs/α, determine minimal $cs^- \subseteq cs$, such that

$$cs/\alpha \quad = \quad cs^-/\alpha \ .$$

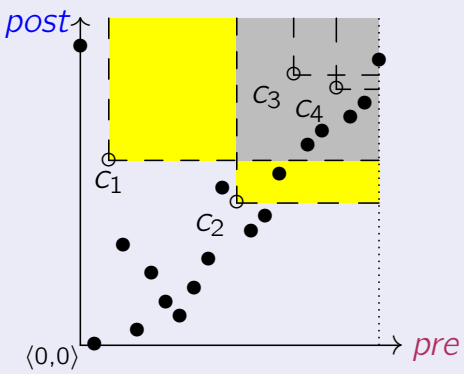
We will see that this minimization leads to axis step evaluation on the *pre*/*post* plane, which never emits duplicate nodes or out-of-order results.[47]

[47] The `ancestor` axis needs a bit more work here.

Context node pruning: `following` axis

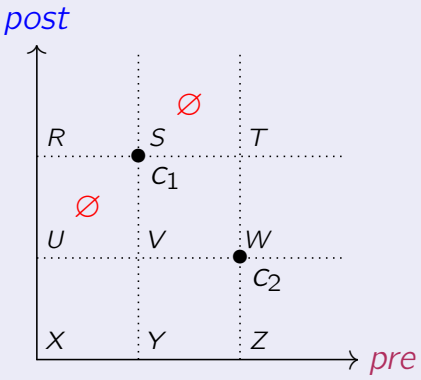
Once context pruning for the `following` axis is complete, all remaining context nodes relate to each other on the `ancestor`/`descendant` axes:

Covering nodes $c_{1,2}$ in `descendant` relationship



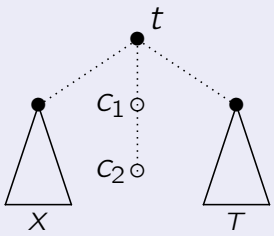
Empty regions in the *pre*/*post* plane

Relating two context nodes (c_1, c_2) on the plane



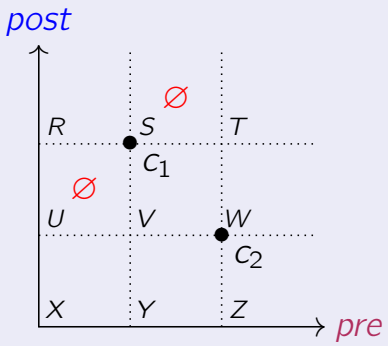
Empty regions?

Given $c_{1,2}$ on the left, why are the regions U,S marked $\varnothing$ guaranteed *to not hold any nodes*?



Context pruning (`following` axis)

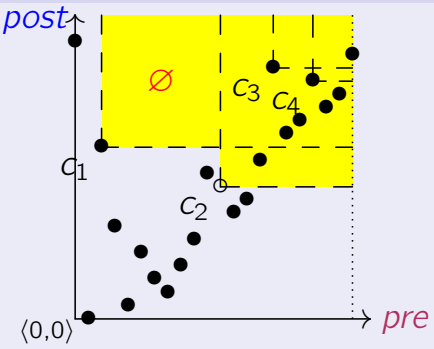
(c_1, c_2)/`following::node()`



$$
\begin{aligned}
(c_1, c_2)\texttt{/following::node()} &\equiv S \cup T \cup W \\
&\equiv T \cup W \\
&\equiv (c_2)\texttt{/following::node()}
\end{aligned}
$$

Context pruning (following axis)

Context pruning (following axis)



Context pruning (following axis)

Replace context node sequence cs by singleton sequence (c), $c \in cs$, with $post(c)$ minimal.

Context pruning (preceding axis)

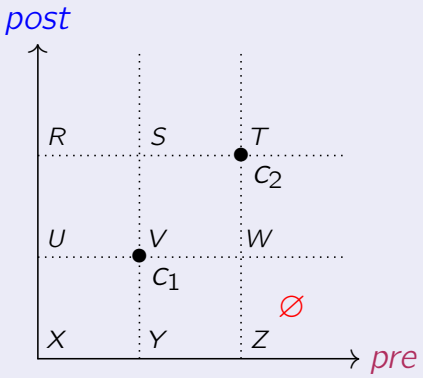
Context pruning (preceding axis)

Replace context node sequence cs by singleton sequence (c), $c \in cs$, with $pre(c)$ maximal.

- Regardless of initial context size, axes `following` and `preceding` yield simple **single region queries.**
- We focus on `descendant` and `ancestor` now.

More empty regions

Remaining context nodes c_1, c_2 after pruning for `descendant` axis

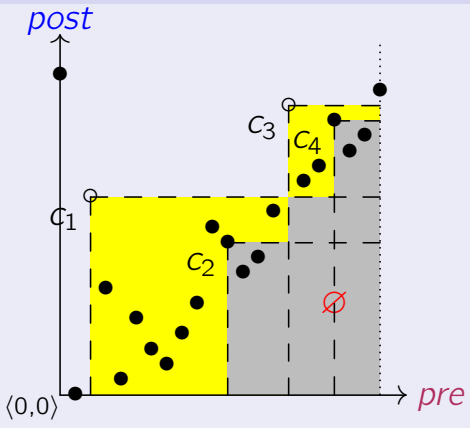


Empty region?

Why is region Z marked ∅ guaranteed to be empty?

Context pruning (`descendant` axis)

Context pruning (`descendant` axis)



- The region marked ∅ above is a region of type Z (previous slide).In general, a **non-singleton sequence remains.**

Context pre-processing: Pruning

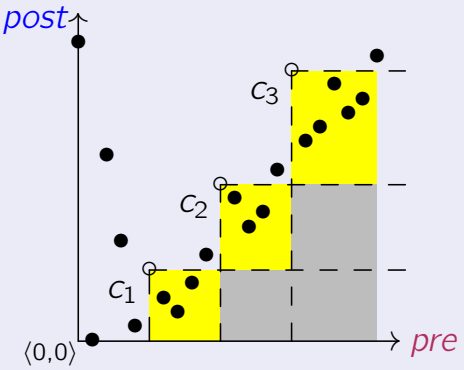
prune_context$_{\texttt{desc}}$(*context* : TABLE(*pre*, *post*))

```
begin
    result ← CREATE TABLE(pre, post);
    prev ← 0;
    foreach c in context do
        /* retain node only if post rank increases */
        if c.post > prev then
            APPEND c TO result;
            prev ← c.post;
    /* return new context table */
    return result;
end
```


"Staircases" in the *pre*/*post* plane

Note that after context pruning, the remaining context nodes form a **proper "staircase"** in the plane. (This is an important assumption in the following.)

Context pruning & "staircase"



Flashback: Intersecting `ancestor` paths

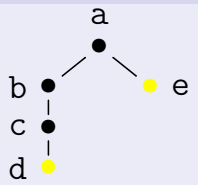
Even with pruning applied, duplicates and out-of-order results may still be generated due to **intersecting** `ancestor` **paths.**

- We have observed this before: apply function `ancestors(`c_1`,` c_2`)` where c_1 (c_2) denotes the element node with tag `d` (`e`) in the sample tree below.
  (Nodes $c_{1,2}$ would *not* have been removed during pruning.)

Simulate XPath `ancestor` via `parent` axis

```
declare function
   ancestors($n as node()*) as node()*
{ if (fn:empty($n)) then ()
  else (ancestors($n/..), $n/..)
}
```

Sample tree



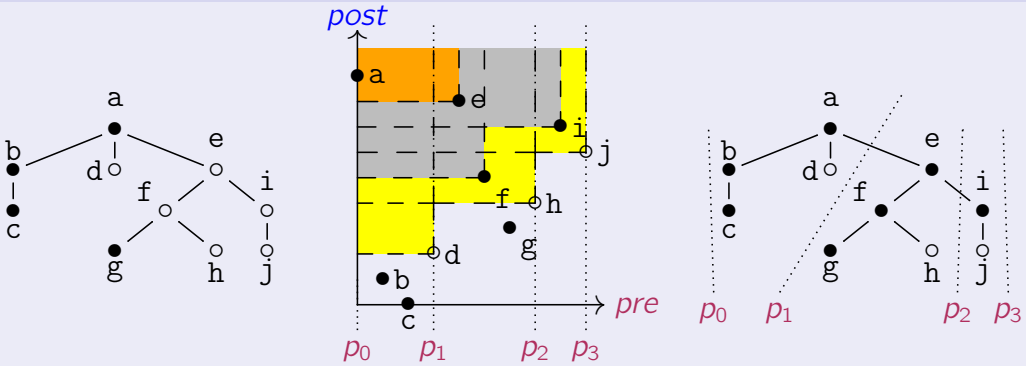
Remember: `ancestors((d,e))` yielded `(a,b,a,c)`.

Separation of `ancestor` paths

Idea: try to **separate** the `ancestor` paths by defining suitable **cuts** in the XML fragment tree.

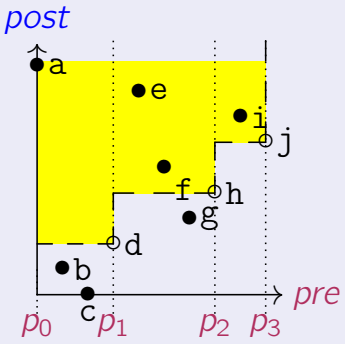
- Stop node-to-root traversal if a cut is encountered.

Path separation (`ancestor` axis)



Parallel scan along the *pre* dimension

Separating `ancestor` paths



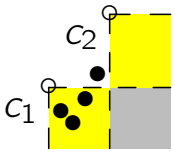
Scan partitions (intervals): $[p_0, p_1)$, $[p_1, p_2)$, $[p_2, p_3)$.

- Can scan in **parallel.** Partition results may be concatenated.
- Context pruning reduces numbers of partitions to scan.

Basic Staircase Join (`descendant`)

$\text{◿}_{\texttt{desc}}(\mathit{accel} : \texttt{TABLE}(\mathit{pre}, \mathit{post}), \mathit{context} : \texttt{TABLE}(\mathit{pre}, \mathit{post}))$

begin
  result ← `CREATE TABLE`(*pre*, *post*);
  foreach *successive pair* (c_1, c_2) **in** *context* **do**
    scanpartition($c_1.pre + 1$, $c_2.pre - 1$, $c_1.post$, $<$);
  c ← *last node in context*;
  n ← *last node in accel*;
  scanpartition($c.pre + 1$, $n.pre$, $c.post$, $<$);
  return *result*;
end



Partition scan (sub-routine)

scanpartition(pre_1, pre_2, $post$, θ)

begin
  for i **from** pre_1 **to** pre_2 **do**
    if $accel[i].post\ \theta\ post$ **then**
      APPEND $accel[i]$ TO *result*;
end

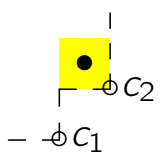
Notation $accel[i]$ does not imply random access to document encoding:

- Access is strictly **forward sequential** (also *between* invocations of *scanpartition*($\cdot$)).

Basic Staircase Join (`ancestor`)

⌐_{anc}(*accel* : TABLE(*pre*, *post*), *context* : TABLE(*pre*, *post*))

begin
  result ← CREATE TABLE(*pre*, *post*);
  c ← *first node in context*;
  n ← *first node in accel*;
  scanpartition(*n.pre*, *c.pre* − 1, *c.post*, >);
  foreach *successive pair* (c_1, c_2) **in** *context* **do**
    scanpartition($c_1.pre + 1$, $c_2.pre - 1$, $c_2.post$, >);
  return *result*;
end



Basic Staircase Join: Summary

- The operation of **staircase join** is perhaps most closely described as **merge join** with a **dynamic range predicate**: the join predicate traces the staircase boundary:
  - ◿ scans the *accel* and *context* tables and populates the *result* table sequentially in document order,
  - ◿ scans both tables once for an entire context sequence,
  - ◿ never delivers duplicate nodes.
- ◿ works correctly only if *prune_context*$(\cdot)$ has previously been applied.

  - *prune_context*$(\cdot)$ may be **inlined** into ◿, thus performing context pruning *on-the-fly*.

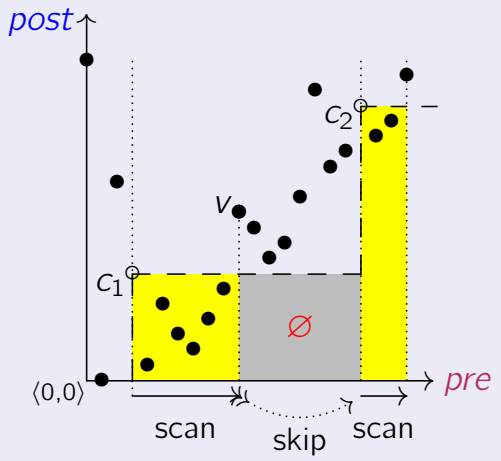
Pruning on-the-fly

◿$_{\texttt{desc}}$(*accel*:TABLE(*pre*, *post*), *context*:TABLE(*pre*, *post*))

```
begin
    result ← CREATE TABLE(pre, post);
    c1 ← first node in context;
    while (c2 ← next node in context) do
        if c2.post < c1.post then
            /* prune */
        else
            scanpartition(c1.pre + 1, c2.pre − 1, c1.post, <);
            c1 ← c2;
    c ← last node in context;
    n ← last node in accel;
    scanpartition(c.pre + 1, n.pre, c.post, <);
    return result;
end
```

Skip ahead, if possible

(c_1, c_2)/descendant::node()



- While scanning the partition associated with $c_{1,2}$:
- v is outside staircase boundary, thus not part of the result.
- No node beyond v in result ($\varnothing$-region of type Z).

$\Rightarrow$ Can **terminate scan early and skip ahead** to $pre(c_2)$.

Skipping for the descendant axis

$scanpartition_{\texttt{desc}}(pre_1, pre_2, post)$

```
begin
    for i from pre_1 to pre_2 do
        if accel[i].post < post then
            APPEND accel[i] TO result;
        else
            /* on the first offside node, terminate scan */ break;
end
```

Note: keyword **break** transfers control out of innermost enclosing loop (cf. C, Java).

Effectiveness of skipping

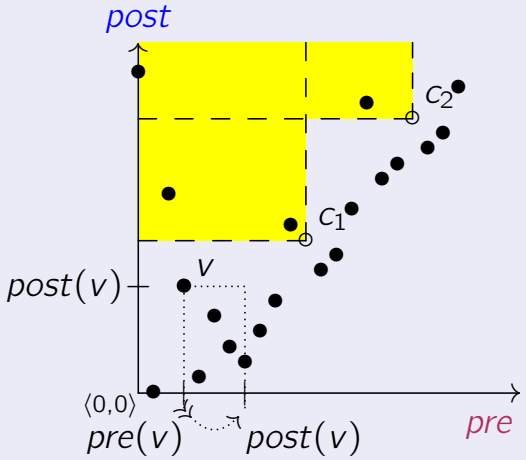
- Enable skipping in *scanpartition*$(\cdot)$. Then, for each node in *context*, we either
  1. hit a node to be copied into table *result*, or
  2. encounter an offside node (node v on slide 1128) which leads to a skip to a known *pre* value ($\rightarrow$ positional access).
- To produce the final result, $\sqsubset$ thus never touches more than

$$| \mathit{context} | + | \mathit{result} |$$

  nodes in the plane (without skipping: $| \mathit{context} | + | \mathit{accel} |$).
  - In practice: $> 90\,\%$ of nodes in table *accel* are skipped.

Skipping for the `ancestor` axis

Skipping over the subtree of v



Encounter v outside staircase boundary

$\Downarrow$

v **and subtree below** v in `preceding` axis of context node.

How far to skip?

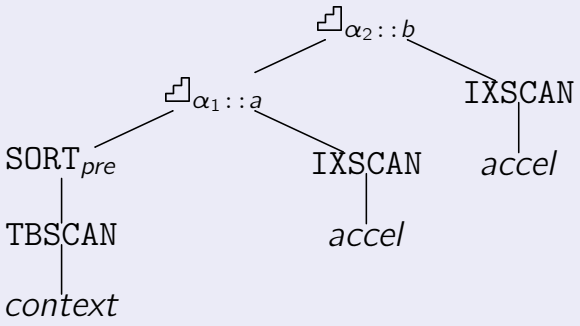
Conservative estimate:
$size(v) \geqslant post(v) - pre(v)$

Injecting ⍁ into PostgreSQL

PostgreSQL (`http://postgresql.org/`): Conventional disk-based RDBMS, SQL interface.

- Detection of ⍁ applicabilty on SQL level (self-join with conjunctive range selection on columns of type `tree`[48]).

Algebraic query plan for two-step XPath location path



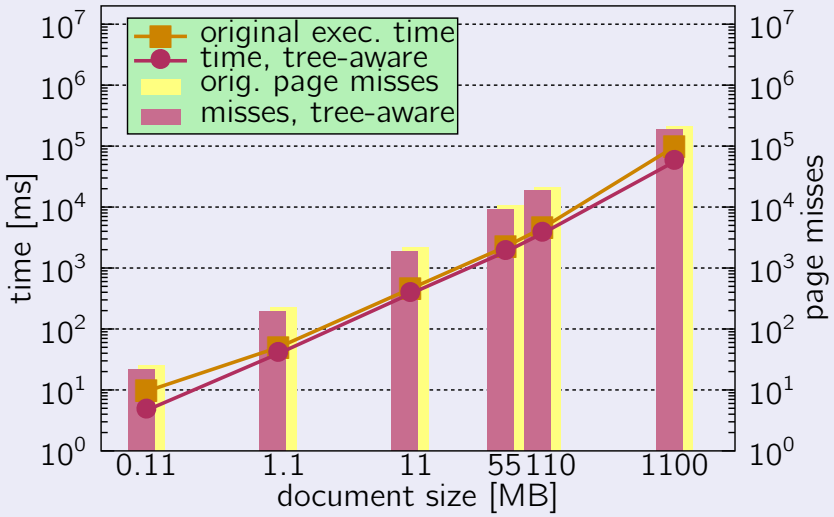
[48] PostgreSQL is highly extensible, also permits introduction of new column types.

Injecting ⍁ into PostgreSQL

- Create clustered ascending B-tree index on column *pre* of table *accel*.
  - Standard no-frills PostgreSQL B-tree index, entered with search predicates of the form $pre \overset{?}{\geqslant} c.pre$ (c context node).
  - B-tree on column *pre* also used for **skipping**.
- Following performance figures obtained on a 2.2 GHz Dual Intel™ Pentium 4, 2 GB RAM, PostgreSQL 7.3.3.
  - Compares ⍁-enabled (tree-aware) PostgreSQL with vanilla PostgreSQL instance.
  - Evaluate XPath location path `/descendant::`a`/`α`::b` on document instances of up to 1.1 GB serialized size.

Injecting ⏍ into PostgreSQL

/descendant::*a*/descendant::*b*



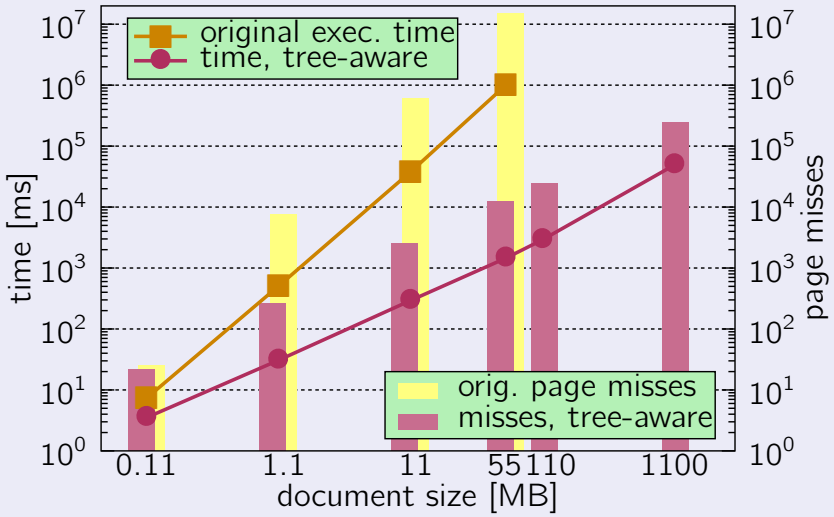
Injecting ⏍ into PostgreSQL

For $\alpha =$ `descendant` observe:

- For *both* PostgreSQL instances, query evaluation time grows **linearly** with the input XML document size (since the results size grows linearly).
- For the original instance, this is due to **window shrink-wrapping** (expressible at the SQL level).

Injecting ⏍ into PostgreSQL

/descendant::*a*/ancestor::*b*

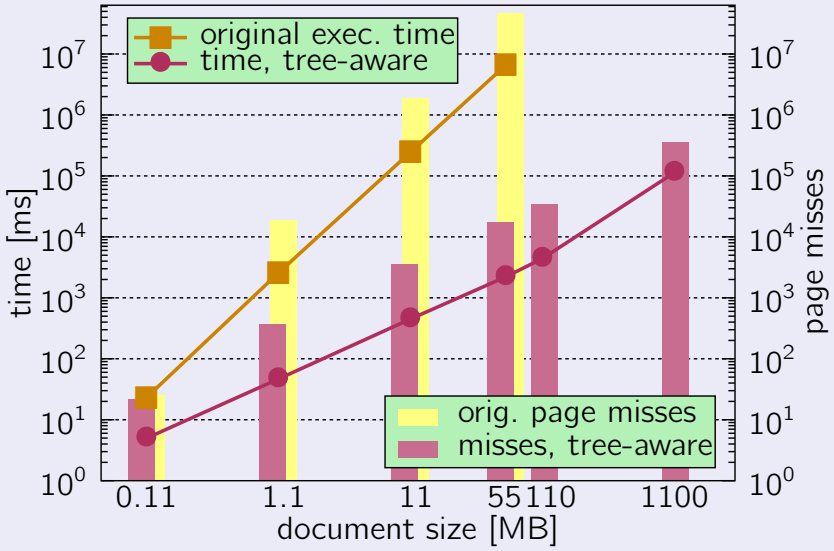


Injecting ⏍ into PostgreSQL

- **For** $\alpha \in \{\texttt{ancestor}, \texttt{preceding}, \texttt{following}\}$ **observe:**
  - For the ⏍**-enabled** PostgreSQL instance, query evaluation time grows **linearly** with the input XML document (and result) size.
    For the **original** instance, query evaluation time grows **quadratically** (| *accel* | scans of table *accel* performed).
  - Original instance is incapable of completing experiment in reasonable time ($>$ 15 mins for XML input size of 55 MB).
- **Generally:**
  - The number of **buffer page misses** (= necessary I/O operations) determines evaluation time.

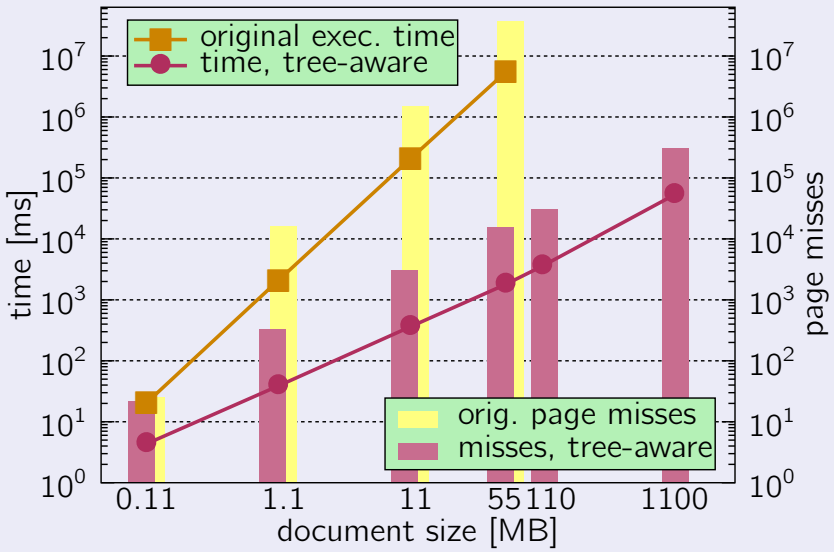
Injecting ⏍ into PostgreSQL

/descendant::*a*/preceding::*b*



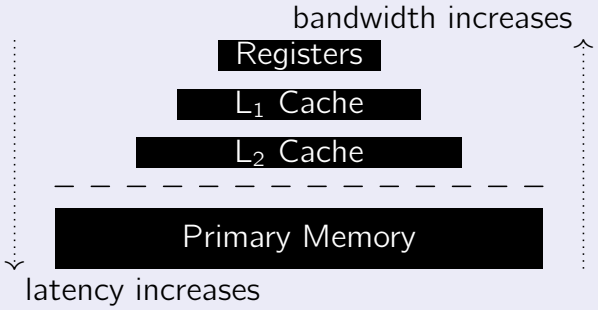
Injecting ⏍ into PostgreSQL

/descendant::*a*/following::*b*



MonetDB/XQuery: Targetting modern CPU/memory architectures

Memory Hierarchy



- Computation performed with CPU registers only.
- **Cache miss may escalate**: $L_1 \rightarrow L_2 \rightarrow$ RAM, data transport all the way back: $L_1 \leftarrow L_2 \leftarrow$ RAM.
- Data transport in **cache line granularity**.

CPU/cache characteristics

Intel™ Dual Pentium 4 (Xeon)[49]

CPU/Cache Characteristics		
Clock frequency		2.2 GHz
L_1/L_2 cache size		8 kB/512 kB
L_1/L_2 cache line size	LS_{L_1}/LS_{L_2}	32 byte/128 byte
L_1 miss latency	L_{L_1}	28 cycles $\hat{=}$ 12.7 ns
L_2 miss latency	L_{L_2}	387 cycles $\hat{=}$ 176 ns

- For this CPU, a **full cache miss** implies a **stall of the CPU** for $28 + 387 = 415$ cycles (cy).

[49] Measure these characteristics for your CPU with Stefan Manegold's *Calibrator*, `http://monetdb.cwi.nl/Calibrator/`.

Staircase join: Wrap-up

- Standard B^+-tree implementation suffices to support ⌐.
  - A **single** B^+-tree indexes the *pre*/*post* plane as well as the context node sequence.

  ⇒ Less index pages compete for valuable buffer space.
- ⌐ derives pruning and skipping information from the plane itself, using **simple integer arithmetic and comparisons.**
  - Simple ⌐ logic leads to **simple memory access pattern and control flow.**

  ⇒ Branches in inner ⌐ loops are highly predictable, facilitating **speculative execution** in the CPU.

Predictable branches?

Explain why!