VQ Encoding is Nearest Neighbor Search

- Given an input vector, find the closest codeword in the codebook and output its index.
- Closest is measured in squared Euclidian distance.
- For two vectors \((w_1, x_1, y_1, z_1)\) and \((w_2, x_2, y_2, z_2)\).

\[
\text{Squared Distance} = (w_1 - w_2)^2 + (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2
\]

k-d Tree

- Jon Bentley, 1975
- Tree used to store spatial data.
  - Nearest neighbor search.
  - Range queries.
  - Fast look-up
- k-d tree are guaranteed \(\log n\) depth where \(n\) is the number of points in the set.
  - Traditionally, k-d trees store points in \(d\)-dimensional space which are equivalent to vectors in \(d\)-dimensional space.

k-d Tree Construction

- If there is just one point, form a leaf with that point.
- Otherwise, divide the points in half by a line perpendicular to one of the axes.
- Recursively construct k-d trees for the two sets of points.
- Division strategies
  - divide points perpendicular to the axis with widest spread.
  - divide in a round-robin fashion.

k-d Tree Construction (1)

- Divide perpendicular to the widest spread.

k-d Tree Construction (2)
k-d Tree Construction Complexity

- First sort the points in each dimension.
  - $O(dn \log n)$ time and $dn$ storage.
  - These are stored in $A[1..d,1..n]$.
- Finding the widest spread and equally divide into two subsets can be done in $O(dn)$ time.
- Constructing the k-d tree can be done in $O(dn \log n)$ and $dn$ storage.
Node Structure for k-d Trees

- A node has 5 fields
  - axis (splitting axis)
  - value (splitting value)
  - left (left subtree)
  - right (right subtree)
  - point (holds a point if left and right children are null)

k-d Tree Nearest Neighbor Search

\[
\text{NNS}(q, n, \text{point}, w, \text{ref distance})
\]

- if \( n.\text{left} = n.\text{right} = \text{null} \) then
  - leaf case
  - \( w' = ||q - n.\text{point}|| \)
  - if \( w' < w \) then \( w = w' \); \( p = n.\text{point} \)
  - else
  - if \( w = \infty \) then
    - if \( q(n.\text{axis}) < n.\text{value} \) then
      - \( \text{NNS}(q, n.\text{left}, p, w) \)
    - if \( q(n.\text{axis}) + w > n.\text{value} \) then
      - \( \text{NNS}(q, n.\text{right}, p, w) \)
    - else
      - \( \text{NNS}(q, n.\text{right}, p, w) \)
  - else
    - if \( q(n.\text{axis}) - w < n.\text{value} \) then
      - \( \text{NNS}(q, n.\text{left}, p, w) \)
    - else
      - \( \text{NNS}(q, n.\text{left}, p, w) \)
    - if \( q(n.\text{axis}) - w < n.\text{value} \) then
      - \( \text{NNS}(q, n.\text{left}, p, w) \)
    - else
      - \( \text{NNS}(q, n.\text{right}, p, w) \)

Explanation

- \( q(n.\text{axis}) - w \leq n.\text{value} \)
  - means the circle overlap the left subtree.
- \( q(n.\text{axis}) + w > n.\text{value} \)
  - means the circle overlap the right subtree.

k-d Tree NNS (1)

- \( q(n.\text{axis}) - w \leq n.\text{value} \)
- \( q(n.\text{axis}) + w > n.\text{value} \)

k-d Tree NNS (2)

- \( q(n.\text{axis}) - w \leq n.\text{value} \)
- \( q(n.\text{axis}) + w > n.\text{value} \)

k-d Tree NNS (3)

- \( q(n.\text{axis}) - w \leq n.\text{value} \)
- \( q(n.\text{axis}) + w > n.\text{value} \)
Notes on k-d Tree NNS

- Has been shown to run in $O(\log n)$ average time per search in a reasonable model. (Assume $d$ a constant)
- For VQ it appears that $O(\log n)$ is correct.
- Storage for the k-d tree is $O(n)$.
- Preprocessing time is $O(n \log n)$ assuming $d$ is a constant.

Alternatives

- Orchard’s Algorithm (1991)
  - Uses $O(n^2)$ storage but is very fast
- Annulus Algorithm
  - Similar to Orchard but uses $O(n)$ storage. Does many more distance calculations.
- PCP Principal Component Partitioning
  - Zatloukal, Johnson, Ladner (1999)
  - Similar to k-d trees
  - Also very fast

Principal Component Partition

PCP Tree vs. k-d tree

Notes on VQ

- Works well in some applications.
  - Requires training
- Has some interesting algorithms.
  - Codebook design
  - Nearest neighbor search
- Variable length codes for VQ.
  - PTSVQ - pruned tree structured VQ (Chou, Lookabaugh and Gray, 1989)
  - ECVQ - entropy constrained VQ (Chou, Lookabaugh and Gray, 1989)

Comparison in Time per Search

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