Temporal databases

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Reading: [Arge01, sec. 1+ “persistent B-trees”/sec. 2.1]
Slides on persistent B-trees by Lars Arge.

Course evaluation

- It is my plan to do a substantial revision of DBT next year.
- Please use the course evaluation to give your input to this process:
  - What parts of the lectures/project worked well (should be kept)?
  - What parts worked less well?
  - What did you miss?
- Your opinion is appreciated! Deadline Friday April 17.

Today

- Temporal data, what and how?
- Indexing temporal data.

- Independent part (afternoon):
  Guest lecture by Philippe Bonnet on flash-based storage technology.

What is a temporal database?

- Database with a notion of ”time”.
- Several possible notions:
  - Valid time
  - Transaction time
- Typically, ”time” is used in a special way in queries:
  - Example: How many employees did we have on April 1, 2008?
- Today, we focus on transaction time.
  - Essentially want to be able to access all previous versions of the database.

Timestamping tuples

- Simple idea: Extend each relation schema with two attributes that encode a time interval:
  - Tst (start time/insertion time)
  - Tet (end time/deletion time). Tet of current tuples have special value **uc** (think ∞).
- A query "for time t" should include the extra condition Tst<=t AND t<=Tet on each relation.
- Important that primary keys do not change – want to be able to relate entities over time.

TSQL2 temporal extensions

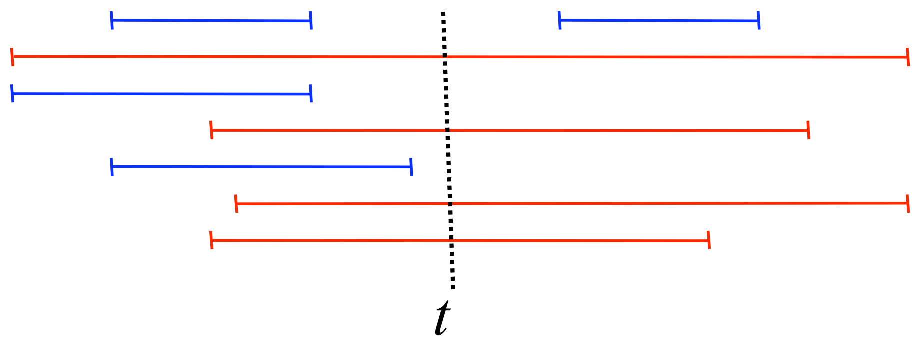
- Gives more convenient ways of expressing temporal conditions, e.g. join conditions as ”the tuples existed at the same time”. (SQL alternative?)
- Gives operations on time intervals (union, intersection,…).
- Ways of ”aggregating” time intervals, e.g., finding time intervals not covered by a set of intervals.
- Today, we do not go further into the language aspects of temporal DBs.

Maintaining time stamps

- New tuples are inserted with current time (transaction time) as Tst.
- Deletions are not performed – instead Tet is set to the current time.
- Changes to tuples are conceptually done by deleting the old version and inserting the new one.
  - Can be wasteful in terms of space. A possibility is to split each relation into many relations with one attribute each in addition to the primary key (”temporal normal form”).

Problem session

- Consider how B-tree indexes might be used to select tuples that satisfy Tst<=t AND t<=Tet.
- Argue that in general, B-trees will **not** allow us to find the matching tuples efficiently.



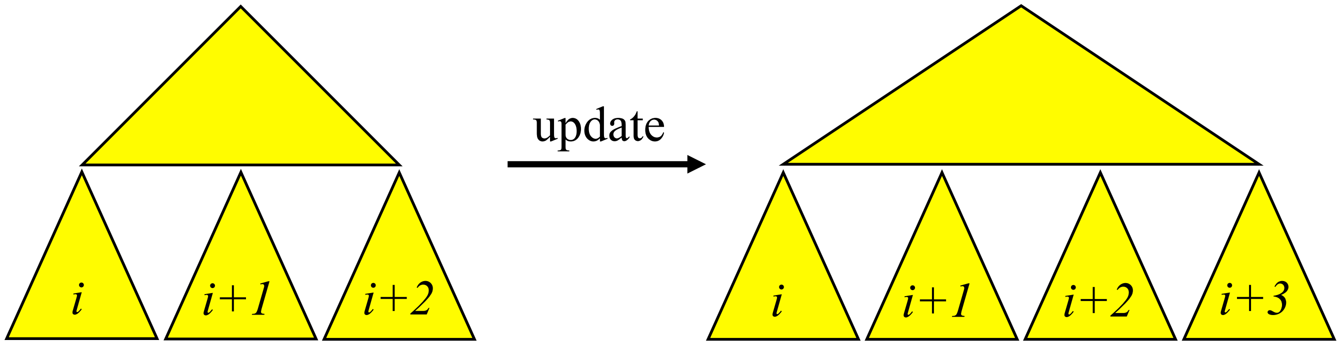
Next: Persistent B-trees

- Multiversion B-trees (aka. partially persistent B-trees) is an efficient index for temporal data.
- Assumption: ”Transaction time” is used, i.e., timestamps may only be set to the current time.

- **Warm-up**: Persistent linked lists. (Board.)

Persistent B-tree

- Easy way to make a B-tree persistent
  - Copy structure at each operation
  - Maintain "version-access" structure (B-tree)



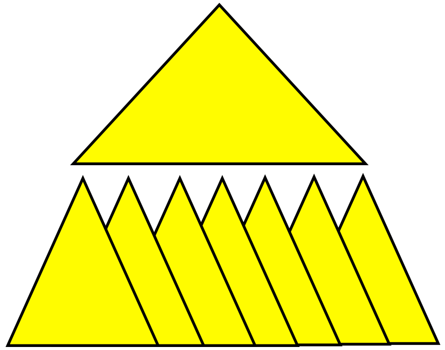
- $O(\log_B N + T/B)$ I/O query, any version ☺
  - $O(N/B)$ I/O update time ☹
  - $O(N^2/B)$ space ☹☹

Persistent B-trees, better way

- Next idea: Instead of copying the whole tree for each update, copy just the nodes that are ”affected”, and re-use the rest.
- Affected nodes:
  - Updated nodes.
  - Nodes on the path to an updated node (specifically, we get a new root at each time instance).
- Now update time is $O(\log_B N)$ ☺
- Space is $O(N \log_B N)$ blocks ☹

Persistent B-tree

- Idea: Elements (in internal and leaf nodes) are augmented with "existence interval" and stored in one structure



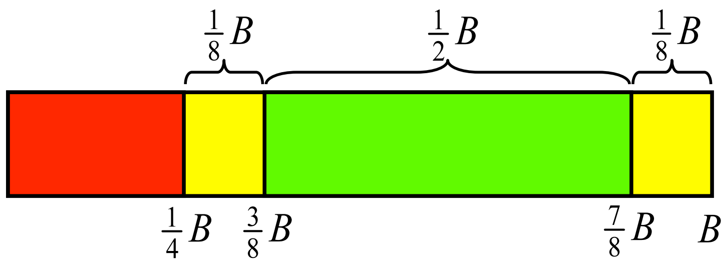
- Persistent B-tree with parameter B:
  - Directed acyclic graph
    * Nodes contain elements augmented with existence interval
    * At any time t, nodes with elements live at time t form B-tree with leaf and branching parameter B *(i.e., each node/leaf has at least B/4 and at most B children/keys in them)*
  - B-tree with leaf and branching parameter b on "root nodes".

$\Downarrow$ Query at any time t in $O(\log_B N + T/B)$ I/Os

Persistent B-tree: Updates

- Updates performed essentially as in a B-tree

- To obtain linear space we maintain new-node invariant:
  - New node contains between $3/8\, B$ and $7/8\, B$ live elements and no dead elements
  - Intuition: Ensure that many update operations take place before the node is replaced.

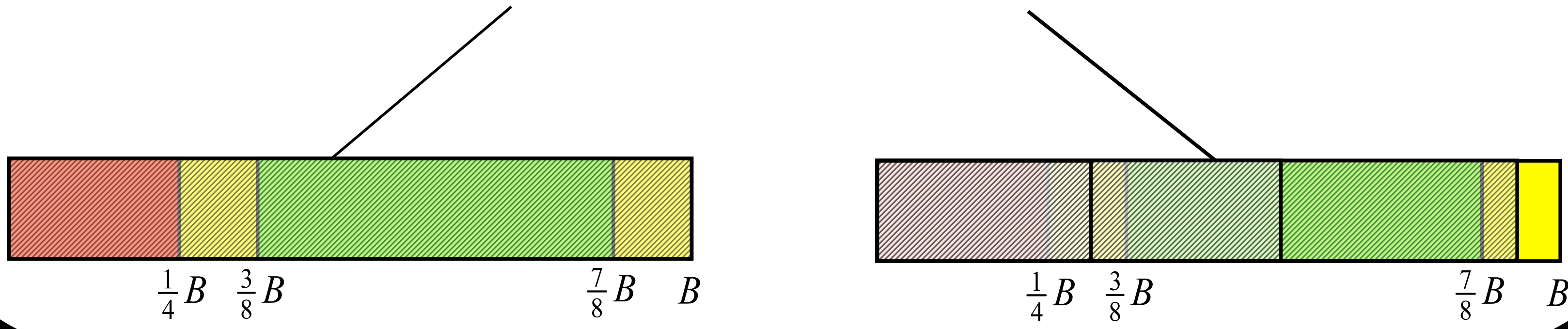


Persistent B-tree Insert

- Search for relevant leaf u and insert new element
- If u contains $B+1$ elements: Block overflow
  - Version split:

    Mark u dead and create new node u' with x live elements
  - If $x > \frac{7}{8}B$: Strong overflow
  - If $x < \frac{3}{8}B$: Strong underflow
  - If $\frac{3}{8}B \leq x \leq \frac{7}{8}B$ then recursively update *parent*(u):

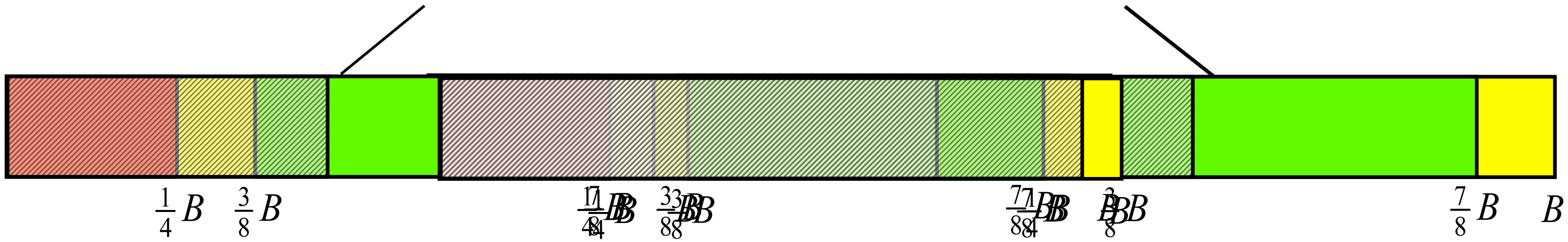
    Delete (persistently) reference to u and insert reference to u'



Persistent B-tree Insert

- Strong overflow ($x > \frac{7}{8}B$)
  - Split u into u' and u'' with $x/2$ elements each ($\frac{3}{8}B < \frac{x}{2} \leq \frac{1}{2}B$)
  - Recursively update *parent*(u):

    Delete reference to u and insert reference to v' and v''



- Strong underflow ($x < \frac{3}{8}B$)
  - Merge x elements with y live elements obtained by version split on sibling ($\frac{1}{2}B \leq x + y \leq \frac{11}{8}B$)
  - If $x + y \geq \frac{7}{8}B$ then (strong overflow) perform split into nodes with $(x+y)/2$ elements each ($\frac{7}{16}B \leq (x+y)/2 \geq \frac{11}{16}B$)
  - Recursively update *parent*(u): Delete two insert one/two references

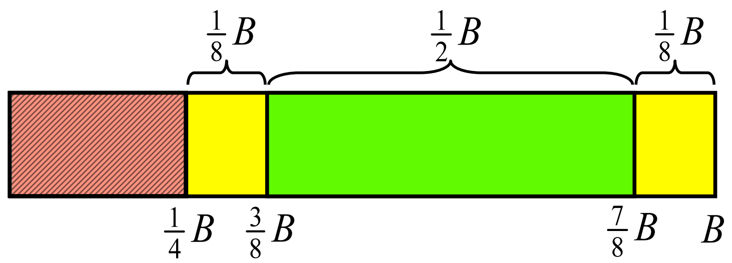
Persistent B-tree Delete

- Search for relevant leaf u and mark element dead
- If u contains $x < \frac{1}{4}B$ live elements: Block underflow
  - Version split:

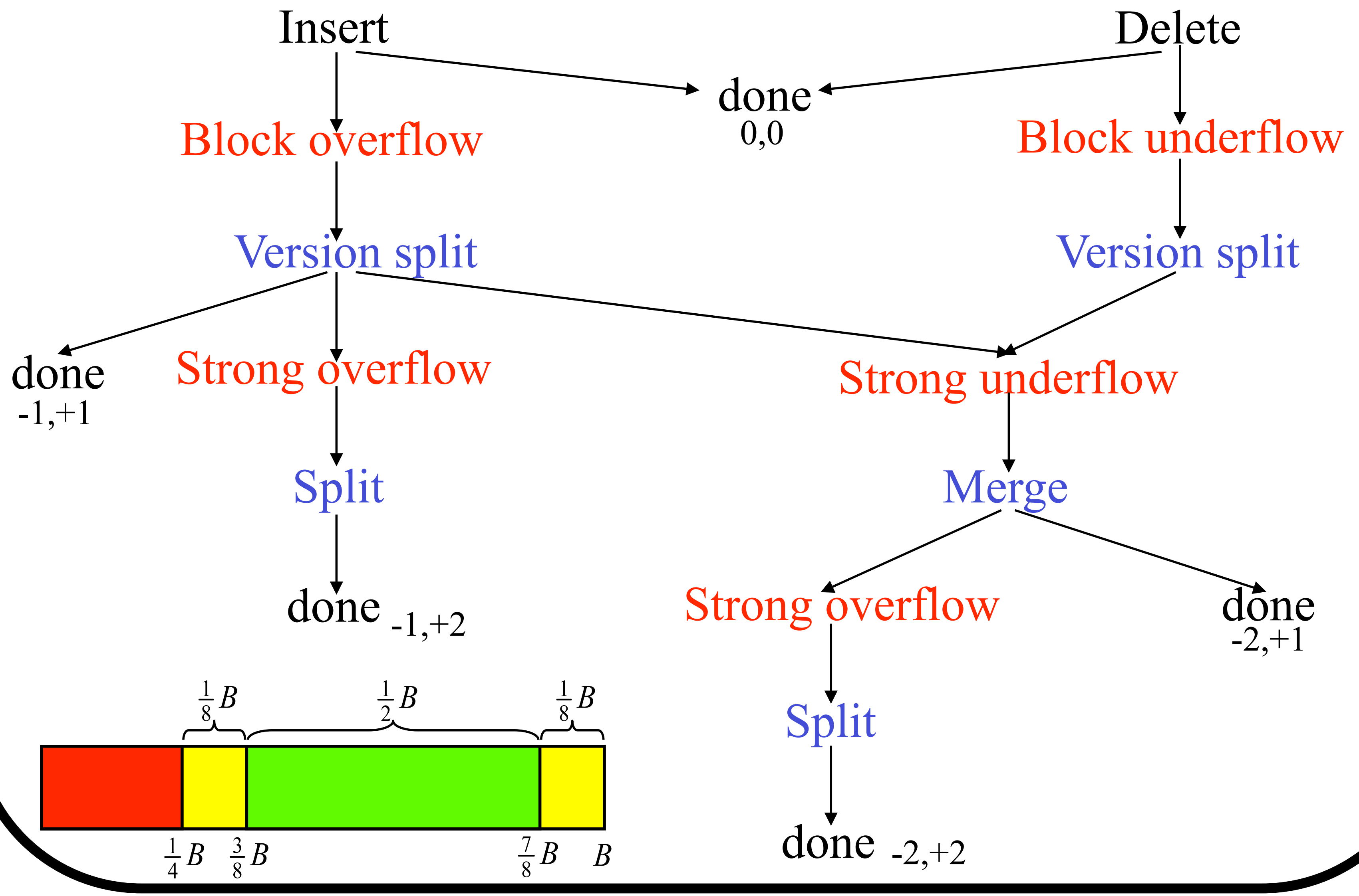
    Mark u dead and create new node u' with x live elements
  - Strong underflow ($x < \frac{3}{8}B$):

    Merge (version split) and possibly split (strong overflow)
  - Recursively update *parent*(u):

    Delete two references insert one or two references



Persistent B-tree



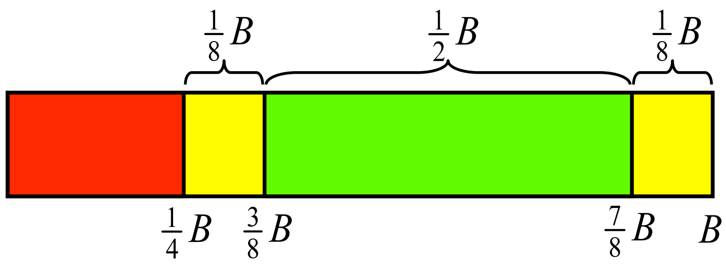
Persistent B-tree Analysis

- Update: $O(\log_B N)$
  - Search and "rebalance" on one root-leaf path
- Space: $O(N/B)$
  - At least $\frac{1}{8}B$ updates in leaf in existence interval
  - When leaf u dies
    * At most two other nodes are created
    * At most one block over/underflow one level up (in $parent(u)$)

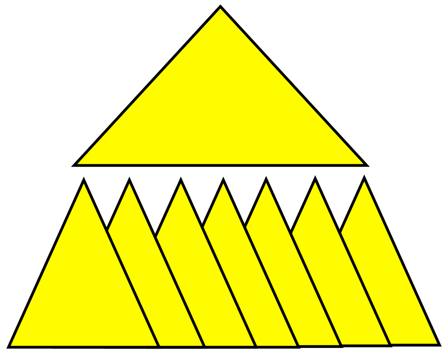
$\Downarrow$

  - During N updates we create:
    * $O(N/B)$ leaves
    * $O(N/B^i)$ nodes i levels up

$\Rightarrow \sum_i O(N/B^i) = O(N/B)$ blocks



Summary/Conclusion: Persistent B-tree



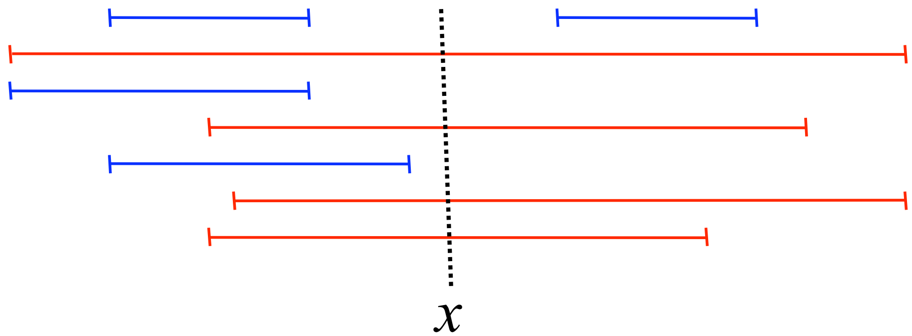
- Persistent B-tree
  - Update current version
  - Query all versions
- Efficient implementation obtained using existence intervals
  - Standard technique

$\Downarrow$

- During N operations
  - $O(N/B)$ space
  - $O(\log_B N)$ update
  - $O(\log_B N + T/B)$ query

Valid time

- Persistent B-trees critically use that timestamps can only be set to "now".
- To index *valid time*, we may use a solution to the "interval management" problem:
  - Index *N* intervals such that a stabbing query at time *x* and updating the set of intervals is efficient.



- Theoretically optimal solution: [Arge01, sec. 4]
  - Note: Cannot search in stabbed intervals.

Bi-temporal databases

- The two notions of time co-exist.
- Possible to make queries that involve both time dimensions.
- A possible indexing approach is to use multi-dimensional indexes such as R-trees.

Exercise

- Suppose we have access to persistent B-trees and standard B-trees.
- Consider how to make efficient indexes for the following queries: Report the tuples that:
  a) were inserted some time after time t.
  b) existed at time t.
  c) existed at some point in $[t_1;t_2]$.
  d) existed in the whole time interval $[t_1;t_2]$.
- Extra: Consider the effect of an additional range condition, e.g. a>10.