

Applying Orthogonal/Power Iterations to Big Graph Mining : PageRank and Kempe-McSherry Algorithms

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Outline

PageRank

- Model and basic algorithm

- Implementation using MapReduce

- Modifications

- PageRank as an orthogonal iteration

Decentralized OI

- Serial BSOI algorithm

Experimental results and analysis

PageRank

Sergey Brin



Larry Page



The Anatomy of a Large-Scale Hypertextual Web Search Engine
Computer Science Department, Stanford University
1998

PageRank

What made them heros of top magazine cover?



PageRank: The model

Measure of importance



The **importance** of a Web page is an inherently subjective matter...But there is still much that can be said **objectively** about the **relative importance** of Web pages.

Page, L.; Brin, S.; Motwani, R.; Winograd, T. (1999) *The PageRank Citation Ranking: Bringing Order to the Web.* Tech.rep. Stanford InfoLab.

Probability of visiting page by idealized random Web surfer

Why this trick works?

- ▶ users of the Web “vote with their feet”
- ▶ users are more likely to visit useful pages

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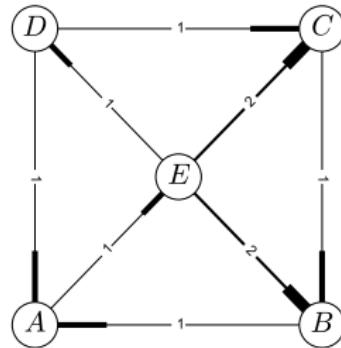
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PageRank: The model

Random surfing as Markov process



Probabilities

1. $\text{Pr} = (1, 0, 0, 0, 0)$
2. $\text{Pr} = (0, 0, 0, 0, 1)$
3. $\text{Pr} = \left(0, \frac{2}{5}, \frac{2}{5}, \frac{1}{5}, 0\right)$

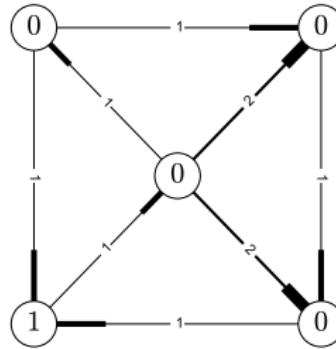
Probability evolution

$$\text{Pr}'(x) = \sum_{y \rightarrow x} \frac{\text{Pr}(y)}{\deg^+(y)}$$

- ▶ $\deg^+(y)$ – outdegree of y

PageRank: The model

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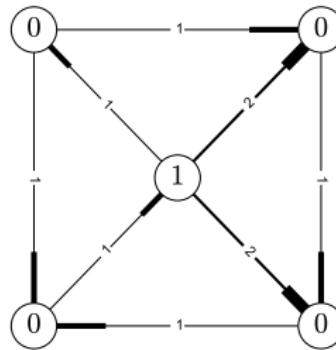
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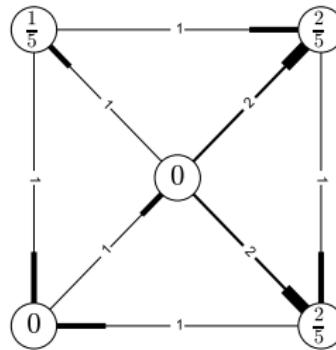
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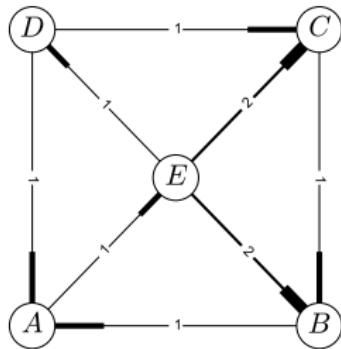
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PageRank: The model

Transition matrix of the Web



$$M = \begin{bmatrix} 0 & 1 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 1 & 0 & \frac{2}{5} \\ 0 & 0 & 0 & \frac{1}{2} & \frac{2}{5} \\ 0 & 0 & 0 & 0 & \frac{1}{5} \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Matrix-vector representation

$$\text{Pr}' = M \cdot \text{Pr}$$

► M :

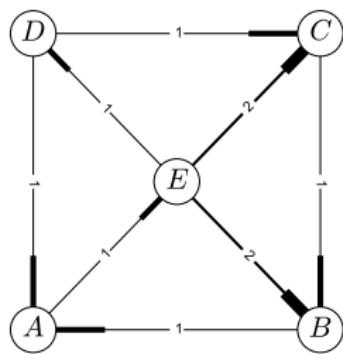
$$m_{xy} = \begin{cases} 1/\deg^+(y), & y \rightarrow x \\ 0, & y \not\rightarrow x \end{cases}$$

M is **stochastic** matrix

$$\forall y : \sum_x m_{xy} = 1$$

PageRank: The model

Simulation of random surfer



Simulation of random surfer

\Pr^i probability distribution for the location of a random surfer at step i

$$\Pr^0 = \left[\frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \right]^T \quad (1)$$

$$\Pr^{i+1} = M \cdot \Pr^i \quad (2)$$

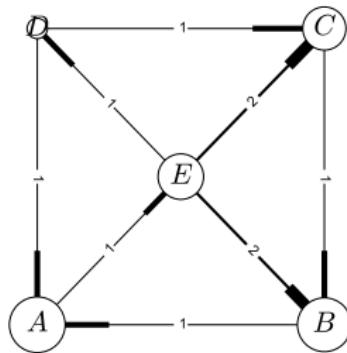
Restrictions

Strongly connected graph

- ▶ no dead-ends
- ▶ no spider traps

PageRank: The model

Simulation of random surfer



Simulation of random surfer

$$\begin{bmatrix} \frac{3}{10} \\ \frac{7}{25} \\ \frac{9}{50} \\ \frac{1}{25} \\ \frac{1}{5} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 1 & 0 & \frac{2}{5} \\ 0 & 0 & 0 & \frac{1}{2} & \frac{2}{5} \\ 0 & 0 & 0 & 0 & \frac{1}{5} \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \frac{1}{5} \\ \frac{1}{5} \\ \frac{1}{5} \\ \frac{1}{5} \\ \frac{1}{5} \end{bmatrix}$$

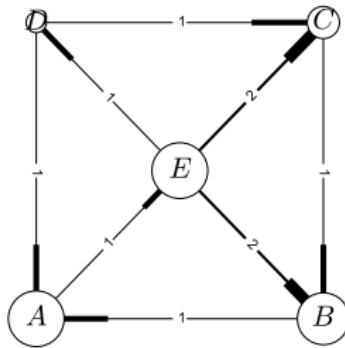
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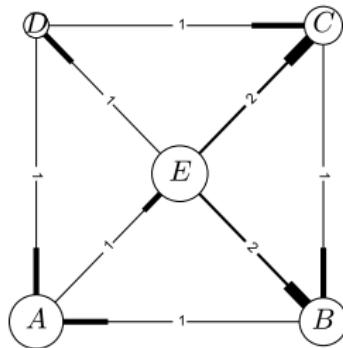
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Simulation of random surfer

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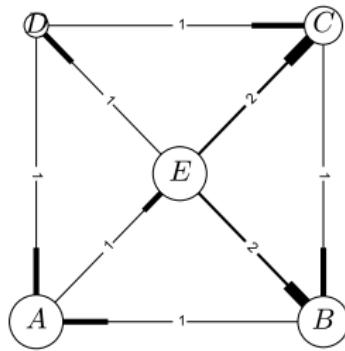
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PageRank: The model

Simulation of random surfer



Simulation of random surfer

$$\underbrace{\begin{bmatrix} 0.28 \\ 0.25 \\ 0.14 \\ 0.06 \\ 0.28 \end{bmatrix}}_{\Pr^\infty} = \underbrace{\begin{bmatrix} 0 & 1 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 1 & 0 & \frac{2}{5} \\ 0 & 0 & 0 & \frac{1}{2} & \frac{2}{5} \\ 0 & 0 & 0 & 0 & \frac{1}{5} \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}}_M \times \underbrace{\begin{bmatrix} 0.28 \\ 0.25 \\ 0.14 \\ 0.06 \\ 0.28 \end{bmatrix}}_{\Pr^\infty}$$

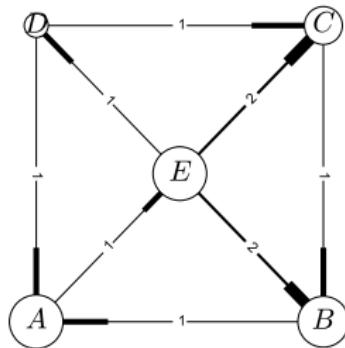
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PageRank: The model

Simulation of random surfer



Simulation of random surfer

$$M \cdot \text{Pr}^\infty = 1 \cdot \text{Pr}^\infty$$

Pr^∞ is eigenvector of M with eigenvalue $\lambda = 1$

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PageRank: The model

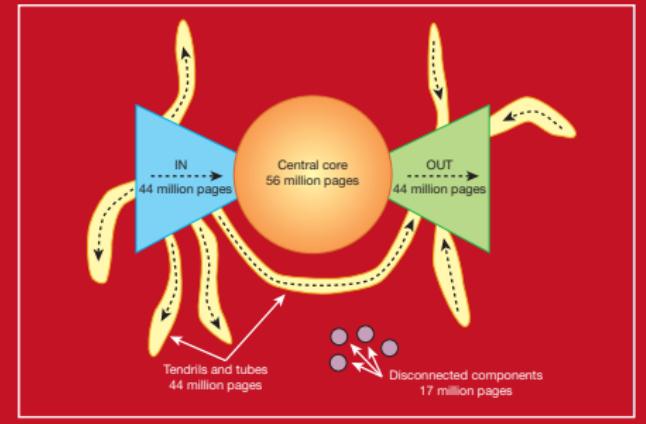
Structure of the Web

The web is a bow tie

A study of the web's structure, five times larger than any attempted previously, reveals that it isn't the fully interconnected network that we've been led to believe. The study suggests that the chance of being able to surf between two randomly chosen pages is less than one in four.

Researchers from three Californian groups — at IBM's Almaden Research Center in San Jose, the Altavista search engine in San Mateo and Compaq Systems Research Center in Palo Alto — have analysed 200 million web pages and 1.5 billion hyperlinks. Their results, which will be presented next week at the World Wide Web 9 Conference in Amsterdam, indicate that the web is made up of four distinct components.

A central core contains pages between which users can surf easily. Another large cluster, labelled 'in', contains pages that link to the core but cannot be reached from it. These are often new pages that have not yet been linked to. A separate 'out' cluster consists of pages that can be reached from the core but do not link to it, such as corporate websites containing only internal links. Other groups of pages, called 'tendrils' and 'tubes', connect to either the in or out clusters, or both, but not to the core, whereas some pages are completely unconnected. To illustrate this structure, the researchers picture the web as a plot shaped like a bow tie with finger-like projections.



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Web as “bowtie”

- ▶ in-component
- ▶ out-component
- ▶ tendrils
 - ▶ tubes
 - ▶ isolated components

Problems

- ▶ dead-ends
- ▶ spider traps

PageRank: The model

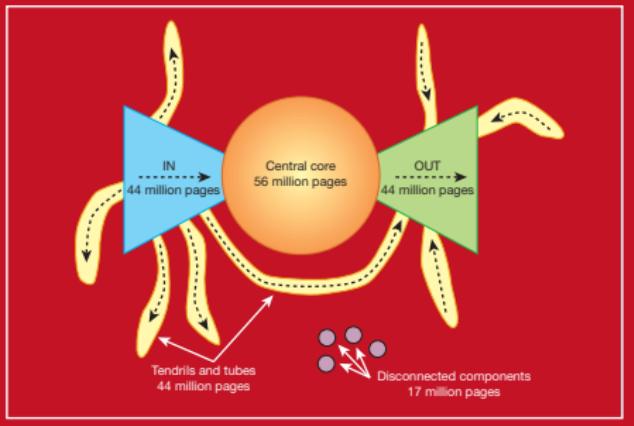
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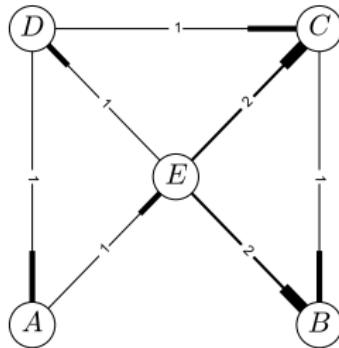
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PageRank: The model

Avoiding dead ends by dropping



Handling dead ends

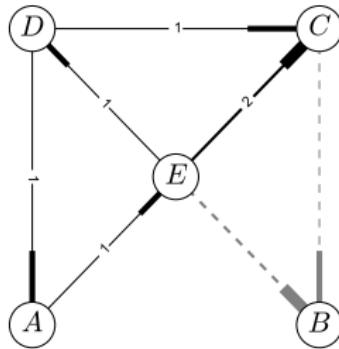
- ▶ $\text{Pr} = \left[\frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \right]^T$
- ▶ $\text{Pr} = \left[\frac{1}{4} \quad * \quad \frac{1}{4} \quad \frac{1}{4} \quad \frac{1}{4} \right]^T$
- ▶ $\text{Pr} = [0.18 \quad * \quad 0.36 \quad 0.18 \quad 0.27]^T$
- ▶ $\text{Pr} = [0.18 \quad 0.42 \quad 0.36 \quad 0.18 \quad 0.27]^T$

Algorithm: dropping dead ends (for substochastic M)

1. Backward graph reduction: remove dead ends iteratively
2. Compute PageRanks of reduced graph
3. Forward PageRank computing

PageRank: The model

Avoiding dead ends by dropping



Handling dead ends

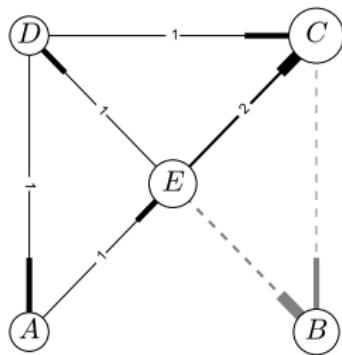
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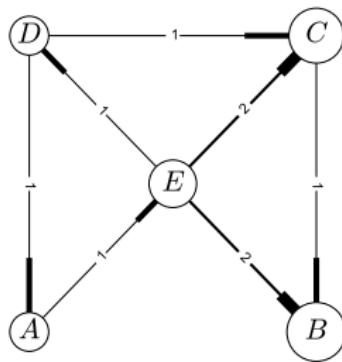
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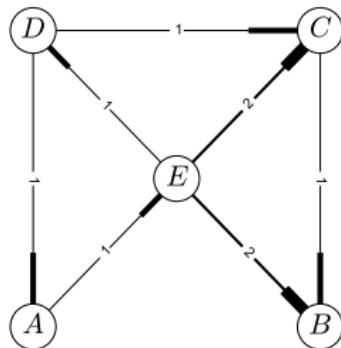
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PageRank: The model

Teleporting



PageRanks with $\beta = 0.8$

- ▶ $\text{Pr}^0 = \left[\frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \quad \frac{1}{5} \right]^T$
- ▶ $\text{Pr}^\infty = \left[0.14 \quad 0.32 \quad 0.21 \quad 0.12 \quad 0.2 \right]^T$

Idea

Introduce small probability $1 - \beta$ of teleporting to a random page
(usually $0 < 1 - \beta \leq 0.2$)

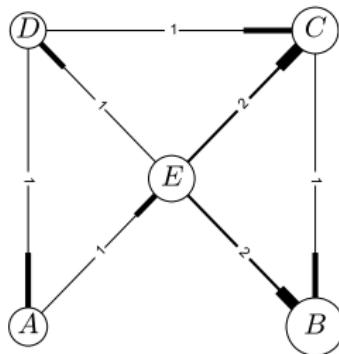
$$\text{Pr}' = \beta \cdot M \cdot \text{Pr} + (1 - \beta) \frac{\mathbf{1}}{n} \quad (1)$$

$$\text{Pr}'(x) = \frac{1 - \beta}{n} + \beta \sum_{y \rightarrow x} \frac{\text{Pr}(y)}{\deg^+(y)} \quad (2)$$

- ▶ Brin and Page: 50-100 iterations to converge

PageRank: The model

Teleporting



PageRanks with $\beta = 0.8$

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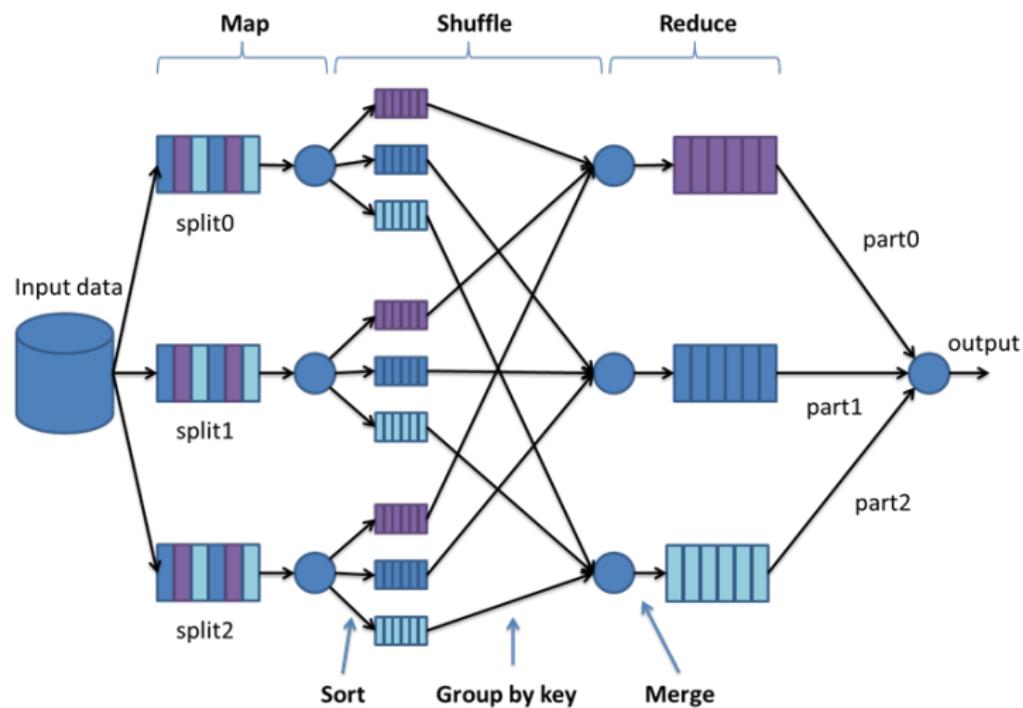
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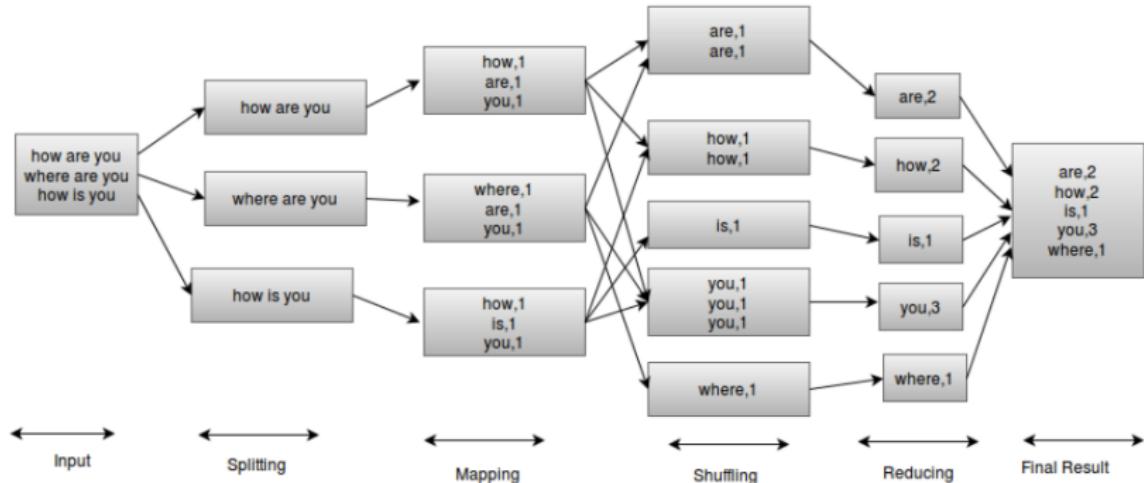
PageRank: MapReduce

MapReduce workflow



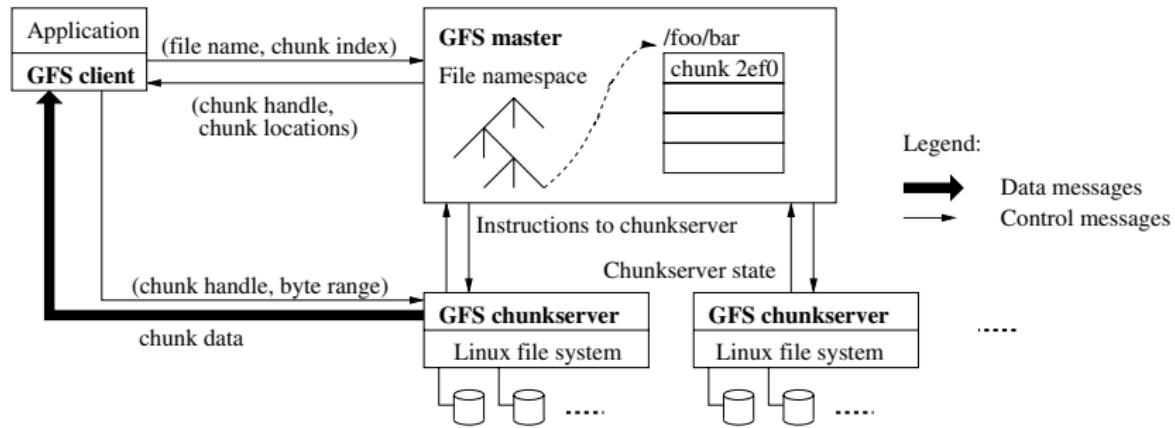
PageRank: MapReduce

Word count with MapReduce



PageRank: MapReduce

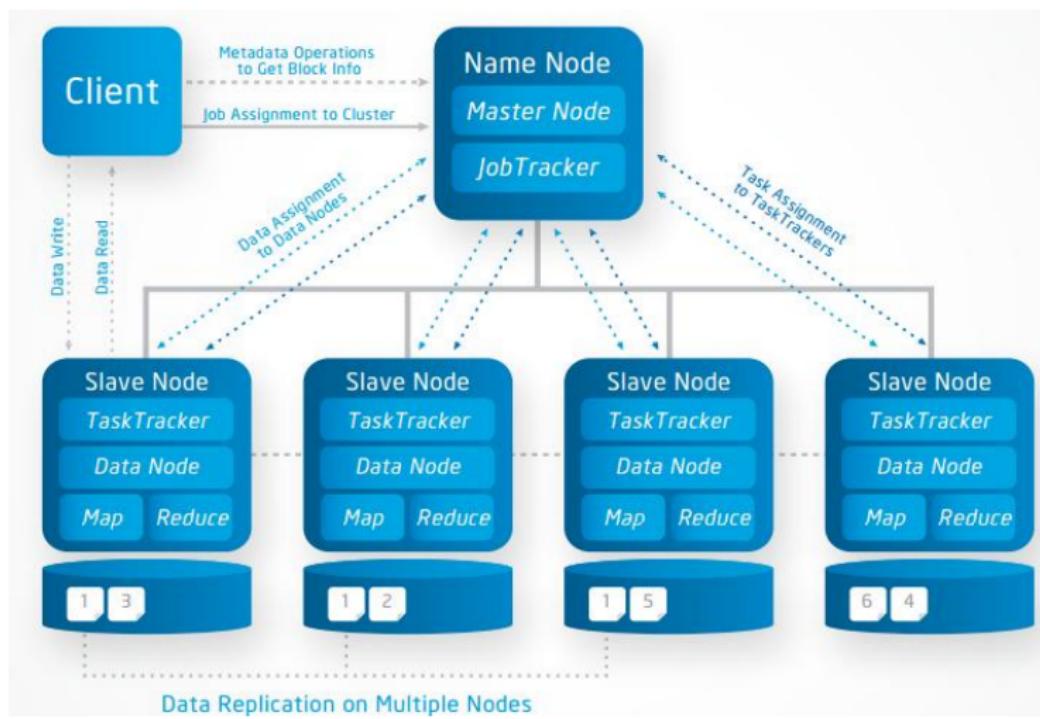
GFS



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PageRank: MapReduce

GFS



PageRank: MapReduce

PageRank using MapReduce

Mapper (node y)

Data: $\langle y | \{x_1, \dots, x_k\}, \Pr(y) \rangle$ (node – outlinks)

```
1 for  $j \in \{1, \dots, k\}$  do  
2   emit  $\left\langle x_j \middle| \frac{\Pr(y)}{\deg^+(y)} \right\rangle$  ;  
3 emit  $\langle y | \{x_1, \dots, x_k\} \rangle$  ;
```

Reducer (node x)

Data: $\left\langle x \middle| \left\{ \frac{\Pr(y_1)}{\deg^+(y_1)}, \dots, \frac{\Pr(y_l)}{\deg^+(y_l)}, \{x_1, \dots, x_k\} \right\} \right\rangle$ (node – $\Delta \Pr$)

```
1  $\Pr(x) \leftarrow \frac{1-\beta}{n} + \beta \sum_{i=1}^l \frac{\Pr(y_i)}{\deg^+(y_i)}$ 
```

PageRank: MapReduce

PageRank using MapReduce

Mapper (node y)

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PageRank: Modifications

Topic-sensitive PageRank

How to organize private PageRank for each user?

- ▶ classify users by interest in each of the selected topics
- ▶ one Pr vector for each of some small number of topics
- ▶ bias the PageRank to favor pages of that topic

$$\text{Pr}' = \beta \cdot M \cdot \text{Pr} + (1 - \beta) \frac{\mathbb{1}_S}{|S|}$$

- ▶ S – set of pages belonging to a certain topic (teleport set)

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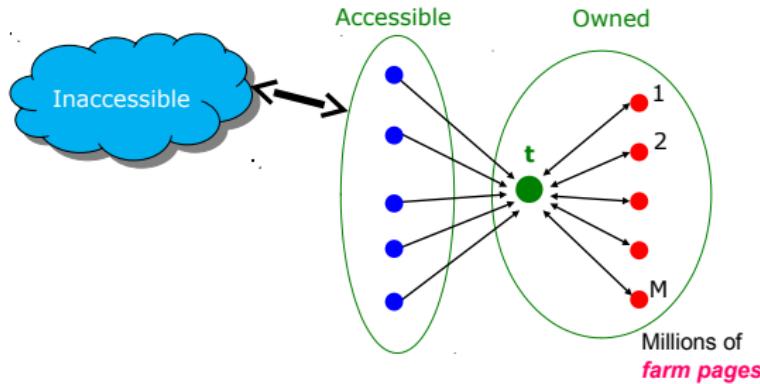
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PageRank: Modifications

Link spam and TrustRank

Yet the war between those who want to make the Web useful and those who would exploit it for their own purposes is never over.

©Jeffrey D. Ullman



- ▶ n pages in total
- ▶ m supporting pages
- ▶ 1 target page t

$$\Pr(t) = \Pr(\text{access.}) + \beta m \underbrace{\left(\frac{\beta \Pr(t)}{m} + \frac{1 - \beta}{n} \right)}_{\Pr(\text{supporting page})} \approx \frac{\Pr(\text{access.})}{1 - \beta^2} + \frac{\beta}{1 + \beta} \frac{m}{n}$$

PageRank: Modifications

Link spam and TrustRank

TrustRank

Topic-sensitive PageRank, where the “topic” is a set of pages believed to be trustworthy

- ▶ suitable teleport set:
domain whose membership is controlled (e.g., .edu)
- ▶ spam mass

$$\text{SpamMass}(y) = \frac{\text{PageRank}(y) - \text{TrustRank}(y)}{\text{PageRank}(y)}$$

negative (small positive) $\text{SpamMass}(y) \implies y$ is probably not a spam

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$$\text{SpamMass}(y) = \frac{\text{PageRank}(y) - \text{TrustRank}(y)}{\text{PageRank}(y)}$$

negative (small positive) $\text{SpamMass}(y) \implies y$ is probably not a spam

PageRank as an orthogonal iteration

Eigenvectors & convergence of OI

Definition

Eigenvalues ($\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_n$) and eigenvectors:

$$Av_i = \lambda_i v_i$$

Convergence of orthogonal iteration

Let $\lambda_i \neq \lambda_j$, $v_i^* \cdot v_j = 0$, $\|v_i\| = 1$.

Take arbitrary $u = c_1 v_1 + c_2 v_2 + \dots + c_n v_n$

$$\begin{aligned} A^k u &= c_1 A^k v_1 + c_2 A^k v_2 + \dots + c_n A^k v_n \\ &= c_1 \lambda_1^k v_1 + c_2 \lambda_2^k v_2 + \dots + c_n \lambda_n^k v_n \\ &= c_1 \lambda_1^k \left(v_1 + \frac{c_2}{c_1} \left(\frac{\lambda_2}{\lambda_1} \right)^k v_2 + \dots + \frac{c_n}{c_1} \left(\frac{\lambda_n}{\lambda_1} \right)^k v_n \right) \end{aligned}$$

$$v_1 \approx \frac{1}{c_1 \lambda_1^k} A^k u + \mathcal{O} \left(\frac{\lambda_2}{\lambda_1} \right)^k$$



PageRank as an orthogonal iteration

Convergence of PageRank

Find v_i : $Av_i = \lambda_i v_i$

Orthogonal iterations

Data: A, k

Result: Q

- 1 Choose initial guess for Q
(random orthonormal $n \times k$ matrix) ;
- 2 **while** error(Q) > ϵ **do**
- 3 $V \leftarrow AQ$;
- 4 $Q \leftarrow \text{Orthonormalize}(V)$

Find Pr : $M \cdot \text{Pr} = 1 \cdot \text{Pr}$

PageRank iterations

Data: $M, 1$

Result: Pr

- 1 Choose initial guess for Pr
($\text{Pr} = \mathbb{1}/n$) ;
- 2 **while** error(Pr) > ϵ **do**
- 3 $\text{Pr} \leftarrow M \cdot \text{Pr}$;
- 4 $\text{Orthonormalize}(\text{Pr})$

- ▶ convergence depends on the λ_2
- ▶ link structure of the Web $\lambda_2 \approx 0.9$

PageRank as an orthogonal iteration

Structured orthogonal factorization

Orthogonal iterations

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Result: Q

- 1 Choose initial guess for Q
(random orthonormal $n \times k$ matrix) ;
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- 4 $\text{Orthonormalize}(\text{Pr})$

Basic algorithms

Complexity

Operation counts

Phase	Routine	Additions	Multiplications	Total Flops
I	BSOF	$\Theta\left(\frac{23}{3}n^3p\right)$	$\Theta\left(\frac{23}{3}n^3p\right)$	$\Theta\left(\frac{46}{3}n^3p\right)$
II	BSTRI_RV	$\Theta\left(\frac{1}{2}n^3p^2\right)$	$\Theta\left(\frac{1}{2}n^3p^2\right)$	$\Theta(n^3p^2)$
	BSTRI_CV	$\Theta(n^3p^2)$	$\Theta(n^3p^2)$	$\Theta(2n^3p^2)$
III	BSOI	$\Theta(3n^3p^2)$	$\Theta(3n^3p^2)$	$\Theta(6n^3p^2)$

To sum up,

$$\text{Total complexity} = \Theta\left(\frac{7}{2}nN^2\right)$$

Basic algorithms

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To sum up,

$$\text{Total complexity} = \Theta\left(\frac{7}{2}nN^2\right)$$

Experimental results

Experimental setup

► Hardware

Single-GPU .. Hybrid node at UCD

- └─ 2 × Intel Xeon X5670
 - └─ 6-cores, 2.9GHz
- └─ 1 × NVIDIA GTX480
 - └─ 15 SMs × 32 cores

Multi-GPU Dirac cluster at NERSC

- └─ 2 × Intel Xeon E5530
 - └─ 4-cores, 2.4 GHz
- └─ 4 × NVIDIA Tesla C1060
 - └─ 240 cores

► Software

- ▶ POSIX threads for threading in step 2 of BSOFTRI
- ▶ CuBlas, Magma, and Intel's MKL for LAPACK interface

► Codes

- ▶ stand-alone CPU, stand-alone GPU, and hybrid CPU+GPU implementations
- ▶ publicly available at <https://github.com/SGo-Go/BSOFI>