Temporal Databases

Outline

- Spatial Databases
  - Indexing, Query processing
- Temporal Databases
- Spatio-temporal
- ….

Temporal DBs – Motivation

- Conventional databases represent the state of an enterprise at a single moment of time
- Many applications need information about the past
  - Financial (payroll)
  - Medical (patient history)
  - Government
- Temporal DBs: a system that manages time varying data

Comparison

- Conventional DBs:
  - Evolve through transactions from one state to the next
  - Changes are viewed as modifications to the state
  - No information about the past
  - Snapshot of the enterprise
- Temporal DBs:
  - Maintain historical information
  - Changes are viewed as additions to the information stored in the database
  - Incorporate notion of time in the system
  - Efficient access to past states

Temporal Databases

- Temporal Data Models: extension of relational model by adding temporal attributes to each relation
- Temporal Query Languages: TQUEL, SQL3
- Temporal Indexing Methods and Query Processing

Taxonomy of time

- Transaction time databases
  - Transaction time is the time when a fact is stored in the database
- Valid time databases:
  - Valid time is the time that a fact becomes effective in reality
- Bi-temporal databases:
  - Support both notions of time

Example

- Sales example: data about sales are stored at the end of the day
- Transaction time is different than valid time
- Valid time can refer to the future also!
  - Credit card: 03/13-04/16

Transaction Time DBs

- Time evolves discretely, usually is associated with the transaction number:

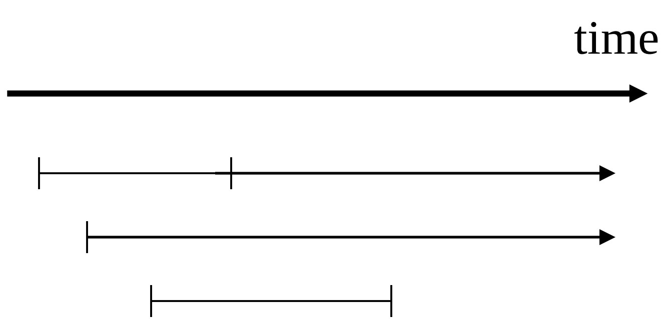
  T1 -> T2 -> T3 -> T4 ….

- A record R is extended with an interval [t.start, t.end). When we insert an object at t1 the temporal attributes are updated -> [t1, now)
- Updates can be made only to the current state!
  - Past cannot be changed
  - “Rollback” characteristics

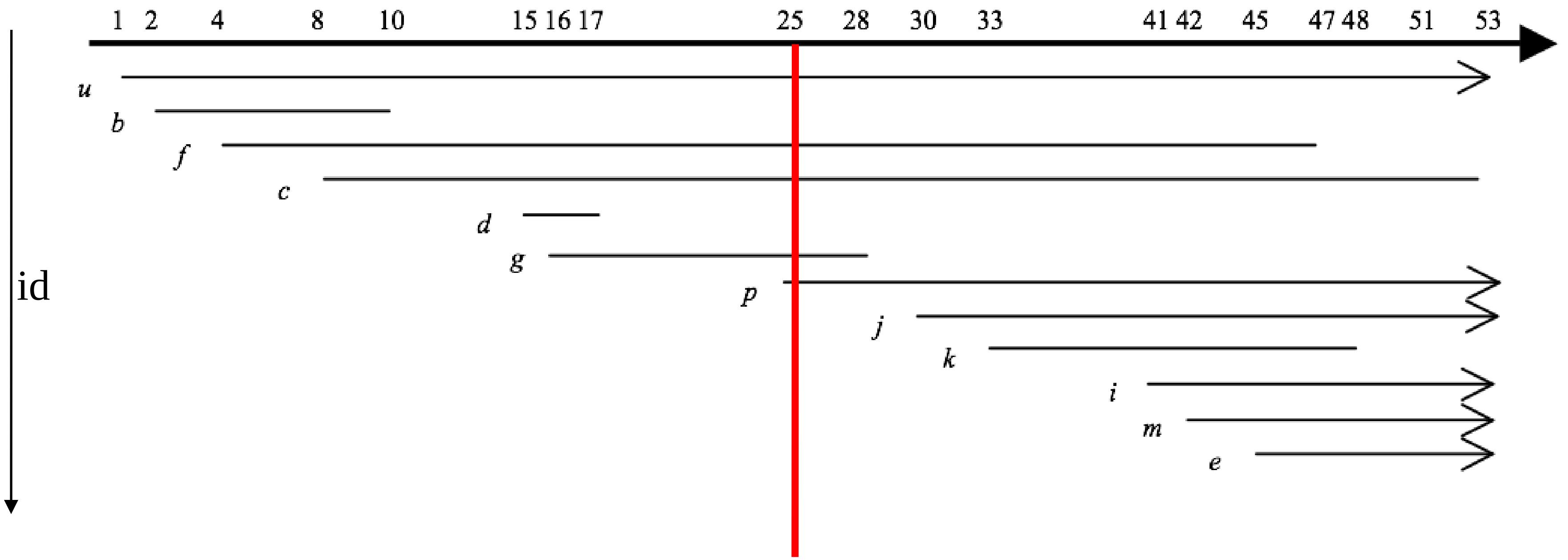
Transaction Time DBs

- Deletion is <u>logical </u>(never physical deletions!)
  - When an object is deleted at t2, its temporal attribute changes from [t1, now) → [t1, t.t2) (lifetime)
  - Object is "alive" from insertion to deletion time, ex. t1 to t2. If "now" then the object is still alive

eid	salary	start	end
10	20K	9/93	10/94
20	50K	4/94	*
33	30K	5/94	6/95
10	50K	1/95	*



Transaction Time DBs



Database evolves through insertions and deletions

Transaction Time DBs

- Requirements for index methods:
  - Store past logical states
  - Support addition/deletion/modification changes on the objects of the current state
  - Efficiently access and query any database state

Transaction Time DBs

- Queries:
  - Timestamp (timeslice) queries: ex. “Give me all employees at 05/94”
  - Range-timeslice: “Find all employees with id between 100 and 200 that worked in the company on 05/94”
  - Interval (period) queries: “Find all employees with id in [100,200] from 05/14 to 06/16”

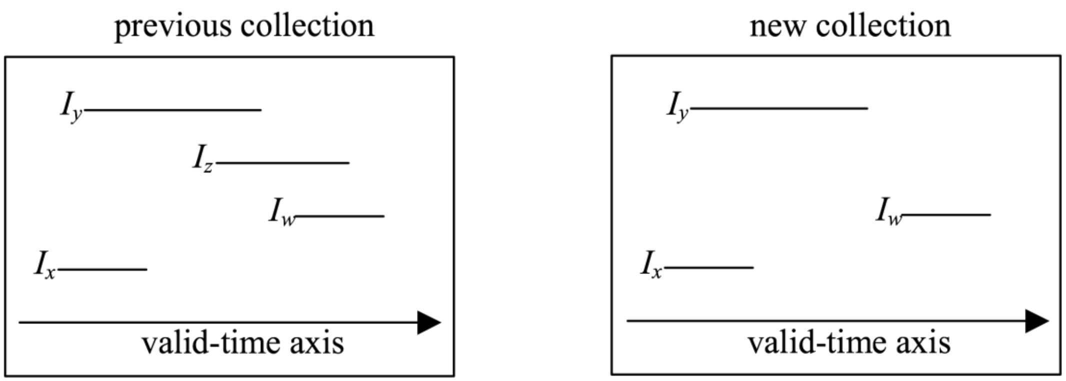
Valid Time DBs

- Time evolves continuously
- Each object is a line segment representing its time span (eg. Credit card valid time)
- Support full operations on interval data:
  - Deletion at any time
  - Insertion at any time
  - Value change (modification) at any time (no ordering)

Valid Time DBs

- Deletion is physical:
  - No way to know about the previous states of intervals
- The notion of “future”, “present” and “past” is relative to a certain timestamp t

Valid Time DBs



The reality “best know now !”

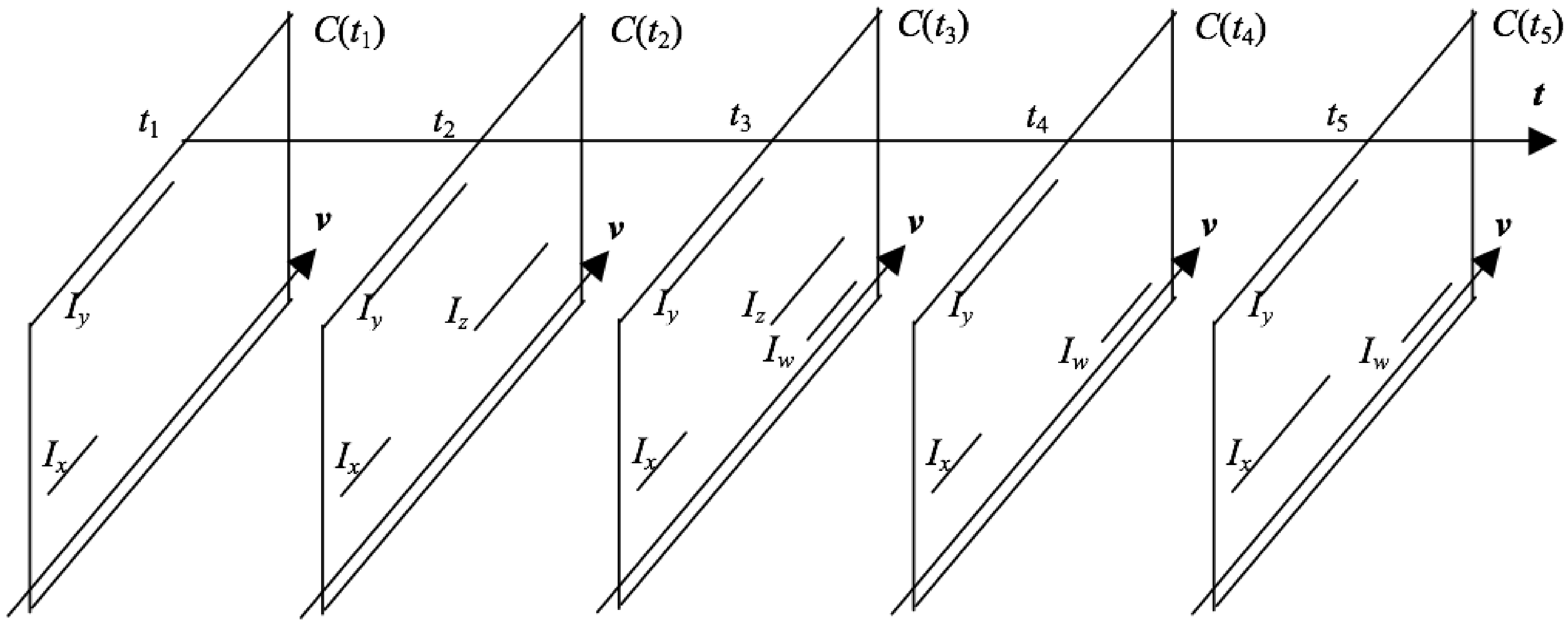
Valid Time DBs

- Requirements for an Index method:
  - Store the latest collection of interval-objects
  - Support add/del/mod changes to this collection
  - Efficiently query the intervals in the collection
    - Timestamp query
    - Interval (period) query

Bitemporal DBs

- A transaction-time Database, but each record is an interval (plus the other attributes of the record)
- Keeping the evolution of a dynamic collection of interval-objects
- At each timestamp, it is a valid time database

Bitemporal DBs



Bitemporal DBs

- Requirements for access methods:
  - Store past/logical states of collections of objects
  - Support add/del/mod of interval objects of the current logical state
  - Efficient query answering

Temporal Indexing

- Straight-forward approaches:
  - B+-tree and R-tree
  - Problems?
- Transaction time:
  - Snapshot Index, TSB-tree, MVB-tree, MVAS
- Valid time:
  - Interval structures: Segment tree, even R-tree
- Bitemporal:
  - Bitemporal R-tree

Temporal Indexing

- Lower bound on answering timeslice and range-timeslace queries:
  - Space $O(n/B)$, search $O(\log_B n + s/B)$
- n: number of changes, s: answer size, B page capacity

Range-timeslice: “Find all employees with id between 100 and 200 that worked in the company on 05/94”

Transaction Time Environment

- Assume that when an event occurs in the real world it is inserted in the DB
- A timestamp is associated with each operation
- Transaction timestamps are <u>monotonically increasing</u>
- Previous transactions cannot be changed → we cannot change the past

Example

- Time evolving set of objects: employees of a company
- Time is discrete and described by a succession of non-negative integers: 1,2,3, …
- Each time instant changes may happen,

i.e., addition, deletion or modification

- We assume only insertion & deletion : modifications can be represented by a deletion and an insertion

Records

- Each object is associated with:
  1. An oid (key, time invariant, eid)
  2. Attributes that can change (salary)
  3. A lifespan interval [t.start, t.end)
- An object is alive from the time it inserted in the set, until it was deleted
- At insertion time deletion is unknown
- Deletions are logical: we change the now variable to the current time,

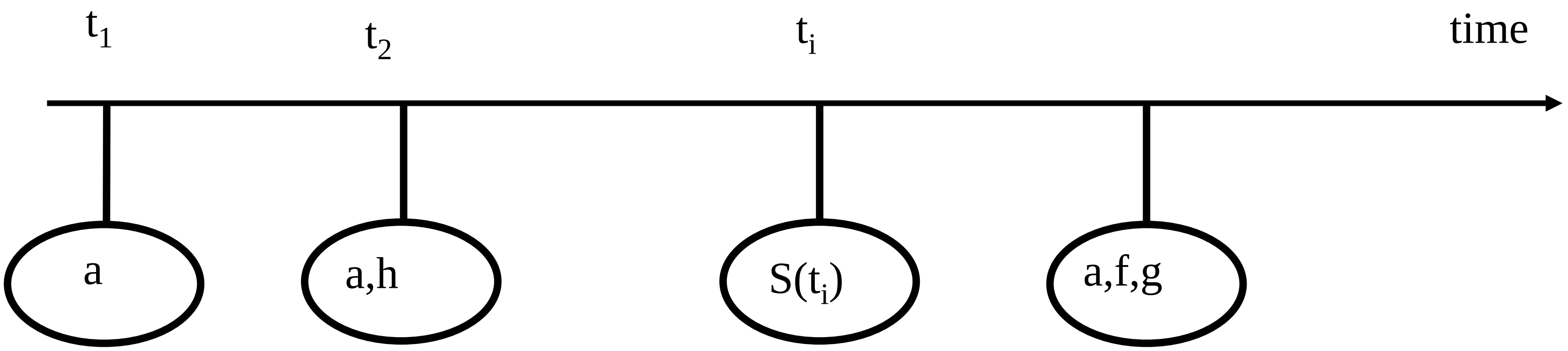
  [t1, now) → [t1, t2)

Evolving set

- The state S(t) of the evolving set at t is defined as: “the collection of alive objects at t”
- The number of changes n represents a good metric for the minimal space needed to store the evolution

Evolving sets

- A new change updates the <u>current state</u> S(t) to create a new state



Transaction-time Queries

- Pure-timeslice (time-point)
- Range-timeslice
- Pure-exact match

Snapshot Index

- Snapshot Index, is a method that answers efficiently pure-timeslice queries
- Based on a main memory method that solves the problem in $O(a+\log_2 n)$,

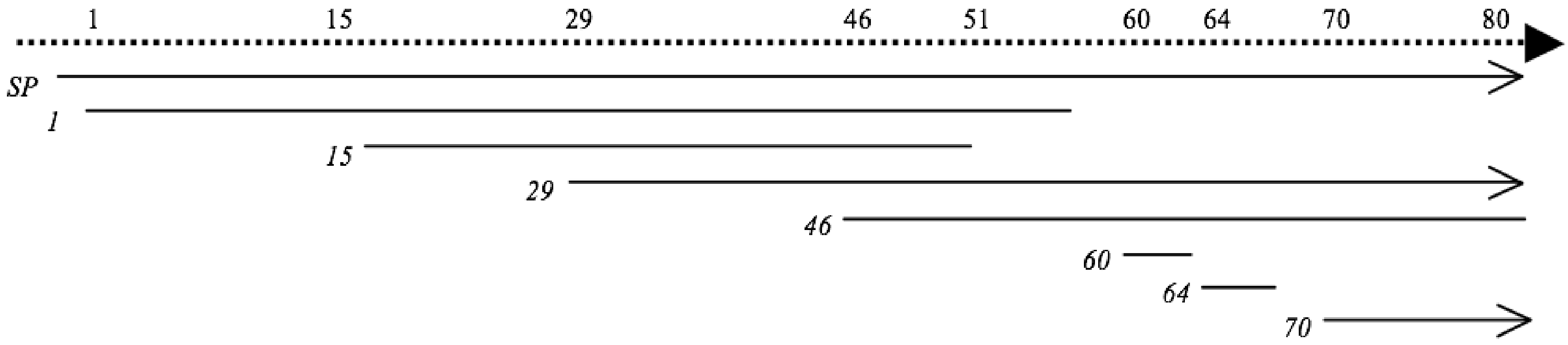
  $O(n)$ space
- External memory: $O(a/B + \log_B n)$

MM solution

- Copy approach: O(a + logn) but $O(n^2)$ space
- Log approach: O(n) space but O(n) query time
- We should combine the fast query time with the small space (and update)

Assumptions

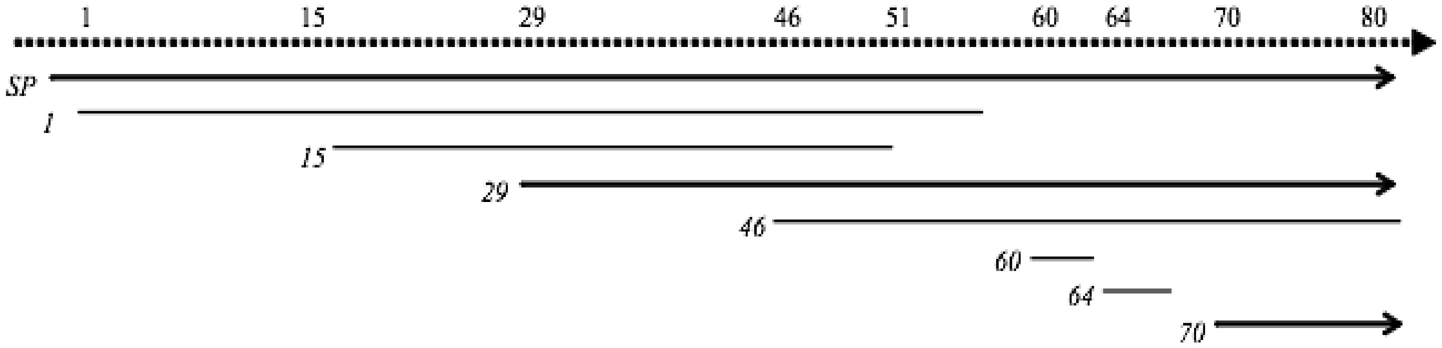
- Assumptions (for clarity)
  - At each time instant there exist exactly one change
  - Each object is named by its creation time

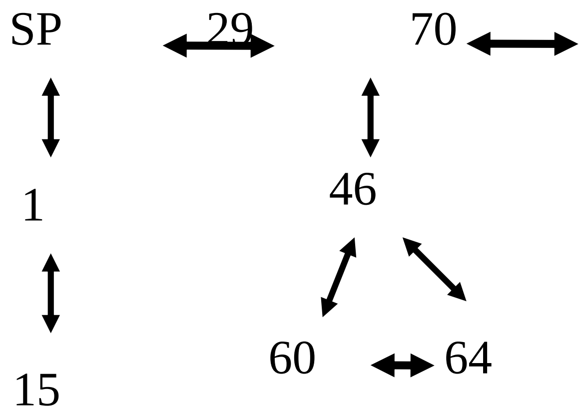


Access Forest

- A double linked list L. Each new object is appended at the right end of L
- A deleted object is removed from L and becomes the next child of its left sibling in L
- Each object stores a pointer to its parent object. Also a parent object points to its first and last children
- So, each node has the following pointers:
  parent, prev, next, Pcs, Pce

AF example





Additional structures

- A hashing scheme that keeps pointers to the positions of the alive elements in L
- An array A that stores the time changes. For **each time change instant**, it keeps the pointer to the current last object in L

Properties of AF

- In each tree of the AF the start times are sorted in preorder fashion
- The lifetime of an object includes the lifetimes of its descendants
- The intervals of two consecutive children under the same parent may have the following orderings:

$s_i < e_i < s_{i+1} < e_{i+1}$ or $s_i < s_{i+1} < e_i < e_{i+1}$

Searching

- Find all objects alive at t_q
- Use A to find the starting object in the access forest L (O(logn))
- Traverse the access forest and report all alive objects at t_q O(a) using the properties

Searching in AF

- Given query time q:
  - Use table A to find the time of the last object in L at time q. Say node Y.
  - Starting from Y go up (if it has a parent) recursively
    - For each node in the path from Y to the current node in list L (or Y itself if it is right now in L), visit the left sibling. If it is alive at q report it and recursively:
      - Visit the rightmost child in its subtree
      - Visit its left sibling
    - Stop the recursion overtime you find a node that is not alive at q

Disk based Solution

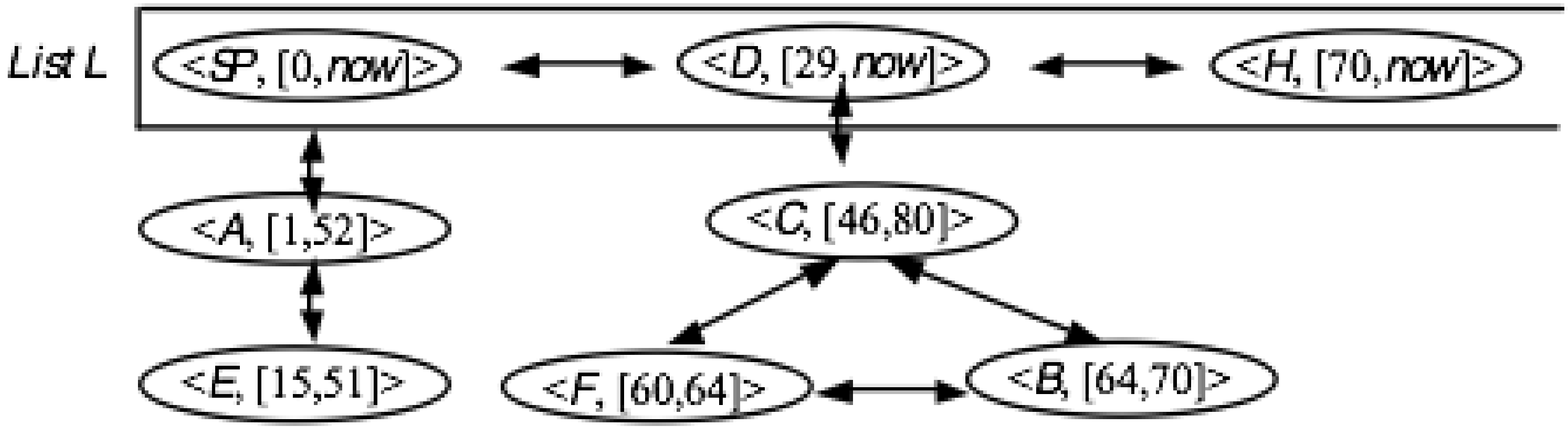
- Keep changes in pages as it was a Log
- Use hashing scheme to find objects by name (update O(1))
- *Acceptor* : the current page that receives objects

Definitions

- A page is useful for the following time instants:
  - I-useful: while this page was the acceptor block
  - II-useful: for all time instants for which it contains at least uB “alive” records
- u is the usefulness parameter

Meta-evolution

- From the actual evolution of objects, now we have the evolution of pages! *meta-evolution*
- The “lifetime” of a page is its usefulness



Searching

- Find all alive objects at t_q → Find all useful pages at t_q
- The search can be done in $O(a/B + \log_B n)$

Copying procedure

- To maintain the answer in few pages we need clustering: controlled copying
- If a page has less than uB alive objects, we artificially delete the remaining alive objects and copy them to the acceptor bock

Optimal Solution

- We can prove that the SI is optimal for pure-timeslice queries:
- O(n) space, O(a/B + $\log_B n$) query and O(1) update (expected, using hashing)