Applications of Indexing

Lecture 14

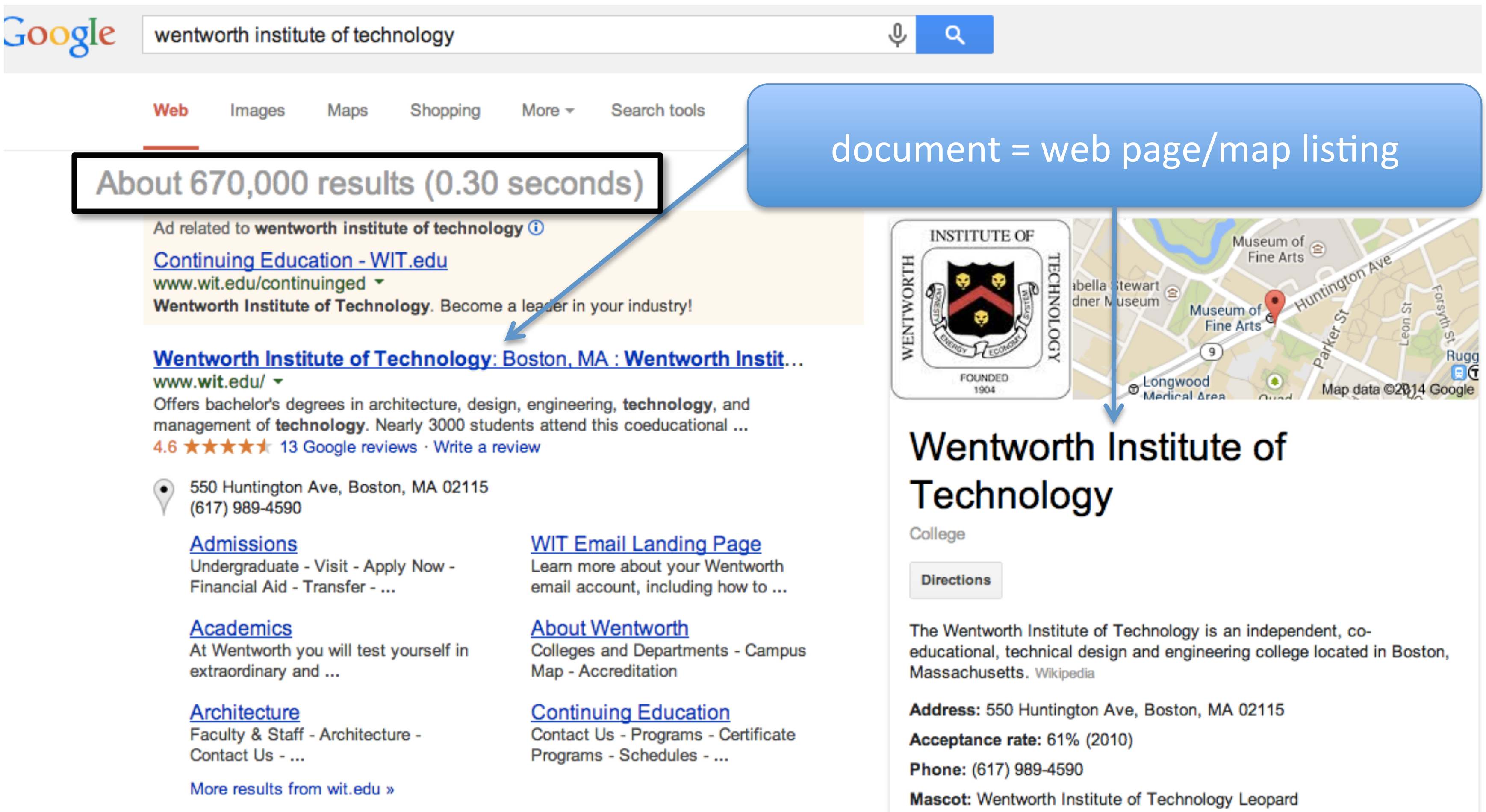
Outline

- Background & Motivation
  - Full-Text Search
  - Big-O Review
  - Indexing
- The Inverted Index
  - An Example
  - Design a relational index
  - Advanced Issues
  - Example in Cognitive Modeling
- The R-tree
  - Overview
  - Application in Optimization

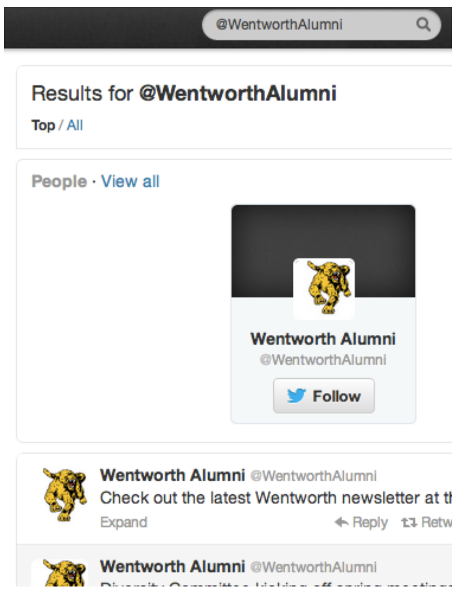
Problem: Full-Text Search

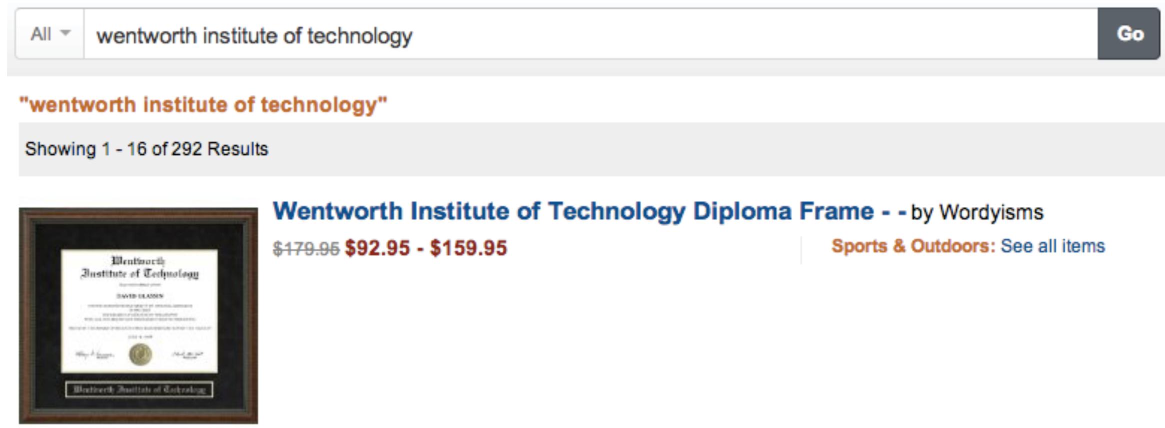
- Given: set of “documents” containing “words”
  - General problem in the field of *Information Retrieval*
- Task: find “best” document(s) that contain a set of words
- Requirements
  - Fast & scalable
  - Relevant results (precision, recall, f-score)
  - Expressive queries
  - Up-to-date

Example: Web Search



Other Examples





Scaling Up: # of "Documents"

Google™	
facebook®	
amazon	

Scaling Up: Search Frequency

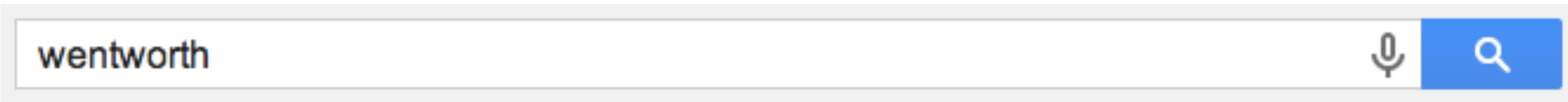
Google™	
facebook®	

Big-O Review

- What does $O(n)$ mean?
- A linear algorithm for full-text search?
  - Find 5 documents that contain “WIT”
- What is the complexity in terms of documents (d) and average-words-per-document (w)?

Is Linear-Time Google Possible?

- Assume simple query:



- Single listing of all web pages + words
  - 60T pages * 250 w/page * 8 bytes/w ~ 106PB
- Require 1s response
  - 7.5M * 2GHz 64-bit CPU (assume 1 cycle/w)
  - (7.5M * 68K) CPUs * 85W/CPU * $.15/kWh ~ **$1.8M/s**

~4M Blu-ray

~70 CPU/ person

3X US GDP

Indexing

- Improve search speed at the cost of extra…
  - **Memory** for data structure(s)
  - **Time** to update the data structure(s)

- Backbone of databases (physical design)
  - Search engines
  - Graphics/game engines
  - Simulation software

  …

Inverted Index by Example

Given documents { D_1, D_2, D_3 }:

- D_1 = "it is what it is"
- D_2 = "what is it"
- D_3 = "it is a banana"

Inverted Index:

Distinct Word List (sorted)

- "a": [D_3]
- "banana": [D_3]
- "is": [D_1, D_2, D_3]
- "it": [D_1, D_2, D_3]
- "what": [D_1, D_2]

Document Lists

Let's try some queries: "what", "a", "banana", "apple"

Describe an algorithm to query this data structure

Describe an algorithm to populate these lists

Time & Memory: O(?)
Construction & Query

Design a **Relational** Inverted Index

Develop a set of table(s) and index(es) that support efficient construction and querying of an inverted index

Assume

- Documents have a unique id and a path
- A document is a sequence of words
  - Document d = [w_1, w_2, … w_n]
- Search for a single, exact-match word
  - Does document D have word w?
  - The list of documents **D** that have word w?

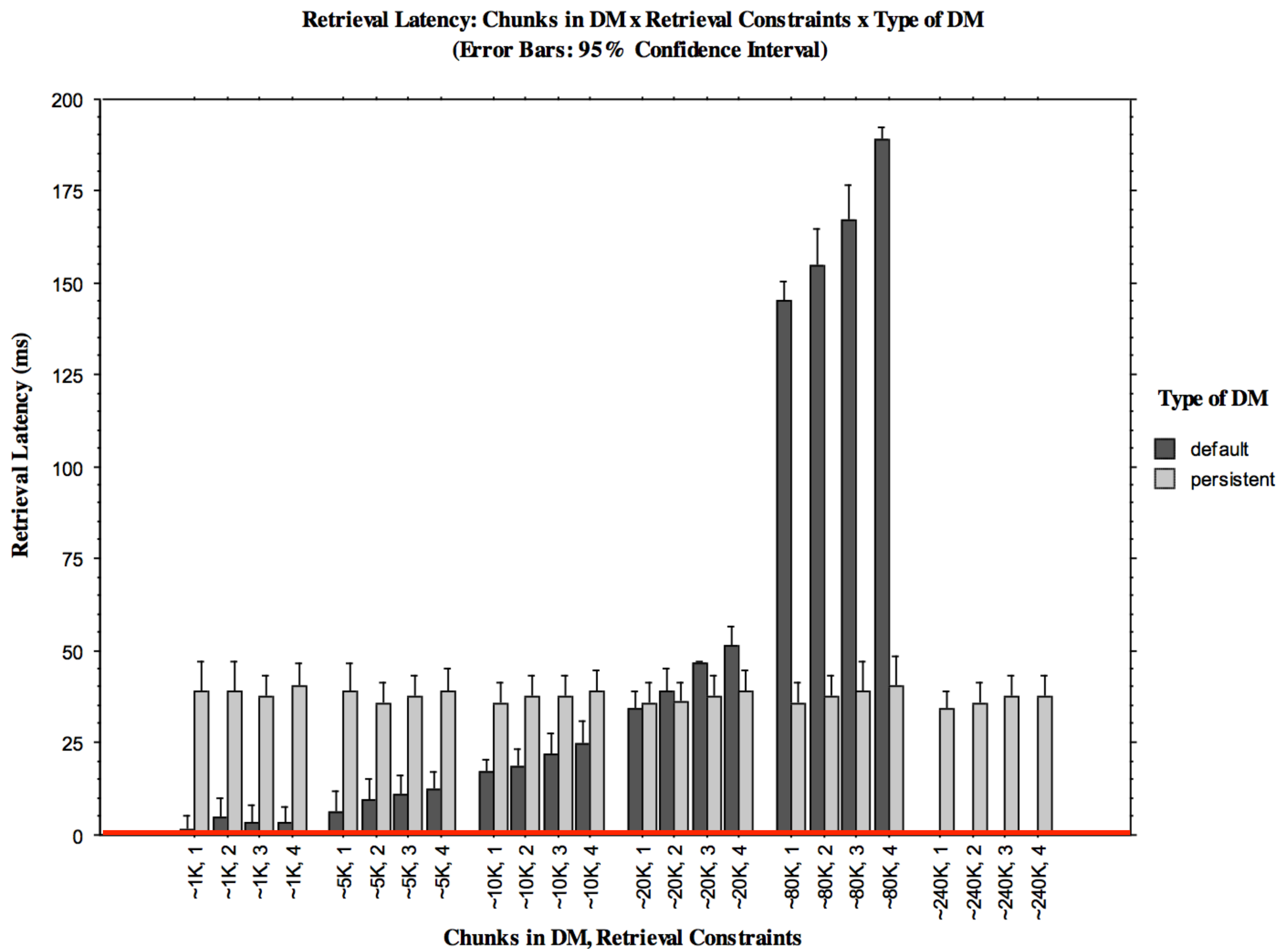
Advanced Issues

- More expressive query semantics
  - Multi-word
  - Locality: [“what is it”] vs. [“what it is”] vs. [“what”, “is”, “it”]
- Ranked results
  - Document-ranking algorithm (e.g. PageRank)
  - Efficient ranked retrieval
- Dynamics
  - Document addition/removal/modification
  - Rank
    - Document changes
    - Integration of real-time variables (e.g. location)

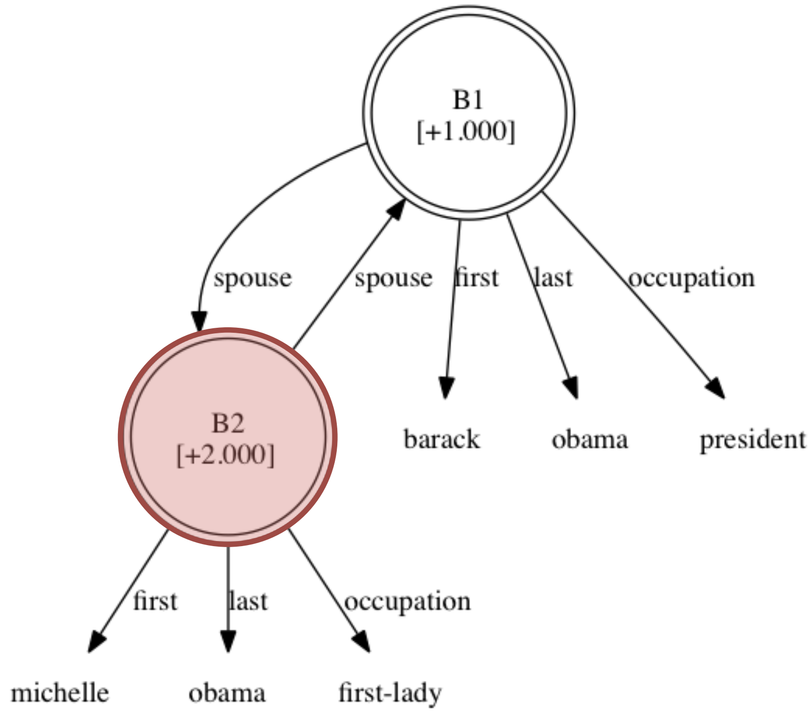
Modeling Semantic Memory

- Semantic memory is a human's long-term store of facts about the world, independent of the context in which they were originally learned
- The ACT-R (http://act-r.psy.cmu.edu) model of semantic memory has been successful at explaining a variety of psychological phenomena (e.g. retrieval bias, forgetting)
- The model does *not* scale to large memory sizes, which hampers complex experiments

Scale Fail [AFRL '09]



Memory Representation



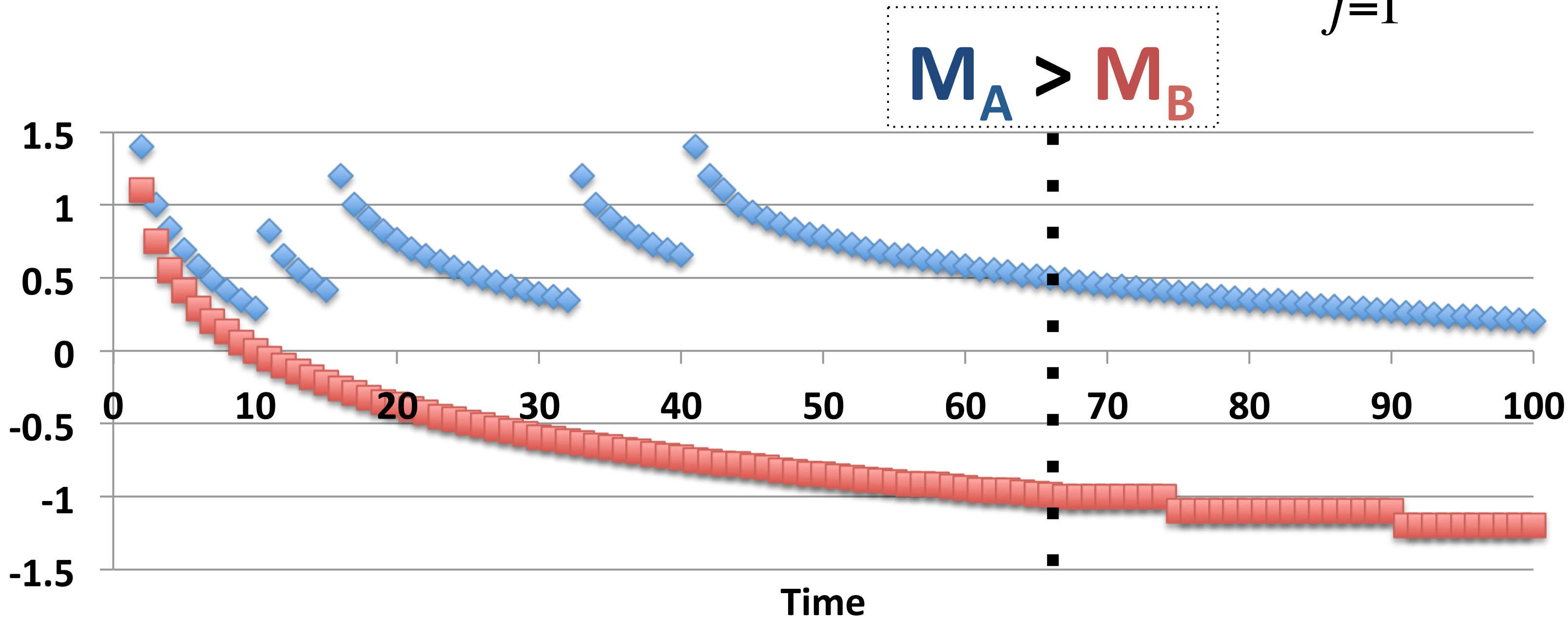
- Document = Node
- Word = edge

Example cue:
`last(obama),spouse(X)`

Ranking [Anderson et al. '04]

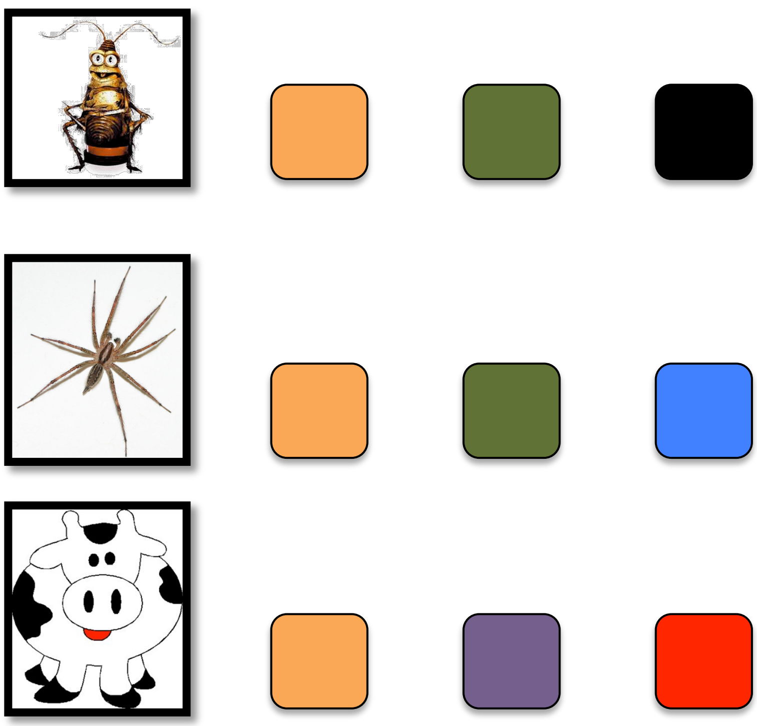
Predict future usage via history

$$\ln\left(\sum_{j=1}^{n} t_j^{-d}\right)$$



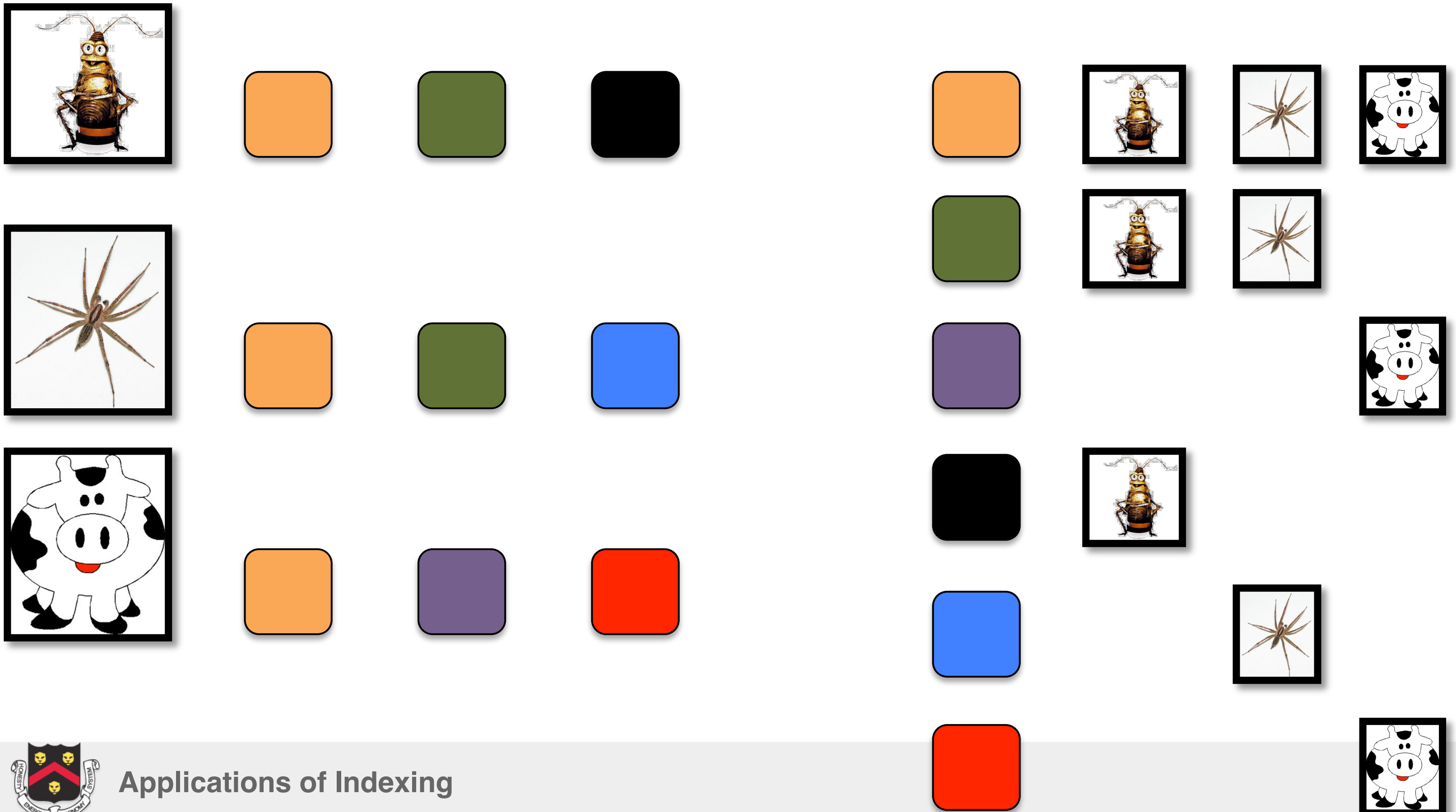
Example

Semantic Objects: Features



Inverted Index

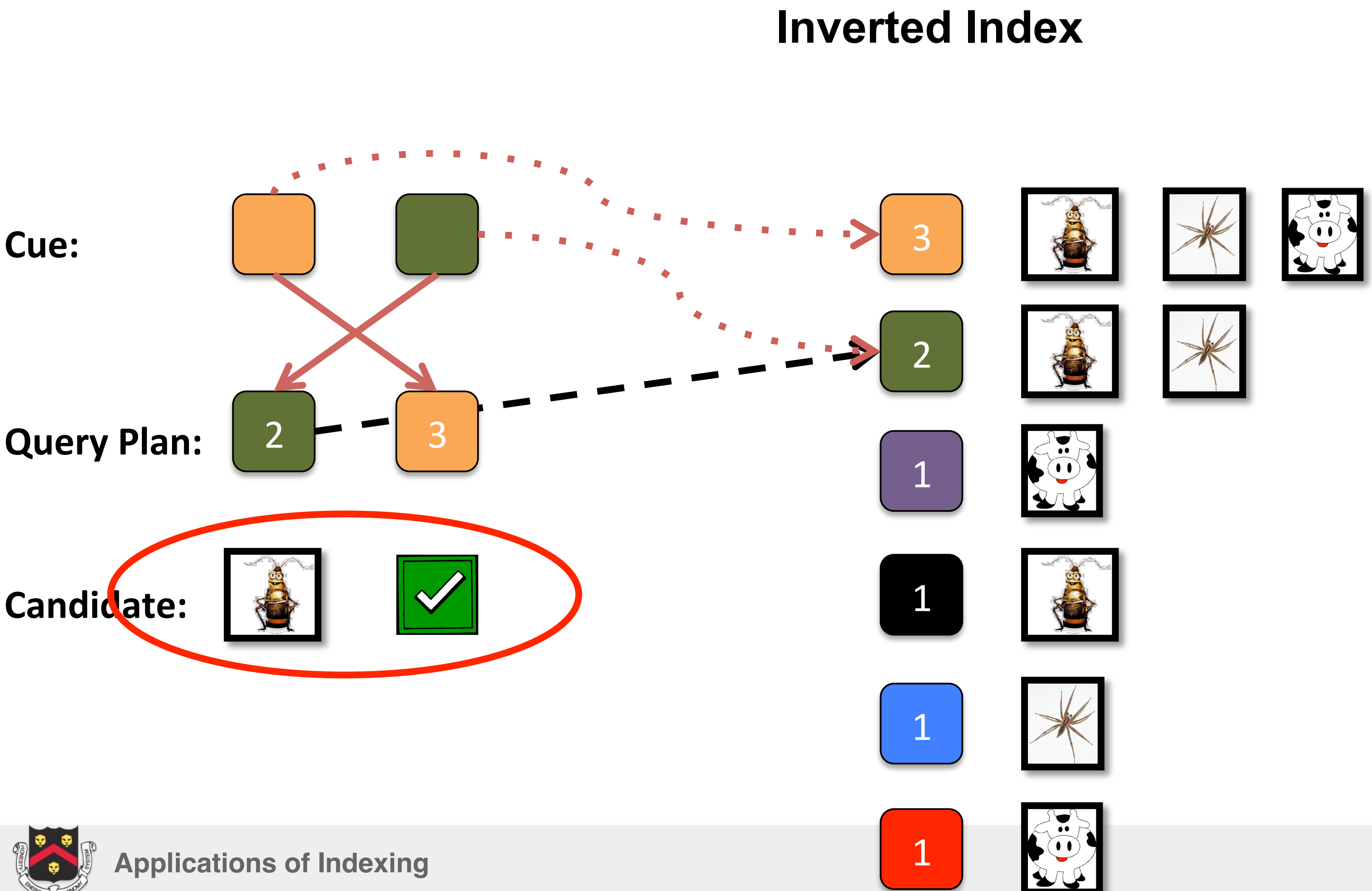
Semantic Objects: Features **Inverted Index**



Index Statistics

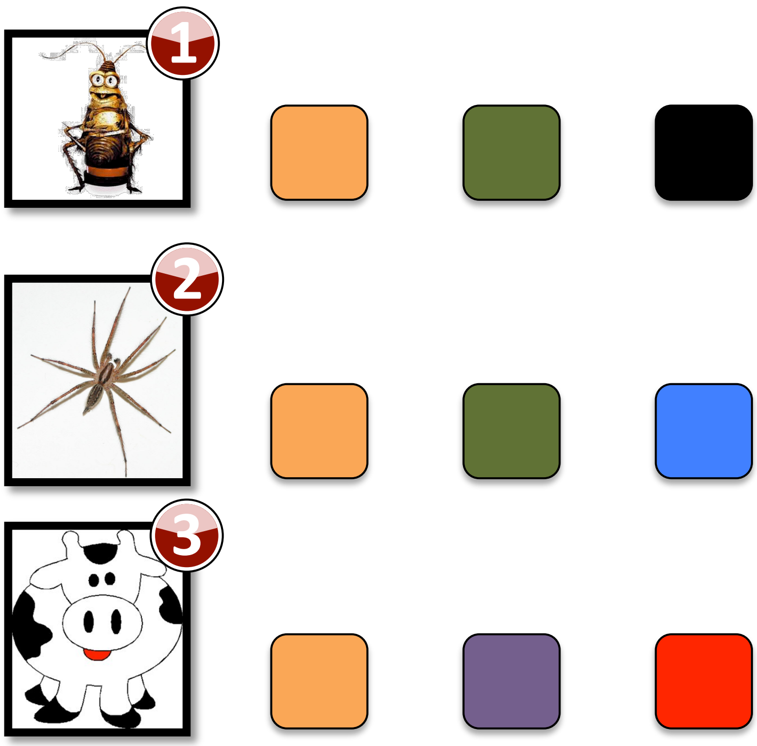
Semantic Objects: Features **Inverted Index**

Top-1 Non-Ranked Retrieval

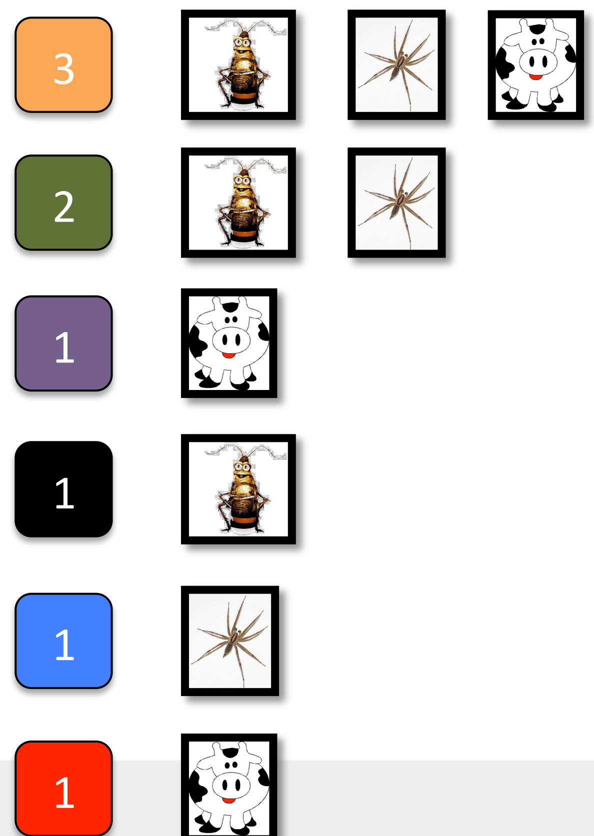


Introducing Rank

Semantic Objects: Features

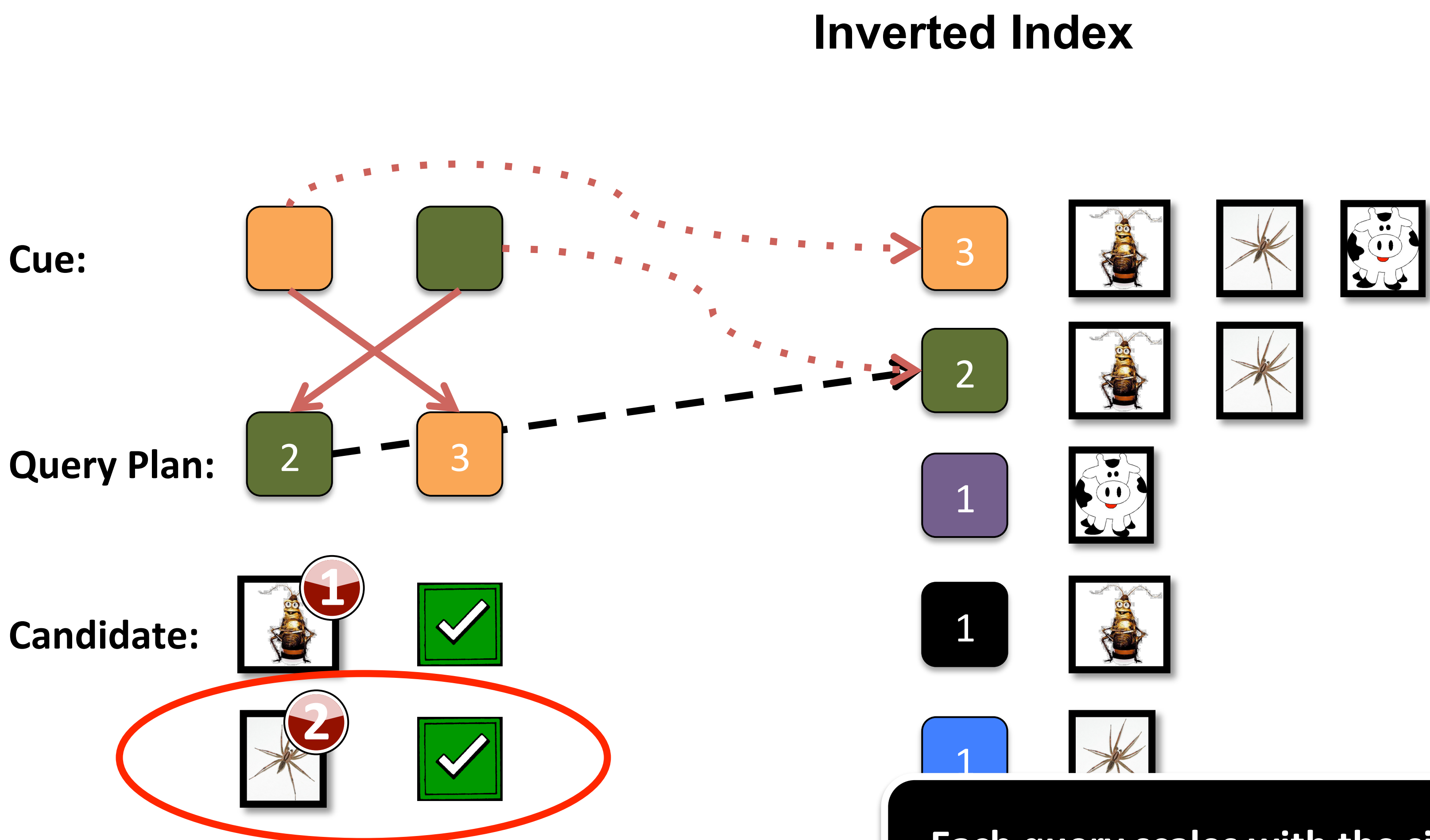


Inverted Index



Ranked Retrieval Algorithm #1

Sort on Query

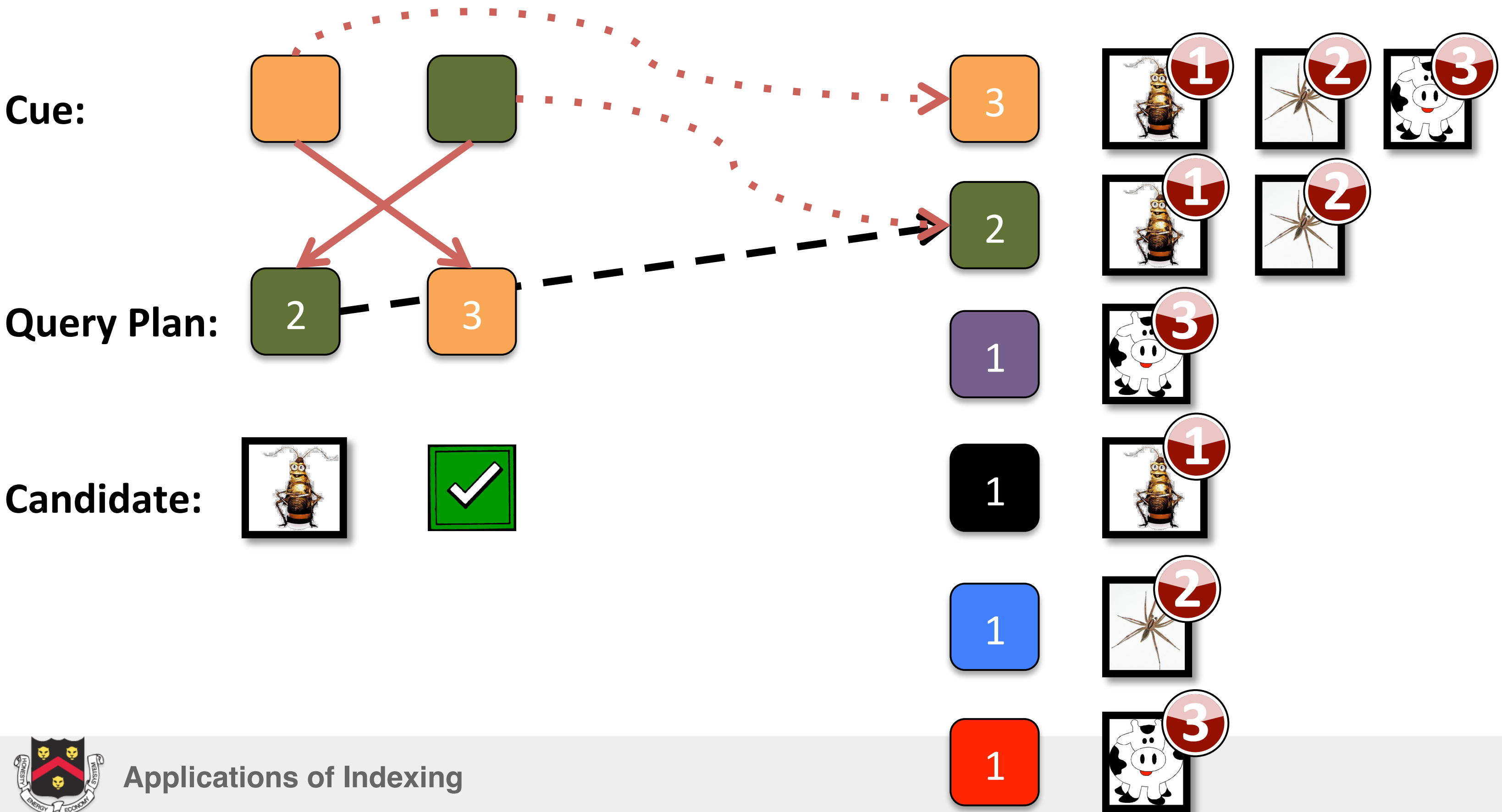


Each query scales with the size of the candidate list!

Ranked Retrieval Algorithm #3

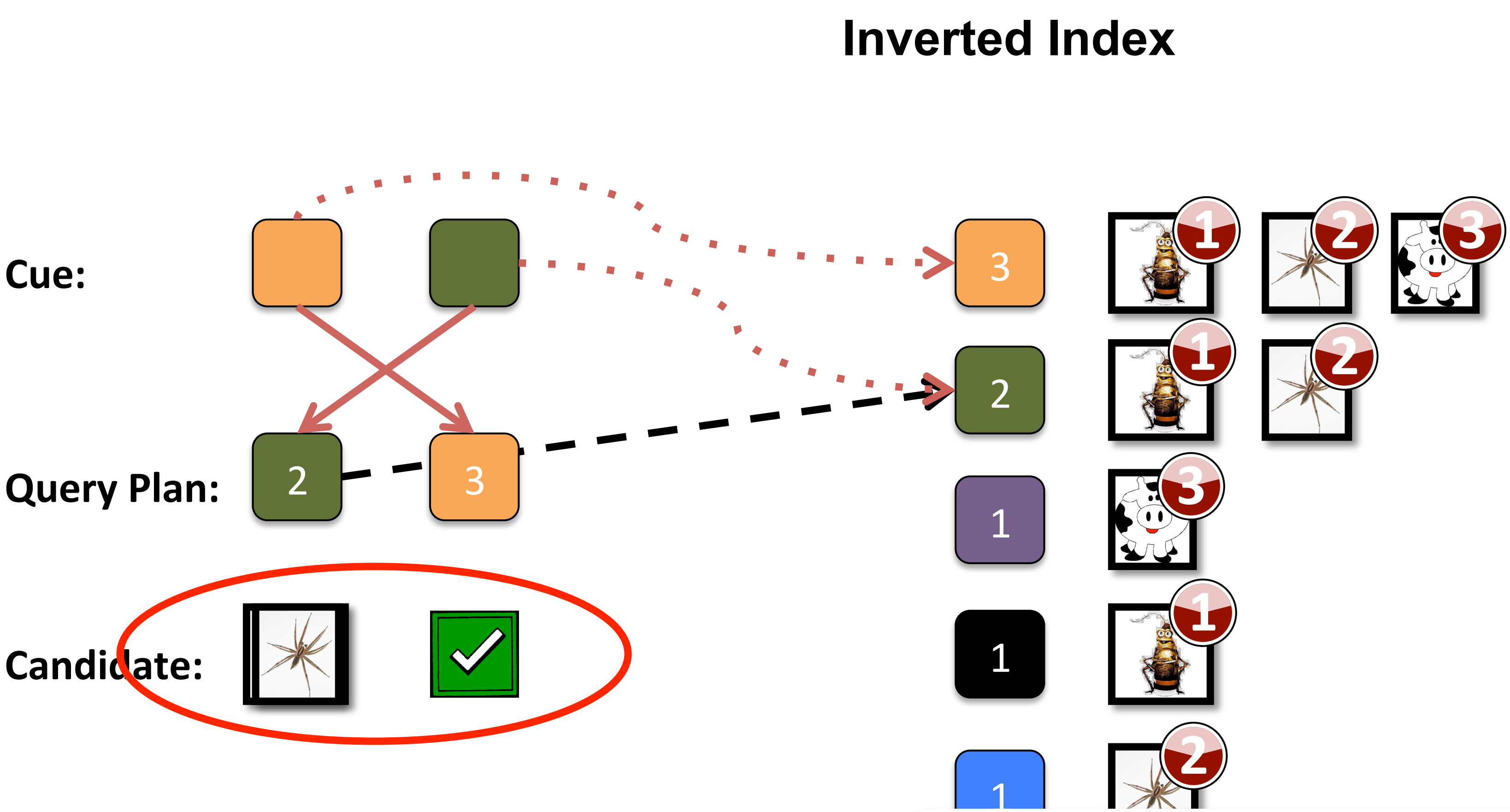
Static Sort

Inverted Index



Ranked Retrieval Algorithm #2

Static Sort



Each rank update scales with feature cardinality!

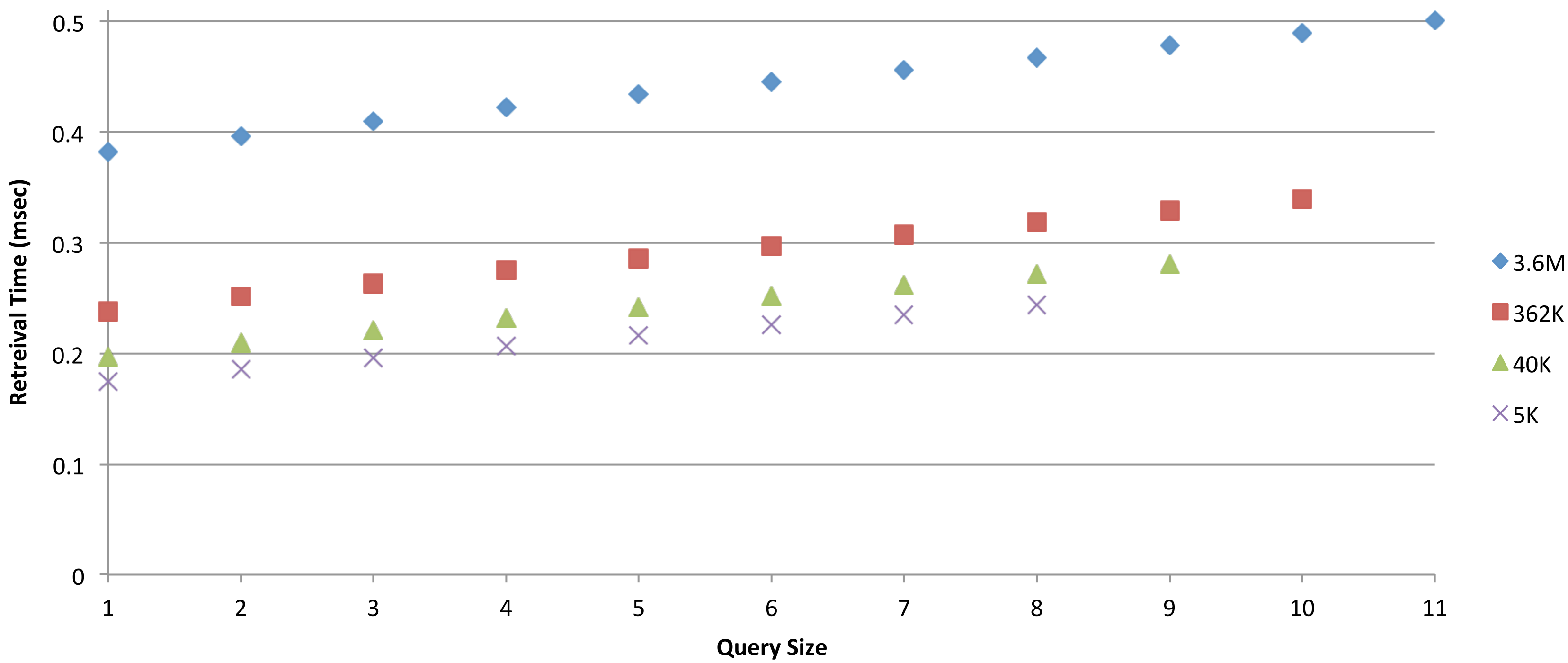
Hybrid Approach

- Empirically supported cardinality threshold, θ
- If (cardinality > θ): Sort on Query [#1]
  - Candidate enumeration scales with # of objects with large cardinality (empirically rare)
- If (cardinality ≤ θ): Static Sort [#2]
  - Bias updates must be locally efficient
    - Objects affected: O(1)
    - Computation: O(1)

Some Results

Inverted index (via SQLite) + new approach was **fast** and **scaled**!

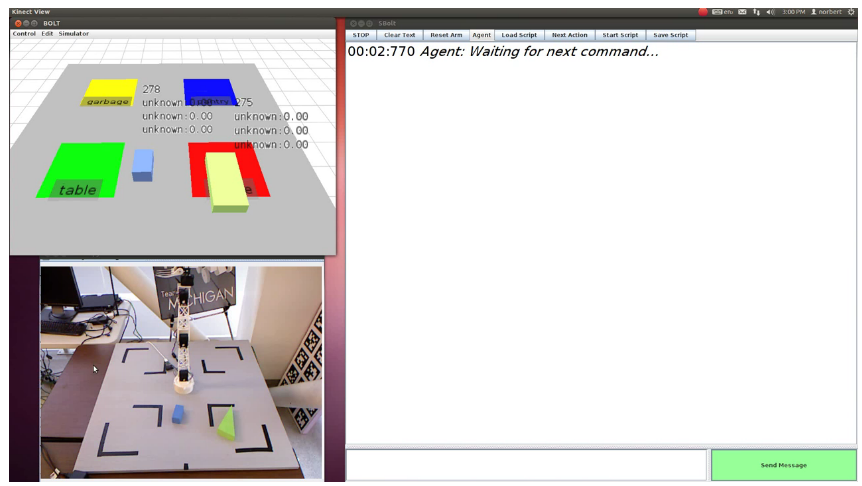
- >30x faster than off-the-shelf database (on >3x data)!



Applications: AI + Inverted Index

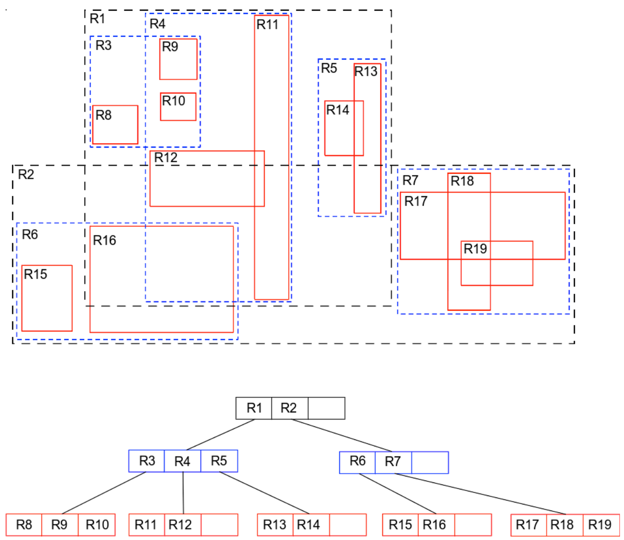
Learned Navigation

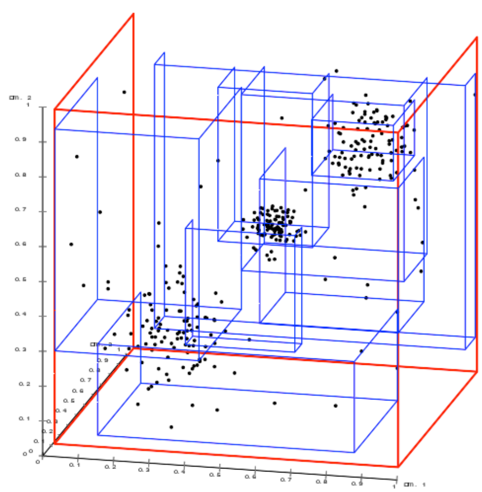
Task Learning



Another Index: R-tree

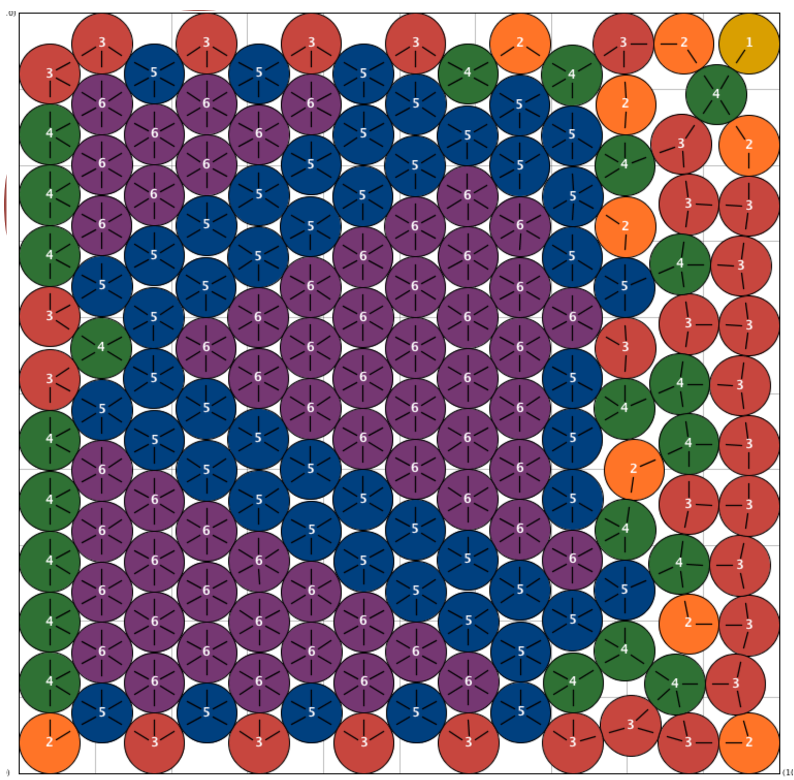
“Group nearby objects and represent them with their **minimum bounding rectangle** in the next higher level of the tree... Since all objects lie within this bounding rectangle, a query that does not intersect the bounding rectangle also cannot intersect any of the contained objects. At the leaf level, each rectangle describes a single object; at higher levels the aggregation of an increasing number of objects.” -- Wikipedia

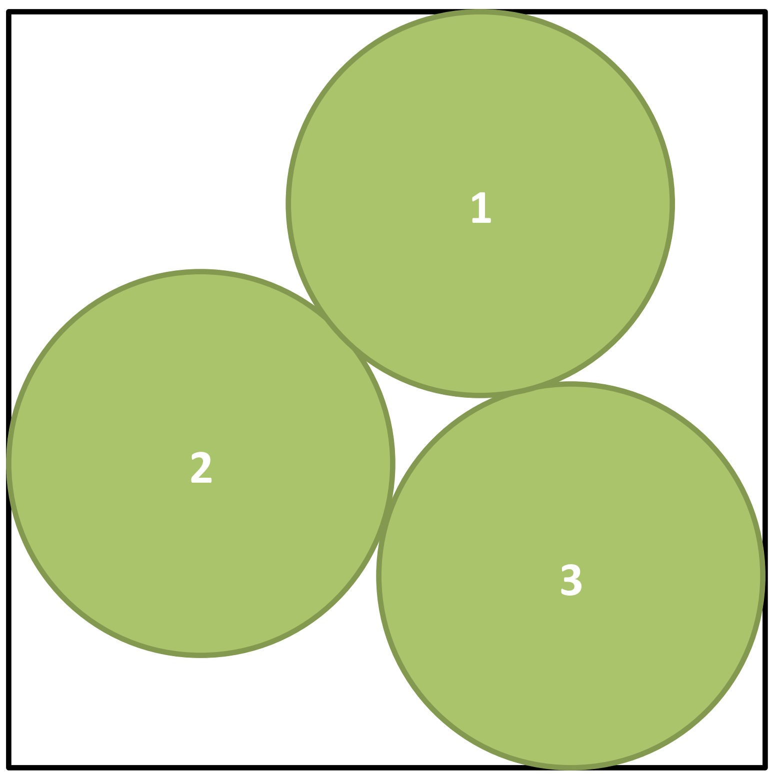




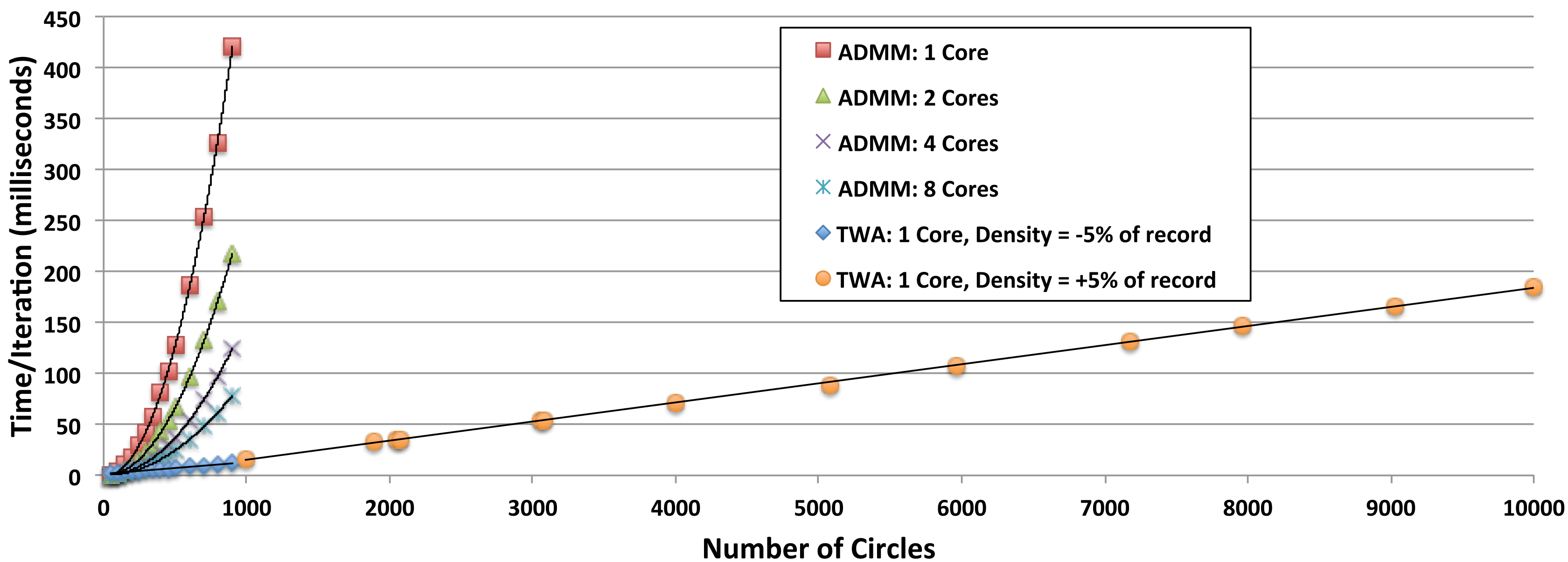
Application: Optimization + R-tree

Packing. Fit n circles of radius r in a square of side-length s without overlap (non-convex, NP-hard, ∞ solutions). Used in making codes, physical packing, computer-assisted origami.





Large-Scale Evaluation



Disney Research

Takeaways

- A common approach to large-scale search is indexing: using data structure(s) to improve access speed
- An inverted index is commonly used for full-text search (even in situations that might not look like it)
  - Inverted indexes are fast, scalable, and straight-forward to implement
- An R-tree is commonly used for spatial queries over objects in 2/3D space (e.g. what is within X miles of Y? are A and B colliding?)
- Know your indexes/data structures! Careful problem analysis and algorithm development can often beat generic approaches
  - Even if you don't use a DBMS, DBMS methods can be very useful in a variety of applications!