Introduction to

Information Retrieval

CS276

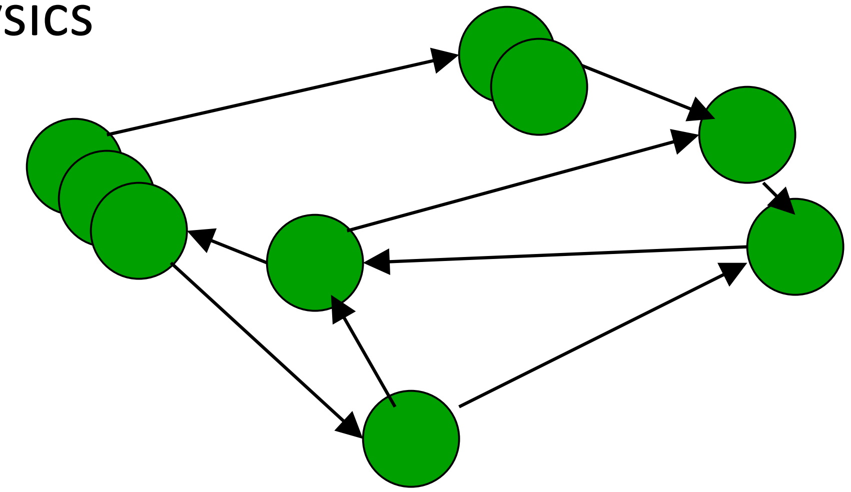
Information Retrieval and Web Search

Chris Manning and Pandu Nayak

Link analysis

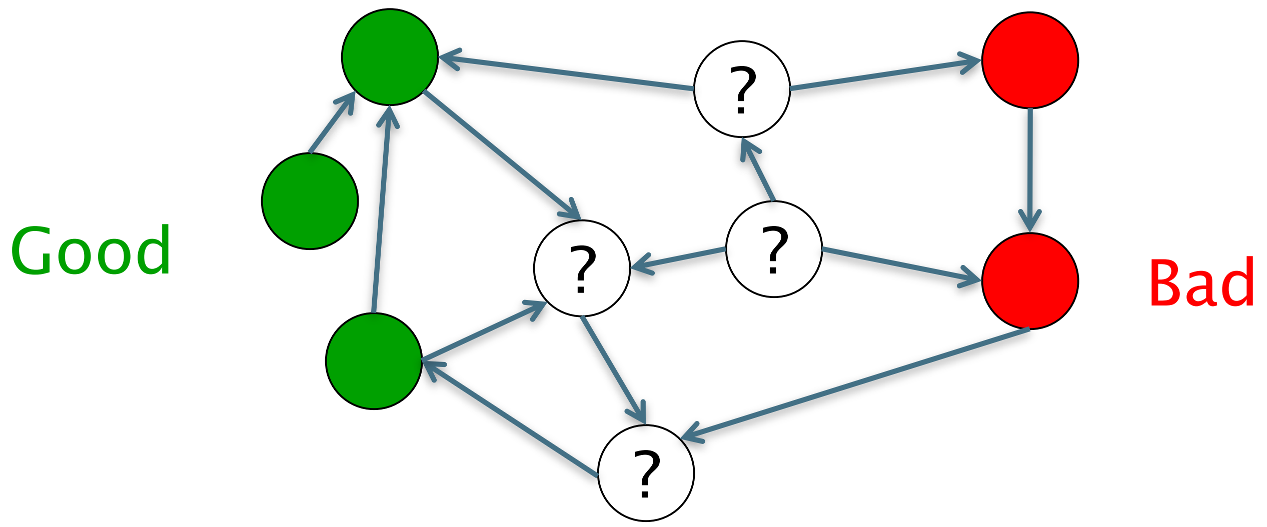
Today's lecture – hypertext and links

- We look beyond the *content* of documents
  - We begin to look at the hyperlinks between them
- Address questions like
  - Do the links represent a conferral of authority to some pages? Is this useful for ranking?
  - How likely is it that a page pointed to by the CERN home page is about high energy physics
- Big application areas
  - The Web
  - Email
  - Social networks



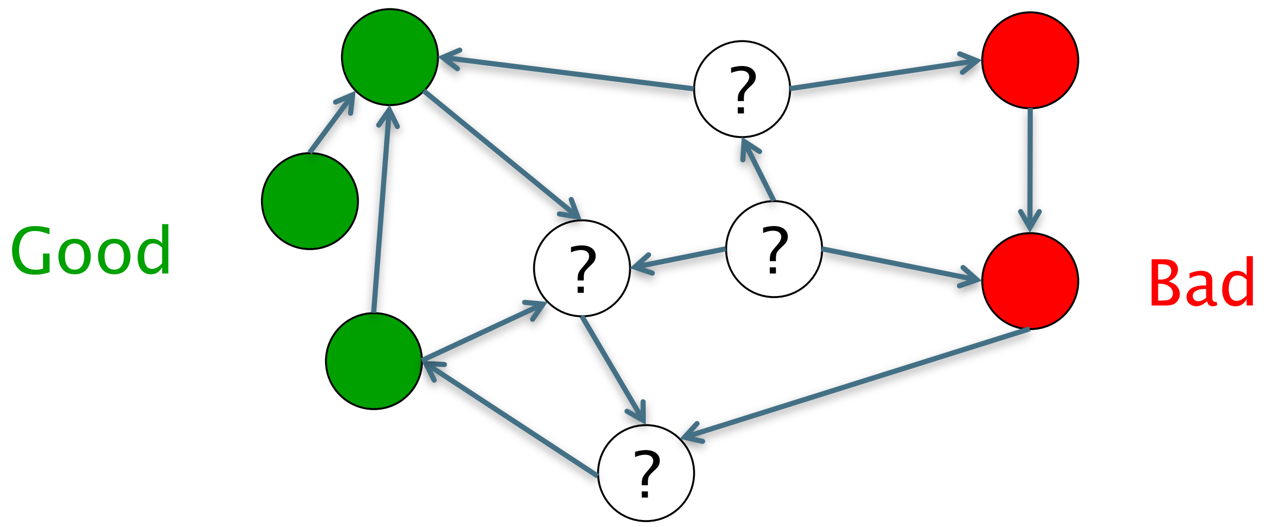
Links are everywhere

- Powerful sources of authenticity and authority
  - Mail spam – which email accounts are spammers?
  - Host quality – which hosts are "bad"?
  - Phone call logs
- The Good, The Bad and The Unknown



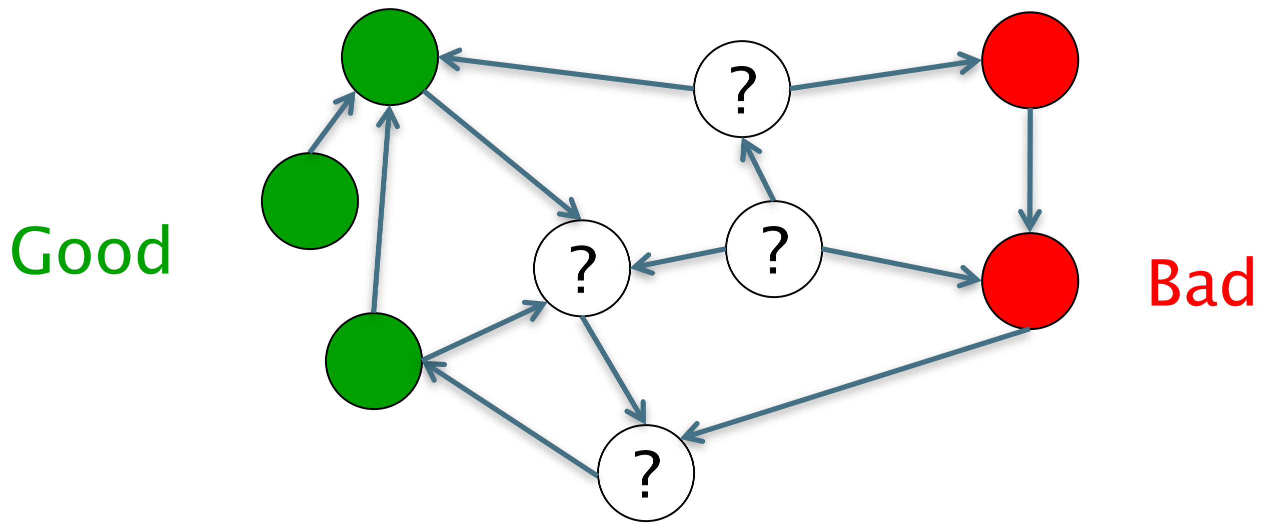
Example 1: Good/Bad/Unknown

- The Good, The Bad and The Unknown
  - Good nodes won't point to Bad nodes
  - All other combinations plausible



Simple iterative logic

- Good nodes won’t point to Bad nodes
  - If you point to a Bad node, you’re Bad
  - If a Good node points to you, you’re Good



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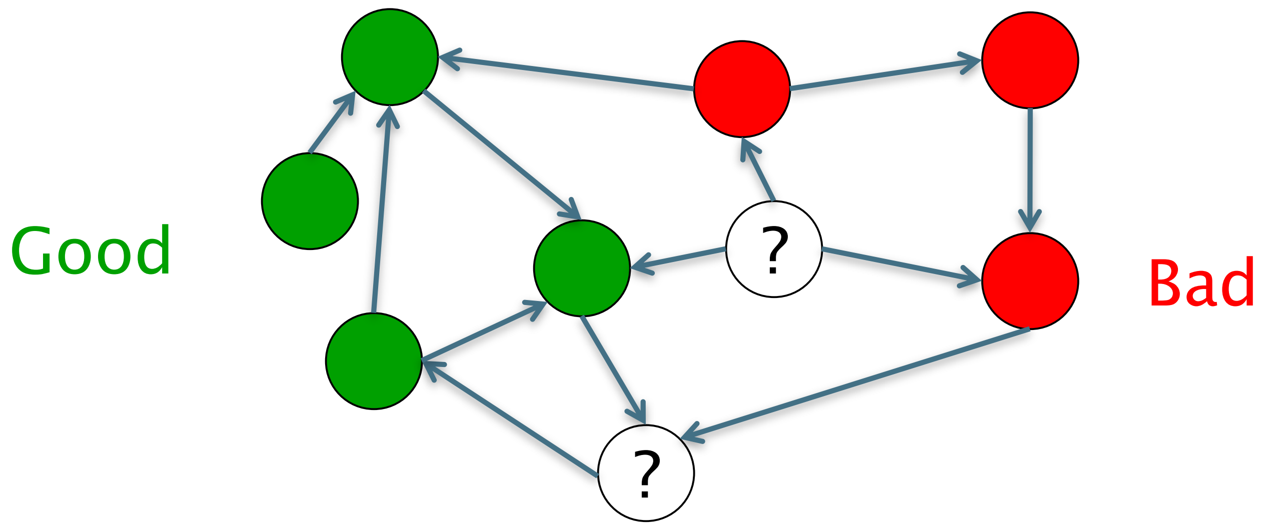

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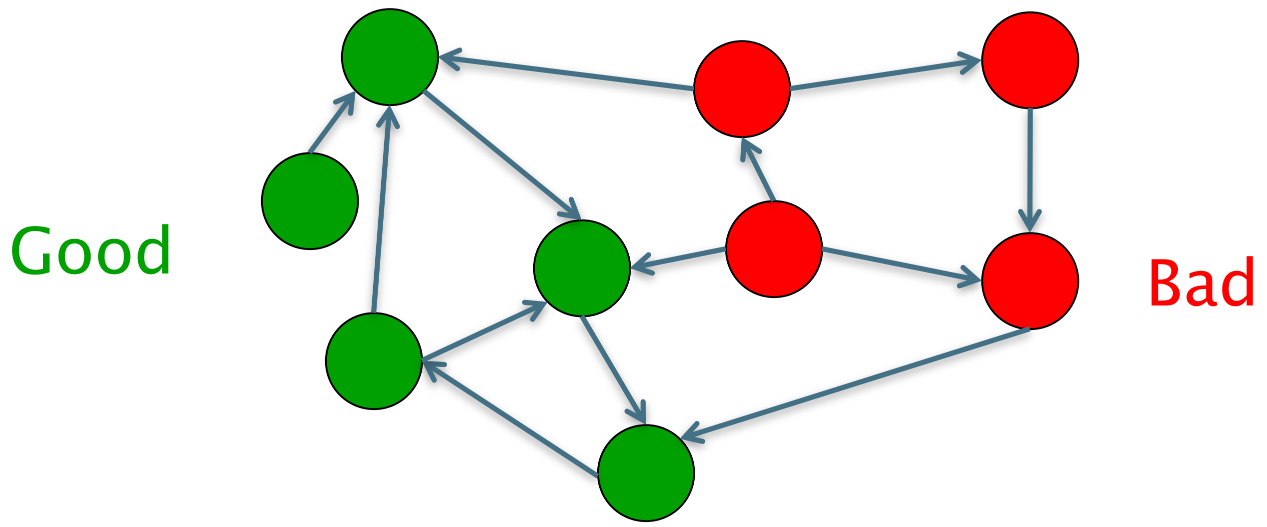
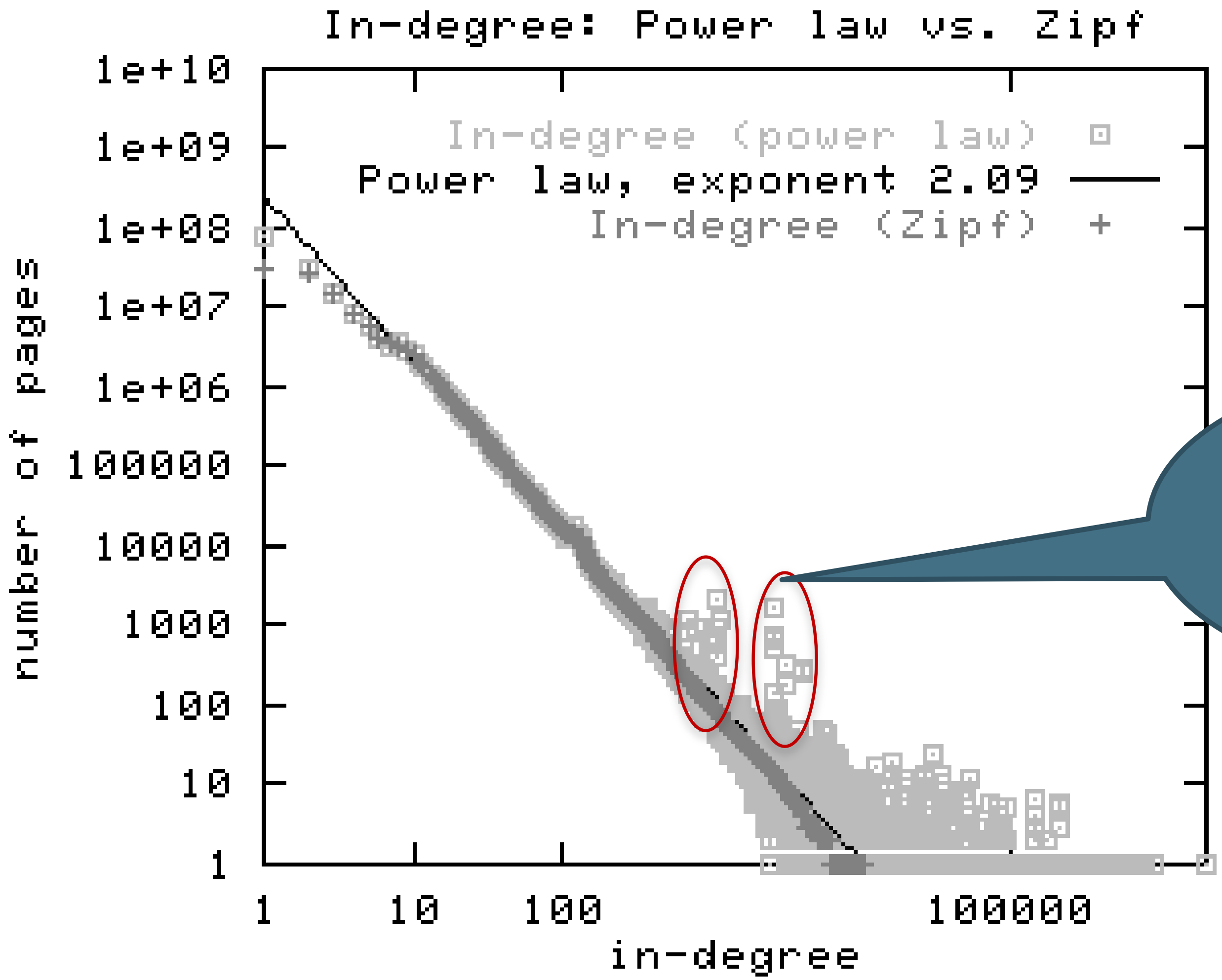


Sometimes need probabilistic analogs – e.g., mail spam

Example 2: In-links to pages – unusual patterns ☺



Spammers violating power laws!

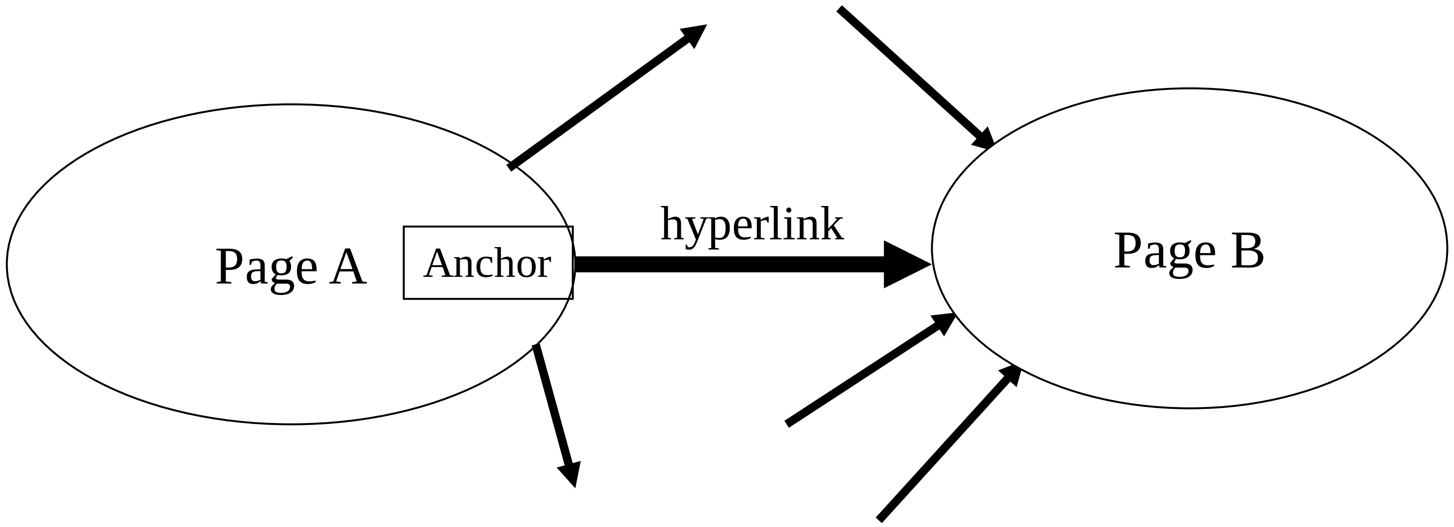
Many other examples of link analysis

- Social networks are a rich source of grouping behavior
- E.g., Shoppers' affinity – Goel+Goldstein 2010
  - Consumers whose friends spend a lot, spend a lot themselves
- http://www.cs.cornell.edu/home/kleinber/networks-book/

Our primary interest in this course

- Link analysis for most IR functionality thus far based purely on text
  - Scoring and ranking
  - Link-based clustering – topical structure from links
  - Links as features in classification – documents that link to one another are likely to be on the same subject
- Crawling
  - Based on the links seen, where do we crawl next?

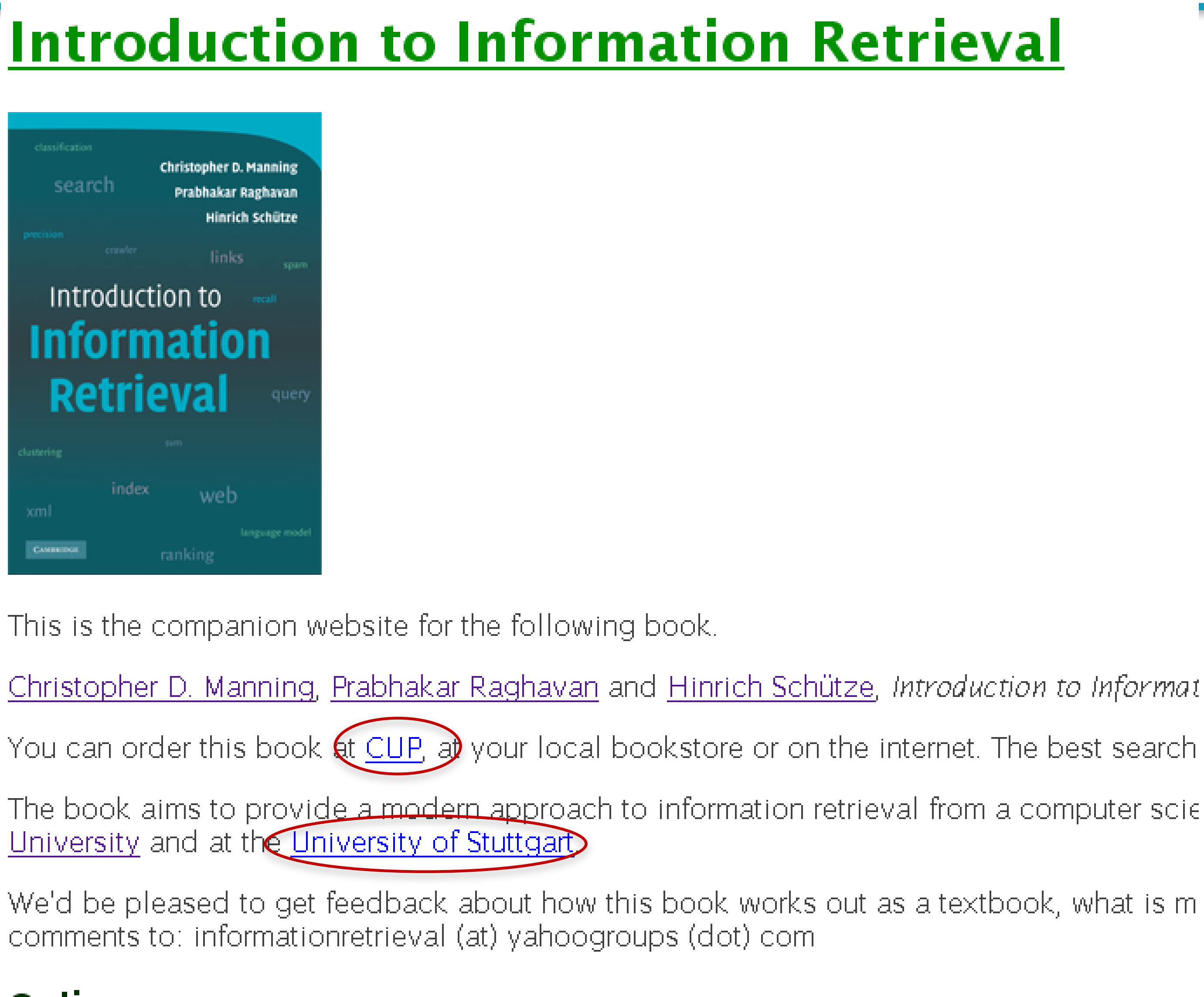
The Web as a Directed Graph



Hypothesis 1: A hyperlink between pages denotes a conferral of authority (quality signal)

Hypothesis 2: The text in the anchor of the hyperlink on page A describes the target page B

Assumption 1: reputed sites



Introduction to Information Retrieval

This is the companion website for the following book.

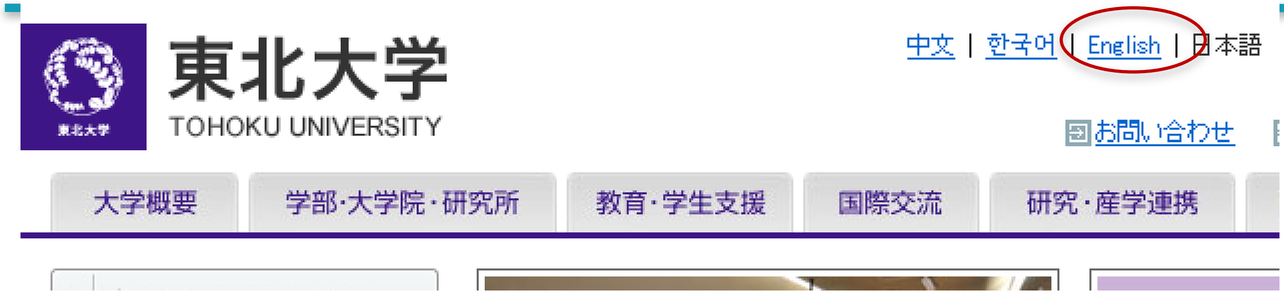
Christopher D. Manning, Prabhakar Raghavan and Hinrich Schütze, *Introduction to Informat*

You can order this book at CUP, at your local bookstore or on the internet. The best search

The book aims to provide a modern approach to information retrieval from a computer scie
University and at the University of Stuttgart.

We'd be pleased to get feedback about how this book works out as a textbook, what is m
comments to: informationretrieval (at) yahoogroups (dot) com

Assumption 2: annotation of target



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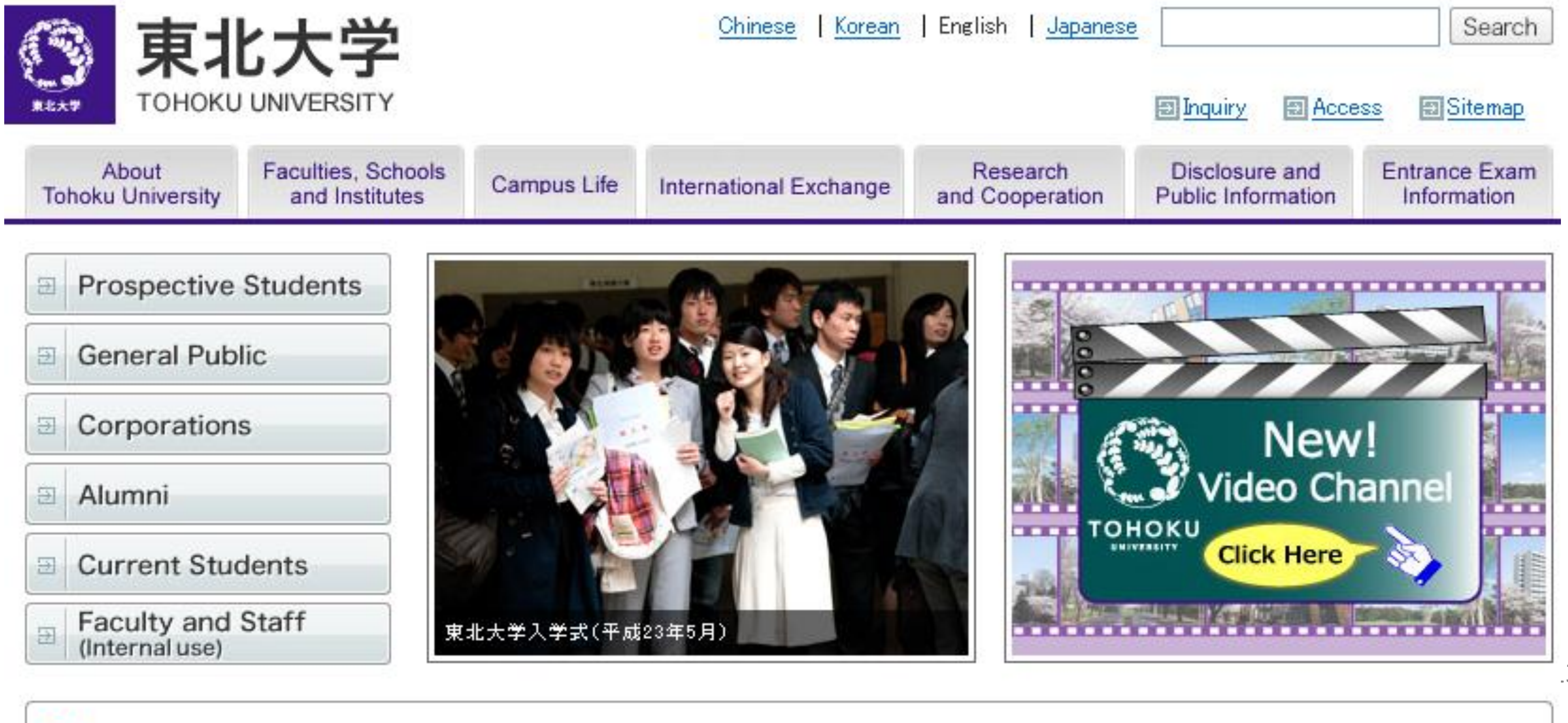

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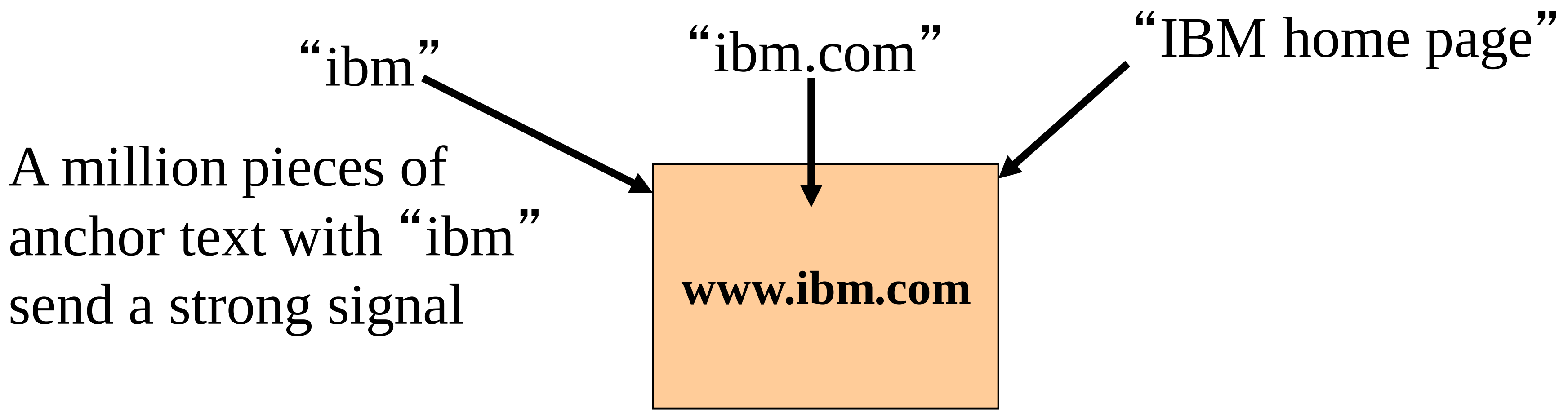
Anchor Text

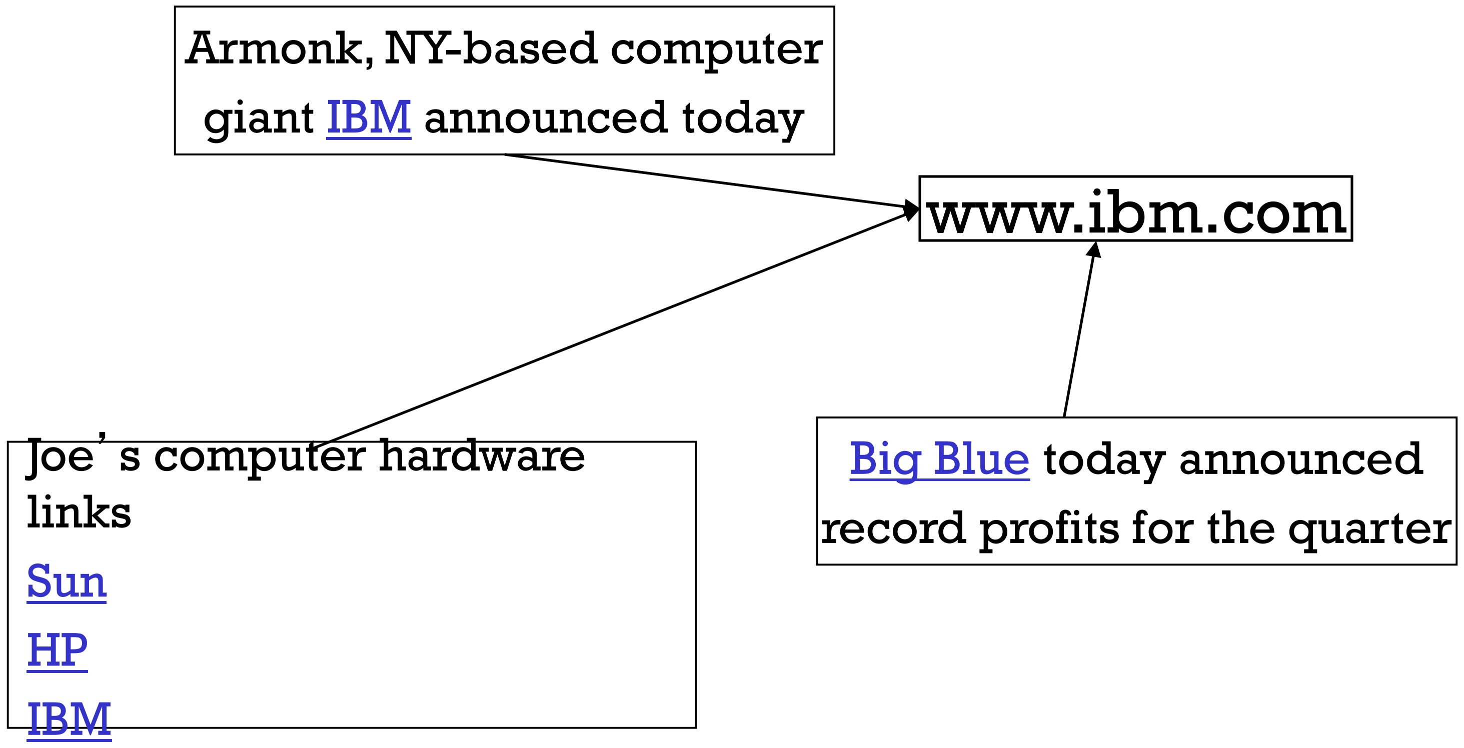
WWW Worm - McBryan [Mcbr94]

- For ***ibm*** how to distinguish between:
  - IBM's home page (mostly graphical)
  - IBM's copyright page (high term freq. for 'ibm')
  - Rival's spam page (arbitrarily high term freq.)


"ibm"
"ibm.com"
"IBM home page"
A million pieces of anchor text with "ibm" send a strong signal
www.ibm.com

Indexing anchor text

- When indexing a document *D*, include (with some weight) anchor text from links pointing to *D*.


Armonk, NY-based computer giant IBM announced today
www.ibm.com
Joe's computer hardware links
Sun
HP
IBM
Big Blue today announced record profits for the quarter

Indexing anchor text

- Can sometimes have unexpected effects, e.g., spam, **miserable failure**
- Can score anchor text with weight depending on the authority of the anchor page' s website
  - E.g., if we were to assume that content from cnn.com or yahoo.com is authoritative, then trust (more) the anchor text from them
  - Increase the weight of off-site anchors (non-nepotistic scoring)

Connectivity servers

Getting at all that link information
Inexpensively

Connectivity Server

- Support for fast queries on the web graph
  - Which URLs point to a given URL?
  - Which URLs does a given URL point to?

Stores mappings in memory from

- URL to outlinks, URL to inlinks

- Applications
  - Link analysis
  - Web graph analysis
    - Connectivity, crawl optimization
  - Crawl control

Boldi and Vigna 2004

- http://www2004.org/proceedings/docs/1p595.pdf
- Webgraph – set of algorithms and a java implementation
- Fundamental goal – maintain node adjacency lists in memory
  - For this, compressing the adjacency lists is the critical component

Adjacency lists

- The set of neighbors of a node
- Assume each URL represented by an integer
- E.g., for a 4 billion page web, need 32 bits per node
- Naively, this demands 64 bits to represent each hyperlink
- Boldi/Vigna get down to an average of ~3 bits/link
    - Further work achieves 2 bits/link

Adjaceny list compression

- Properties exploited in compression:
  - Similarity (between lists)
  - Locality (many links from a page go to "nearby" pages)
  - Use gap encodings in sorted lists
  - Distribution of gap values

Main ideas of Boldi/Vigna

- Consider lexicographically ordered list of all URLs, e.g.,
  - www.stanford.edu/alchemy
  - www.stanford.edu/biology
  - www.stanford.edu/biology/plant
  - www.stanford.edu/biology/plant/copyright
  - www.stanford.edu/biology/plant/people
  - www.stanford.edu/chemistry

Boldi/Vigna

- Each of these URLs has an adjacency list
- Main idea: due to templates, the adjacency list of a node is similar to one of the 7 preceding URLs in the lexicographic ordering
- Express adjacency list in terms of one of these
- E.g., consider these adjacency lists
  - 1, 2, 4, 8, 16, 32, 64
  - 1, 4, 9, 16, 25, 36, 49, 64
  - 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144
  - 1, 4, 8, 16, 25, 36, 49, 64

Why 7?

Encode as (-2), remove 9, add 8

Gap encodings

- Given a sorted list of integers x, y, z, …, represent by x, y-x, z-y, …
- Compress each integer using a code
  - γ code - Number of bits = $1 + 2\lfloor \lg x \rfloor$
  - δ code: …
  - Information theoretic bound: $1 + \lfloor \lg x \rfloor$ bits
  - ζ code: Works well for integers from a power law Boldi Vigna DCC 2004

Main advantages of BV

- Depends only on locality in a canonical ordering
  - Lexicographic ordering works well for the web
- Adjacency queries can be answered very efficiently
  - To fetch out-neighbors, trace back the chain of prototypes
  - This chain is typically short in practice (since similarity is mostly intra-host)
  - Can also explicitly limit the length of the chain during encoding
- Easy to implement one-pass algorithm

Link analysis: Pagerank

Citation Analysis

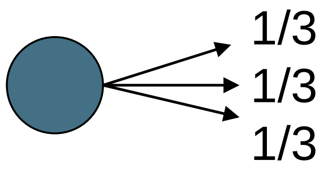
- Citation frequency
- Bibliographic coupling frequency
  - Articles that co-cite the same articles are related
- Citation indexing
  - Who is this author cited by? (Garfield 1972)
- Pagerank preview: Pinsker and Narin ’60s
  - Asked: which journals are authoritative?

The web isn’t scholarly citation

- Millions of participants, each with self interests
- Spamming is widespread
- Once search engines began to use links for ranking (roughly 1998), link spam grew
  - You can join a *link farm* – a group of websites that heavily link to one another

Pagerank scoring

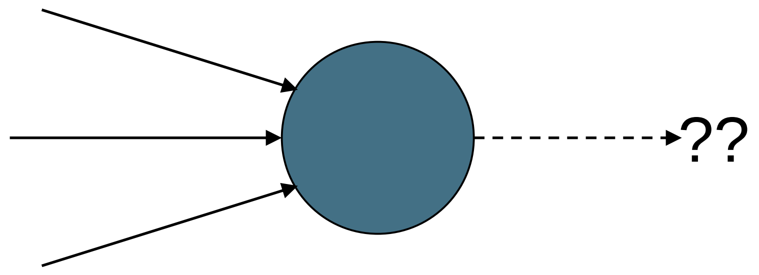
- Imagine a user doing a random walk on web pages:
  - Start at a random page
  - At each step, go out of the current page along one of the links on that page, equiprobably



- "In the long run" each page has a long-term visit rate - use this as the page's score.

Not quite enough

- The web is full of dead-ends.
  - Random walk can get stuck in dead-ends.
  - Makes no sense to talk about long-term visit rates.



Teleporting

- At a dead end, jump to a random web page.
- At any non-dead end, with probability 10%, jump to a random web page.
  - With remaining probability (90%), go out on a random link.
  - 10% - a parameter.

Result of teleporting

- Now cannot get stuck locally.
- There is a long-term rate at which any page is visited (not obvious, will show this).
- How do we compute this visit rate?

Markov chains

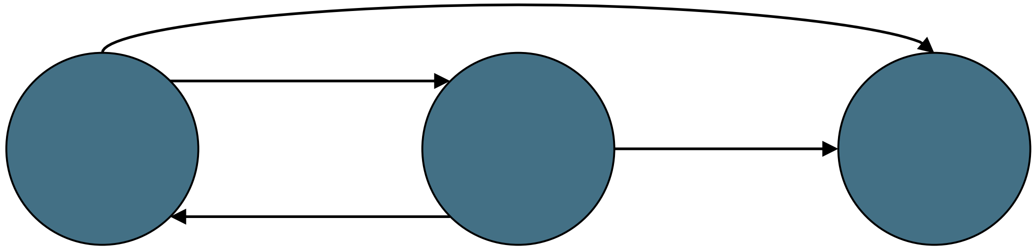
- A Markov chain consists of *n* states, plus an $n \times n$ transition probability matrix **P**.
- At each step, we are in one of the states.
- For $1 \leq i,j \leq n$, the matrix entry P_{ij} tells us the probability of *j* being the next state, given we are currently in state *i*.

$P_{ii}>0$ is OK.

$$\begin{tikzcd} i \arrow[r, "P_{ij}"'] & j \end{tikzcd}$$

Markov chains

- Clearly, for all *i*, $\sum_{j=1}^{n} P_{ij} = 1.$
- Markov chains are abstractions of random walks.
- *Exercise*: represent the teleporting random walk from 3 slides ago as a Markov chain, for this case:



Ergodic Markov chains

- For any *ergodic* Markov chain, there is a unique long-term visit rate for each state.
  - *Steady-state probability distribution*.
- Over a long time-period, we visit each state in proportion to this rate.
- It doesn't matter where we start.

Probability vectors

- A probability (row) vector **x** = $(x_1, \ldots x_n)$ tells us where the walk is at any point.
- E.g., (000…1…000) means we're in state *i*.

  1 *i* *n*

More generally, the vector **x** = $(x_1, \ldots x_n)$ means the walk is in state *i* with probability x_i.

$$\sum_{i=1}^{n} x_i = 1.$$

Change in probability vector

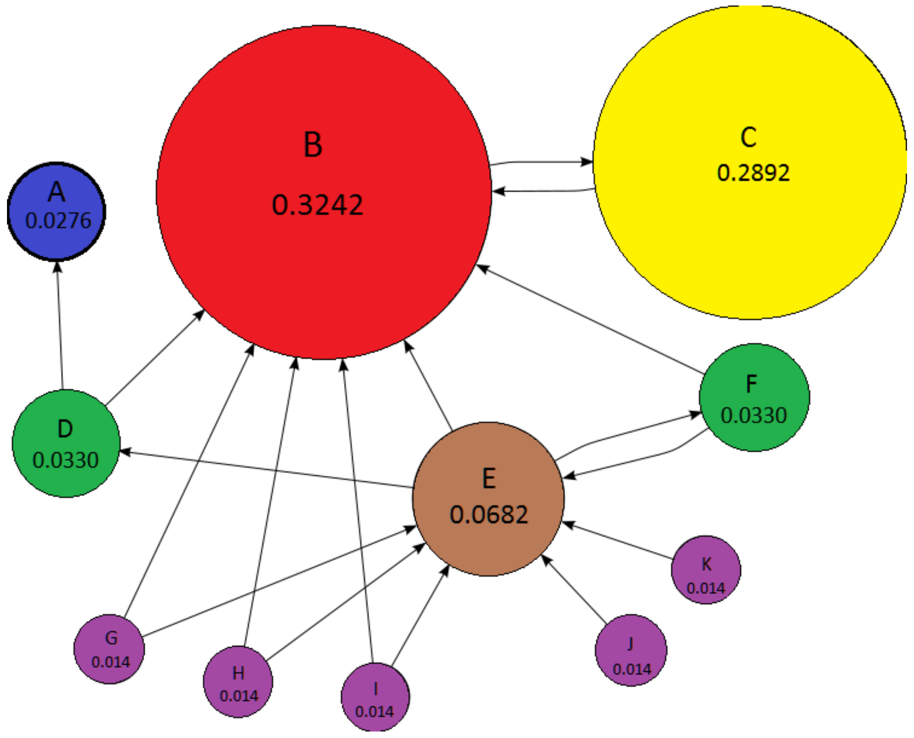
- If the probability vector is $\mathbf{x} = (x_1, \ldots x_n)$ at this step, what is it at the next step?
- Recall that row *i* of the transition prob. Matrix **P** tells us where we go next from state *i*.
- So from **x**, our next state is distributed as **xP**
  - The one after that is $\mathbf{xP}^2$, then $\mathbf{xP}^3$, etc.
  - (Where) Does this converge?

How do we compute this vector?

- Let **a** = $(a_1, \ldots a_n)$ denote the row vector of steady-state probabilities.
- If our current position is described by **a**, then the next step is distributed as **aP**.
- But **a** is the steady state, so **a=aP**.
- Solving this matrix equation gives us **a**.
  - So **a** is the (left) eigenvector for **P**.
  - (Corresponds to the "principal" eigenvector of **P** with the largest eigenvalue.)
  - Transition probability matrices always have largest eigenvalue 1.

- الگوریتم PageRank

$$PR(p) = \frac{1-d}{N} + d\sum_{i} \frac{PR(in_i)}{C(in_i)}$$



Link analysis: HITS

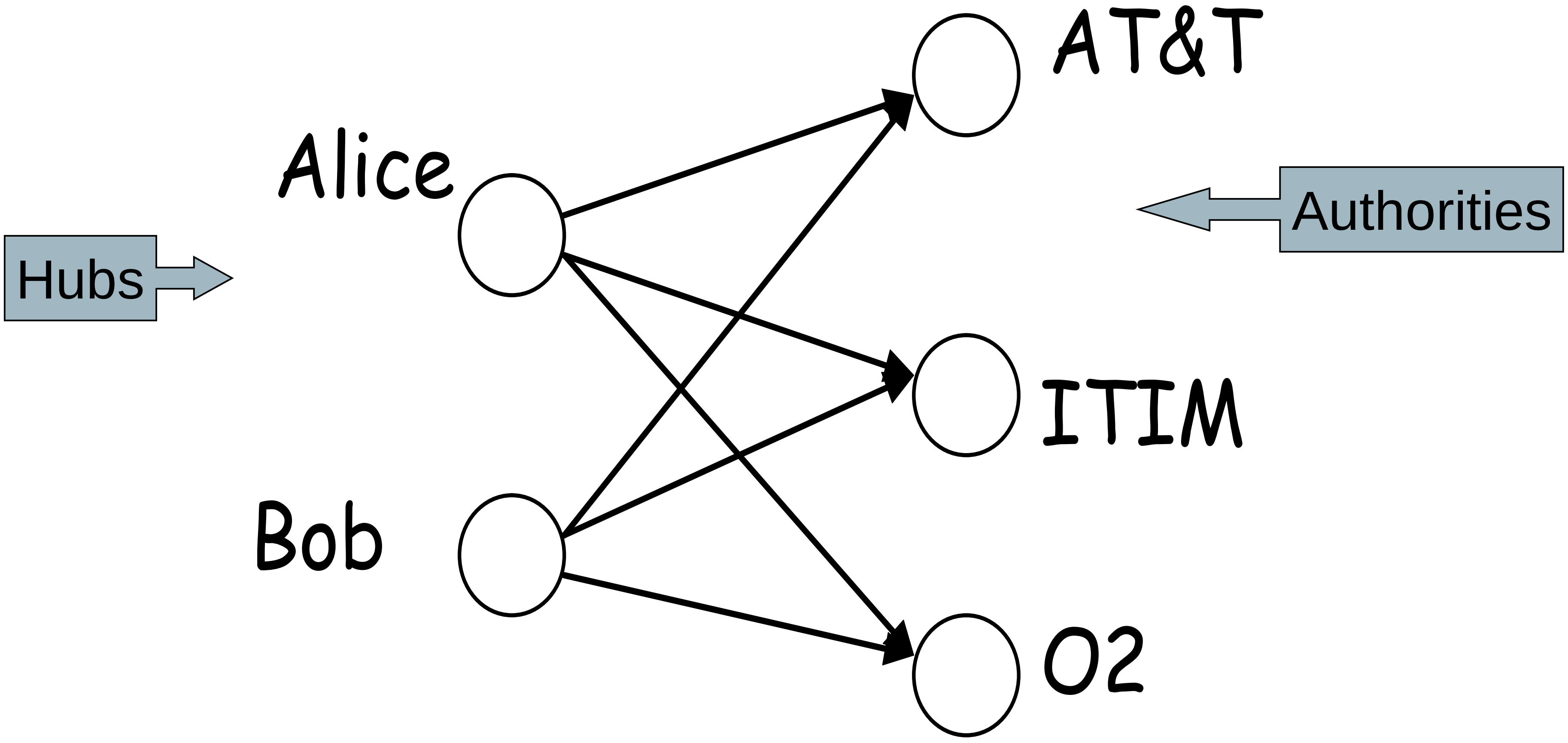
Hyperlink-Induced Topic Search (HITS)

- In response to a query, instead of an ordered list of pages each meeting the query, find two sets of inter-related pages:
  - *Hub pages* are good lists of links on a subject.
    - e.g., "Bob's list of cancer-related links."
  - *Authority pages* occur recurrently on good hubs for the subject.
- Best suited for "broad topic" queries rather than for page-finding queries.
- Gets at a broader slice of common *opinion*.

Hubs and Authorities

- Thus, a good hub page for a topic *points* to many authoritative pages for that topic.
- A good authority page for a topic is *pointed* to by many good hubs for that topic.
- Circular definition - will turn this into an iterative computation.

The hope



Mobile telecom companies

High-level scheme

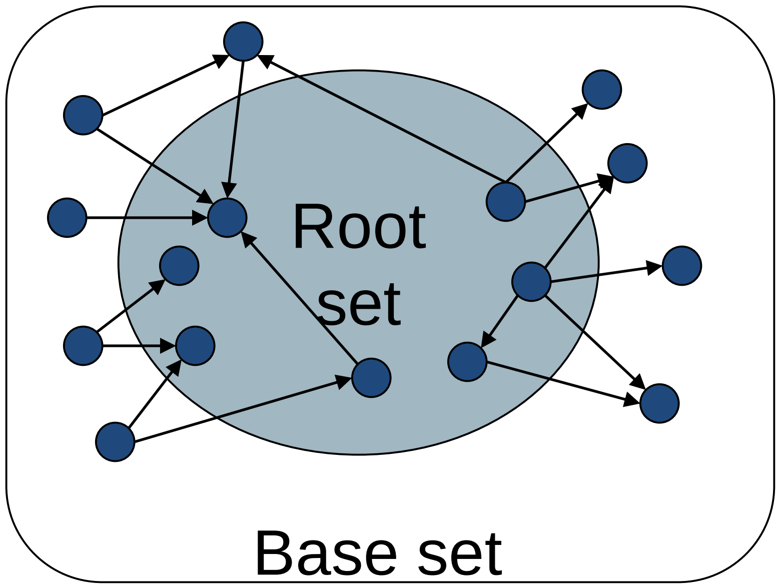
- Extract from the web a base set of pages that *could* be good hubs or authorities.
- From these, identify a small set of top hub and authority pages;

  $\rightarrow$iterative algorithm.

Base set

- Given text query (say ***browser***), use a text index to get all pages containing ***browser.***
  - Call this the root set of pages.
- Add in any page that either
  - points to a page in the root set, or
  - is pointed to by a page in the root set.
- Call this the base set.

Visualization



Get in-links (and out-links) from a *connectivity server*

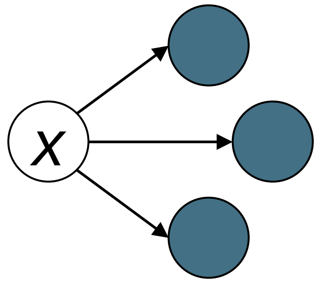
Distilling hubs and authorities

- Compute, for each page *x* in the base set, a hub score *h(x)* and an authority score *a(x).*
- Initialize: for all *x, h(x)*$\leftarrow$*1; a(x)* $\leftarrow$*1;*
- Iteratively update all *h(x), a(x)*; ⇦ Key
- After iterations
  - output pages with highest *h()* scores as top hubs
  - highest *a()* scores as top authorities.

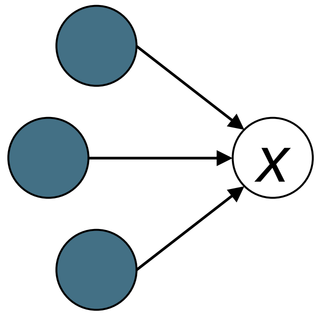
Iterative update

- Repeat the following updates, for all *x*:

$$h(x) \leftarrow \sum_{x \mapsto y} a(y)$$



$$a(x) \leftarrow \sum_{y \mapsto x} h(y)$$



Scaling

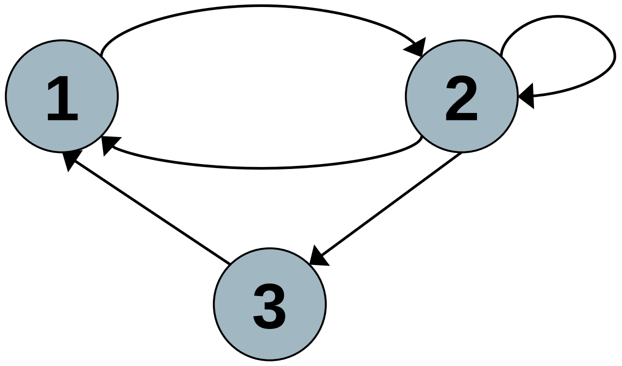
- To prevent the *h()* and *a()* values from getting too big, can scale down after each iteration.
- Scaling factor doesn’t really matter:
  - we only care about the *relative* values of the scores.

How many iterations?

- Claim: relative values of scores will converge after a few iterations:
  - in fact, suitably scaled, *h()* and *a()* scores settle into a steady state!
  - proof of this comes later.
- In practice, ~5 iterations get you close to stability.

Proof of convergence

- $n \times n$ adjacency matrix **A**:
  - each of the n pages in the base set has a row and column in the matrix.
  - Entry $A_{ij} = 1$ if page i links to page j, else = 0.



$$\begin{array}{c|ccc|} & 1 & 2 & 3 \\ \hline 1 & 0 & 1 & 0 \\ 2 & 1 & 1 & 1 \\ 3 & 1 & 0 & 0 \\ \hline \end{array}$$

Hub/authority vectors

- View the hub scores *h()* and the authority scores *a()* as vectors with *n* components.
- Recall the iterative updates

$$h(x) \leftarrow \sum_{x \mapsto y} a(y)$$

$$a(x) \leftarrow \sum_{y \mapsto x} h(y)$$

Rewrite in matrix form

- **h=Aa.**
- **a=A^{t}h.**

Recall A^t is the transpose of A.

Substituting, **h=AA^{t}h** and **a=A^{t}Aa**.

Thus, **h** is an eigenvector of **AA^t** and **a** is an eigenvector of **A^{t}A**.

Further, our algorithm is a particular, known algorithm for computing eigenvectors: the *power iteration* method.

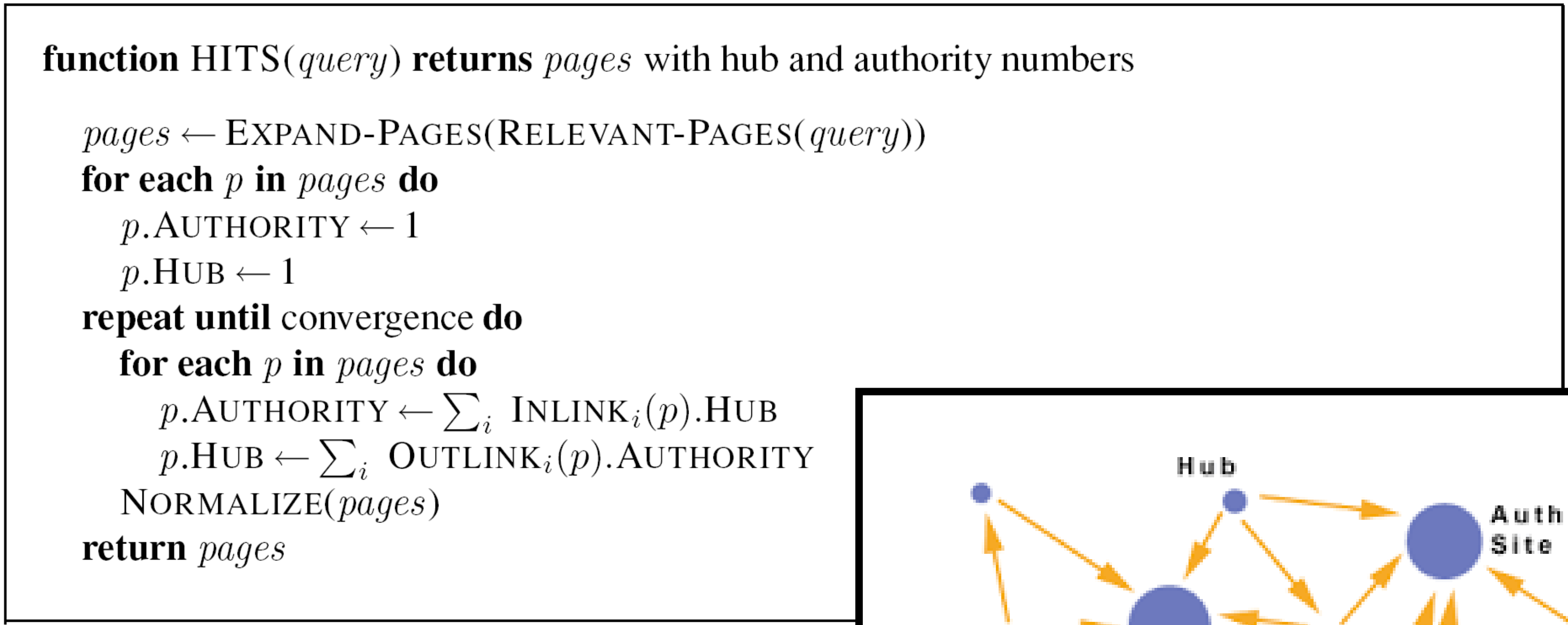
Guaranteed to converge.

Issues

- Topic Drift
  - Off-topic pages can cause off-topic "authorities" to be returned
    - E.g., the neighborhood graph can be about a "super topic"
- Mutually Reinforcing Affiliates
  - Affiliated pages/sites can boost each others' scores
    - Linkage between affiliated pages is not a useful signal

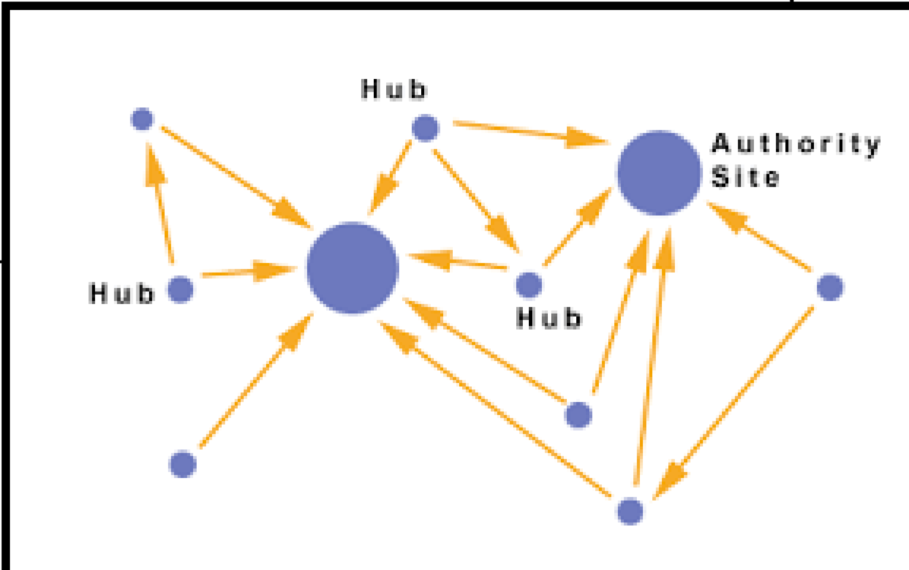
HITS

- الگوریتم HITS (Hyperlink-Induced Topic Search):



```
function HITS($query$) returns $pages$ with hub and authority numbers

  $pages \leftarrow$ EXPAND-PAGES(RELEVANT-PAGES($query$))
  for each $p$ in $pages$ do
    $p$.AUTHORITY $\leftarrow 1$
    $p$.HUB $\leftarrow 1$
  repeat until convergence do
    for each $p$ in $pages$ do
      $p$.AUTHORITY $\leftarrow \sum_i$ INLINK$_i(p)$.HUB
      $p$.HUB $\leftarrow \sum_i$ OUTLINK$_i(p)$.AUTHORITY
    NORMALIZE($pages$)
  return $pages$
```



Resources

- IIR Chap 21
- http://www2004.org/proceedings/docs/1p309.pdf
- http://www2004.org/proceedings/docs/1p595.pdf
- http://www2003.org/cdrom/papers/refereed/p270/kamvar-270-xhtml/index.html
- http://www2003.org/cdrom/papers/refereed/p641/xhtml/p641-mccurley.html
- The WebGraph framework I: Compression techniques (Boldi et al. 2004)