HIERARCHICAL REPRESENTATIONS OF POINT DATA

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PRELIMINARIES

- File \( \equiv \) collection of records \( (N) \)
- Each record contains several attributes or keys \( (k) \)

Queries:
1. Point query
2. Range query (includes partial match)
3. Boolean query \( \equiv \) combine 1 and 2 with AND, OR, NOT

Search methods
1. Organize data to be stored
   - boundaries of regions in the search space are determined by the data
   - e.g., binary search tree

2. Organize the embedding space from which the data is drawn
   - region boundaries in the search space are fixed
   - e.g., address computation methods such as digital searching

3. Hybrid
   - use 1 for some attributes and 2 for others

Extreme solution:
- Bitmap representation where one bit is reserved for every possible record in the multidimensional point space whether or not it is present
- Problems:
  1. large number of attributes
  2. continuous data (non-discrete)
SIMPLE NON-HIERARCHICAL DATA STRUCTURES

1. Sequential list

<table>
<thead>
<tr>
<th>NAME</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>Mobile</td>
<td>52</td>
<td>10</td>
</tr>
<tr>
<td>Toronto</td>
<td>62</td>
<td>77</td>
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<tr>
<td>Buffalo</td>
<td>82</td>
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<tr>
<td>Denver</td>
<td>5</td>
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<tr>
<td>Omaha</td>
<td>27</td>
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<tr>
<td>Atlanta</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>Miami</td>
<td>90</td>
<td>5</td>
</tr>
</tbody>
</table>

2. Inverted List

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver</td>
<td>Miami</td>
</tr>
<tr>
<td>Omaha</td>
<td>Mobile</td>
</tr>
<tr>
<td>Chicago</td>
<td>Atlanta</td>
</tr>
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<td>Mobile</td>
<td>Omaha</td>
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<tr>
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<td>Buffalo</td>
</tr>
<tr>
<td>Miami</td>
<td>Toronto</td>
</tr>
</tbody>
</table>

- 2 sorted lists
- Data is pointers
- Enables pruning the search with respect to one key
GRID METHOD

- Divide space into squares of width equal to the search region
- Each cell contains a list of all points within it
- Assume $L_\infty$ distance metric (i.e., chessboard)
- Assume $C = \text{uniform distribution of points per cell}$
- Average search time for k-dimensional space is $O(F \cdot 2^k)$

$F = \text{number of records found} = C$ since query region has the width of a cell

$2^k = \text{number of cells examined}$
POINT QUADTREE (Finkel/Bentley)

- Marriage between a uniform grid and a binary search tree

Chicago
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PROBLEM OF DELETION IN POINT QUADTREES

- Delete node A
- Conventional algorithm takes one son as the new root and reinserts the remaining subtrees
PROBLEM OF DELETION IN POINT QUADTREES

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1. B is the new root
PROBLEM OF DELETION IN POINT QUADTREES

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2. D is the new root
PROBLEM OF DELETION IN POINT QUADTREES

- Delete node A
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3. G is the new root
PROBLEM OF DELETION IN POINT QUADTREES

- Delete node A
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4. I is the new root
PROBLEM OF DELETION IN POINT QUADTREES

• Delete node A
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• Optimal solution is to use H as the new root since the shaded region is empty
PROBLEM OF DELETION IN POINT QUADTREES

- Delete node A
- Conventional algorithm takes one son as the new root and reinserts the remaining subtrees

- Optimal solution is to use H as the new root since the shaded region is empty

- Problems:
  1. must search for H
  2. a node such as H may possibly not exist as is the case if node J is present
MECHANICS OF DELETION IN POINT QUADTREES

- Ideally, want to replace deleted node (A) with a node (B) that leaves an empty shaded region.
MECHANICS OF DELETION IN POINT QUADTREES

• Ideally, want to replace deleted node (A) with a node (B) that leaves an empty shaded region.

• Involves search and instead settle on a set of candidate nodes obtained using a method analogous to searching a binary search tree.
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D is the closest node
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\[ B \] is the closest node.

• Set of candidates = "closest" node in each quadrant.
  1. choose the candidate node that is closer to each of its bordering axes than any other candidate node which is on the same side of those axes.
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  Condition does not always hold: more than one node satisfies it.
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- Set of candidates = "closest" node in each quadrant
  1. choose the candidate node that is closer to each of its bordering axes than any other candidate node which is on the same side of those axes.
  2. Use the L1 metric to break ties or deadlocks
    - L1 metric is the sum of the displacements from the bordering x and y axes
    - rationale: area of shaded region is \( L_x \cdot d_y + L_y \cdot d_x - d_x \cdot d_y \)
      which can be approximated by \( 2d_x \cdot (L_x + L_y) \) assuming \( d_x \approx d_y \) and \( d_x \) being very small.
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   • at most one of the remaining candidates will be in the shaded region.

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ALGORITHM FOR DELETION IN POINT QUADTREES

- Select a node satisfying the "closest" criteria to the deleted node \( A \) to serve as the new root (\( B \) in the NE quadrant)
ALGORITHM FOR DELETION IN POINT QUADTREES

• Select a node satisfying the "closest" criteria to the deleted node A to serve as the new root (B in the NE quadrant)
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1. no reinsertion in opposite quadrant (sw)
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1. no reinsertion in opposite quadrant (SW)
2. ADJ: apply to adjacent quadrants (NW,SE):
   if root remains in the quadrant (J) then
   • no reinsertion in 2 subquadrants (NW,NE)
   • apply ADJ to remaining 2 subquadrants (SW,SE)
   else reinsert entire quadrant
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   - else reinsert entire quadrant

3. NEWROOT: apply to quadrant containing replacement node (NE)
   - same subquadrant (NE): no reinsertion
   - adjacent subquadrants (NW, SE): ADJ
   - opposite subquadrant (SW): NEWROOT
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     - opposite subquadrant (SW): NEWROOT

- Comparison with conventional reinsertion algorithm
  1. 5/6 reduction in number of nodes requiring reinsertion (2/3 if pick a candidate at random)
  2. number of comparisons during reinsertion was observed to be ~log_4 n vs. a much larger factor
  3. (average total path length)/(optimal total path length) was observed to be constant vs. an increase
MX QUADTREE (Hunter)

- Points are like black pixels in a region quadtree
- Useful for raster to vector conversion
- Empty cells are merged to form larger empty cells
- Only good for discrete data
- Good for sparse matrix applications
- Assume that the point is associated with the lower left corner of each cell
- Ex: assume an 8 x 8 array
  divide coordinate values by 12.5

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1. Regular decomposition point representation
2. Decomposition occurs whenever a block contains more than one point
3. Useful when the domain of data points is not discrete but finite
4. Maximum level of decomposition depends on the minimum separation between two points
   - if two points are very close, then decomposition can be very deep
   - can be overcome by viewing blocks as buckets with capacity $c$ and only decomposing the block when it contains more than $c$ points

Ex: $c = 1$
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Ex: $c = 1$
- Ex: Find all points within radius $r$ of point A

- Use of quadtree results in pruning the search space
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- Use of quadtree results in pruning the search space

- If a quadrant subdivision point $p$ lies in a region $l$, then search the quadrants of $p$ specified by $l$

1. SE
2. SE, SW
3. SW
4. SE, NE
5. SW, NW
6. NE
7. NE, NW
8. NW
9. All but NW
10. All but NE
11. All but SW
12. All but SE
13. All

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• Ex: Find all points within radius \( r \) of point A

![Diagram of a circle with a radius and point A]

• Use of quadtree results in pruning the search space

• If a quadrant subdivision point \( p \) lies in a region \( l \), then search the quadrants of \( p \) specified by \( l \)

1. SE 6. NE 11. All but SW
2. SE, SW 7. NE, NW 12. All but SE
3. SW 8. NW 13. All
4. SE, NE 9. All but NW
5. SW, NW 10. All but NE
FINDING THE NEAREST OBJECT

- Ex: find the nearest object to \( P \)

- Assume PR quadtree for points (i.e., at most one point per block)
- Search neighbors of block 1 in counterclockwise order
- Points are sorted with respect to the space they occupy which enables pruning the search space
- Algorithm:

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  1. start at block 2 and compute distance to \( P \) from \( A \)

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FINDING THE NEAREST OBJECT

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  1. start at block 2 and compute distance to $P$ from $A$
  2. ignore block 3 whether or not it is empty as $A$ is closer to $P$ than any point in 3
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Algorithm:
1. start at block 2 and compute distance to \( P \) from A
2. ignore block 3 whether or not it is empty as A is closer to \( P \) than any point in 3
3. examine block 4 as distance to SW corner is shorter than the distance from \( P \) to A; however, reject B as it is further from \( P \) than A
Finding the Nearest Object

- Ex: find the nearest object to P

```
 12  8  7  6
 13  9  1  4  2
 10 11
```

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  4. ignore blocks 6, 7, 8, 9, and 10 as the minimum distance to them from P is greater than the distance from P to A
FINDING THE NEAREST OBJECT

- Ex: find the nearest object to $P$

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  4. ignore blocks 6, 7, 8, 9, and 10 as the minimum distance to them from $P$ is greater than the distance from $P$ to $A$
  5. examine block 11 as the distance from $P$ to the southern border of 1 is shorter than the distance from $P$ to $A$; however, reject $F$ as it is further from $P$ than $A$
**FINDING THE NEAREST OBJECT**

- **Ex:** find the nearest object to \( P \)

![Diagram of a quadtree with points and blocks labeled from 1 to 12]

- Assume PR quadtree for points (i.e., at most one point per block)
- Search neighbors of block 1 in counterclockwise order
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- **Algorithm:**
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  5. examine block 11 as the distance from \( P \) to the southern border of 1 is shorter than the distance from \( P \) to \( A \); however, reject \( F \) as it is further from \( P \) than \( A \)

- If \( F \) was moved, a better order would have started with block 11, the southern neighbor of 1, as it is closest
## COMPARISON OF POINT, MX, AND PR QUADTREES

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>MX</th>
<th>PR</th>
<th>POINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular decomposition</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Type of nodes</td>
<td>Data Stored in leaf nodes and non-leaf nodes are for control</td>
<td>Data stored in leaf nodes and non-leaf nodes are for control</td>
<td>Data stored in leaf nodes and non-leaf nodes</td>
</tr>
<tr>
<td>Shape of tree depends on order of inserting nodes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Deletion</td>
<td>Simple but may have to collapse WHITE nodes</td>
<td>Simple but may have to collapse WHITE nodes</td>
<td>Complex</td>
</tr>
<tr>
<td>Size of space represented</td>
<td>Finite</td>
<td>Finite</td>
<td>Unbounded</td>
</tr>
<tr>
<td>Type of data represented</td>
<td>Discrete</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Shape of space represented</td>
<td>Square</td>
<td>Rectangle</td>
<td>Unbounded</td>
</tr>
<tr>
<td>Stores coordinates</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Depth of tree (d); assume M points</td>
<td>All nodes are at the same depth, n for a $2^n$ by $2^n$ region</td>
<td>For square region with side length L and minimum separation S between two points, (\lfloor \log_4(M-1) \rfloor \leq d ) and ( d \leq \lfloor \log_2((L/S)^{2.5}) \rfloor )</td>
<td>( \lfloor \log_4(3M) \rfloor \leq d ) and ( d \leq M-1 )</td>
</tr>
</tbody>
</table>

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APPLICATION OF THE MX QUADTREE (Hunter)

- Represent the boundary as a sequence of BLACK pixels in a region quadtree
- Useful for a simple digitized polygon (i.e., non-intersecting edges)
- Three types of nodes
  1. interior - treat like WHITE nodes
  2. exterior - treat like WHITE nodes
  3. boundary - the edge of the polygon passes through them and treated like BLACK nodes
- Disadvantages
  1. a thickness is associated with the line segments
  2. no more than 4 lines can meet at a point
APPLICATION OF THE MX QUADTREE (Hunter)

- Represent the boundary as a sequence of **BLACK** pixels in a region quadtree
- Useful for a simple digitized polygon (i.e., non-intersecting edges)
- Three types of nodes
  1. interior - treat like **WHITE** nodes
  2. exterior - treat like **WHITE** nodes
  3. boundary - the edge of the polygon passes through them and treated like **BLACK** nodes
- Disadvantages
  1. a thickness is associated with the line segments
  2. no more than 4 lines can meet at a point
MX-CIF QUADTREE (Kedem)

1. Collections of small rectangles for VLSI applications
2. Each rectangle is associated with its minimum enclosing quadtree block
3. Like hashing: quadtree blocks serve as hash buckets
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   - one for x-axis

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K-D TREE (Bentley)

- Test one attribute at a time instead of all simultaneously as in the point quadtree
- Usually cycle through all the attributes
- Shape of the tree depends on the order in which the data is encountered
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K-D TREE DELETION

- Similar to deletion in binary search trees
- Assume branch to HISON if test value is $\geq$ root value
- Assume root discriminates on the $x$ coordinate and subsequent alternation with the $y$ coordinate value

Algorithm:

1. replace root by node in HISON with the minimum $x$ coordinate value
2. repeat the process for the position of the replacement node using the $x$ or $y$ coordinate values depending on whether the replacement node is an $x$ or a $y$ discriminator
EXAMPLE OF K-D TREE DELETION

Ex:  

A (20,20)  x

B (10,30)  D (40,50)  y

C (10,20)  E (30,40)  F (35,60)  x

G (25,30)  y

H (29,40)  x

I (27,35)  y

J (28,45)  x
EXAMPLE OF K-D TREE DELETION

Ex: A (20,20) x
    /                     /
   B (10,30) D (40,50) y
  /                 /       /
C (10,20) E (30,40) F (35,60) x
 /                   /
min x G (25,30) y
     /               /
    H (29,40) x
     /               /
    I (27,35) y
     /               /
    J (28,45) x
EXAMPLE OF K-D TREE DELETION

Ex:  A (20,20)  x

            B (10,30)  D (40,50)  y
            /         /
C (10,20)   E (30,40)  F (35,60)  x

        min x  G (25,30)  y

               H (29,40)  x

        min y  I (27,35)  y

J (28,45)  x
EXAMPLE OF K-D TREE DELETION

Ex: A (20,20) x
    B (10,30) D (40,50) y
    C (10,20) E (30,40) F (35,60) x

min x G (25,30) y
    H (29,40) x

min y I (27,35) y
    J (28,45) x

G (25,30) y
    B (10,30) D (40,50)
    C (10,20) E (30,40) F (35,60)
EXAMPLE OF K-D TREE DELETION

Ex: A (20,20) x G (25,30)
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- Analogy with binary search trees implies that we can replace the root by the node in LOSON with the max x coordinate value. However, if there is more than one node with the same max value, then after replacement there would be a node in LOSON which is not strictly less than the new root (e.g., nodes B and C)
EXAMPLE OF K-D TREE DELETION

Ex:  A (20,20)  x  G (25,30)
     B (10,30) D (40,50)  y  B (10,30) D (40,50)
     C (10,20) E (30,40) F (35,60)  x  C (10,20) E (30,40) F (35,60)

min x  G (25,30)  y  I (27,35)
     H (29,40)  x  H (29,40)
min y  I (27,35)  y  J (28,45)
     J (28,45)  x

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• What if the HISON of the root is empty?
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- B (10,30)
- C (10,20)
- D (40,50)
- E (30,40)
- F (35,60)
- G (25,30)
- H (29,40)
- I (27,35)
- J (28,45)

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- Analogy with binary search trees implies that we can replace the root by the node in **LOSON** with the max x coordinate value. However, if there is more than one node with the same max value, then after replacement there would be a node in **LOSON** which is not strictly less than the new root (e.g., nodes B and C)

- **What if the HISON of the root is empty?**
  1. replace root node A with the node B in **LOSON** having the minimum x coordinate value and set the HISON pointer of A to be the old **LOSON** pointer of A
  2. repeat process for the position of the replacement node

---

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K-D TREE SEARCH

- Search space can be pruned by testing if the search region is completely contained in one of the partitions of the node as now only one subtree must be examined.
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- Ex: find all points within 10 of (20,30)
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- Ex: find all points within 10 of (20,30)
  1. search the region entirely to the left of Chicago \((x=35)\)
K-D TREE SEARCH

• Search space can be pruned by testing if the search region is completely contained in one of the partitions of the node as now only one subtree must be examined

• Ex: find all points within 10 of (20,30)
  1. search the region entirely to the left of Chicago (x=35)
  2. search the region entirely below Denver (y=45)
K-D TREE SEARCH

• Search space can be pruned by testing if the search region is completely contained in one of the partitions of the node as now only one subtree must be examined.

• Ex: find all points within 10 of (20,30)
  1. search the region entirely to the left of Chicago \((x=35)\)
  2. search the region entirely below Denver \((y=45)\)
  3. search yields Omaha
PR K-D TREE (Knowlton)

- A region contains at most one data point
- Analogous to EXCELL with bucket size of 1
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ADAPTIVE K-D TREE

• Data is only stored in terminal nodes
• An interior node contains the median of the set as the discriminator
• The discriminator key is the one for which the spread of the values of the key is a maximum

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```
(5,45) Denver
(27,35) Omaha
(35,42) Chicago
(52,10) Mobile
(62,77) Toronto
(82,65) Buffalo
(85,15) Atlanta
(90,5) Miami

(0,100) (100,100)
(0,0) (100,0)
```

```
57,X
31,X
16,X
Denver Omaha

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```
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GRID FILE (Nievergelt,Hinterberger,Sevcik)

• Two level grid for storing points

• Uses a grid directory (a 2d array of grid blocks) on disk that contains the address of the bucket (i.e., page) that contains the data associated with the grid block

• Linear scales (a pair of 1d arrays) in core that access the grid block in the grid directory (on disk) that is associated with a particular point thereby enabling the decomposition of the space to be arbitrary

• Guarantees access to any record with two disk operations — one for each level of the grid
  1. access the grid block
  2. access the bucket

• Each bucket has finite capacity

• Partition upon overflow
  1. bucket partition — overflowing bucket is associated with more than one grid block
  2. grid partition — overflowing bucket is associated with just one grid block

• Splitting policies
  1. split at midpoint and cycle through attributes
  2. adaptive
    • increases granularity of frequently queried attributes
    • favors some attributes over others
GRID FILE EXAMPLE

• Assume bucket size = 2

Linear scales

1. Initially Chicago and Mobile in bucket A
GRID FILE EXAMPLE

• Assume bucket size = 2

1. Initially Chicago and Mobile in bucket A
2. Insert Toronto causing a grid partition yielding bucket B
GRID FILE EXAMPLE

- Assume bucket size = 2

1. Initially Chicago and Mobile in bucket A
2. Insert Toronto causing a grid partition yielding bucket B
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GRID FILE EXAMPLE

• Assume bucket size = 2

1. Initially Chicago and Mobile in bucket A
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4. Insert Denver causing no change
GRID FILE EXAMPLE

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1. Initially Chicago and Mobile in bucket A
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4. Insert Denver causing no change
5. Insert Omaha causing a grid partition yielding bucket D

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1. Initially Chicago and Mobile in bucket A
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6. Insert Atlanta causing a bucket partition yielding bucket E

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6. Insert Atlanta causing a bucket partition yielding bucket E
7. Insert Miami causing a grid partition yielding bucket F

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EXCELL (Tamminen)

- Uses regular decomposition
- Like grid file, guarantees access to any record with two disk operations
- Differentiated from grid file by absence of linear scales which enable decomposition of space to be arbitrary
- Grid partition results in doubling the size of grid directory
- Ex: bucket size = 2

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7. Insert Atlanta causing no change
8. Insert Miami causing a bucket partition yielding bucket F
SUMMARY

• Data structures can be grouped:
  N = No data organization
  D = Organize data to be stored (e.g., binary search tree)
  E = Organize the embedding space from which the data is drawn (e.g., digital searching)
  H = Hybrid (combines at least two of N, D, and E)
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Hierarchical structures:

- **Sequential List**
- **Inverted List**
- **Grid Method**
- **Grid File**
- **Point Quadtree**
- **K-d tree**
- **Adaptive K-d tree**

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DRAWBACKS OF MOST HASHING METHODS

- Require rehashing all the data when the hash table becomes too full
- Goal: only move a few records
- Solutions:
  1. Knott
     - use a trie in the form of a binary tree
  2. extendible hashing
     (Fagin, Nievergelt, Pippenger, Strong)
     - like a trie except that all buckets are at same level
     - buckets are accessed by use of a directory
     - directory elements are NOT the same as buckets
  3. Linear hashing (Litwin)
     - provides for linear growth in the number of buckets (i.e., the hash table grows at a rate of one bucket at a time)
     - does not make use of a directory
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     - implemented as a directory of pointers to buckets
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     - directory elements are NOT the same as buckets
     - implemented as a directory of pointers to buckets
     - accessing a bucket requires 1 operation
     - bucket overflow may cause doubling the directory
     - e.g., EXCELL

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     - does not make use of a directory
MECHANICS OF LINEAR HASHING

- Assume a file with $m$ buckets
- Use two hashing functions $h_i(k) = f(k) \mod 2^{i+1}$ for $i = n$ and $i = n+1$
  1. compute $h_{n+1}(k) = x$ and use the result if $x < m$
  2. otherwise use $h_n(k)$
- Such a file is said to be at level $n,n+1$
- There exist primary and overflow buckets
- When a record hashes to a full primary bucket, then it is inserted into an overflow bucket corresponding to the primary bucket
- $\tau$: storage utilization factor
  $$\tau = \frac{\text{number of records in file}}{\text{total of available slots in primary and overflow buckets}}$$
- When $\tau > \alpha$, then one of the buckets is split
- When bucket $i$ is split, it and its overflow bucket’s records are rehashed using $h_{n+1}$ and distributed into buckets $i$ and $i + 2^n$ as is appropriate
LINEAR HASHING INSERTION ALGORITHM

- Let $s$ denote the identity of the next bucket to be split and cycles from 0 to $2^n - 1$
- Insertion algorithm
  1. compute bucket address $i$ for record $r$
  2. insert $r$ in bucket $i$
  3. if $\tau > \alpha$, then split bucket $i$ creating bucket $i + 2^n$ and reinsert in buckets $i$ and $i + 2^n$
  4. if $s = 2^n$, then all buckets have been split
    - increment $n$
    - reset $s$ to 0
  5. if buckets $i$ or $i+1$ overflow, then allocate an overflow bucket
  6. if rehashing causes some overflow buckets to be reclaimed, repeat steps 3-5
- Notes
  1. a bucket split need not necessarily occur when a record hashes to a full bucket, nor does the bucket being split need to be full
  2. key principle is that eventually every bucket will be split and ideally all overflow buckets will be emptied and reclaimed
  3. if the storage utilization gets too low, then buckets should be reclaimed

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BIT INTERLEAVING HASHING FUNCTIONS

- Bit interleaving takes one bit from the binary representation of the $x$ coordinate value and one bit from the binary representation of the $y$ coordinate value and alternates them.
- Use city coordinate values and divide by 12.5 so that each coordinate value requires just three binary digits.
- Example with $y$ being more significant than $x$

<table>
<thead>
<tr>
<th>City</th>
<th>$x$</th>
<th>$y$</th>
<th>$f(z)=z \div 12.5$</th>
<th>Bit Interleaved Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>35</td>
<td>42</td>
<td>2, 3</td>
<td>14</td>
</tr>
<tr>
<td>Mobile</td>
<td>52</td>
<td>10</td>
<td>4, 0</td>
<td>16</td>
</tr>
<tr>
<td>Toronto</td>
<td>62</td>
<td>77</td>
<td>4, 6</td>
<td>56</td>
</tr>
<tr>
<td>Buffalo</td>
<td>82</td>
<td>65</td>
<td>6, 5</td>
<td>54</td>
</tr>
<tr>
<td>Denver</td>
<td>5</td>
<td>45</td>
<td>0, 3</td>
<td>10</td>
</tr>
<tr>
<td>Omaha</td>
<td>27</td>
<td>35</td>
<td>2, 2</td>
<td>12</td>
</tr>
<tr>
<td>Atlanta</td>
<td>85</td>
<td>15</td>
<td>6, 1</td>
<td>22</td>
</tr>
<tr>
<td>Miami</td>
<td>90</td>
<td>5</td>
<td>7, 0</td>
<td>21</td>
</tr>
</tbody>
</table>
BIT INTERLEAVING HASHING FUNCTIONS

- Bit interleaving takes one bit from the binary representation of the $x$ coordinate value and one bit from the binary representation of the $y$ coordinate value and alternates them.
- Use city coordinate values and divide by 12.5 so that each coordinate value requires just three binary digits.
- Example with $y$ being more significant than $x$

<table>
<thead>
<tr>
<th>City</th>
<th>$x$</th>
<th>$y$</th>
<th>$f(z) = z \text{ div } 12.5$</th>
<th>Bit Interleaved Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>35</td>
<td>42</td>
<td>2</td>
<td>$1$</td>
</tr>
<tr>
<td>Mobile</td>
<td>52</td>
<td>10</td>
<td>4</td>
<td>$0$</td>
</tr>
<tr>
<td>Toronto</td>
<td>62</td>
<td>77</td>
<td>4</td>
<td>$6$</td>
</tr>
<tr>
<td>Buffalo</td>
<td>82</td>
<td>65</td>
<td>6</td>
<td>$5$</td>
</tr>
<tr>
<td>Denver</td>
<td>5</td>
<td>45</td>
<td>0</td>
<td>$3$</td>
</tr>
<tr>
<td>Omaha</td>
<td>27</td>
<td>35</td>
<td>2</td>
<td>$2$</td>
</tr>
<tr>
<td>Atlanta</td>
<td>85</td>
<td>15</td>
<td>6</td>
<td>$1$</td>
</tr>
<tr>
<td>Miami</td>
<td>90</td>
<td>5</td>
<td>7</td>
<td>$0$</td>
</tr>
</tbody>
</table>

- Ex: **Atlanta (6,1)**
BIT INTERLEAVING HASHING FUNCTIONS

- Bit interleaving takes one bit from the binary representation of the $x$ coordinate value and one bit from the binary representation of the $y$ coordinate value and alternates them.
- Use city coordinate values and divide by 12.5 so that each coordinate value requires just three binary digits.
- Example with $y$ being more significant than $x$.

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<thead>
<tr>
<th>City</th>
<th>$x$</th>
<th>$y$</th>
<th>$f(z) = \frac{z}{12.5}$</th>
<th>Bit Interleaved Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>35</td>
<td>42</td>
<td>2 3</td>
<td>14</td>
</tr>
<tr>
<td>Mobile</td>
<td>52</td>
<td>10</td>
<td>4 0</td>
<td>16</td>
</tr>
<tr>
<td>Toronto</td>
<td>62</td>
<td>77</td>
<td>4 6</td>
<td>56</td>
</tr>
<tr>
<td>Buffalo</td>
<td>82</td>
<td>65</td>
<td>6 5</td>
<td>54</td>
</tr>
<tr>
<td>Denver</td>
<td>5</td>
<td>45</td>
<td>0 3</td>
<td>10</td>
</tr>
<tr>
<td>Omaha</td>
<td>27</td>
<td>35</td>
<td>2 2</td>
<td>12</td>
</tr>
<tr>
<td>Atlanta</td>
<td>85</td>
<td>15</td>
<td>6 1</td>
<td>22</td>
</tr>
<tr>
<td>Miami</td>
<td>90</td>
<td>5</td>
<td>7 0</td>
<td>21</td>
</tr>
</tbody>
</table>

- **Ex:** Atlanta (6,1) $0\ 1\ 0\ 1\ 1\ 0 = 22$
EXAMPLE OF LINEAR HASHING

• Assume primary and overflow bucket capacity is 2
• A bucket is split whenever $\tau \geq \alpha = 0.66$
• Initially, only bucket 0 exists

\[ \rightarrow 0 \]

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EXAMPLE OF LINEAR HASHING

- Assume primary and overflow bucket capacity is 2
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<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>Mobile</td>
</tr>
</tbody>
</table>

- Insert Chicago (14) and Mobile (16):
  $\tau = 1$ and split bucket 0 creating bucket 1
EXAMPLE OF LINEAR HASHING

- Assume primary and overflow bucket capacity is 2
- A bucket is split whenever $\tau \geq \alpha = 0.66$
- Initially, only bucket 0 exists

```
<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chicago</td>
<td>Toronto</td>
<td>Mobile</td>
</tr>
</tbody>
</table>
```

- Insert Chicago (14) and Mobile (16): $\tau=1$ and split bucket 0 creating bucket 1
- Insert Toronto (56) into bucket 0: $\tau=0.75$ and split bucket 0 creating bucket 2; move Chicago to bucket 2
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- Initially, only bucket 0 exists

```
0    1    2    3
Chicago  Toronto  Mobile
        Chicago  Buffalo
        Denver
```

- Insert Chicago (14) and Mobile (16): $\tau=1$ and split bucket 0 creating bucket 1
- Insert Toronto (56) into bucket 0: $\tau=0.75$ and split bucket 0 creating bucket 2; move Chicago to bucket 2
- Insert Buffalo (54) into bucket 2: $\tau=0.67$ and split bucket 1 creating bucket 3
- Insert Denver (10) into bucket 2 which causes it to overflow
EXAMPLE OF LINEAR HASHING

• Assume primary and overflow bucket capacity is 2
• A bucket is split whenever $\tau \geq \alpha = 0.66$
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- Insert Chicago (14) and Mobile (16): $\tau=1$ and split bucket 0 creating bucket 1
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- Insert Omaha (12) into bucket 0 which causes it to overflow
EXAMPLE OF LINEAR HASHING

• Assume primary and overflow bucket capacity is 2
• A bucket is split whenever \( \tau \geq \alpha = 0.66 \)
• Initially, only bucket 0 exists

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- Insert Denver (10) into bucket 2 which causes it to overflow
- Insert Omaha (12) into bucket 0 which causes it to overflow
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EXAMPLE OF LINEAR HASHING

- Assume primary and overflow bucket capacity is 2
- A bucket is split whenever $\tau \geq \alpha = 0.66$
- Initially, only bucket 0 exists

1. Insert Chicago (14) and Mobile (16):
   $\tau=1$ and split bucket 0 creating bucket 1
2. Insert Toronto (56) into bucket 0:
   $\tau=0.75$ and split bucket 0 creating bucket 2; move Chicago to bucket 2
3. Insert Buffalo (54) into bucket 2:
   $\tau=0.67$ and split bucket 1 creating bucket 3
4. Insert Denver (10) into bucket 2 which causes it to overflow
5. Insert Omaha (12) into bucket 0 which causes it to overflow
6. Insert Atlanta (22) into bucket 2's overflow area
7. Insert Miami (21) into bucket 1:
   $\tau=0.67$ and split bucket 0 creating bucket 4; move Omaha to bucket 4
EXAMPLE OF LINEAR HASHING

- Assume primary and overflow bucket capacity is 2
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- Initially, only bucket 0 exists

- Insert Chicago (14) and Mobile (16): $\tau = 1$ and split bucket 0 creating bucket 1
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- Insert Omaha (12) into bucket 0 which causes it to overflow
- Insert Atlanta (22) into bucket 2's overflow area
- Insert Miami (21) into bucket 1: $\tau = 0.67$ and split bucket 0 creating bucket 4; move Omaha to bucket 4
- Reclaim the overflow area of bucket 0: $\tau = 0.67$ again and split bucket 1 creating bucket 5; move Miami to bucket 5
ORDER PRESERVING LINEAR HASHING (OPLH)

- Problem: the hash function \( h_n(k) = k \mod 2^n \) implies that all records in a given bucket agree in the least \( n \) significant bits
  
  1. OK for random access
  2. unacceptable for sequential access as each record will be in a different bucket

- Solution: use the hash function \( h_n(k) = (\text{reverse}(k)) \mod 2^n \)
  
  1. tests the \( n \) most significant bits
  2. all records in a bucket are within a given range

<table>
<thead>
<tr>
<th>City</th>
<th>x</th>
<th>y</th>
<th>( f(z) = z \mod 12.5 )</th>
<th>Bit Interleaved Value</th>
<th>x most sig</th>
<th>y most sig</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chicago</td>
<td>35</td>
<td>42</td>
<td>2</td>
<td>3</td>
<td>44</td>
<td>28</td>
</tr>
<tr>
<td>Mobile</td>
<td>52</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Toronto</td>
<td>62</td>
<td>77</td>
<td>4</td>
<td>6</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Buffalo</td>
<td>82</td>
<td>65</td>
<td>6</td>
<td>5</td>
<td>39</td>
<td>27</td>
</tr>
<tr>
<td>Denver</td>
<td>5</td>
<td>45</td>
<td>0</td>
<td>3</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Omaha</td>
<td>27</td>
<td>35</td>
<td>2</td>
<td>2</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Atlanta</td>
<td>85</td>
<td>15</td>
<td>6</td>
<td>1</td>
<td>37</td>
<td>26</td>
</tr>
<tr>
<td>Miami</td>
<td>90</td>
<td>5</td>
<td>7</td>
<td>0</td>
<td>21</td>
<td>42</td>
</tr>
</tbody>
</table>

- Shortcomings
  
  1. records may not be scattered too well
     - overflow is much more common than with traditional hashing methods
     - random access is slower since several overflow buckets may have to be examined
  2. creates a large number of sparsely filled buckets
     - sequential access may be slower as may have to examine many empty buckets

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- Assume primary and overflow bucket capacity is 2
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- Insert Omaha (12) into 0: $\tau = 0.75$ and split bucket 0 creating bucket 4; move Denver and Chicago to bucket 4
EXAMPLE OF ORDER PRESERVING LINEAR HASHING

- Assume primary and overflow bucket capacity is 2
- A bucket is split whenever \( t \geq \alpha = 0.66 \)
- Initially, only bucket 0 exists

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2. Insert Toronto (7) into bucket 1: \( t = 0.75 \) and split bucket 0 creating bucket 2; move Mobile to bucket 2
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5. Insert Omaha (12) into 0: \( t = 0.75 \) and split bucket 0 creating bucket 4; move Denver and Chicago to bucket 4
6. Insert Atlanta (26) into bucket 2
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- Insert Atlanta (26) into bucket 2
- Insert Miami (42) into bucket 2: $\tau = 0.67$ and split bucket 1 creating bucket 5; move Miami to bucket 2's overflow area
### COMPARISON OF OPLH WITH EXCELL

<table>
<thead>
<tr>
<th>OPLH</th>
<th>EXCELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Implicit directory</td>
<td>1. Explicit directory</td>
</tr>
<tr>
<td>• one directory element per primary bucket</td>
<td>• set of primary buckets</td>
</tr>
<tr>
<td>• all buckets stored at one of two levels</td>
<td></td>
</tr>
<tr>
<td>• overflow buckets</td>
<td></td>
</tr>
<tr>
<td>2. Reverse bit interleaving</td>
<td>2. Reverse bit interleaving</td>
</tr>
<tr>
<td>• allocate at most two additional buckets (one</td>
<td>• triggers bucket split or directory doubling</td>
</tr>
<tr>
<td>for the bucket that has been split and one for</td>
<td></td>
</tr>
<tr>
<td>the overflowing bucket)</td>
<td></td>
</tr>
<tr>
<td>4. Retrieval of a record requires examining</td>
<td>4. Retrieve any record with two disk accesses</td>
</tr>
<tr>
<td>primary and overflow buckets</td>
<td></td>
</tr>
</tbody>
</table>

- **Summary**: order preserving linear hashing (OPLH) yields a more gradual growth in the size of the directory at the expense of the loss of the guarantee of retrieval of any record with just two disk accesses.
EXAMPLES OF COMPARISON OF OPLH WITH EXCELL

1. Reversed bit interleaving with the y coordinate value as the most significant (i.e., y is split first)
   
   **OPLH:**
   
   **EXCELL:**
   
   - 6 primary buckets
   - 2 overflow buckets
   - 7 buckets
   - 16 directory elements

2. Reversed bit interleaving with the x coordinate value as the most significant (i.e., x is split first)
   
   **OPLH:**
   
   **EXCELL:**
   
   - 7 primary buckets
   - no overflow buckets
   - 6 buckets
   - 8 directory elements
• Drawbacks of linear hashing:
  1. order in which buckets are split is unrelated to the probability of the occurrence of overflow
  2. all buckets that are candidates for a split have the same probability of overflowing

• Central idea is the existence of an ever-changing (and growing) address space of active bucket addresses
  1. records are distributed in the active buckets in an uneven manner
  2. split the bucket with the highest probability of overflowing

• When a bucket $s$ is split
  1. create $d$ new buckets
  2. rehash the contents of $s$ into the $d$ new buckets
  3. bucket $s$ is no longer used

• If $[s, t]$ are the active buckets, then $[s + 1, t + d]$ are the active buckets after the split

• Ex: assume that initially there are $d - 1$ active buckets starting at address 1

  $d = 2$: 1

• After $s$ bucket splits, there are $(s + 1) \cdot (d + 1)$ active buckets starting at address $s + 1$ (prove by induction)
SPIRAL HASHING (Martin)

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\[
d = 2: \begin{array}{c}
1 \\
2 \\
3 
\end{array}
\]

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- Ex: assume that initially there are $d - 1$ active buckets starting at address 1

\[
d = 2: \begin{array}{c}
1 \\
2 & 3 \\
3 & 4 & 5
\end{array}
\]

- After $s$ bucket splits, there are $(s + 1) \times (d + 1)$ active buckets starting at address $s + 1$ (prove by induction)

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SPIRAL HASHING (Martin)

- Drawbacks of linear hashing:
  1. order in which buckets are split is unrelated to the probability of the occurrence of overflow
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- Ex: assume that initially there are $d - 1$ active buckets starting at address 1

  $d = 2$: 

  $\begin{array}{c}
  \text{1} \\
  \text{2} \quad \text{3} \\
  \text{3} \quad \text{4} \quad \text{5} \\
  \text{4} \quad \text{5} \quad \text{6} \quad \text{7}
  \end{array}$

- After $s$ bucket splits, there are $(s + 1) \cdot (d + 1)$ active buckets starting at address $s + 1$ (prove by induction)
SPIRAL HASHING FUNCTION

• Assume that initially there are \(d-1\) active buckets starting at address 1
• Key idea is the behavior of the function \(y = d^x\)
 1. \(d^{k+1} - d^k = d^k \cdot (d -1)\)
 2. bucket \(s\) has just been split
 3. let \(d^x = s +1\) = address of first active bucket
 4. implies \(d^{k+1} - d^k = (s +1) \cdot (d -1) = \text{number of active buckets}\)
 5. last active bucket is at address \(d^{k+1} -1\)
 6. \([d^x, d^{k+1})\) is range of active buckets
• Use two hashing functions
 1. \(h(k)\) maps key \(k\) uniformly into \([0,1)\) which is the range of the difference in exponent values of addresses in \(y = d^{k+1} - d^k\)
 2. \(y(k)\) maps \(h(k)\) into an address in \([s+1, (s+1)+(s+1)\cdot(d-1))\)
    • \(y(k) = \lfloor d^{x(k)} \rfloor\) with \(x(k)\) in range \([\log_d (s+1), \log_d (s+1)+1)\)
    • before split, active buckets lay in range \([\log_d s, \log_d s+1)\)
    • want to make sure that all key values previously in bucket \(s\) – i.e., \(x(k)\) in \([\log_d s, \log_d (s+1))\) are rehashed into one of the new buckets with an \(x(k)\) value in \([\log_d s+1, \log_d (s+1)+1)\)
    • leave other key values in \([\log_d (s+1), \log_d s+1)\) unchanged
    • difficult to choose \(x(k)\)
      a. \(x(k) = \log_d (s+1) + h(k)\)
        • drawback: must rehash all keys when a bucket is split
      b. \(x(k) = \lceil \log_d (s+1) - h(k) \rceil + h(k)\)
        • guarantees that if \(k\) is hashed into bucket \(b \geq s +1\)
          then it continues to hash there until bucket \(b\) is split
        • implies that \(x(k)\) is a number in the range \([\log_d (s+1), \log_d (s+1) +1)\) whose fractional part is \(h(k)\)
BEHAVIOR OF THE SPIRAL HASHING FUNCTION

- Ex: \( d = 2 \)

<table>
<thead>
<tr>
<th>Bucket address</th>
<th>Hash interval</th>
<th>Relative load</th>
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The function \( y = 2^x \)

Relative load of buckets 1-15

Copyright © 1998 by Hanan Samet
BEHAVIOR OF THE SPIRAL HASHING FUNCTION

- Ex: $d = 2$

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- Split bucket 3

The function $y = 2^x$

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- **Split bucket 3**
- **Yields buckets 6 and 7**
TABLES FOR EXAMPLE OF SPIRAL HASHING

- Use bit interleaving to form a value $k$ - i.e., take one bit from the binary representation of the $x$ coordinate value and one bit from the binary representation of the $y$ coordinate value and alternate them
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- Example with $y$ being more significant than $x$

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- Ex: Atlanta (6,1)
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- Ex: Atlanta $(6,1)$

```
1 1 0
```

```
0 1 0 1 1 0
```

```
= 22
```

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MECHANICS OF EXAMPLE OF SPIRAL HASHING

- Assume $d = 2$ and primary and overflow bucket capacity of 2
- A bucket is split whenever $\tau \geq \alpha = 0.66$
- Initially, only bucket 1 exists
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Insert Atlanta (.34) into bucket 5: \( \tau = 0.7 \) and split bucket 4 creating buckets 8 and 9; Denver is moved to bucket 8, while Chicago, Mobile, and Omaha are moved to bucket 9 which causes it to overflow
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- Insert Miami (.33) into bucket 5: \( \tau=0.67 \) and split bucket 5 creating buckets 10 and 11; Move Atlanta and Miami to bucket 10
COMPARISON OF SPIRAL AND LINEAR HASHING

• Main advantage of spiral hashing over linear hashing is that the bucket being split is the one most likely to overflow

• Disadvantages of spiral hashing:
  1. the buckets that have been split are not reused
     • overcome by using a mapping between logical and physical addresses
  2. expensive to calculate function \( y = d^x \)
     • overcome by use of an approximation

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WHY SPIRAL?

- Can rewrite $y = \sum d^k$ as $\rho = e^{j\theta}$ using polar coordinates which yields the equation of a spiral

- Ex: $\rho = e^{(\ln 2) \cdot \theta / 2\pi}$

- Polar coordinates mean that the active buckets are always within one complete arc of the spiral – i.e., $\theta = 2\pi$

- Mechanics of a bucket split
  1. let first active bucket be at $a = e^{jb}$ (i.e., $\theta = b$)
  2. last active bucket is at $c = e^{j(b+2\pi)} - 1$
  3. bucket split means that the contents of the active bucket at $\rho = a$ (i.e., $\theta = b$) are distributed into buckets $c + 1$ through $g$ where $g = e^{j(b+2\pi+\phi)}$ and $\phi$ is the solution of $a + 1 = e^{j(b+\phi)}$ – i.e., $\phi = (\ln (a + 1)) / j - b$
  4. buckets $a + 1$ through $g$ are now the active buckets

- Ex: $d = 2$
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- Ex: \( d = 2 \)
  1. active buckets 6 through 11
WHY SPIRAL?

- Can rewrite \( y = \lfloor d^k \rfloor \) as \( \rho = e^{j\theta} \) using polar coordinates which yields the equation of a spiral
- Ex: \( \rho = e^{(\ln 2)\cdot\theta/2\pi} \)

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  4. buckets \( a + 1 \) through \( g \) are now the active buckets
- Ex: \( d = 2 \)
  1. active buckets 6 through 11
  2. split bucket 6 to yield buckets 12 and 13

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WHY SPIRAL?

• Can rewrite \( y = \sqrt{d^k} \) as \( \rho = e^{j\theta} \) using polar coordinates which yields the equation of a spiral

\[ \rho = e^{(\ln 2) \cdot \theta / 2\pi} \]

• Polar coordinates mean that the active buckets are always within one complete arc of the spiral – i.e., \( \theta = 2\pi \)

• Mechanics of a bucket split
  1. let first active bucket be at \( a = e^{jrb} \) (i.e., \( \theta = b \))
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• Ex: \( d = 2 \)
  1. active buckets 6 through 11
  2. split bucket 6 to yield buckets 12 and 13
  3. active buckets 7 through 13
WHY SPIRAL?

- Can rewrite $y = \lceil \alpha x \rceil$ as $\rho = e^{i\theta}$ using polar coordinates which yields the equation of a spiral
- Ex: $\rho = e^{(\ln 2) \cdot \theta / 2\pi}$

- Polar coordinates mean that the active buckets are always within one complete arc of the spiral – i.e., $\theta = 2\pi$
- Mechanics of a bucket split
  1. let first active bucket be at $a = \lceil e^{i\theta b} \rceil$ (i.e., $\theta = b$)
  2. last active bucket is at $c = \lceil e^{i(b+2\pi)} \rceil - 1$
  3. bucket split means that the contents of the active bucket at $\rho = a$ (i.e., $\theta = b$) are distributed into buckets $c + 1$ through $g$ where $g = \lceil e^{i(b+2\pi+\phi)} \rceil$ and $\phi$ is the solution of $a + 1 = e^{i(b+\phi)}$ – i.e., $\phi = (\ln (a + 1))/j - b$
  4. buckets $a + 1$ through $g$ are now the active buckets
- Ex: $d = 2$
  1. active buckets 6 through 11
  2. split bucket 6 to yield buckets 12 and 13
  3. active buckets 7 through 13
- Observations
  1. Instead of $h(k)$ uniformly mapping key $k$ into $[0,1)$, use $h_\phi(k)$ to uniformly map $k$ into $[0,2\pi)$
  2. length of arc has constant value between successive integer values of $\rho$