

# Introduction to **Information Retrieval**

CS276

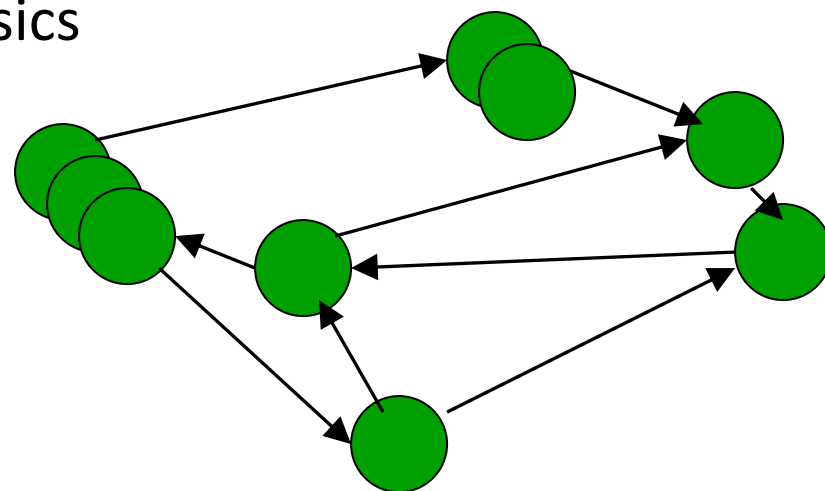
Information Retrieval and Web Search

Chris Manning and Pandu Nayak

Link analysis

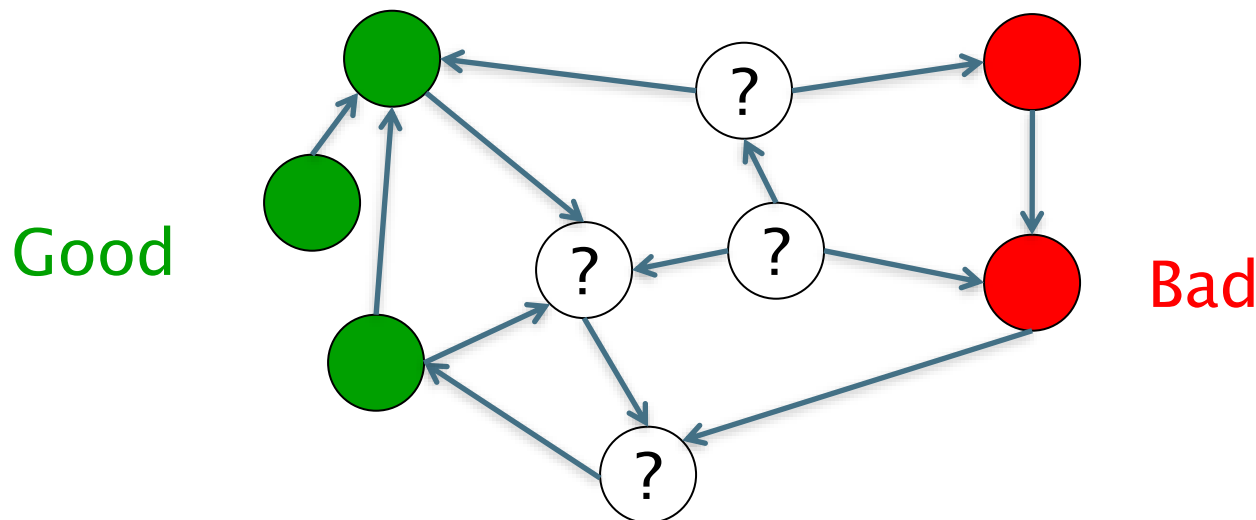
# Today's lecture – hypertext and links

- 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



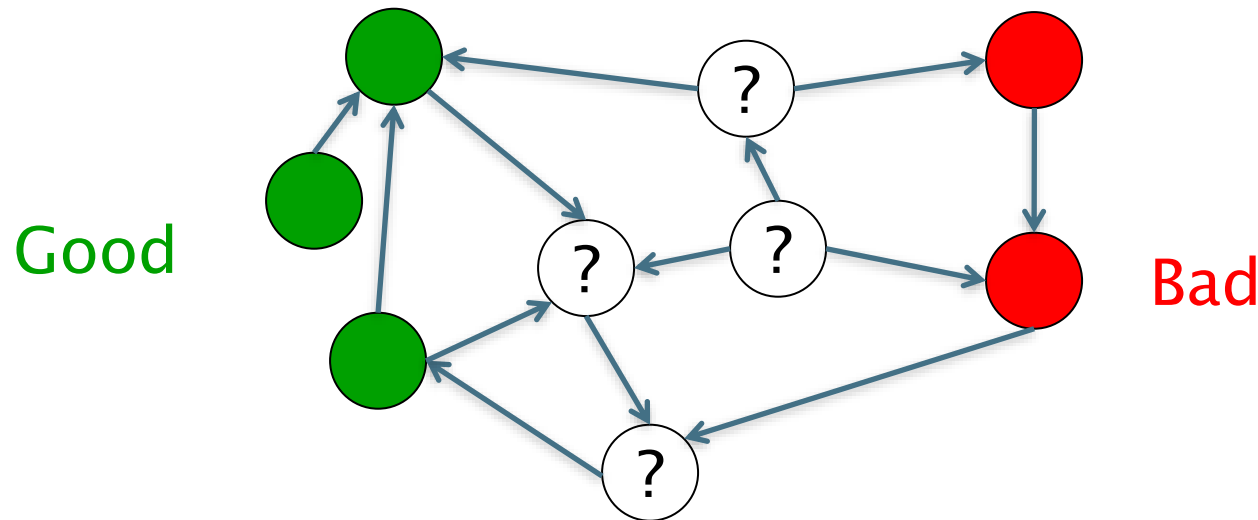
# Links are everywhere

- 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



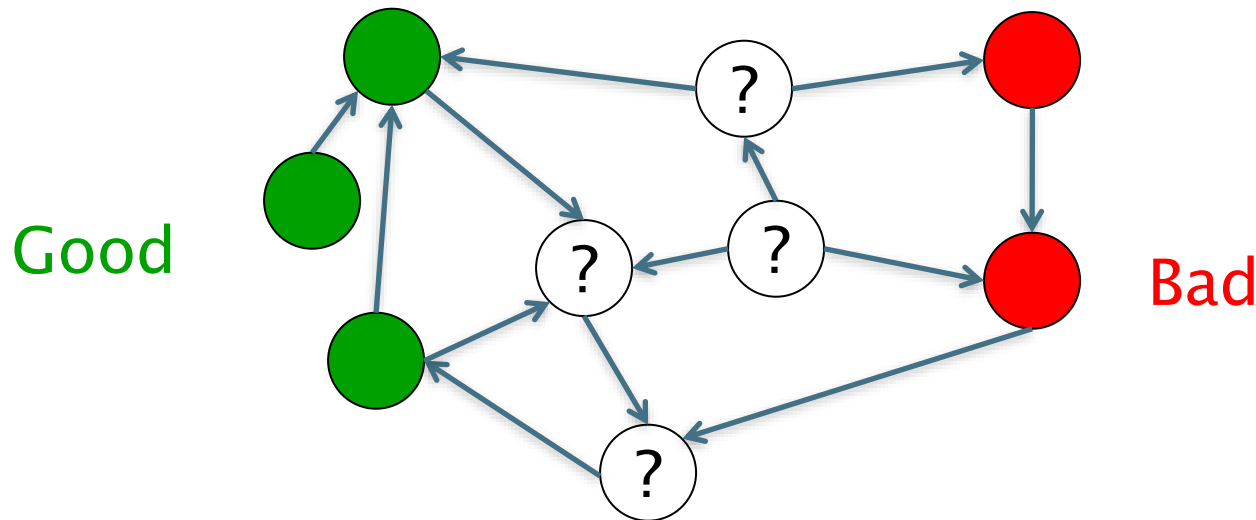
# Example 1: Good/Bad/Unknown

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



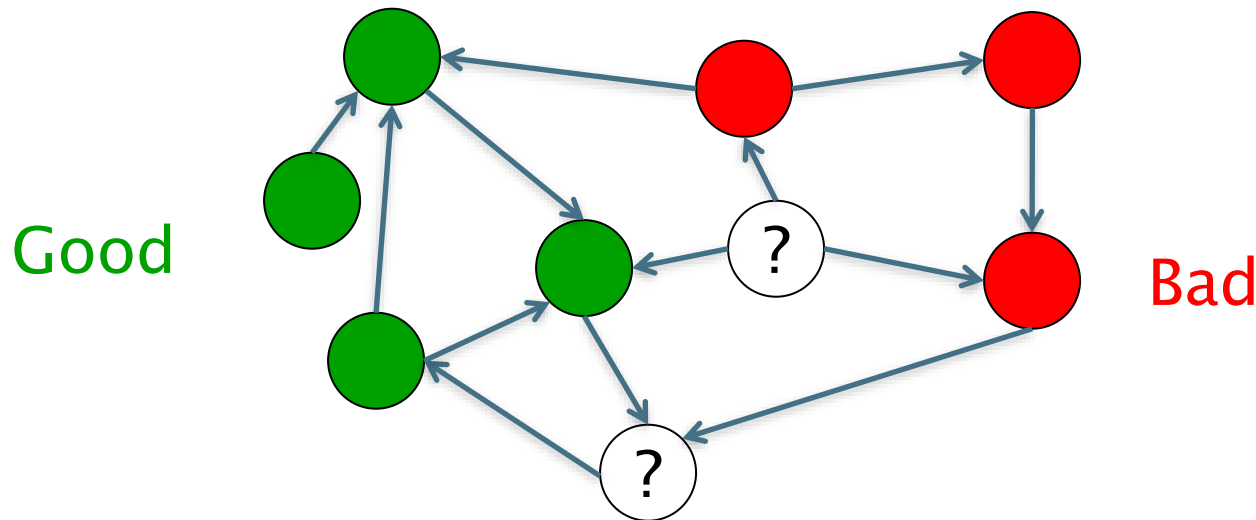
# Simple iterative logic

- **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**



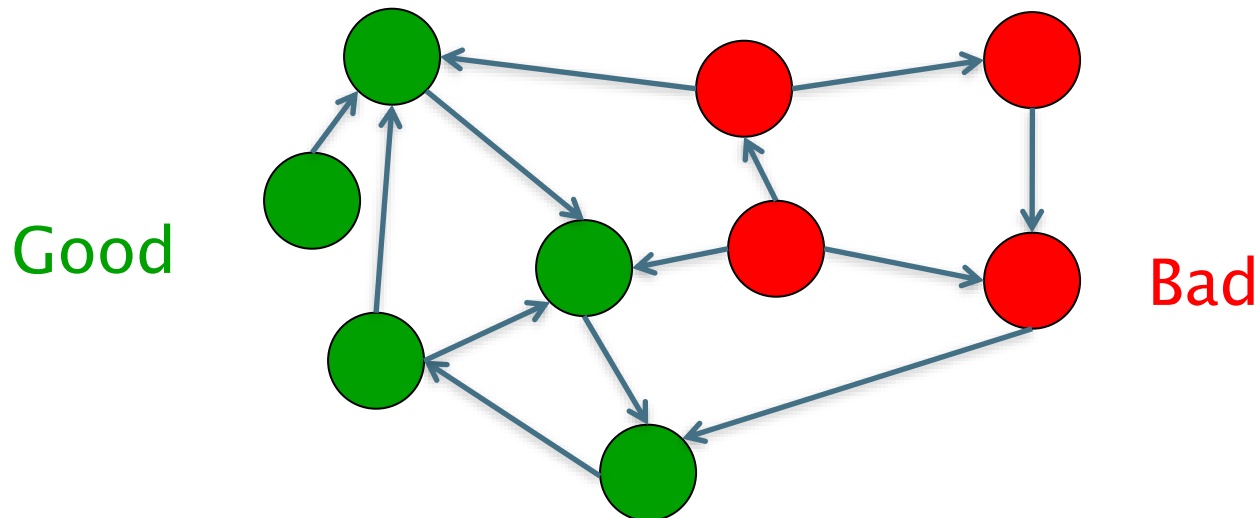
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# Simple iterative logic

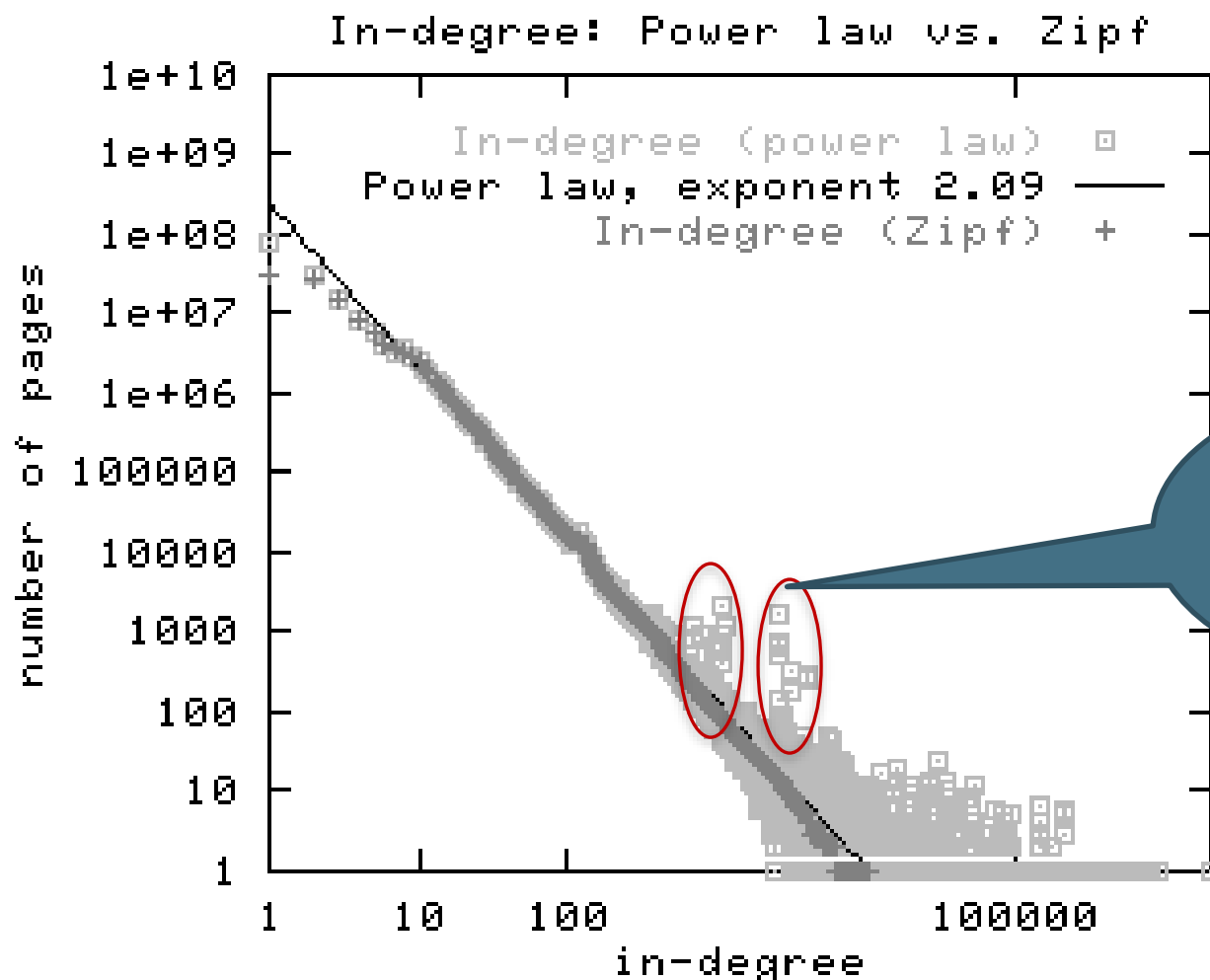
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Sometimes need probabilistic analogs – e.g., mail spam

# Example 2:

## In-links to pages – unusual patterns 😊



Spammers  
violating  
power laws!



# Many other examples of link analysis

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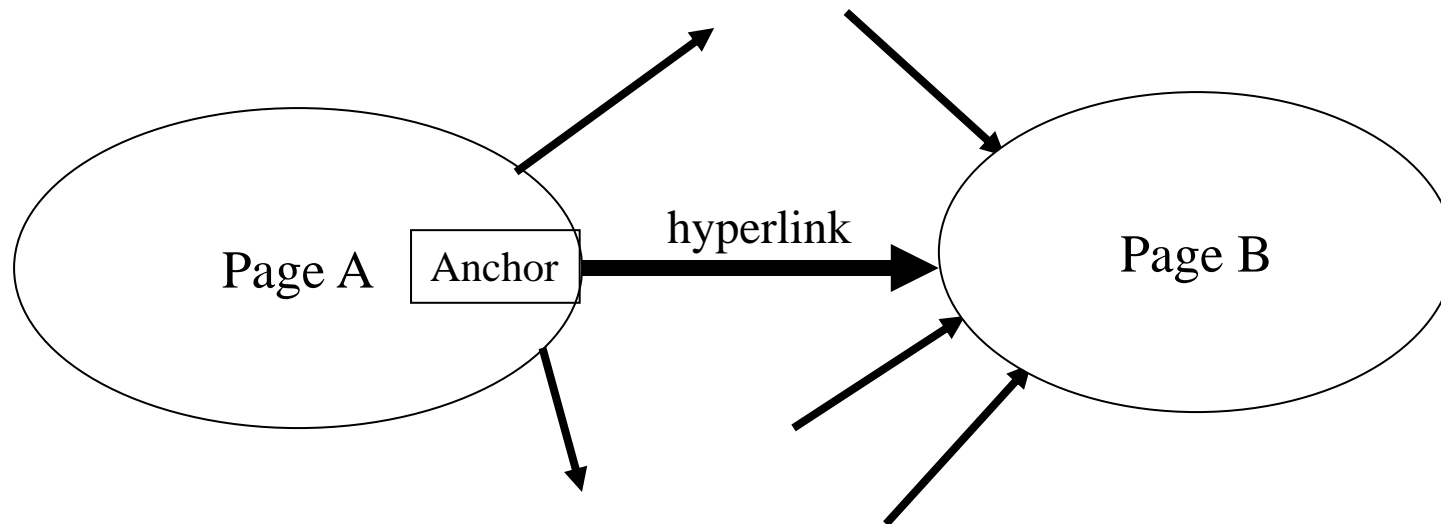
- Social networks are a rich source of grouping behavior
- E.g., Shoppers' affinity – Goel+Goldstein 2010
  - Consumers whose friends spend a lot, spend a lot themselves
- <http://www.cs.cornell.edu/home/kleinber/networks-book/>

# Our primary interest in this course

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- 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

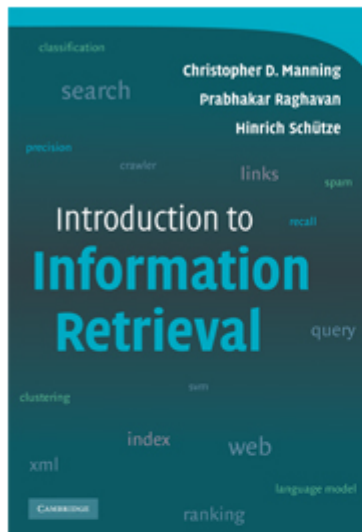


**Hypothesis 1:** A hyperlink between pages denotes a conferral of authority (quality signal)

**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 Information Retrieval*

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 science [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 missing, and what comments to: [informationretrieval \(at\) yahoogroups \(dot\) com](mailto:informationretrieval@yahoo.com)

# Assumption 2: annotation of target

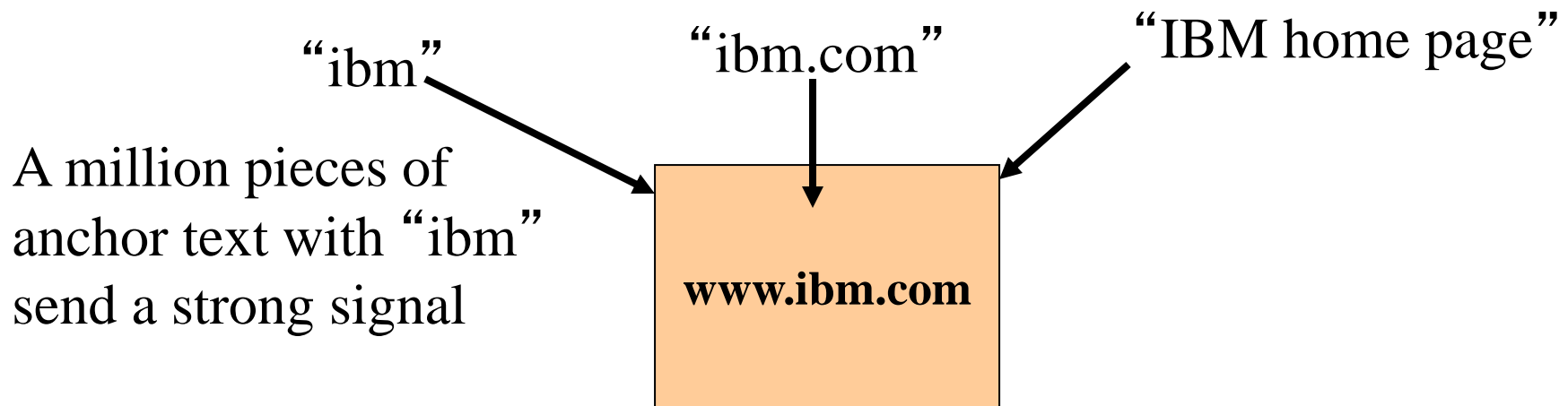


# Anchor Text

## *WWW Worm* - McBryan [Mcbr94]

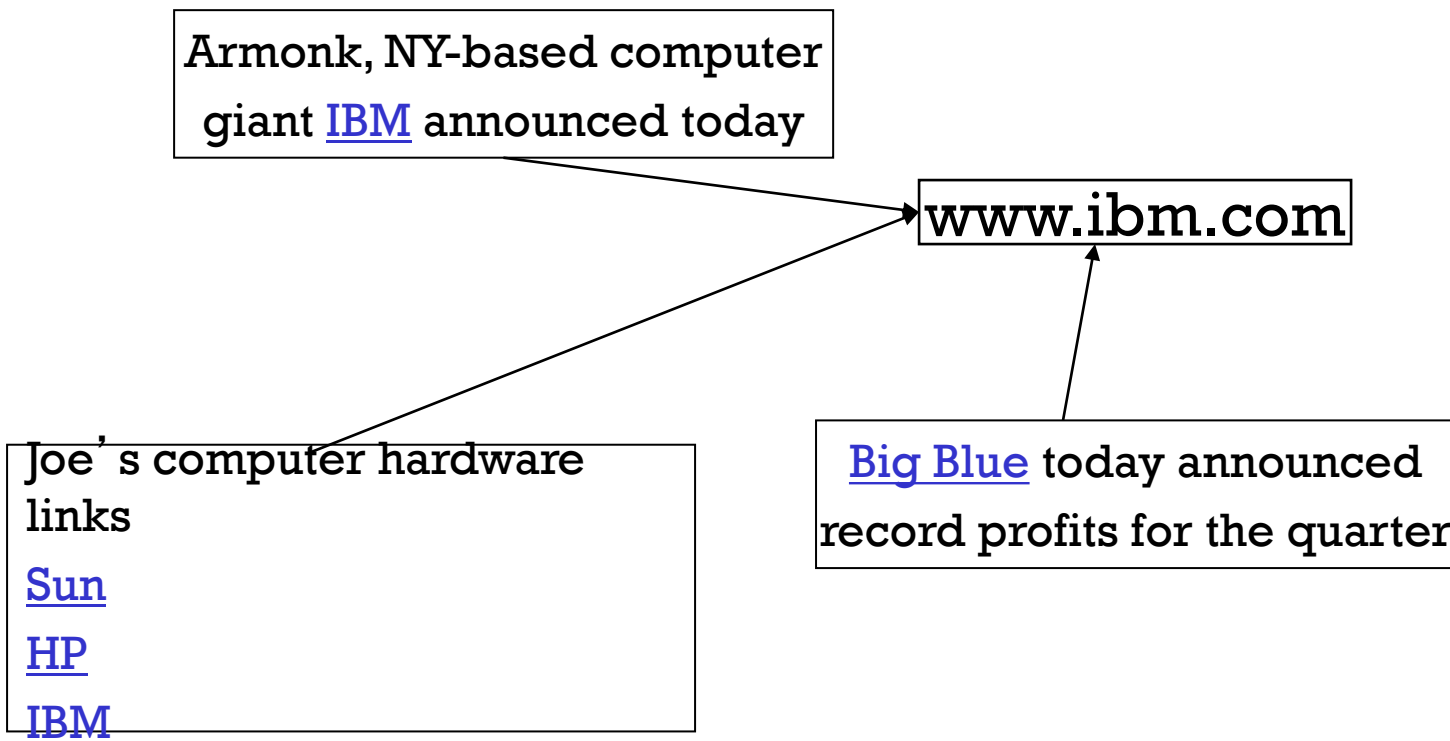
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- For *ibm* how to distinguish between:
  - IBM's home page (mostly graphical)
  - IBM's copyright page (high term freq. for 'ibm' )
  - Rival's spam page (arbitrarily high term freq.)



# Indexing anchor text

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



# Indexing anchor text

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- 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

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- 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

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- <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

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- 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  $\sim 3$  bits/link
  - Further work achieves 2 bits/link

# Adjacency list compression

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- 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

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- Consider lexicographically ordered list of all URLs, e.g.,
  - [www.stanford.edu/alchemy](http://www.stanford.edu/alchemy)
  - [www.stanford.edu/biology](http://www.stanford.edu/biology)
  - [www.stanford.edu/biology/plant](http://www.stanford.edu/biology/plant)
  - [www.stanford.edu/biology/plant/copyright](http://www.stanford.edu/biology/plant/copyright)
  - [www.stanford.edu/biology/plant/people](http://www.stanford.edu/biology/plant/people)
  - [www.stanford.edu/chemistry](http://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

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



# Main advantages of BV

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- 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

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- 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: Pinski and Narin ' 60s
  - Asked: which journals are authoritative?

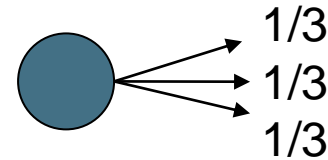
# The web isn't scholarly citation

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- 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

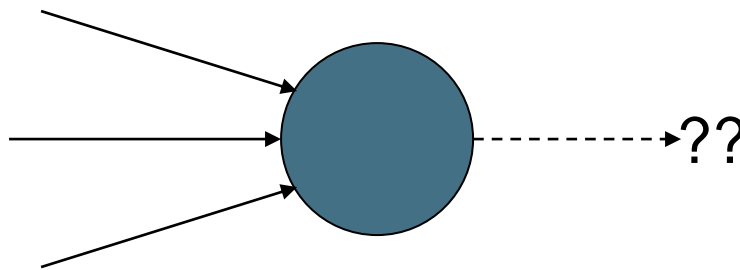
- Imagine a user doing a random walk on web pages:
  - Start at a random page
  - At each step, go out of the current page along one of the links on that page, equiprobably
- “In the long run” each page has a long-term visit rate - use this as the page’s score.



# Not quite enough

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- 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

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- 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

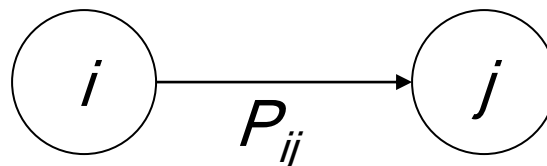
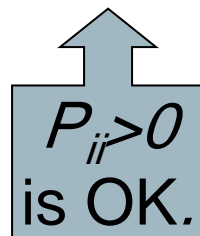
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- Now cannot get stuck locally.
- There is a long-term rate at which any page is visited (not obvious, will show this).
- How do we compute this visit rate?



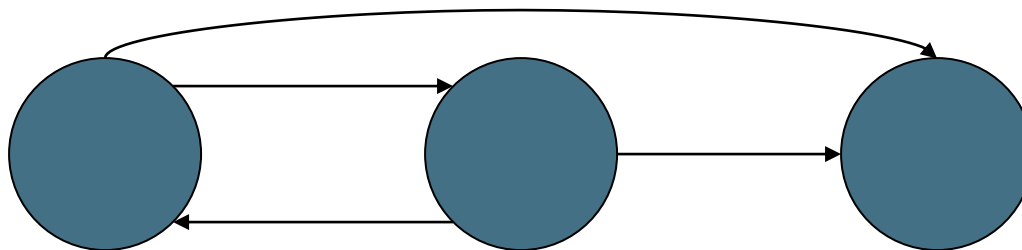
# Markov chains

- A Markov chain consists of  $n$  states, plus an  $n \times n$  transition probability matrix  $\mathbf{P}$ .
- **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  $i$ .



# 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

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- 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  $\mathbf{x} = (x_1, \dots, x_n)$  tells us where the walk is at any point.
- E.g.,  $(\underset{1}{000}\dots\underset{i}{1}\dots\underset{n}{000})$  means we're in state  $i$ .

More generally, the vector  $\mathbf{x} = (x_1, \dots, x_n)$  means the walk is in state  $i$  with probability  $x_i$ .

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

# Change in probability vector

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

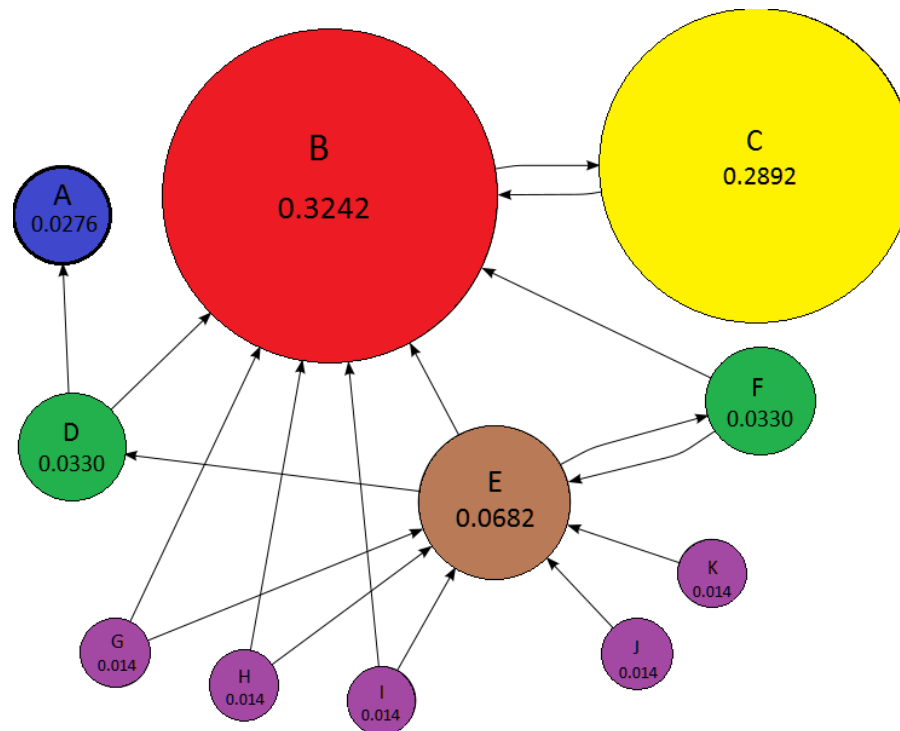
# How do we compute this vector?

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- Let  $\mathbf{a} = (a_1, \dots, a_n)$  denote the row vector of steady-state probabilities.
- If our current position is described by  $\mathbf{a}$ , then the next step is distributed as  $\mathbf{aP}$ .
- But  $\mathbf{a}$  is the steady state, so  $\mathbf{a} = \mathbf{aP}$ .
- Solving this matrix equation gives us  $\mathbf{a}$ .
  - So  $\mathbf{a}$  is the (left) eigenvector for  $\mathbf{P}$ .
  - (Corresponds to the “principal” eigenvector of  $\mathbf{P}$  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)

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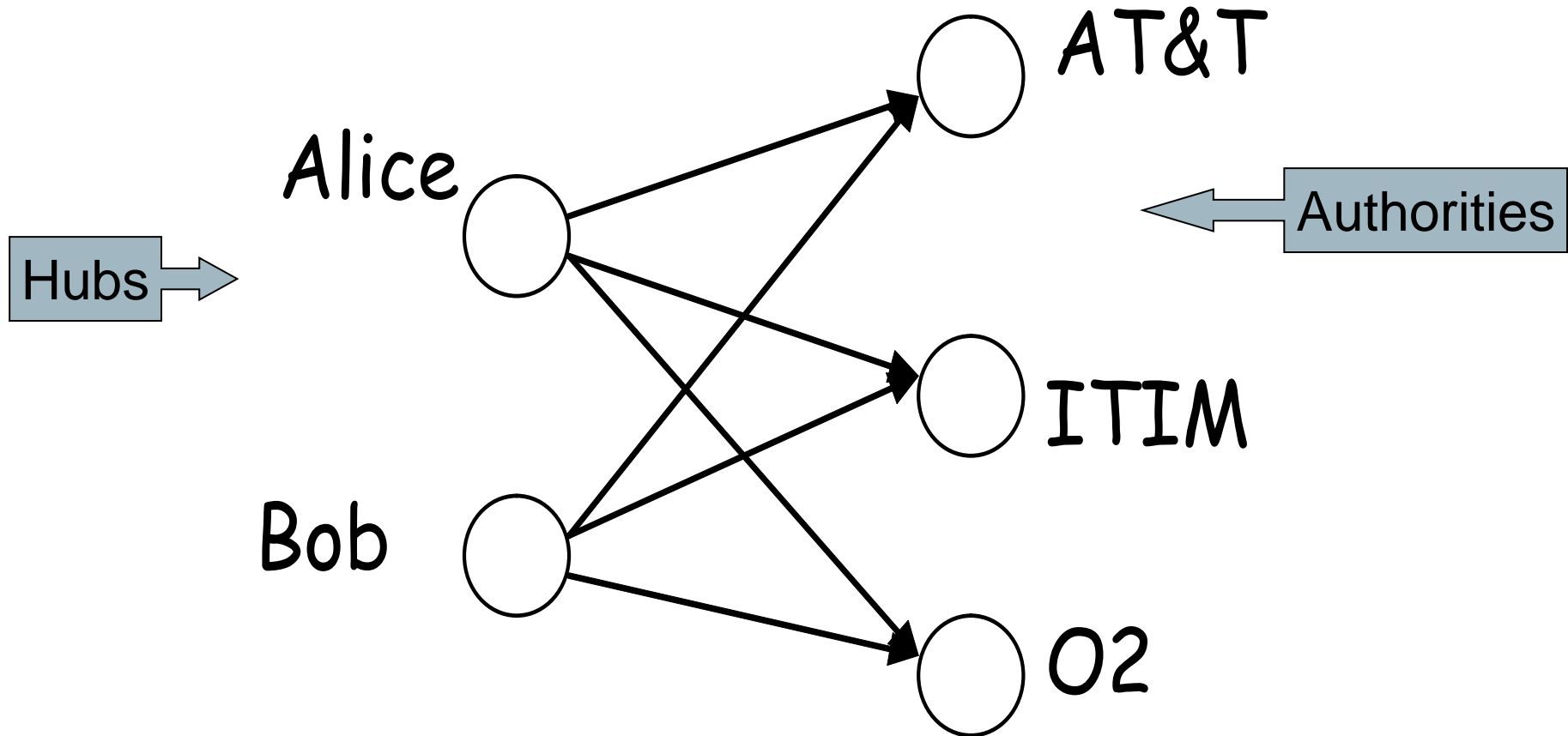
- In response to a query, instead of an ordered list of pages each meeting the query, find two sets of inter-related pages:
  - *Hub pages* are good lists of links on a subject.
    - e.g., “Bob’s list of cancer-related links.”
  - *Authority pages* occur recurrently on good hubs for the subject.
- Best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

# Hubs and Authorities

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- 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

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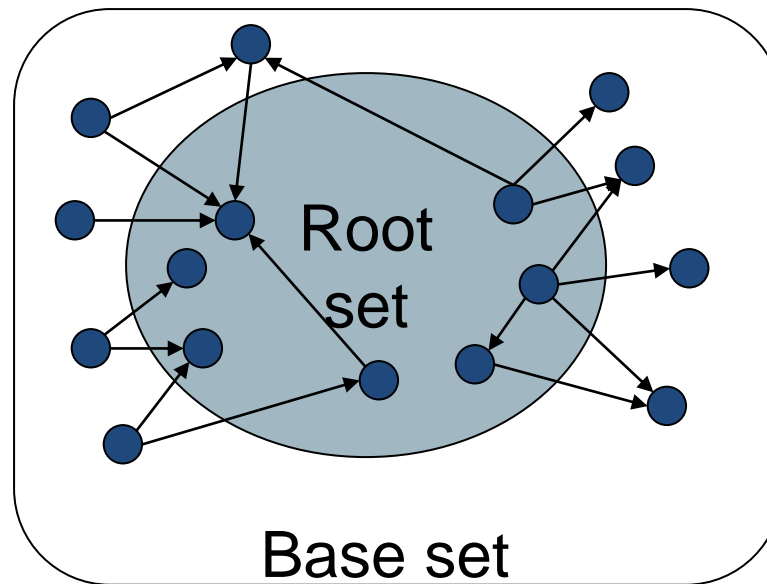
- Extract from the web a base set of pages that *could* be good hubs or authorities.
- From these, identify a small set of top hub and authority pages;
  - iterative algorithm.

# Base set

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- 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.

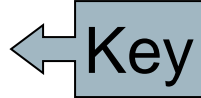
# Visualization



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

# Distilling hubs and authorities

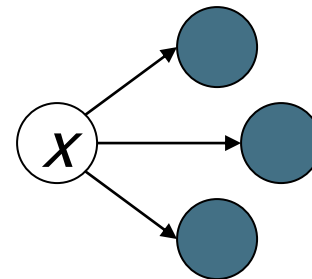
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- Compute, for each page  $x$  in the base set, a hub score  $h(x)$  and an authority score  $a(x)$ .
- Initialize: for all  $x$ ,  $h(x) \leftarrow 1$ ;  $a(x) \leftarrow 1$ ;
- Iteratively update all  $h(x)$ ,  $a(x)$ ; 
- After iterations
  - output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

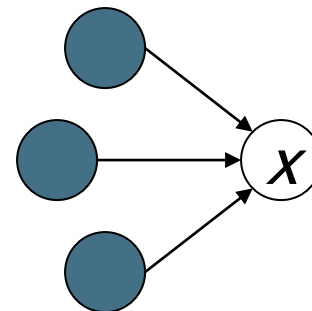
# Iterative update

- 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

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- 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.

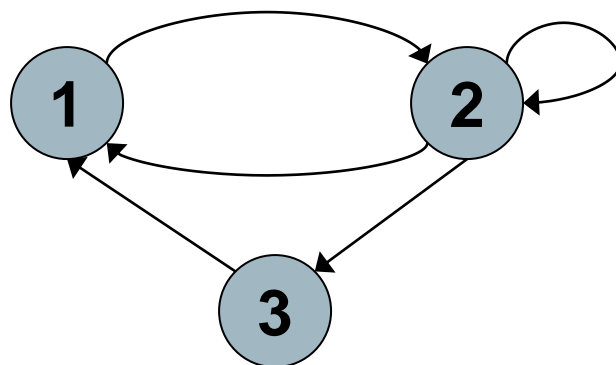
# How many iterations?

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- 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  $= 0$ .



	1	2	3
1	0	1	0
2	1	1	1
3	1	0	0

# Hub/authority vectors

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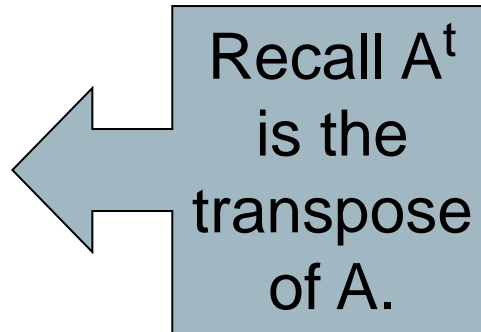
- View the hub scores  $h()$  and the authority scores  $a()$  as vectors with  $n$  components.
- Recall the iterative updates

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

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

# Rewrite in matrix form

- $\mathbf{h} = \mathbf{A}\mathbf{a}$ .
- $\mathbf{a} = \mathbf{A}^t\mathbf{h}$ .



Recall  $\mathbf{A}^t$   
is the  
transpose  
of  $\mathbf{A}$ .

Substituting,  $\mathbf{h} = \mathbf{A}\mathbf{A}^t\mathbf{h}$  and  $\mathbf{a} = \mathbf{A}^t\mathbf{A}\mathbf{a}$ .

Thus,  $\mathbf{h}$  is an eigenvector of  $\mathbf{A}\mathbf{A}^t$  and  $\mathbf{a}$  is an eigenvector of  $\mathbf{A}^t\mathbf{A}$ .

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



Guaranteed to converge.

# Issues

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- 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**

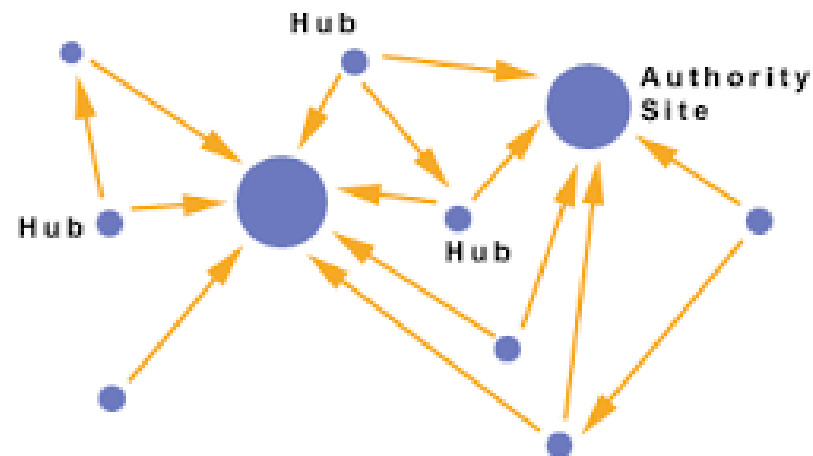
**for each** *p* **in** *pages* **do**

*p*.AUTHORITY  $\leftarrow \sum_i \text{INLINK}_i(p).\text{HUB}$

*p*.HUB  $\leftarrow \sum_i \text{OUTLINK}_i(p).\text{AUTHORITY}$

NORMALIZE(*pages*)

**return** *pages*



# Resources

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- 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 \(Boldi et al. 2004\)](#)