

Introduction to **Information Retrieval**

CS276: Information Retrieval and Web Search

Pandu Nayak and Prabhakar Raghavan

Lecture 12: Clustering

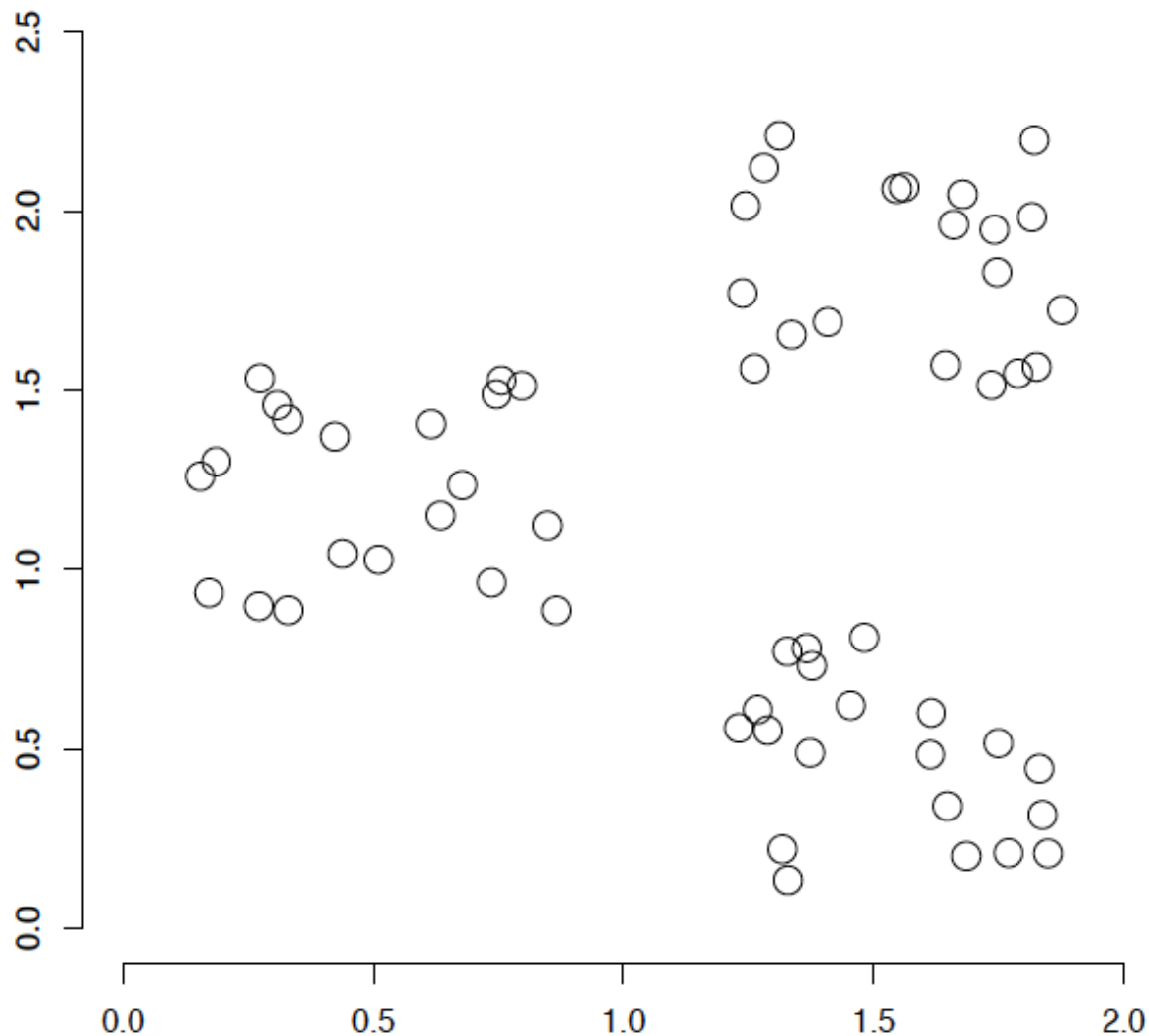
Today's Topic: Clustering

- Document clustering
 - Motivations
 - Document representations
 - Success criteria
- Clustering algorithms
 - Partitional
 - Hierarchical

What is clustering?

- **Clustering**: the process of grouping a set of objects into classes of similar objects
 - Documents within a cluster should be similar.
 - Documents from different clusters should be dissimilar.
- The commonest form of *unsupervised learning*
 - Unsupervised learning = learning from raw data, as opposed to supervised data where a classification of examples is given
 - A common and important task that finds many applications in IR and other places

A data set with clear cluster structure



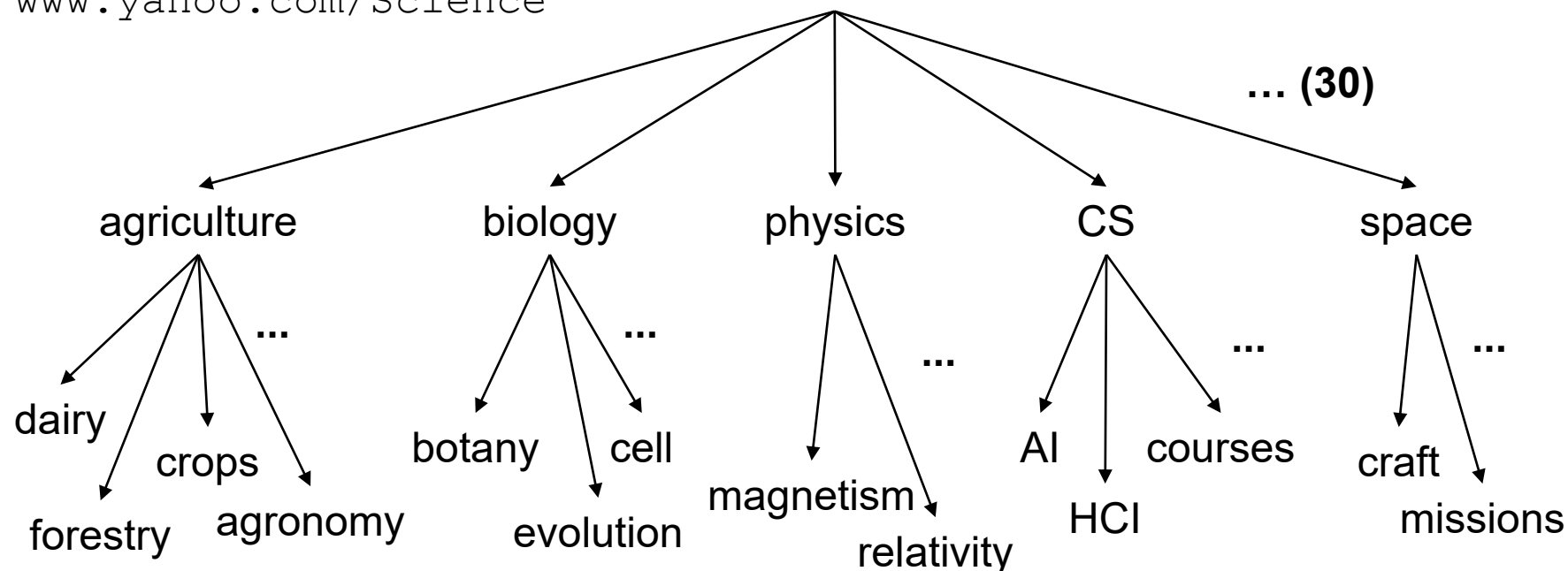
- How would you design an algorithm for finding the three clusters in this case?

Applications of clustering in IR

- Whole corpus analysis/navigation
 - Better user interface: search without typing
- For improving recall in search applications
 - Better search results (like pseudo RF)
- For better navigation of search results
 - Effective “user recall” will be higher
- For speeding up vector space retrieval
 - Cluster-based retrieval gives faster search

Yahoo! Hierarchy *isn't* clustering but *is* the kind of output you want from clustering


www.yahoo.com/Science





Google News: automatic clustering gives an effective news presentation metaphor

The screenshot shows the Google News interface with a grid of news stories. The stories are organized into two main columns: 'World' and 'U.S.'. Each story includes a headline, a timestamp (e.g., '36 minutes ago'), a brief summary, and a list of source links. The layout uses a grid to present related stories side-by-side, demonstrating the automatic clustering metaphor.

World » [edit](#)


Pirates Demand \$25 Million Ransom for Hijacked Tanker (Update1) 
 Bloomberg - 36 minutes ago
 By Caroline Alexander and Hamsa Omar Nov. 20 (Bloomberg) -- Somali pirates are demanding \$25 million in ransom to release an oil-laden Saudi supertanker seized off the East African coast, and called on the ship's owners to pay up "soon."
[Somali pirates demand \\$25M for Saudi ship](#) United Press International
[African Union says Somali politicians fuel piracy](#) Washington Post
[BBC News](#) - [guardian.co.uk](#) - [Aljazeera.net](#) - [RIA Novosti](#)
[all 4,015 news articles »](#)


Pakistan protests over US missile strikes 
 Reuters - 2 hours ago
 By Simon Cameron-Moore ISLAMABAD (Reuters) - Pakistan summoned US ambassador Anne Patterson on Thursday to protest over missile strikes launched by pilotless drone aircraft against militant targets in Pakistan.
[Pakistan protests US drone attacks, Taliban warns of reprisals](#) AFP
[Pakistan warns US over missile strike](#) CNN International
[Telegraph.co.uk](#) - [China Daily](#) - [Xinhua](#) - [PRESS TV](#)
[all 560 news articles »](#)


Nighttime attack on Thai antigovernment protesters wounds at least 20 
 Christian Science Monitor - 30 minutes ago
 The government denied attacking demonstrators, who have called for the ouster of the prime minister. By Huma Yusuf One person has been killed and 23 others wounded in a grenade attack Thursday against antigovernment protesters occupying the Thai prime ...
[Blast Kills 1, Wounds 23 at Thai Prime Minister's Office](#) Washington Post
[Anti-government protestor in Thailand dies in grenade attack](#) International Herald Tribune
[Xinhua](#) - [United Press International](#) - [The Associated Press](#) - [AsiaOne](#)
[all 688 news articles »](#)

[Show more stories](#) [Show fewer stories](#)

U.S. » [edit](#)

Top Court in California Will Review Proposition 8 
 New York Times - 1 hour ago
 By JESSE MCKINLEY SAN FRANCISCO - Responding to pleas for legal clarity from those on both sides of the issue, the California Supreme Court said Wednesday that it would take up the case of whether a voter-approved ban on same-sex unions was ...
[California Supreme Court to decide fate of Prop. 8 same-sex ...](#)
 San Jose Mercury News
[Prop. 8 gay marriage ban goes to Supreme Court](#) Los Angeles Times
[The Miami Herald](#) - [San Diego Union Tribune](#) - [Indiana Daily Student](#) - [San Francisco Chronicle](#)
[all 1,241 news articles »](#)

Drop That Cigarette, Today Is The Great American Smokeout 
 dBTechno - 1 hour ago
 Washington (dbTechno) - Today marks the annual Great American Smokeout hosted by the American Cancer Society, and is trying to get people all across the US to drop their cigarettes for just one day.
[Great American Smokeout: Time to kick the habit](#) Capital Times
[National Smoke Out Day is Thursday; be a quitter](#) Las Cruces Sun-News
[MPNnow.com](#) - [eMaxHealth.com](#) - [Times Tribune of Corbin](#) - [ABC15.com \(KNXV-TV\)](#)
[all 338 news articles »](#)

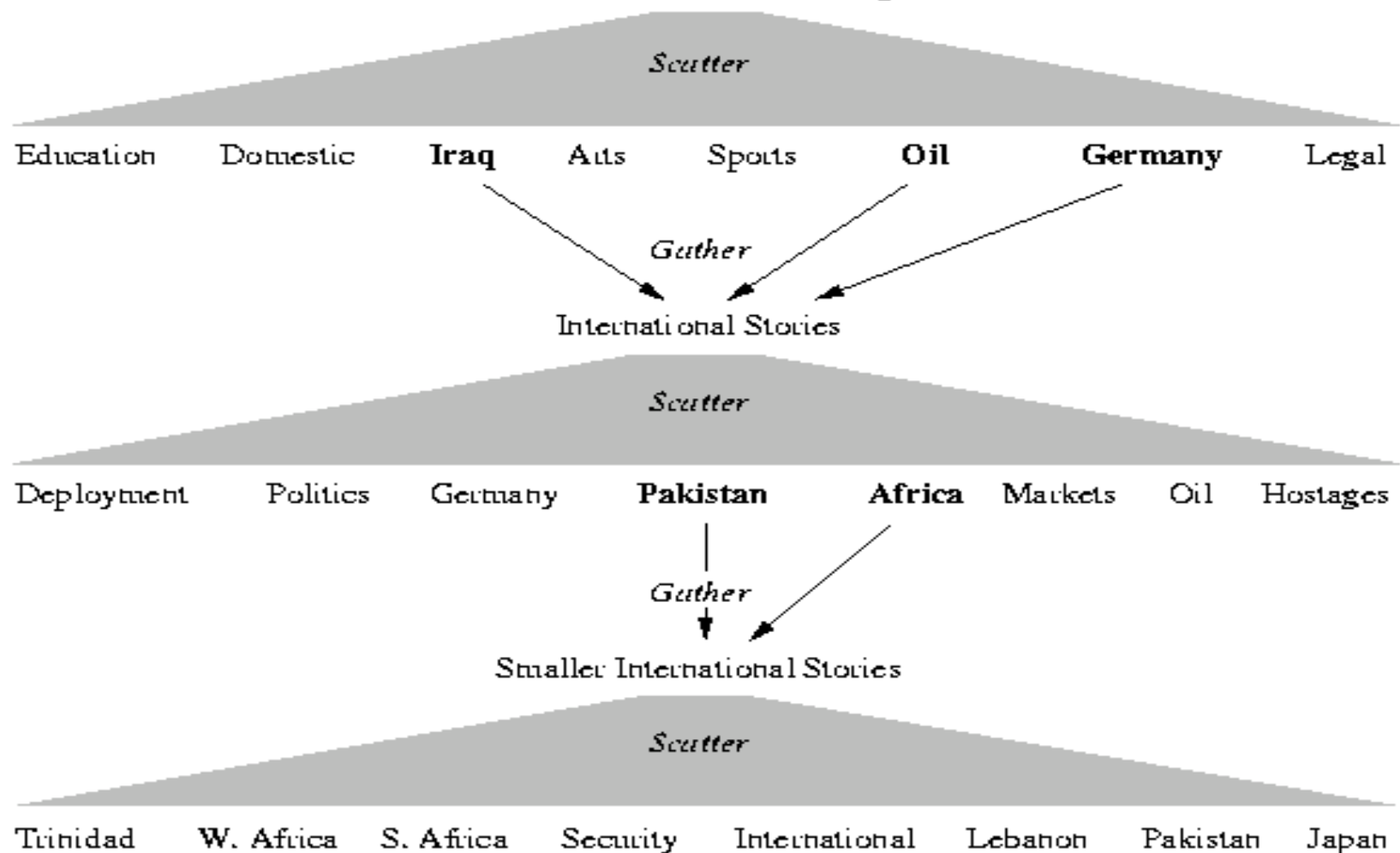
Perino: Bush would sign jobless benefits extension 
 The Associated Press - 47 minutes ago
 WASHINGTON (AP) - With weekly jobless claims benefits at a 16-year high, the White House said Thursday that President George W. Bush would quickly sign legislation pending in Congress to provide further unemployment benefits.
[Bush would sign measure to extend jobless benefits](#) Houston Chronicle
[Jobless claims show need for benefits extension: White House](#) AFP
[Washington Times](#) - [Wall Street Journal Blogs](#) - [WOI](#) - [Tampabay.com](#)
[all 599 news articles »](#)

[Show more stories](#) [Show fewer stories](#)

<http://www.google.com/hostednews/ap/article/ALeqM5hGjNbXI6O23C8QzqZMY0pGPAik-AD94ILNTG1>

Scatter/Gather: Cutting, Karger, and Pedersen

New York Times News Service, August 1990



- [Mountain height = cluster size]



For improving search recall

- *Cluster hypothesis* - Documents in the same cluster behave similarly with respect to relevance to information needs
- Therefore, to improve search recall:
 - Cluster docs in corpus a priori
 - When a query matches a doc D , also return other docs in the cluster containing D
- Hope if we do this: The query “car” will also return docs containing *automobile*
 - Because clustering grouped together docs containing *car* with those containing *automobile*.



Why might this happen?

The screenshot shows a web browser window with the address bar displaying a URL from search.yippy.com. The browser's address bar shows the URL: `http://search.yippy.com/search?v%3aproject=clusty&v%3afile=viv_Xpo6AV&v%3arecluster=&`. Below the address bar, there are navigation buttons for 'Most Visited', 'Getting Started', 'Latest Headlines', and 'Fridge Filters'. The Yippy logo is visible on the left, and a search bar with the text 'clustering' is in the center. To the right of the search bar are buttons for 'Search', 'advanced', and 'preferences'. Below the search bar, there are tabs for 'clouds', 'sources', and 'sites'. The 'clouds' tab is selected, showing a list of categories: 'All Results (185)', 'Analysis (23)', 'Method (22)', 'Computing (15)', 'Search, Engine (13)', 'Hierarchical (16)', 'Definition (11)', 'High availability (13)', 'Linux (11)', 'Windows, Microsoft (9)', and 'Papers (8)'. A 'remix' button is also present. Below the categories, there is a 'find in clouds' search bar and a 'Find' button. The main content area displays the top 179 results for the query 'clustering'. The first result is 'Clustering' from Intel, followed by 'Load Balancing 101' from F5, and 'Affordable Load Balancers' from KEMP. Below these, there are links to Wikipedia, a prewriting resource, and a CT Community Colleges resource. At the bottom, there is a 'Yippy Approved Shakespeare Searched' banner.

Top 179 results retrieved for the query **clustering** ([definition](#)) ([details](#))

Clustering
Lower Latency In Your Data Center w/ Intel's **Cluster** Ready Solutions!
www.intel.com

Load Balancing 101
Learn the 'Nuts & Bolts' of Load Balancing with F5's White Paper
www.f5.com/load_balancing

Affordable Load Balancers
High Performance Load Balancing Solutions From KEMP- See Demo Today
kemptechnologies.com

Computer cluster - Wikipedia, the free encyclopedia
Middleware such as MPI (Message Passing Interface) or PVM (Parallel Virtual Machine) permits compute **clustering** programs to be portable to a /Computer_ **cluster**
en.wikipedia.org/wiki/Computer_cluster - [cache] - Bing, Yahoo!

Writer's Web: Prewriting: Clustering
Prewriting: **Clustering** Melanie Dawson & Joe Essid (printable version here) **Clustering** is a type of prewriting that allows you to explore many ideas
writing2.richmond.edu/writing/wwb/cluster.html
writing2.richmond.edu/writing/wwb/cluster.html - [cache] - Bing, Yahoo!

Getting Started: Clustering Ideas - CT Community Colleges
Clustering. **Clustering** is similar to another process called Brainstorming. **Clustering** is something that you can do on your own or with friends or
grammar.ccc.commnet.edu/grammar/composition/brainstorm_cluster.htm
grammar.ccc.commnet.edu/grammar/composition/brainstorm_cluster.htm - [cache] - Bing, Yahoo!

[Advanced Clustering](#) | [Home](#)

Issues for clustering

- Representation for clustering
 - Document representation
 - Vector space? Normalization?
 - Centroids aren't length normalized
 - Need a notion of similarity/distance
- How many clusters?
 - Fixed a priori?
 - Completely data driven?
 - Avoid “trivial” clusters - too large or small
 - If a cluster's too large, then for navigation purposes you've wasted an extra user click without whittling down the set of documents much.

Notion of similarity/distance

- Ideal: semantic similarity.
- Practical: term-statistical similarity
 - We will use cosine similarity.
 - Docs as vectors.
 - For many algorithms, easier to think in terms of a *distance* (rather than similarity) between docs.
 - We will mostly speak of Euclidean distance
 - But real implementations use cosine similarity

Clustering Algorithms

- Flat algorithms
 - Usually start with a random (partial) partitioning
 - Refine it iteratively
 - K means clustering
 - (Model based clustering)
- Hierarchical algorithms
 - Bottom-up, agglomerative
 - (Top-down, divisive)

Hard vs. soft clustering

- Hard clustering: Each document belongs to exactly one cluster
 - More common and easier to do
- Soft clustering: A document can belong to more than one cluster.
 - Makes more sense for applications like creating browsable hierarchies
 - You may want to put a pair of sneakers in two clusters: (i) sports apparel and (ii) shoes
 - You can only do that with a soft clustering approach.
- We won't do soft clustering today. See IIR 16.5, 18

Partitioning Algorithms

- Partitioning method: Construct a partition of n documents into a set of K clusters
- Given: a set of documents and the number K
- Find: a partition of K clusters that optimizes the chosen partitioning criterion
 - Globally optimal
 - Intractable for many objective functions
 - Ergo, exhaustively enumerate all partitions
 - Effective heuristic methods: K -means and K -medoids algorithms

See also Kleinberg NIPS 2002 – impossibility for natural clustering

K-Means

- Assumes documents are real-valued vectors.
- Clusters based on *centroids* (aka the *center of gravity* or mean) of points in a cluster, c :

$$\vec{\mu}(c) = \frac{1}{|c|} \sum_{\vec{x} \in c} \vec{x}$$

- Reassignment of instances to clusters is based on distance to the current cluster centroids.
 - (Or one can equivalently phrase it in terms of similarities)

K-Means Algorithm

Select K random docs $\{s_1, s_2, \dots, s_K\}$ as seeds.

Until clustering *converges* (or other stopping criterion):

For each doc d_i :

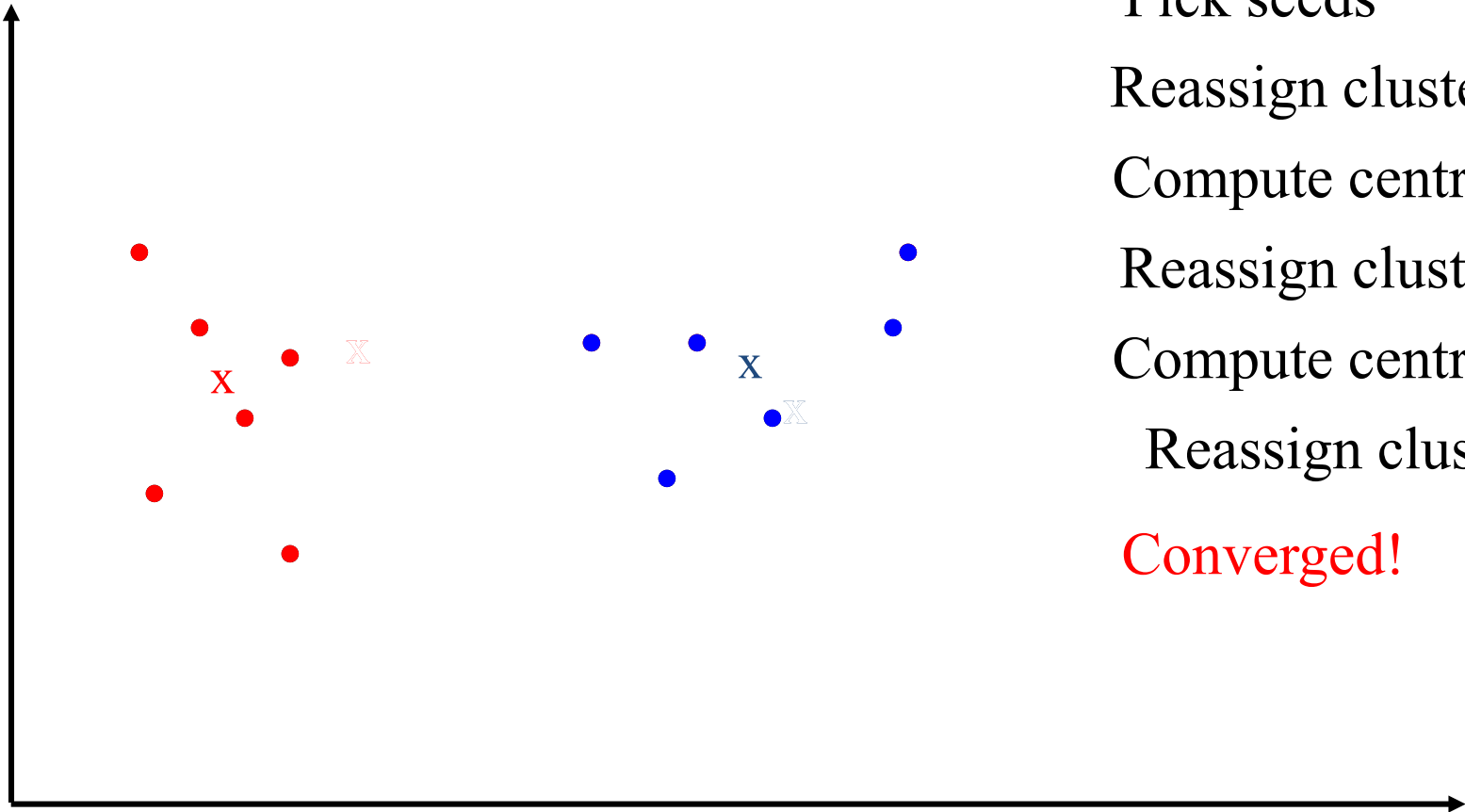
Assign d_i to the cluster c_j such that $\text{dist}(d_i, s_j)$ is minimal.

(Next, update the seeds to the centroid of each cluster)

For each cluster c_j

$$s_j = \mu(c_j)$$

K Means Example ($K=2$)



Pick seeds

Reassign clusters

Compute centroids

Reassign clusters

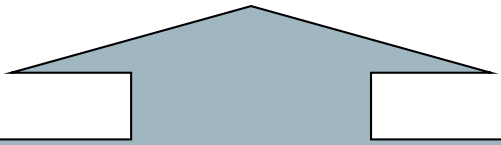
Compute centroids

Reassign clusters

Converged!

Termination conditions

- Several possibilities, e.g.,
 - A fixed number of iterations.
 - Doc partition unchanged.
 - Centroid positions don't change.



Does this mean that the docs in a cluster are unchanged?

Convergence

- Why should the K -means algorithm ever reach a *fixed point*?
 - A state in which clusters don't change.
- K -means is a special case of a general procedure known as the *Expectation Maximization (EM) algorithm*.
 - EM is known to converge.
 - Number of iterations could be large.
 - But in practice usually isn't

Lower case!

Convergence of K -Means

- Define goodness measure of cluster k as sum of squared distances from cluster centroid:
 - $G_k = \sum_i (d_i - c_k)^2$ (sum over all d_i in cluster k)
- $G = \sum_k G_k$
- Reassignment monotonically decreases G since each vector is assigned to the closest centroid.

Convergence of K -Means

- Recomputation monotonically decreases each G_k since (m_k is number of members in cluster k):
 - $\sum (d_i - a)^2$ reaches minimum for:
 - $\sum -2(d_i - a) = 0$
 - $\sum d_i = \sum a$
 - $m_k a = \sum d_i$
 - $a = (1/m_k) \sum d_i = c_k$
- K -means typically converges quickly

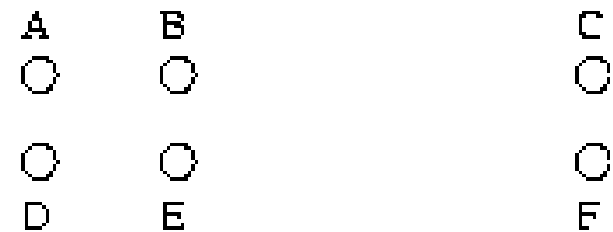
Time Complexity

- Computing distance between two docs is $O(M)$ where M is the dimensionality of the vectors.
- Reassigning clusters: $O(KN)$ distance computations, or $O(KNM)$.
- Computing centroids: Each doc gets added once to some centroid: $O(NM)$.
- Assume these two steps are each done once for I iterations: $O(IKNM)$.

Seed Choice

- Results can vary based on random seed selection.
- Some seeds can result in poor convergence rate, or convergence to sub-optimal clusterings.
 - Select good seeds using a heuristic (e.g., doc least similar to any existing mean)
 - Try out multiple starting points
 - Initialize with the results of another method.

Example showing sensitivity to seeds



In the above, if you start with B and E as centroids you converge to {A,B,C} and {D,E,F}

If you start with D and F you converge to {A,B,D,E} {C,F}

K -means issues, variations, etc.

- Recomputing the centroid after every assignment (rather than after all points are re-assigned) can improve speed of convergence of K -means
- Assumes clusters are spherical in vector space
 - Sensitive to coordinate changes, weighting etc.
- Disjoint and exhaustive
 - Doesn't have a notion of "outliers" by default
 - But can add outlier filtering

Dhillon et al. ICDM 2002 – variation to fix some issues with small document clusters

How Many Clusters?

- Number of clusters K is given
 - Partition n docs into predetermined number of clusters
- Finding the “right” number of clusters is part of the problem
 - Given docs, partition into an “appropriate” number of subsets.
 - E.g., for query results - ideal value of K not known up front - though UI may impose limits.
- Can usually take an algorithm for one flavor and convert to the other.

K not specified in advance

- Say, the results of a query.
- Solve an optimization problem: penalize having lots of clusters
 - application dependent, e.g., compressed summary of search results list.
- Tradeoff between having more clusters (better focus within each cluster) and having too many clusters

K not specified in advance

- Given a clustering, define the Benefit for a doc to be the cosine similarity to its centroid
- Define the Total Benefit to be the sum of the individual doc Benefits.



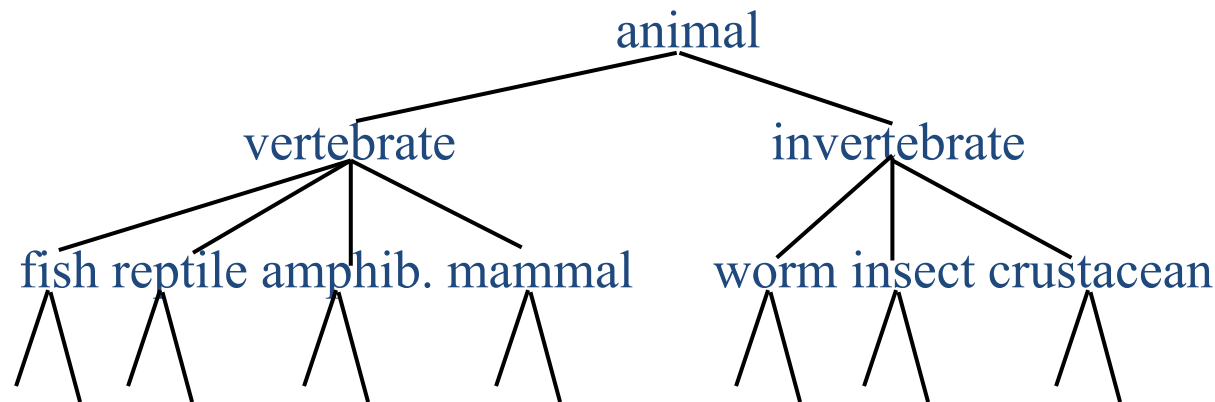
Why is there always a clustering of Total Benefit n ?

Penalize lots of clusters

- For each cluster, we have a Cost C .
- Thus for a clustering with K clusters, the Total Cost is KC .
- Define the Value of a clustering to be =
 $\text{Total Benefit} - \text{Total Cost}$.
- Find the clustering of highest value, over all choices of K .
 - Total benefit increases with increasing K . But can stop when it doesn't increase by "much". The Cost term enforces this.

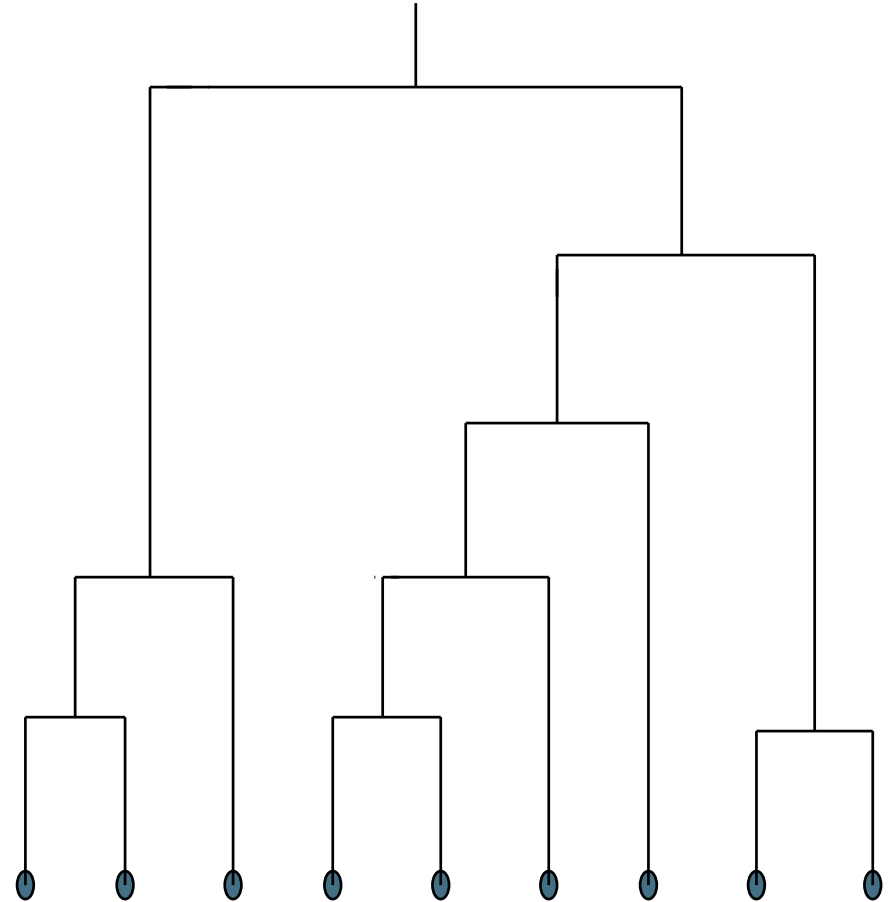
Hierarchical Clustering

- Build a tree-based hierarchical taxonomy (*dendrogram*) from a set of documents.



- One approach: recursive application of a partitional clustering algorithm.

- Clustering obtained by cutting the dendrogram at a desired level: each connected component forms a cluster.



Hierarchical Agglomerative Clustering (HAC)

- Starts with each doc in a separate cluster
 - then repeatedly joins the closest pair of clusters, until there is only one cluster.
- The history of merging forms a binary tree or hierarchy.

Note: the resulting clusters are still “hard” and induce a partition

Closest pair of clusters

- Many variants to defining closest pair of clusters
- **Single-link**
 - Similarity of the *most* cosine-similar (single-link)
- **Complete-link**
 - Similarity of the “furthest” points, the *least* cosine-similar
- **Centroid**
 - Clusters whose centroids (centers of gravity) are the most cosine-similar
- **Average-link**
 - Average cosine between pairs of elements

Single Link Agglomerative Clustering

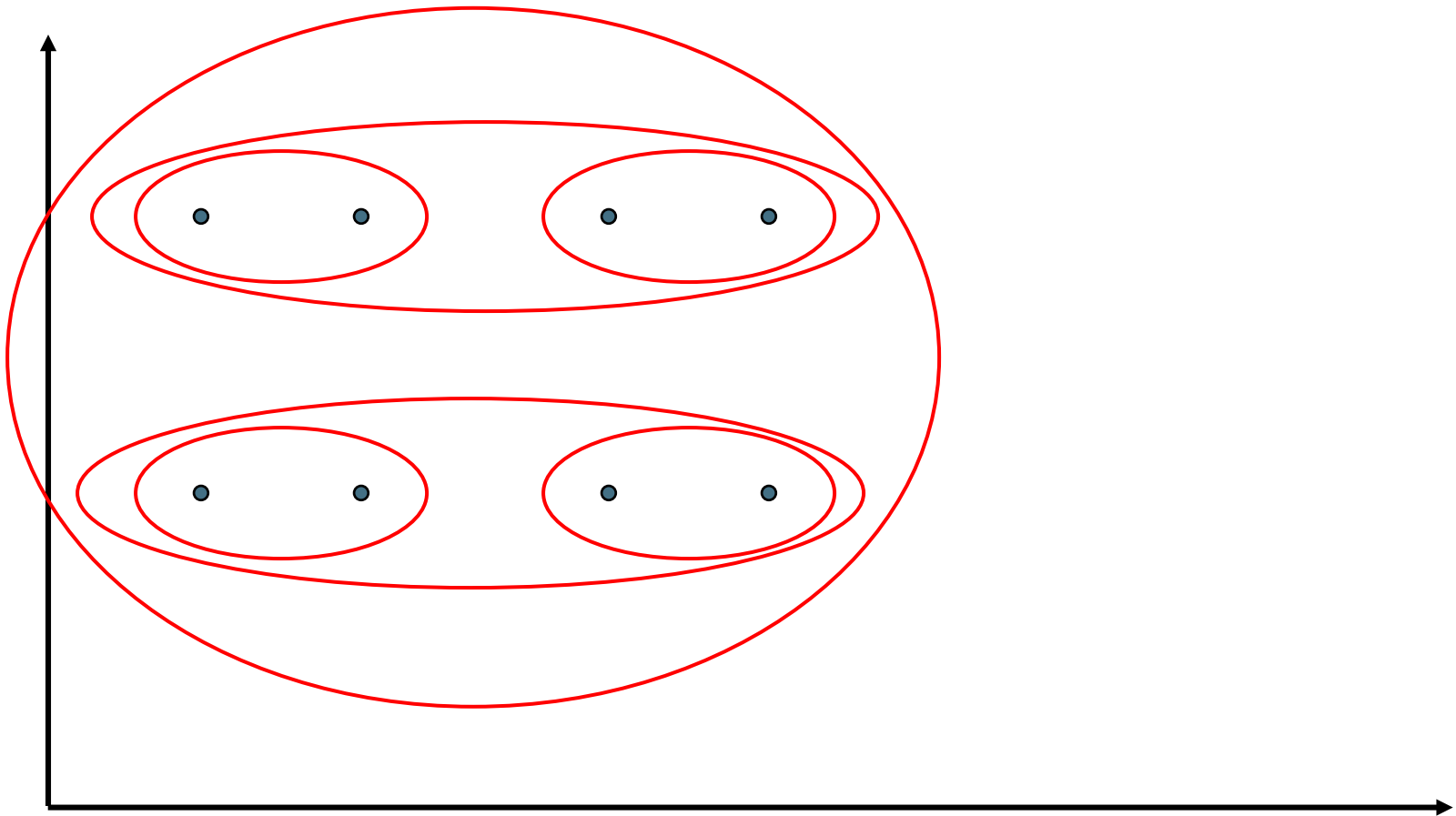
- Use maximum similarity of pairs:

$$sim(c_i, c_j) = \max_{x \in c_i, y \in c_j} sim(x, y)$$

- Can result in “straggly” (long and thin) clusters due to chaining effect.
- After merging c_i and c_j , the similarity of the resulting cluster to another cluster, c_k , is:

$$sim((c_i \cup c_j), c_k) = \max(sim(c_i, c_k), sim(c_j, c_k))$$

Single Link Example



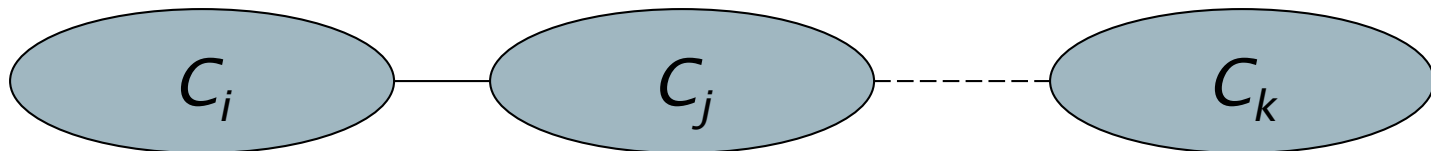
Complete Link

- Use minimum similarity of pairs:

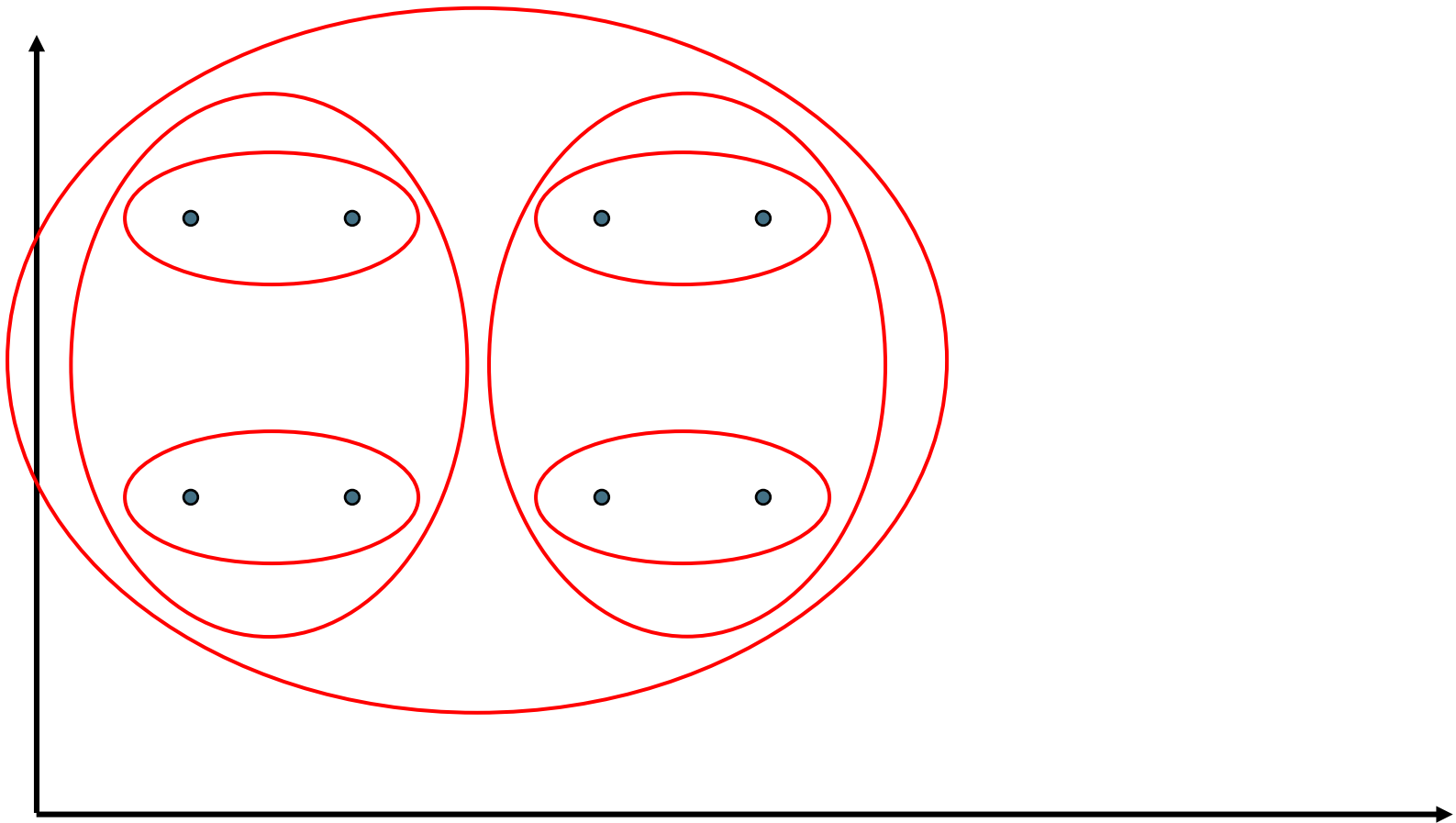
$$\text{sim}(c_i, c_j) = \min_{x \in c_i, y \in c_j} \text{sim}(x, y)$$

- Makes “tighter,” spherical clusters that are typically preferable.
- After merging c_i and c_j , the similarity of the resulting cluster to another cluster, c_k , is:

$$\text{sim}((c_i \cup c_j), c_k) = \min(\text{sim}(c_i, c_k), \text{sim}(c_j, c_k))$$



Complete Link Example



Computational Complexity

- In the first iteration, all HAC methods need to compute similarity of all pairs of N initial instances, which is $O(N^2)$.
- In each of the subsequent $N-2$ merging iterations, compute the distance between the most recently created cluster and all other existing clusters.
- In order to maintain an overall $O(N^2)$ performance, computing similarity to each other cluster must be done in constant time.
 - Often $O(N^3)$ if done naively or $O(N^2 \log N)$ if done more cleverly

Group Average

- Similarity of two clusters = average similarity of all pairs within merged cluster.

$$sim(c_i, c_j) = \frac{1}{|c_i \cup c_j|(|c_i \cup c_j| - 1)} \sum_{\vec{x} \in (c_i \cup c_j)} \sum_{\vec{y} \in (c_i \cup c_j): \vec{y} \neq \vec{x}} sim(\vec{x}, \vec{y})$$

- Compromise between single and complete link.
- Two options:
 - Averaged across all ordered pairs in the merged cluster
 - Averaged over all pairs *between* the two original clusters
- No clear difference in efficacy

Computing Group Average Similarity

- Always maintain sum of vectors in each cluster.

$$\vec{s}(c_j) = \sum_{\vec{x} \in c_j} \vec{x}$$

- Compute similarity of clusters in constant time:

$$\text{sim}(c_i, c_j) = \frac{(\vec{s}(c_i) + \vec{s}(c_j)) \bullet (\vec{s}(c_i) + \vec{s}(c_j)) - (|c_i| + |c_j|)}{(|c_i| + |c_j|)(|c_i| + |c_j| - 1)}$$

What Is A Good Clustering?

- Internal criterion: A good clustering will produce high quality clusters in which:
 - the intra-class (that is, intra-cluster) similarity is high
 - the inter-class similarity is low
 - The measured quality of a clustering depends on both the document representation and the similarity measure used

External criteria for clustering quality

- Quality measured by its ability to discover some or all of the hidden patterns or latent classes in gold standard data
- Assesses a clustering with respect to ground truth ... requires *labeled data*
- Assume documents with C gold standard classes, while our clustering algorithms produce K clusters, $\omega_1, \omega_2, \dots, \omega_K$ with n_i members.

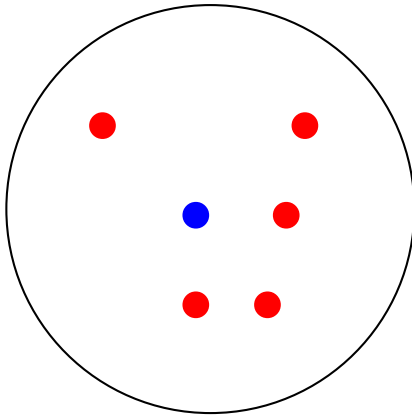
External Evaluation of Cluster Quality

- Simple measure: purity, the ratio between the dominant class in the cluster π_i and the size of cluster ω_i

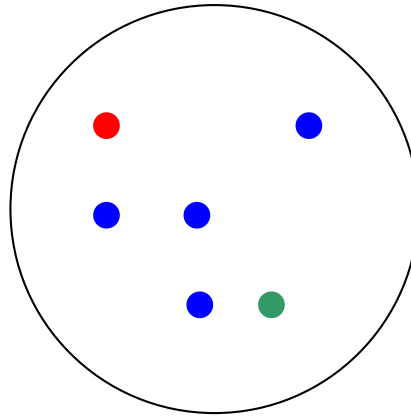
$$Purity(\omega_i) = \frac{1}{n_i} \max_j (n_{ij}) \quad j \in C$$

- Biased because having n clusters maximizes purity
- Others are entropy of classes in clusters (or mutual information between classes and clusters)

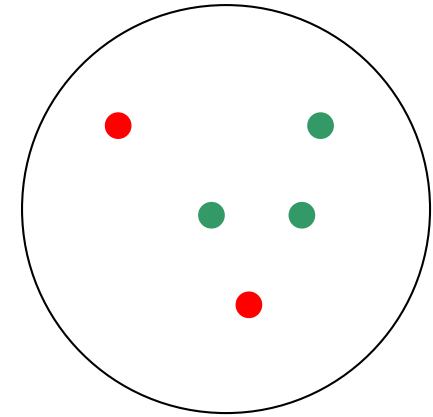
Purity example



Cluster I



Cluster II



Cluster III

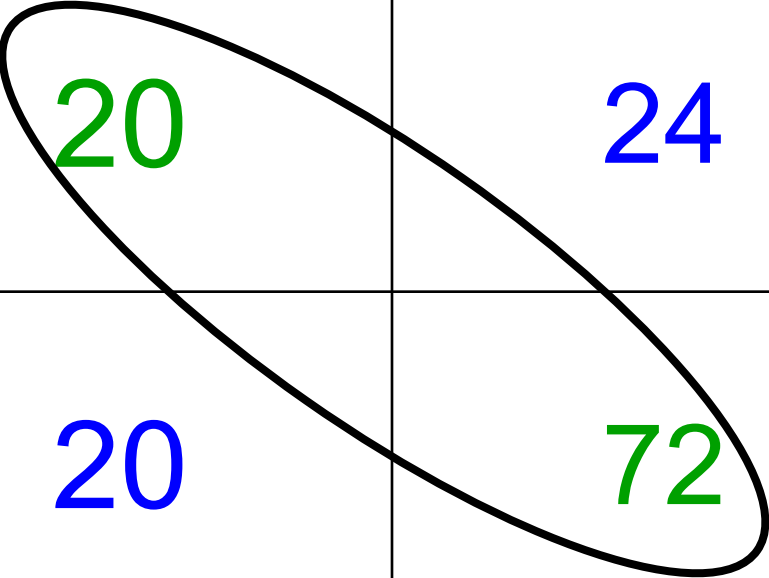
Cluster I: Purity = $1/6 (\max(5, 1, 0)) = 5/6$

Cluster II: Purity = $1/6 (\max(1, 4, 1)) = 4/6$

Cluster III: Purity = $1/5 (\max(2, 0, 3)) = 3/5$

Rand Index measures between pair decisions. Here $RI = 0.68$

Number of points	Same Cluster in clustering	Different Clusters in clustering
Same class in ground truth	20	24
Different classes in ground truth	20	72



Rand index and Cluster F-measure

$$RI = \frac{A + D}{A + B + C + D}$$

Compare with standard Precision and Recall:

$$P = \frac{A}{A + B} \qquad R = \frac{A}{A + C}$$

People also define and use a cluster F-measure, which is probably a better measure.

Final word and resources

- In clustering, clusters are inferred from the data without human input (unsupervised learning)
- However, in practice, it's a bit less clear: there are many ways of influencing the outcome of clustering: number of clusters, similarity measure, representation of documents, .
..
- Resources
 - IIR 16 except 16.5
 - IIR 17.1–17.3