minted

Page Rank

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Contents

1 Introduction

The centrality score of a graph is a metric that measures the importance and popularity of a vertex. [1]

The *PageRank* method asserts that the centrality of a vertex can be measured by the frequency of incidence with that vertex during a random walk.

2 Implementing PageRank Generally

A graph can be expressed as an adjacency matrix $\mathbf{A}$:

$$A_{i,j} \in \{0, 1\}$$

Where each element of the matrix indicates whether or not travel from vertex j to vertex i is possible with a value of 1. [2]

During a random walk the probability of arriving at vertex j from vertex i can similarly be described as an element of a transition probability matrix $\mathbf{T}_{i,j}$, this matrix can be described by the following relationship [3]:

[1] For a small graph drawn in a way to minimise overlapping edges the centremost geometric vertex will coincide with the highest centrality score, for example in figure 2 vertex D is the vertex with the highest frequency during a random walk

[2] Some authors define an adjacency matrix transposed (see e.g. [**AdjacencyMatrix2020a**, 1, 22]) this unfourtunately includes the `igraph` library [12] but that convention will not be followed in this paper

[3] In this paper $\vec{1}$ refers to a vector containing only values of 1, the size of which should be clear from the context

$$\mathbf{T} = \mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1} : \tag{1}$$

$$\mathbf{D}_{\mathbf{A}} = \operatorname{diag}\left(\vec{1}\mathbf{A}\right) \tag{2}$$

The value of $\mathbf{D}$ is such that under matrix multiplication $\mathbf{A}$ will have columns that sum to 1 (i.e. a *column stochastic matrix*, see § 2.1), for a reducible or non-stochastic graph the definition of $\mathbf{D}$ would need to be adjusted to acheive this, this is discussed below

During the random walk, the running tally of frequencies, at the i^{th} step of the walk, can be described by a vector $\vec{p}$, this vector can be determined for each step by matrix multiplication:

$$\vec{p_{i+1}} = \mathbf{T}\vec{p_i} \tag{3}$$

This relationship is a linear recurrence relation, more importantly however it is a *Markov Chain* [19, §4.4].

Finding the Stationary point for this relationship will give a frequency distribution for the nodes and a metric to measure the centrality of vertices.

2.1 Definitions

The following definitions are used in this report [4] :

Markov Chains are discrete mathematical model such that future values depend only on current values [**foussAlgorithmsModelsNetwork2016**]

Stochastic Matrices contain only positive values where each column sums to 1 [19, 10] (i.e. $\mathbf{T}$ is stochastic $\iff \vec{1}\mathbf{T} = \vec{1}$)

- some authors use rows (see e.g. [19, §15.3]), in this paper columns will be used, i.e. columns will add to one and an entry $\mathbf{A}_{i,j} \neq 0$ will indicate that travel is permitted from vertex j to vertex i.
  - *Column Stochastic* and *Row Stochastic* can be used to more clearly distinguish between which type of stochastic matrix is being used.
- Many programming languages return *unit-eigenvectors* $\vec{x}$ such that $||\vec{x}|| = 1$ as opposed to $\texttt{sum}\left(\vec{\texttt{x}}\right) = 1$, so when solving for a stationary vector it can be necessary to perform $\vec{\texttt{p}} \leftarrow \frac{\vec{\texttt{p}}}{\sum \vec{p}}$

Irreducible graphs have a path from from any given vertex to another vertex. [19, §15.2]

Ergodic graphs are irreducible graphs with further constraints outside the scope of this report (see e.g. [24, 8])

- It is a necessary but not a sufficient condition of ergodic graphs that all vertices be reachable from any other vertices (see [27] for a counter example.)

Primitive Matrices are non-negative irreducible matrices that have only one eigenvalue on the unit circle.

[4] see generally [19, Ch. 15] for further reading

- If a matrix is primitive it will approach a limit under exponentiation [19, §15.2]

Transition Probability Matrix is a stochastic matrix where each column is a vector of probabilities such that $\mathbf{T}_{i,j}$ represents the probability of travelling from vertex j to vertex i during a random walk.

- Some Authors consider the transpose (see e.g. [19]).

Aperiodic Markov chains are markov chains with an irreducible and primitive transition probability matrix.

- If the transition probability matrix is irreducible and imprimitive it is said to be a periodic Markov chain.

Regular Markov Chains are regular irreducible and aperiodic.

Sparse Matrices contain a majority of elements with values equal to 0 [19, §4.2]

Sparse Iterating the

PageRank A process of measuring graph centrality by using a random walk algorithm and measuring the most frequent node

- In the literature (see e.g. [15, 19]) the Random Surfer model is usually used to refer to the introduction of a probability of travelling to any other node, this is discussed in CROSSREF

2.1.1 Notation

$\mathbf{A}$ Is the adjacency matrix of a graph

$\mathbf{A}_{i,j} = 1$ Indicates that j and i are adjacent vertices.

$\mathbf{A}\left[:, j\right]$ Refers to the j^{th} column vector of A

- This syntax is much like *Julia* or *Python* but also occurs in the literature, see e.g. [14, §1.1.8]

$\mathbf{T}$ Is the transition probability matrix of a graph

- $T_{i,j}$ is equal to the probability of travelling $j \to i$ during a random walk.
  - $\mathbf{T} = \mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1}$
    - Where $\mathbf{D}^{-1}$ is a matrix such that multiplication with which scales each column of $\mathbf{A}$ to 1.
      - $\mathbf{D}_{\mathbf{A}}^{-1} = \vec{1}\mathbf{D}_{\mathbf{A}}^{-1} = \frac{1}{\vec{1}\mathbf{D}_{\mathbf{A}}}$ for some stochastic matrix $\mathbf{A}$

n Refers to the number of vertices in a graph elements of a matrix

- $n = \texttt{nrow}\left(\mathbf{A}\right) = \texttt{ncol}\left(\mathbf{A}\right)$

$\mathbf{B}_{i,j} = \frac{1}{n}$ Is a matrix of size $n \times n$ representing the background probability of uniformly selecting any vertex of a graph.

$\vec{1}$ is a vector of length n containing only the value 1.

- The convention that a vector behaves as a vertical $n \times 1$ matrix will be used here.
- Some authors use $\mathbf{e}$, see e.g. [19]

$\mathbf{J} = \vec{1} \cdot \vec{1}^{\mathrm{T}} \iff \mathbf{J}_{i,j} = 1$ Is a completely dense $n \times n$ matrix.

- It's worth noting that $\mathbf{E}, \mathbf{J}$ are common choices for this matrix.

α The probability of teleporting from one vertex to another during a random walk.

- In the literature α is often referred to as a damping factor (see e.g. [5, 7, 11, 16, 6])

  or a smoothing constant (see e.g [17]).

$\vec{p_i} = \frac{\deg(v_1)}{\mathrm{vol}(G)}$

- $\mathrm{vol}(G) = \sum_{i=1}^{n} [\mathrm{indeg}(v)] = \sum_{i=1}^{n} [\mathrm{outdeg}(v)] = \sum_{i=1}^{n} [\deg(v)]$

2.2 Random Surfer Model

2.2.1 Issues

The approach in 2 has the following issues

1. Convergence of (3)
   (a) Will this relationship converge or diverge?
   (b) How quickly will it converge?
   (c) Will it converge uniquely?
2. Reducible graphs
   (a) If it is not possible to perform a random walk across an entire graph for all initial conditions, this approach doesn't have a clear analogue.
3. Cycles
   (a) A graph that is cyclical may not converge uniquely
      i. Consider for example the graph $A \to B$.

2.2.2 Markov Chains

The relationship in (3) is a *Markov Chain* and it is known that the power method will converge: [5]

- for a stochastic irreducible markov chain [10, §1.5.5],
- regardless of the initial condition of the process for an *aperiodic* Markov chain [19, §4.4]

[5] A *Markov Chain* is simply any process that evolves depending on it's current condition, it's interesting to note however that the theory of *Markov Chains* is not mentioned in any of the original papers by page and brin [19, §4.4]

Stochastic If a vertex had a 0 outdegree the corresponding column sum for the adjacency matrix describing that graph would also be zero and the matrix non-stochastic, this could occur in the context of a random walk where a link to a page with no outgoing links was followed (e.g. an image), this would be the end of the walk.

So to ensure that (3) will converge, the probability transition matrix must be made stochastic, to acheive this a uniform probability of teleporing from a dead end to any other vertex can be introduced:

$$\mathrm{S} = \mathrm{T} + \frac{\vec{a} \cdot \vec{1}^{\mathrm{T}}}{n} \tag{4}$$

This however would not be sufficient to ensure that (3) would converge, in addition the transition probability matrix must be made irreducible and aperiodic (i.e. primitive). [19]

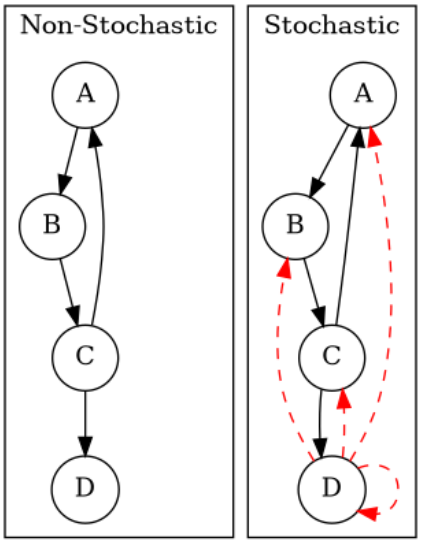


Figure 1: D is a *dangling node*, a dead end during a random walk, the corresponding probability transition matrix ($\mathbf{T}$) is hence non-stochastic (and also reducible), Introducing some probability of teleporting from a dead end to any other vertex as per (4) (denoted in red) will cause $\mathbf{T}$ to be stochastic.

Irreducible A graph that allows travel from any given vertex to any other vertex is said to be irreducible [19], see for example figure 2, this is important in the context of a random walk because only in an irreducible graph can all vertexes be reached from any initial condition.

Aperiodic An a periodic graph has only one eigenvalue that lies on the unit circle, this is important because $\lim_{k\to\infty}\left(\frac{\mathbf{A}}{r}^k\right)$ exists for a non-negative irreducible matrix $\mathbf{A}$ if and only if A is aperiodic. A graph that is a periodic can be made aperiodic by interlinking nodes [6]

[6] Actually it would be sufficient to merely link one vertex to itself [19, §15.2] but this isn't very illustrative or helpful in this context

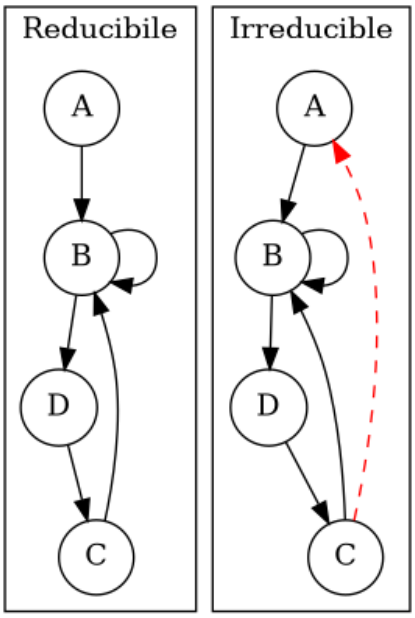


Figure 2: Example of a reducible graph, observe that although C is not a dead end as discussed in 2.2.2 , there is no way to travel from C to A, by adding an edge such an edge in the resulting graph is irreducible. The resulting graph is also aperiodic (due to the loop on B) and stochastic, so there will be a stationary distribution corresponding to (3).

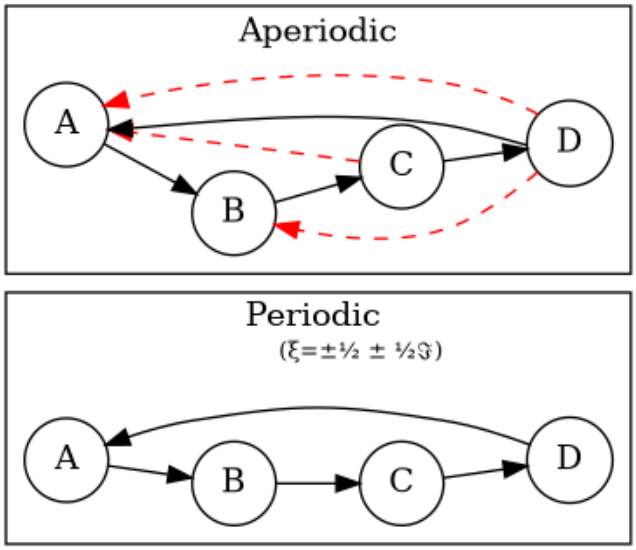


Figure 3: A periodic graph with all eigenvalues on the unit circle $\xi = \frac{\sqrt{2}}{2} e^{\frac{\pi i}{4} k}$, by adding in extra edges the graph is now aperiodic, this does not represent the random surfer model, which would in theory connect every vertex but with some probability.

The Fix To ensure that the transition probability matrix is primitive (i.e. irreducible and aperiodic) as well as stochastic, instead of introducing the possible to teleport out of dead ends, introduce a probability of teleporting to any node at any time (α), this approach is known as the *Random Surfer* model and the transition probability matrix is given by [20] :

$$\mathbf{S} = \alpha\mathbf{T} + \frac{(1-\alpha)}{n}\mathbf{J} \tag{5}$$

This matrix is primitive and stochastic and so will converge (it is also unfourtunately completely dense, see 3.1 [19, §4.5].

The relation ship in (3) can now be re expressed as:

$$\vec{p_{i+1}} \to \mathbf{T}\vec{p_i} \tag{6}$$

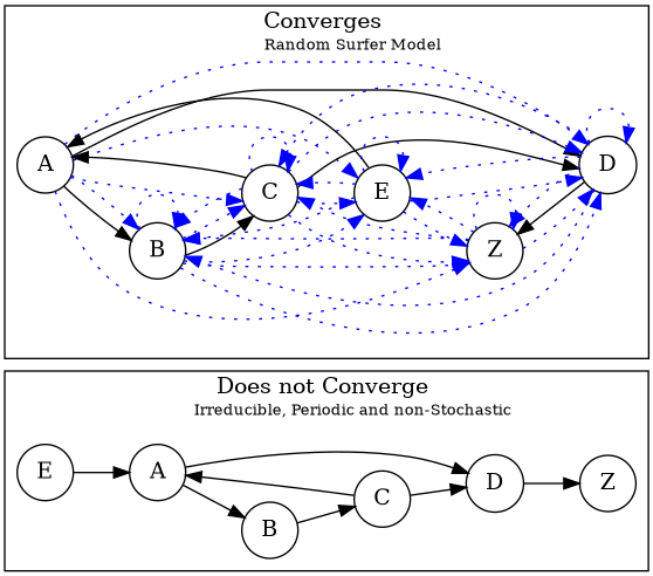


Figure 4: A graph that is aperiodic, reducible and non-stochastic, by applying the random surfer model (5) blue *teleportation* edges are introduced, these may be followed with a probability of $1-\alpha$

2.2.3 Limitations

The *Random Surfer* Model can only consider positively weighted edges, it cannot take into account negatively weighted edges. This limitation is increasingly important as techniques of sentiment analysis are developed which could indicate that links promote aversion rather than endorsement (e.g. a negative review or an innapropriate advertisement).

2.3 Power walk

The *Power Walk* method is an alternative approach to develop a probability transition matrix to use in place of (3).

Let the probability of travelling to a non-adjacent vertex be some value x and β be the ratio of probability between following an edge or teleporting to another vertex.

This transition probability matrix would be such that the probability of travelling some vertex $j \to i$ would be :

$$\mathbf{W}_{i,j} = x\beta^{\mathbf{A_{i,j}}} \tag{7}$$

Where $\mathbf{W}$ denotes the power walk probability transition matrix.

Whe probability of travelling to any given vertex must be 1 and so:

$$1 = \sum_{j=1}^{n} \left[x\beta^{\mathbf{A_{i,j}}} \right] \tag{8}$$

$$\implies x = \left(\sum_{j=1}^{n} \beta^{\mathbf{A_{i,j}}} \right)^{-1} \tag{9}$$

Substituting the value of x from (9) into (**??**) gives the probability as:

$$\mathbf{W}_{i,j} = \frac{\beta^{\mathbf{A}_{i,j}}}{\sum_{i=j}^{n} \left[\beta^{\mathbf{A}_{i,j}} \right]} \tag{10}$$

In this model all vertices are interconnected by some probability of jumping to another vertex, so much like the random surfer model (5) discussed at 2.2.2 $\mathbf{W}$ will be a primitive stochastic matrix and so if $\mathbf{W}$ was used in place of $\mathbf{T}$ in (3) a solution would exist.

3 Sparse Matrices

Most Adjacency matrices resulting from webpages and analagous networks result in sparse adjacency matrices (see figure 8), this is a good thing because it requires far less computational resources to work with a sparse matrix than a dense matrix [19, §4.2] .

Sparse matrices can be expressed in alternetive forms so as to reduce the memory footprint associated with that matrix, one such method is the *Compressed Row Storage* method, this involves listing the elements as a table as in (11) and (12).

This is implemented in ***R*** with the `Matrix` package [**batesMatrixSparseDense2019a**] .

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

Row Index	Col Index	Value
1	1	1
3	2	ϕ
4	5	π

(12)

3.1 Solving the Stationary Distribution

The relationship in (3) [7] is equivelant to the eigenvalue value problem, where $\vec{p} = \lim_{i\to\infty}(\vec{p_i})$ is the eigenvector [8] $\vec{x}$ that corresponds to the eigenvalue $\xi = 1$:

$$\vec{p}(1) = \mathbf{S}\vec{p} \tag{13}$$

Solving eigenvectors for large matrices can be very resource intensive and so this approach isn't suitable for analysing large networks.

Upon iteration (3) will converge to stable stationary point, as discussed in 2.2.2 , this approach is known as the power method [21] and is what in practice must be implemented to solve the stationary distribution of (6) and (3).

As mentioned in 2.2.2 and 2.3 , the *Random Surfer* and *Power Walk* transtition probability matrices are completely dense, that means applying the power method will not be able to take advantage of using sparse matrix algorithms.

With some effort however it is possible to express the algorithms in such a way that only involves sparse matrices.

4 Implementing the Models

To Implement the models, first they'll be implemented using an ordinary matrix and then improved to work with sparse matrices and algorithms, the implementation has been performed with ***R*** and the preamble is provided in listings 1

```
  if (require("pacman")) {
     library(pacman)
   }else{
     install.packages("pacman")
     library(pacman)
   }

   pacman::p_load(tidyverse, Matrix, igraph, plotly, mise, docstring, mise)
#  options(scipen=20) # Resist Scientific Notation
```

Listing 1: Implemented Packages used in this report

4.1 Implementing the Random Surfer

4.1.1 Small Graph, Ordinary Matrices

Example Graph Consider the following graph:

[7] This assumes that the transition probability matrix is stochastic and primitive as it would be for $\mathbf{S}$ and $\mathbf{W}$

[8] More accurately the eigenvector specifically scaled specifically to 1, so it would be more correct to say the eigenvector $\frac{\vec{x}}{\sum\vec{x}}$

```
g1 <- igraph::graph.formula(1++2, 1+-8, 1+-5, 2+-5, 2+-7, 2+-8, 2+-6, 2+-9, 3++4,
    ↪ 3+-5, 3+-6, 3+-9, 3+-10, 4+-9, 4+-10, 4+-5, 5+-8, 6+-8, 7+-8)
 plot(g1)
```

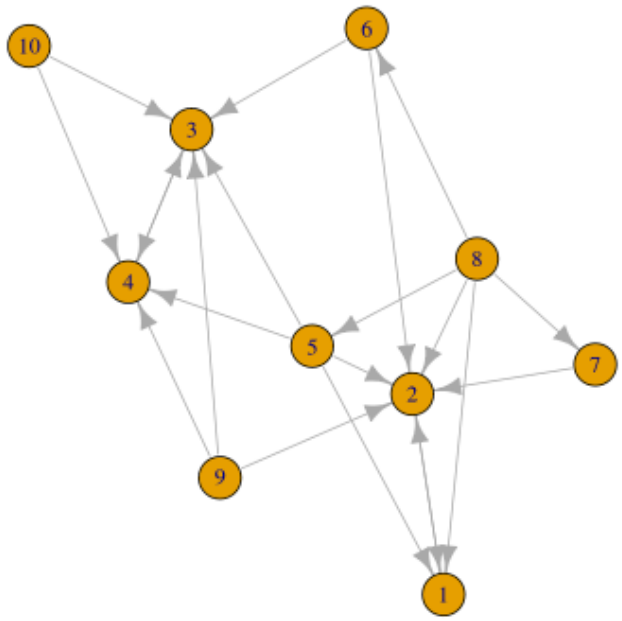


Figure 5: Exemplar graph to solve Random Surfer Model with

Adjacency Matrix The adjacency Matrix is given by:

```
A <- igraph::get.adjacency(g1, names = TRUE, sparse = FALSE)

## igraph gives back the transpose
(A <- t(A))
```

Listing 2: Return the Adjacency Matrix corresponding to figure 5

```
   1 2 8 5 7 6 9 3 4 10
1  0 1 1 1 0 0 0 0 0  0
2  1 0 1 1 1 1 1 0 0  0
8  0 0 0 0 0 0 0 0 0  0
5  0 0 1 0 0 0 0 0 0  0
7  0 0 1 0 0 0 0 0 0  0
6  0 0 1 0 0 0 0 0 0  0
9  0 0 0 0 0 0 0 0 0  0
3  0 0 0 1 0 1 1 0 1  1
4  0 0 0 1 0 0 1 1 0  1
10 0 0 0 0 0 0 0 0 0  0

   1 2 8 5 7 6 9 3 4 10
1  0 1 1 1 0 0 0 0 0  0
2  1 0 1 1 1 1 1 0 0  0
8  0 0 0 0 0 0 0 0 0  0
5  0 0 1 0 0 0 0 0 0  0
7  0 0 1 0 0 0 0 0 0  0
6  0 0 1 0 0 0 0 0 0  0
9  0 0 0 0 0 0 0 0 0  0
3  0 0 0 1 0 1 1 0 1  1
4  0 0 0 1 0 0 1 1 0  1
10 0 0 0 0 0 0 0 0 0  0
```

Probability Transition Matrix The probability transition matrix is such that each column of the initial state distribution (i.e. the transposed adjacency matrix) is scaled to 1.

if $\mathbf{A}$ had vertices with a 0 out-degree, the relationship in (1) would not work, instead columns that sum to 0 would need to be left while all other columns be divided by the column sum to get $\mathbf{T}$. An alternative approach using sparse matrices will be presented below and in this case there exists corresponding $\mathbf{T}$ that is stochastic and so it is sufficient to use the relationship at (1), this is shown in listing 3.

```
(T <- A %*% diag(1/colSums(A)))
```

Listing 3: Solve the Transition Probability Matrix by scaling each column to 1 using matrix multiplication.

```
   [,1] [,2] [,3] [,4] [,5] [,6]      [,7] [,8] [,9] [,10]
1     0    1  0.2 0.25    0  0.0 0.0000000    0    0   0.0
2     1    0  0.2 0.25    1  0.5 0.3333333    0    0   0.0
8     0    0  0.0 0.00    0  0.0 0.0000000    0    0   0.0
5     0    0  0.2 0.00    0  0.0 0.0000000    0    0   0.0
7     0    0  0.2 0.00    0  0.0 0.0000000    0    0   0.0
6     0    0  0.2 0.00    0  0.0 0.0000000    0    0   0.0
9     0    0  0.0 0.00    0  0.0 0.0000000    0    0   0.0
3     0    0  0.0 0.25    0  0.5 0.3333333    0    1   0.5
```

```
4     0     0  0.0 0.25     0  0.0 0.3333333     1     0   0.5
10    0     0  0.0 0.00     0  0.0 0.0000000     0     0   0.0
```

1. Create a Function

```
adj_to_probTrans <- function(A) {
  A %*% diag(1/colSums(A))
}

(T <- adj_to_probTrans(A)) %>% round(2)
```

```
   [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
1     0    1  0.2 0.25    0  0.0 0.00    0    0   0.0
2     1    0  0.2 0.25    1  0.5 0.33    0    0   0.0
8     0    0  0.0 0.00    0  0.0 0.00    0    0   0.0
5     0    0  0.2 0.00    0  0.0 0.00    0    0   0.0
7     0    0  0.2 0.00    0  0.0 0.00    0    0   0.0
6     0    0  0.2 0.00    0  0.0 0.00    0    0   0.0
9     0    0  0.0 0.00    0  0.0 0.00    0    0   0.0
3     0    0  0.0 0.25    0  0.5 0.33    0    1   0.5
4     0    0  0.0 0.25    0  0.0 0.33    1    0   0.5
10    0    0  0.0 0.00    0  0.0 0.00    0    0   0.0
```

```
##    [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
## 1     0    1    0    0 0.25  0.0    0  0.2 0.00   0.0
## 2     1    0    0    0 0.25  0.5    1  0.2 0.33   0.0
## 3     0    0    0    1 0.25  0.5    0  0.0 0.33   0.5
## 4     0    0    1    0 0.25  0.0    0  0.0 0.33   0.5
## 5     0    0    0    0 0.00  0.0    0  0.2 0.00   0.0
## 6     0    0    0    0 0.00  0.0    0  0.2 0.00   0.0
## 7     0    0    0    0 0.00  0.0    0  0.2 0.00   0.0
## 8     0    0    0    0 0.00  0.0    0  0.0 0.00   0.0
## 9     0    0    0    0 0.00  0.0    0  0.0 0.00   0.0
## 10    0    0    0    0 0.00  0.0    0  0.0 0.00   0.0
```

Page Rank Random Surfer Recall from 2.2.2 the following variables of the *Random Surfer* model:

$$\mathbf{B} = \alpha T + (1 - \alpha)\, B : \tag{14}$$

$$\tag{15}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} \\ \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} \end{bmatrix} \tag{16}$$

$$n = ||V|| \tag{17}$$

$$\alpha \in [0, 1] \tag{18}$$

These are assigned to ***R*** variables in listing 4.

```
B <- matrix(rep(1/nrow(T), length.out = nrow(T)**2), nrow = nrow(T))
l <- 0.8123456789

(S <- l*T+(1-l)*B) %>% round(2)
```

Listing 4: Assign Random Surfer Variables, observe the unique value given to `l`, this will be relevant later.

```
   [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
1  0.02 0.83 0.18 0.22 0.02 0.02 0.02 0.02 0.02  0.02
2  0.83 0.02 0.18 0.22 0.83 0.42 0.29 0.02 0.02  0.02
8  0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02  0.02
5  0.02 0.02 0.18 0.02 0.02 0.02 0.02 0.02 0.02  0.02
7  0.02 0.02 0.18 0.02 0.02 0.02 0.02 0.02 0.02  0.02
6  0.02 0.02 0.18 0.02 0.02 0.02 0.02 0.02 0.02  0.02
9  0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02  0.02
3  0.02 0.02 0.02 0.22 0.02 0.42 0.29 0.02 0.83  0.42
4  0.02 0.02 0.02 0.22 0.02 0.02 0.29 0.83 0.02  0.42
10 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02  0.02
```

Eigen Value Method The eigenvector corresponding to the the eigenvalue of 1 will be the stationary point, this is shown in listing 5

```
print(eigen(S, symmetric = FALSE, only.values = TRUE)$values, 9)
print(eigen(S, symmetric = FALSE)$vectors, 3)
```

Listing 5: Solve the Eigen vectors and Eigen values of the transition probability matrix corresponding to the graph.

```
 [1]  1.00000000e+00+0.0000000e+00i -8.12345679e-01+0.0000000e+00i
 [3]  8.12345679e-01+0.0000000e+00i -8.12345679e-01+0.0000000e+00i
 [5]  5.81488197e-10+0.0000000e+00i -5.81487610e-10+0.0000000e+00i
 [7] -6.74980227e-16+0.0000000e+00i  3.21036747e-17+0.0000000e+00i
 [9]  1.34928172e-18+1.1137323e-17i  1.34928172e-18-1.1137323e-17i
          [,1]         [,2]         [,3]         [,4]         [,5]
 [1,] 0.4873+0i -7.07e-01+0i  5.00e-01+0i -2.07e-03+0i -6.74e-01+0i
 [2,] 0.5268+0i  7.07e-01+0i  5.00e-01+0i  2.07e-03+0i -9.62e-02+0i
 [3,] 0.0424+0i  9.09e-18+0i -3.50e-17+0i -5.05e-17+0i  1.38e-09+0i
 [4,] 0.0493+0i -1.25e-18+0i -1.65e-16+0i  4.25e-17+0i  3.85e-01+0i
 [5,] 0.0493+0i -8.30e-18+0i -3.75e-17+0i  3.71e-17+0i  3.85e-01+0i
 [6,] 0.0493+0i -8.30e-18+0i -3.75e-17+0i  9.76e-18+0i  3.85e-01+0i
 [7,] 0.0424+0i -1.32e-18+0i -3.50e-17+0i  1.60e-17+0i -3.01e-08+0i
 [8,] 0.4915+0i -2.98e-03+0i -5.00e-01+0i -7.07e-01+0i -9.62e-02+0i
 [9,] 0.4804+0i  2.98e-03+0i -5.00e-01+0i  7.07e-01+0i -2.89e-01+0i
[10,] 0.0424+0i  5.57e-18+0i -3.77e-17+0i  3.14e-18+0i -3.24e-08+0i
              [,6]         [,7]         [,8]                [,9]
 [1,]  6.74e-01+0i  6.53e-01+0i -2.15e-01+0i -2.00e-01+1.53e-01i
 [2,]  9.62e-02+0i  1.09e-01+0i -1.96e-01+0i -1.59e-01+0.00e+00i
 [3,]  1.38e-09+0i  1.42e-15+0i -2.84e-16+0i -6.73e-17+1.32e-16i
 [4,] -3.85e-01+0i -4.37e-01+0i  7.85e-01+0i  6.37e-01+0.00e+00i
 [5,] -3.85e-01+0i -3.56e-01+0i  2.81e-01+0i  2.84e-02-1.63e-01i
 [6,] -3.85e-01+0i -3.58e-01+0i -3.68e-01+0i  4.84e-02-2.68e-01i
 [7,] -3.01e-08+0i -2.63e-02+0i -2.34e-01+0i -3.47e-02+4.29e-01i
 [8,]  9.62e-02+0i  1.32e-01+0i -6.40e-02+0i -1.09e-01-2.84e-01i
 [9,]  2.89e-01+0i  3.11e-01+0i  1.20e-01+0i -1.34e-01-1.50e-01i
[10,] -3.24e-08+0i -2.82e-02+0i -1.08e-01+0i -7.64e-02+2.83e-01i
                   [,10]
 [1,] -2.00e-01-1.53e-01i
 [2,] -1.59e-01-0.00e+00i
 [3,] -6.73e-17-1.32e-16i
 [4,]  6.37e-01+0.00e+00i
 [5,]  2.84e-02+1.63e-01i
 [6,]  4.84e-02+2.68e-01i
 [7,] -3.47e-02-4.29e-01i
 [8,] -1.09e-01+2.84e-01i
 [9,] -1.34e-01+1.50e-01i
[10,] -7.64e-02-2.83e-01i
```

So in this case the stationary point corresponds to the eigenvector given by:

$$\langle -0.49, -0.53, -0.49, -0.48, -0.05, -0.05, -0.05, -0.04, -0.04, -0.04 \rangle$$

this can be verified by using identity (13):

$$1\vec{p} = S\vec{p}$$

```
(p    <- eigen(S)$values[1] * eigen(S)$vectors[,1]) %>% Re() %>% round(2)
```

```
[1] 0.49 0.53 0.04 0.05 0.05 0.05 0.04 0.49 0.48 0.04
```

```
(p_new <- S %*% p) %>% Re() %>% as.vector() %>% round(2)
```

```
[1] 0.49 0.53 0.04 0.05 0.05 0.05 0.04 0.49 0.48 0.04
```

However this vector does not sum to 1 so the scale should be adjusted (for probabilities the vector should sum to 1):

```
(p_new <- p_new/sum(p_new)) %>% Re() %>% as.vector() %>% round(2)
```

```
[1] 0.22 0.23 0.02 0.02 0.02 0.02 0.02 0.22 0.21 0.02
```

Power Value Method Using the power method should give the same result as the eigenvalue method, again but for scale:

```
p_new <- p_new *123456789

while (sum(round(p, 9) != round(p_new, 9))) {
    (p    <- p_new)
    (p_new <- S %*% p)
}

round(Re(p_new), 2) %>% as.vector()
```

```
[1] 26602900 28759738  2316720  2693115  2693115  2693115  2316720 26834105
[9] 26230539  2316720
```

If scaled to 1 the same value will be returned:

```
(p_new <- p_new/sum(p_new)) %>% Re %>% as.vector() %>% round(2)
```

```
[1] 0.22 0.23 0.02 0.02 0.02 0.02 0.02 0.22 0.21 0.02
```

Scaling If the initial state sums to 1, then the scale of the stationary vector will also sum to 1, so this isn't in practice an issue for the power method:

```
p     <- c(1, 0, 0, 0, 0, 0, 0, 0, 0, 0)
p_new <- S %*% p

while (sum(round(p, 9) != round(p_new, 9))) {
    (p     <- p_new)
    (p_new <- S %*% p)
}

cbind(p_new, p)
```

```
          [,1]       [,2]
1  0.21548349 0.21548349
2  0.23295388 0.23295388
8  0.01876543 0.01876543
5  0.02181424 0.02181424
7  0.02181424 0.02181424
6  0.02181424 0.02181424
9  0.01876543 0.01876543
3  0.21735625 0.21735625
4  0.21246737 0.21246737
10 0.01876543 0.01876543
```

```
##          [,1]      [,2]
## 1  0.2129185 0.2129185
## 2  0.2313481 0.2313481
## 3  0.2156444 0.2156444
## 4  0.2104889 0.2104889
## 5  0.0232000 0.0232000
## 6  0.0232000 0.0232000
## 7  0.0232000 0.0232000
## 8  0.0200000 0.0200000
## 9  0.0200000 0.0200000
## 10 0.0200000 0.0200000
```

4.1.2 Large Graph, Sparse Matrices using CRS

Creating the Probability Transition Matrix Implementing the page rank method on a larger graph requires the use of more efficient form of matrix storage as discussed at 3

A sparse matrix can be created using the following syntax, which will return a matrix of the class `dgCMatrix`:

```
library(Matrix)
## Create Example Matrix
n <- 20
m <- 10^6
i <- sample(1:m, size = n); j <- sample(1:m, size = n); x <- rpois(n, lambda = 90)
A <- sparseMatrix(i, j, x = x, dims = c(m, m))

summary(A)
```

```
1000000 x 1000000 sparse Matrix of class "dgCMatrix", with 20 entries
        i      j   x
1  343874  62034  90
2  620555 188720 112
3  150966 209725 102
4  764638 222146  98
5  799107 231057  72
6  914309 235736  95
7  259820 296541  79
8  250848 405410  87
9  471817 462384  79
10 864226 470524  98
11 860729 586366  95
12 348239 635279  90
13 317038 672329  98
14 488483 678811  91
15 650014 688822  89
16 527889 702831  85
17 725910 772908  70
18 460036 780390  97
19 512626 809085  97
20 358993 862259  99
```

As before in section 4.1.1 , the probability transition matrix can be found by:

1. Creating adjacency matrix
   (a) Transposing as necessary such that $\mathbf{A}_{i,j} \neq 0$ indicates that j is connected to i by a directed edge.
2. Scaling the columns to one

To implement this for a sparseMatrix of the class `dgCMatrix`, the same technique of multiplying by a diagonalised matrix as in (2) may be implemented, using sparse matrices has the advantage however that only non-zero elements will be operated on, meaning that columns that some to zero can still be used to create a probability transition matrix [9] pracice an error however to create this new matrix, a new `sparseMatrix` will need to be created using the properties of the original matrix, this can be done like so:
,captionpos=b,numbers=none

```
sparse_diag <- function(mat) {

 ## Get the Dimensions
 n <- nrow(mat)

 ## Make a Diagonal Matrix of Column Sums
 D <- sparseMatrix(i = 1:n, j = 1:n, x = colSums(mat), dims = c(n,n))

 ## Throw away explicit Zeroes
 D <- drop0(D)

 ## Inverse the Values
 D@x <- 1/D@x

 ## Return the Diagonal Matrix
 return(D)
}
```

Listing 6: A function that takes in a column $\rightarrow$ row adjacency matrix ($\mathbf{A}$) and returns a diagonal matrix ($\mathbf{D}_{\mathbf{A}}^{-1}$) such that $\vec{1}\mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1}$

Applying this to the previously created sparse matrix:

```
D <- sparse_diag(t(A))
summary(D)
```

```
1000000 x 1000000 sparse Matrix of class "dgCMatrix", with 20 entries
        i      j           x
1  150966 150966 0.009803922
2  250848 250848 0.011494253
3  259820 259820 0.012658228
4  317038 317038 0.010204082
5  343874 343874 0.011111111
```

[9] Although this matrix may still have columns that sum to zero and will hence be non-stochastic

```
6  348239 348239 0.011111111
7  358993 358993 0.010101010
8  460036 460036 0.010309278
9  471817 471817 0.012658228
10 488483 488483 0.010989011
11 512626 512626 0.010309278
12 527889 527889 0.011764706
13 620555 620555 0.008928571
14 650014 650014 0.011235955
15 725910 725910 0.014285714
16 764638 764638 0.010204082
17 799107 799107 0.013888889
18 860729 860729 0.010526316
19 864226 864226 0.010204082
20 914309 914309 0.010526316
```

and hence the probability transition matrix may be implemented by performing matrix multiplication accordingly:

```
summary((T <- t(A) %*% D))
```

```
1000000 x 1000000 sparse Matrix of class "dgCMatrix", with 20 entries
        i      j x
1  209725 150966 1
2  405410 250848 1
3  296541 259820 1
4  672329 317038 1
5   62034 343874 1
6  635279 348239 1
7  862259 358993 1
8  780390 460036 1
9  462384 471817 1
10 678811 488483 1
11 809085 512626 1
12 702831 527889 1
13 188720 620555 1
14 688822 650014 1
15 772908 725910 1
16 222146 764638 1
17 231057 799107 1
18 586366 860729 1
19 470524 864226 1
20 235736 914309 1
```

Solving the Random Surfer via the Power Method Solving the eigenvalues for such a large matrix will not feasible, instead the power method will need to be used to find the stationary point.

However, creating a matrix of background probabilites (denoted by `B` in section 4.1.1) will not be feasible, it would simply be too large, instead some algebra can be used to reduce B from a matrix into a vector containing only $\frac{1-\alpha}{N}$.

The power method is given by:

$$\vec{p} = \mathbf{S}\vec{p} \tag{19}$$

where:

$$S = \alpha\mathbf{T} + (1-\alpha)\,\mathbf{B} \tag{20}$$

$$\vec{p} = (\alpha\mathbf{T} + (1-\alpha)\,\mathbf{B})\,\vec{p} \tag{21}$$

$$= \alpha\mathbf{T}\vec{p} + (1-\alpha)\,\mathbf{B}\vec{p} \tag{22}$$

Let $\mathbf{F} = \mathbf{B}\vec{p}$, consider the value of $\mathbf{F}$:

$$\mathbf{F} = \begin{bmatrix} \frac{1}{N} & \frac{1}{N} & \cdots & \frac{1}{N} \\ \frac{1}{N} & \frac{1}{N} & \cdots & \frac{1}{N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{N} & \frac{1}{N} & \cdots & \frac{1}{N} \end{bmatrix} \begin{bmatrix} \vec{p_1} \\ \vec{p_2} \\ \vdots \\ \vec{p_m} \end{bmatrix} \tag{23}$$

$$= \begin{bmatrix} (\sum_{i=0}^{m} [p_i]) \times \frac{1}{N} \\ (\sum_{i=0}^{m} [p_i]) \times \frac{1}{N} \\ \vdots \\ (\sum_{i=0}^{m} [p_i]) \times \frac{1}{N} \end{bmatrix} \tag{24}$$

Probabilities sum to 1 and hence: (25)

$$= \begin{bmatrix} \frac{1}{N} \\ \frac{1}{N} \\ \frac{1}{N} \\ \vdots \\ \frac{1}{N} \end{bmatrix} \tag{26}$$

So instead the power method can be implemented by performing an algorithm that involves only sparse matrices:

```
## Find Stationary point of random surfer
N     <- nrow(A)
alpha <- 0.85
F     <- rep((1-alpha)/N, nrow(A)) ## A nx1 vector of (1-alpha)/N

## Solve using the power method
p     <- rep(0, length.out = ncol(T)); p[1] <- 1
p_new <- alpha*T %*% p + F

## use a Counter to debug
```

```
i <- 0
while (sum(round(p, 9) != round(p_new, 9))) {
    p     <- p_new
    p_new <- alpha*T %*% p + F
    (i <- i+1) %>% print()
}

p %>% head() %>% print()
```

```
[1] 1
[1] 2
6 x 1 Matrix of class "dgeMatrix"
         [,1]
[1,] 1.5e-07
[2,] 1.5e-07
[3,] 1.5e-07
[4,] 1.5e-07
[5,] 1.5e-07
[6,] 1.5e-07
```

4.2 Power Walk Method

4.2.1 Introduction

Recall from 2.3 that the power walk is given by:

$$\mathbf{T} = \mathbf{B}\mathbf{D}_B^{-1}$$

where:

- $\mathbf{B} = \beta^{\mathbf{A}}$

  $x\beta^1$ probability of following an edge of weight 1

  $x\beta^0$ probability of following an edge of weight 0

  $x\beta^{-1}$ probability of following an edge of weight -

- $\mathbf{D_B} = \texttt{colsums}(\mathbf{B})$

$\mathbf{A}$ The Adjacency Matrix

4.2.2 Ordinary Matrices

Implementing the Power walk using ordinary matrices is very similar to the *Random Surfer* model be done pretty much the same as it is with the random surfer, but doing it with Sparse Matrices is a bit trickier.

Create the Adjacency Matrix

```
  A <- igraph::get.adjacency(g1, names = TRUE, sparse = FALSE)

## * Function to create Prob Trans Mat
adj_to_probTrans <- function(A, beta) {
   B    <- A
   B    <- beta^A        # Element Wise exponentiation
   D    <- diag(colSums(B)) # B is completely dense so D  0
   D_in <- solve(D)      # Solve returns inverse of matrix
   W    <- B %*% D_in

   return(as.matrix(W))
}

beta <-  <- 0.867
(W <- adj_to_probTrans(A, beta =  )) %>% round(2)
```

```
   [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
1  0.10 0.09  0.1 0.10 0.10 0.10  0.1 0.11 0.11   0.1
2  0.09 0.11  0.1 0.10 0.10 0.10  0.1 0.11 0.11   0.1
8  0.09 0.09  0.1 0.09 0.09 0.09  0.1 0.11 0.11   0.1
5  0.09 0.09  0.1 0.10 0.10 0.10  0.1 0.09 0.09   0.1
7  0.10 0.09  0.1 0.10 0.10 0.10  0.1 0.11 0.11   0.1
6  0.10 0.09  0.1 0.10 0.10 0.10  0.1 0.09 0.11   0.1
9  0.10 0.09  0.1 0.10 0.10 0.10  0.1 0.09 0.09   0.1
3  0.10 0.11  0.1 0.10 0.10 0.10  0.1 0.11 0.09   0.1
4  0.10 0.11  0.1 0.10 0.10 0.10  0.1 0.09 0.11   0.1
10 0.10 0.11  0.1 0.10 0.10 0.10  0.1 0.09 0.09   0.1
```

Look at the Eigenvalues:

```
eigen(W, only.values = TRUE)$values %>% round(9)
eigen(W)$vectors/sum(eigen(W)$vectors)
```

```
[1]  1.000000000+0.000000000i  0.014269902+0.000000000i
[3] -0.014148391+0.000000000i  0.014147087+0.000000000i
[5]  0.007672842+0.004095136i  0.007672842-0.004095136i
[7]  0.000000000+0.000000000i  0.000000000+0.000000000i
[9]  0.000000000+0.000000000i  0.000000000+0.000000000i
              [,1]              [,2]             [,3]             [,4]
[1,] 0.10153165+0i  5.107247e-02+0i  0.073531664+0i  0.009918277+0i
[2,] 0.10159353+0i -1.161249e-01+0i  0.071987451+0i -0.009531974+0i
[3,] 0.09609664+0i -2.162636e-01+0i  0.198568750+0i  0.141245296+0i
```

```
 [4,] 0.09725145+0i  6.794340e-02+0i -0.012230606+0i -0.001148014+0i
 [5,] 0.10153165+0i  5.107247e-02+0i  0.073531664+0i  0.009918277+0i
 [6,] 0.10008449+0i  1.115133e-01+0i -0.005625969+0i -0.156796770+0i
 [7,] 0.09865794+0i  1.175228e-01+0i -0.084225633+0i  0.008563891+0i
 [8,] 0.10157348+0i -6.053608e-02+0i -0.078607240+0i  0.165540590+0i
 [9,] 0.10155286+0i -6.104664e-03+0i -0.079165209+0i -0.166535117+0i
[10,] 0.10012631+0i -9.522175e-05+0i -0.157764873+0i -0.001174456+0i
                         [,5]                    [,6]             [,7]
 [1,]  0.00633946+0.04208220i  0.00633946-0.04208220i  3.014602e-16+0i
 [2,]  0.00757768+0.03910216i  0.00757768-0.03910216i  1.909248e-16+0i
 [3,]  0.22697603+0.00000000i  0.22697603+0.00000000i  3.985744e-02+0i
 [4,] -0.11628681-0.11808928i -0.11628681+0.11808928i -2.471407e-01+0i
 [5,]  0.00633946+0.04208220i  0.00633946-0.04208220i  7.520823e-02+0i
 [6,] -0.03494625-0.01031801i -0.03494625+0.01031801i  1.719325e-01+0i
 [7,] -0.07581902-0.06371153i -0.07581902+0.06371153i  6.131013e-03+0i
 [8,]  0.00717270+0.04008639i  0.00717270-0.04008639i  5.526770e-17+0i
 [9,]  0.00675977+0.04107970i  0.00675977-0.04107970i  1.105354e-16+0i
[10,] -0.03411300-0.01231382i -0.03411300+0.01231382i -4.598845e-02+0i
                  [,8]             [,9]             [,10]
 [1,] -1.791605e-17+0i -4.365749e-17+0i  1.179767e-17+0i
 [2,] -7.334385e-17+0i -8.731498e-17+0i -5.190977e-17+0i
 [3,] -1.241234e-01+0i -1.401965e-01+0i -8.894098e-02+0i
 [4,]  1.691000e-01+0i  1.687523e-01+0i  1.041947e-01+0i
 [5,] -2.144546e-01+0i  2.715852e-02+0i  3.085359e-02+0i
 [6,]  4.535455e-02+0i -1.959109e-01+0i -1.350483e-01+0i
 [7,]  7.398187e-02+0i  3.163948e-02+0i -1.260060e-01+0i
 [8,]  8.062225e-17+0i  3.638124e-17+0i  5.898837e-18+0i
 [9,]  2.687408e-17+0i  3.638124e-17+0i  5.662884e-17+0i
[10,]  5.014155e-02+0i  1.085570e-01+0i  2.149470e-01+0i
```

Unlike the *Random Surfer* Model in listing 5 at 4.1.1 the relationship between the second eigenvalue and the model parameters is not as clear, this provides that the

Use the power method

```
## * Power Method
p    <- rep(0, nrow(W))
p[1] <- 1
p_new   <- rep(0, nrow(W))
p_new[2]  <- 1

while (sum(round(p, 9) != round(p_new, 9))) {
   (p    <- p_new)
   (p_new <- W %*% p)
}


p %>% as.vector()
```

```
[1] 0.10153165 0.10159353 0.09609664 0.09725145 0.10153165 0.10008449
[7] 0.09865794 0.10157348 0.10155286 0.10012631
```

4.2.3 Sparse Matrices

Theory; Simplifying Power Walk to be solved with Sparse Matrices The Random Surfer model is:

$$\mathbf{S} = \alpha\mathbf{T} + \mathbf{F}$$

where:

- $\mathbf{T}$
  - is an $i \times j$ matrix that describes the probability of travelling from vertex j to i
    - This is transpose from the way that `igraph` produces an adjacency matrix.
- $\mathbf{F} = \begin{bmatrix} \frac{1}{n} \\ \frac{1}{n} \\ \frac{1}{n} \vdots \end{bmatrix}$

Interpreting the transition probability matrix in this way is such that $\mathbf{T} = \mathbf{A}\mathbf{D}_A^{-1}$ under the following conditions:

- No column of $\mathbf{A}$ sums to zero
  - If this does happen the question arises how to deal with $\mathbf{D}_{\mathbf{A}}^{-\mathbf{1}}$
    - I've been doing $\mathbf{D}^{\mathrm{T}}_{\mathbf{A},i,j} := \texttt{diag}\left(\frac{1}{\texttt{colsums}(\mathbf{A})}\right)$ and then replacing any 0 on the diagonal with 1.
  - What is done in the paper is to make another matrix $\mathbf{Z}$ that is filled with 0, if a column sum of $\mathbf{A}$ adds to zero then that column in $\mathbf{Z}$ becomes $\frac{1}{n}$
    - This has the effect of making each row identical
    - The probability of going from an orphaned vertex to any other vertex would hence be $\frac{1}{n}$
    - The idea with this method is then to use $D^{-1}_{(\mathbf{A}+\mathbf{Z})}$ this will be consistent with the *Random Surfer* the method using $\mathbf{F}$ in [[#eq:sparse-RS][]] (4.2.3)

    where each row is identical that is a 0

The way to deal with the *Power Walk* is more or less the same.
observe that:

$$\left(\mathbf{B} = \beta^{\mathbf{A}}\right) \wedge (\mathbf{A}_{i,j}) \in \mathbb{R} \implies |\mathbf{B}_{i,j}| > 0 \quad \forall i, j > n \in \mathbb{Z}^+ \tag{27}$$

Be mindful that the use of exponentiation in (27) is not an element wise exponentiation and not an actual matrix exponential.
So if I have:

- $\mathbf{O}_{i,j} := 0, \quad \forall i, j \leq n \in \mathbb{Z}^+$

- $\vec{p_i}$ as the state distribution, being a vector of length n

Then It can be shown (see (4.2.3) at 4.2.3):

$$\mathbf{OD_B}^{-1}\vec{p_i} = (\overrightarrow{\delta^T}\overrightarrow{p_i})\vec{1} \tag{28}$$

$$= \texttt{repeat}\left(\vec{p} \bullet \vec{\delta^{\mathrm{T}}}, \texttt{n}\right) \tag{29}$$

$$\tag{30}$$

where:

- $\vec{\delta_i} = \frac{1}{\texttt{colsums}(\mathbf{B})}$
  - A vector...($n \times 1$ matrix)

$\vec{1}$ is a vector containing all 1's

  - A vector...($n \times 1$ matrix)

$\vec{\delta^{\mathrm{T}}}$ refers to the transpoxe of$\vec{}$($1 \times n$ matrix)

$\vec{\delta^{\mathrm{T}}}\vec{p_i}$ is some number (because it's a dot product)

This means we can do:

$$\overrightarrow{p_{i+1}} = \mathbf{T}_{\mathrm{pw}}\overrightarrow{p_i} \tag{31}$$

$$= \mathbf{B}\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} \tag{32}$$

$$= (\mathbf{B} - \mathbf{O} + \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} \tag{33}$$

$$= \left((\mathbf{B} - \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1} + \mathbf{O}\mathbf{D}_{\mathbf{B}}^{-1}\right)\overrightarrow{p_i} \tag{34}$$

$$= (\mathbf{B} - \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} + \mathbf{O}\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} \tag{35}$$

$$= (\mathbf{B} - \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} + \vec{1}(\overrightarrow{\delta^{\mathrm{T}}}\overrightarrow{p_i}) \tag{36}$$

$$= (\mathbf{B} - \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} + \texttt{rep}(\overrightarrow{\delta^{\mathrm{T}}}\overrightarrow{p_i}) \tag{37}$$

where:
Let $(\mathbf{B} - \mathbf{O}) = \mathbf{B_O}$:

$$\overrightarrow{p_{i+1}} \quad = \mathbf{B_O}\mathbf{D}_{\mathbf{B}}^{-1}\overrightarrow{p_i} + \texttt{rep}(\overrightarrow{\delta^{\mathrm{T}}}\overrightarrow{p_i})$$

Now solve D_B^{-1} in terms of $\mathbf{B_O}$:

$$\mathbf{B_O} = (\mathbf{B} - \mathbf{O}) \tag{38}$$

$$\mathbf{B} = \mathbf{B_O} + \mathbf{O} \tag{39}$$

If we have $\delta_{\mathbf{B}}$ as the column sums of $\mathbf{B}$:

$$
\begin{aligned}
\delta_{\mathbf{B}}^{-1} &= \vec{1}\mathbf{B} && (40)\\
&= \vec{1}\left(\mathbf{B_O} + \mathbf{O}\right) && (41)\\
&= \vec{1}\mathbf{B_O} + \vec{1}\mathbf{O} && (42)\\
&= \vec{1}\mathbf{B_O} + \langle n, n, n, ...n\rangle && (43)\\
&= \vec{1}\mathbf{B_O} + \vec{1}n && (44)\\
\delta_{\mathbf{B}} &= 1/(\texttt{colSums}(\mathbf{B_O}) + \texttt{n}) && (45)
\end{aligned}
$$

Then if we have $D_B = \texttt{diag}(\delta_B)$:

$$
\begin{aligned}
D_B^{-1} &= \text{diag}\left(\delta_{\mathbf{B}}^{-1}\right)\\
&= \texttt{diag}\left(\texttt{ColSums}(\texttt{B}_\texttt{O}) + \texttt{n}\right)^{-1}
\end{aligned}
$$

And so the the power method can be implemented using sparse matrices:

$$
p_{i+1}^{\rightarrow} = \text{B}_\text{O}\ \ \text{diag}\left(\vec{1}\mathbf{B_O} + \vec{1}n\right)\vec{p_i} + \vec{1}\vec{\delta^{\text{T}}}\vec{p_i} \tag{46}
$$

in terms of ***R***:

```
p_new <- Bo %*% diag(colSums(B)+n) %*% p + rep(t () %*% p, n)

# It would also be possible to sum the element-wise product
(t () %*% p) == sum ( * p)

# Because R treats vectors the same as a nX1 matrix we could also
# perform the dot product of the two vectors, meaning the following
# would be true in R but not true generally

(t () %*% p) ==  ( %*% p)
```

Solving the Background Probability In this case a vertical single column matrix will represent a vector and $\otimes$ will represent the outer product (i.e. the *Kronecker Product*):

Define $\vec{\delta}$ as the column sums of

$$
\begin{aligned}
\vec{\delta} &= \texttt{colsum}(\mathbf{B})^{-1}\\
&= \frac{1}{\vec{1^T}\boldsymbol{B}}
\end{aligned}
$$

Then we have:

$$
\begin{aligned}
\mathbf{OD}_{\mathbf{B}}^{-1}\overrightarrow{p_i} &= \begin{pmatrix} 1 & 1 & 1 & \\ 1 & 1 & 1 & \dots \\ 1 & 1 & 1 & \\ & \vdots & & \ddots \end{pmatrix} \begin{pmatrix} \frac{1}{\delta_1} & 0 & 0 & \\ 0 & \frac{1}{\delta_2} & 0 & \dots \\ 0 & 0 & \frac{1}{\delta_{13}} & \\ & \vdots & & \ddots \end{pmatrix} \begin{pmatrix} p_{i,1} \\ p_{i,2} \\ p_{i,3} \\ \vdots \end{pmatrix} \\
&= \begin{pmatrix} \frac{p_{i,1}}{\delta 1} & + & \frac{p_{i,2}}{\delta_2} & + & \frac{p_{i,3}}{\delta_3} & \\ \frac{p_{i,1}}{\delta 1} & + & \frac{p_{i,2}}{\delta_2} & + & \frac{p_{i,3}}{\delta_3} & \dots \\ \frac{p_{i,1}}{\delta 1} & + & \frac{p_{i,2}}{\delta_2} & + & \frac{p_{i,3}}{\delta_3} & \\ & & \vdots & & & \ddots \end{pmatrix} \\
&= \begin{pmatrix} \sum_{k=1}^{n}[p_{i,k}\delta_i] \\ \sum_{k=1}^{n}[p_{i,k}\delta_i] \\ \sum_{k=1}^{n}[p_{i,k}\delta_i] \\ \vdots \end{pmatrix} \\
&= \begin{pmatrix} \overrightarrow{\delta^T}\overrightarrow{p_i} \\ \overrightarrow{\delta^T}\vec{p}_i \\ \overrightarrow{\delta^T}\vec{p}_i \\ \vdots \end{pmatrix} \\
&= \overrightarrow{\delta^T}\overrightarrow{p_i} \begin{pmatrix} 1 \\ 1 \\ 1 \\ \vdots \end{pmatrix} \\
&= (\overrightarrow{\delta^T}\overrightarrow{p_i})\vec{1} \\
&= \texttt{repeat}(\overrightarrow{\delta}\overrightarrow{p_i}, \texttt{n})
\end{aligned}
$$

Observe also that If we let $\vec{\delta}$ and p_i be 1 dimensional vectors, this can also be expressed as a dot product:

Matrices	Vectors
$\vec{\delta^{\mathrm{T}}}\vec{p_i}$	$\vec{\delta}\vec{p_i}$

Practical; Implementing the Power Walk on Sparse Matrices

Inspect the newly created matrix and create constants

Setup

1. Define function to create DiagonalsSparse Diagonal Function

   Unlike the Random Surfer model the diagonal scaling matrix will always be given by $\mathbf{D}_B^{-1} = \mathbf{B}\ \mathrm{diag}\left(\frac{1}{\vec{1}\mathbf{B}}\right)$ because $\beta^{\mathbf{A}_{i,j}} \neq 0 \quad \forall \mathbf{A}_{i,j}$, this is convenient but in any case the `sparse_diag` function in listing 6 will still work.

Power Walk

1. Define B

```
B     <- A
B@x   <-  ^(A@x)
B     <- A
B      <-  ^A

Bo    <- A

# These two approaches are equivalent
Bo@x  <-  ^(A@x) -1 # This in theory would be faster
# Bo    <-  ^(A) -1
# Bo    <- drop0(Bo)


 n <- nrow(A)
```

```
print(round(B, 2))
```

```
20 x 20 Matrix of class "dgeMatrix"
      [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10] [,11] [,12] [,13]
 [1,] 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  1.00  0.84  1.00  1.00
 [2,] 1.00 1.00 0.84 1.00 1.00 1.00 1.00 1.00 1.00  1.00  0.84  1.00  1.00
 [3,] 1.00 0.84 1.00 1.00 1.00 0.84 1.00 1.00 1.00  1.00  1.00  1.00  0.84
 [4,] 1.00 1.00 1.00 1.00 1.00 0.84 1.00 1.00 1.00  1.00  1.00  1.00  1.00
 [5,] 1.00 1.00 1.00 1.00 1.00 1.00 0.84 0.84 1.00  0.84  1.00  1.00  1.00
 [6,] 1.00 1.00 0.84 0.84 1.00 1.00 1.00 1.00 1.00  1.00  1.00  1.00  1.00
 [7,] 1.00 1.00 1.00 1.00 0.84 1.00 1.00 1.00 1.00  1.00  1.00  0.84  1.00
 [8,] 1.00 1.00 1.00 1.00 0.84 1.00 1.00 1.00 1.00  1.00  1.00  1.00  0.84
 [9,] 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  1.00  0.84  0.84  0.84
[10,] 1.00 1.00 1.00 1.00 0.84 1.00 1.00 1.00 1.00  1.00  1.00  1.00  0.84
[11,] 0.84 0.84 1.00 1.00 1.00 1.00 1.00 1.00 0.84  1.00  1.00  1.00  1.00
[12,] 1.00 1.00 1.00 1.00 1.00 1.00 0.84 1.00 0.84  1.00  1.00  1.00  1.00
[13,] 1.00 1.00 0.84 1.00 1.00 1.00 1.00 0.84 0.84  0.84  1.00  1.00  1.00
[14,] 0.84 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  1.00  1.00  1.00  1.00
[15,] 0.84 1.00 1.00 1.00 1.00 1.00 0.84 0.84 1.00  1.00  1.00  1.00  0.84
[16,] 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  1.00  1.00  1.00  1.00
[17,] 0.84 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  0.84  0.84  1.00  1.00
[18,] 1.00 1.00 1.00 1.00 1.00 1.00 0.84 1.00 0.84  1.00  1.00  0.84  0.84
```

```
[19,] 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  0.84  1.00  1.00  1.00
[20,] 0.84 1.00 1.00 1.00 1.00 0.84 0.84 1.00 0.84  1.00  1.00  1.00  1.00
      [,14] [,15] [,16] [,17] [,18] [,19] [,20]
 [1,]  0.84  0.84  1.00  0.84  1.00  1.00  0.84
 [2,]  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 [3,]  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 [4,]  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 [5,]  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 [6,]  1.00  1.00  1.00  1.00  1.00  1.00  0.84
 [7,]  1.00  0.84  1.00  1.00  0.84  1.00  0.84
 [8,]  1.00  0.84  1.00  1.00  1.00  1.00  1.00
 [9,]  1.00  1.00  1.00  1.00  0.84  1.00  0.84
[10,]  1.00  1.00  1.00  0.84  1.00  0.84  1.00
[11,]  1.00  1.00  1.00  0.84  1.00  1.00  1.00
[12,]  1.00  1.00  1.00  1.00  0.84  1.00  1.00
[13,]  1.00  0.84  1.00  1.00  0.84  1.00  1.00
[14,]  1.00  1.00  1.00  1.00  0.84  1.00  0.84
[15,]  1.00  1.00  1.00  1.00  0.84  1.00  1.00
[16,]  1.00  1.00  1.00  1.00  1.00  1.00  0.84
[17,]  1.00  1.00  1.00  1.00  1.00  1.00  1.00
[18,]  0.84  0.84  1.00  1.00  1.00  1.00  0.84
[19,]  1.00  1.00  1.00  1.00  1.00  1.00  1.00
[20,]  0.84  1.00  0.84  1.00  0.84  1.00  1.00
```

```
print(Bo,2)
```

```
20 x 20 sparse Matrix of class "dgCMatrix"

 [1,] .        .        .        .        .        .        .        .
 [2,] .        .           -0.16 .        .        .        .        .
 [3,] .           -0.16 .        .        .           -0.16 .        .
 [4,] .        .        .        .        .           -0.16 .        .
 [5,] .        .        .        .        .        .           -0.16    -0.16
 [6,] .        .           -0.16    -0.16 .        .        .        .
 [7,] .        .        .        .           -0.16 .        .        .
 [8,] .        .        .        .           -0.16 .        .        .
 [9,] .        .        .        .        .        .        .        .
[10,] .        .        .        .           -0.16 .        .        .
[11,]    -0.16    -0.16 .        .        .        .        .        .
[12,] .        .        .        .        .        .           -0.16 .
[13,] .        .           -0.16 .        .        .        .           -0.16
[14,]    -0.16 .        .        .        .        .        .        .
```

```
[15,]    -0.16 .         .         .         .         .           -0.16    -0.16
[16,] .        .         .         .         .         .         .         .
[17,]    -0.16 .         .         .         .         .         .         .
[18,] .        .         .         .         .         .           -0.16 .
[19,] .        .         .         .         .         .         .         .
[20,]    -0.16 .         .         .         .           -0.16    -0.16 .

 [1,] .        .           -0.16 .         .           -0.16    -0.16 .
 [2,] .        .           -0.16 .         .         .         .         .
 [3,] .        .         .         .           -0.16 .         .         .
 [4,] .        .         .         .         .         .         .         .
 [5,] .           -0.16 .         .         .         .         .         .
 [6,] .        .         .         .         .         .         .         .
 [7,] .        .         .           -0.16 .         .           -0.16 .
 [8,] .        .         .         .           -0.16 .           -0.16 .
 [9,] .        .           -0.16    -0.16    -0.16 .         .         .
[10,] .        .         .         .           -0.16 .         .         .
[11,]    -0.16 .         .         .         .         .         .         .
[12,]    -0.16 .         .         .         .         .         .         .
[13,]    -0.16    -0.16 .         .         .         .           -0.16 .
[14,] .        .         .         .         .         .         .         .
[15,] .        .         .         .           -0.16 .         .         .
[16,] .        .         .         .         .         .         .         .
[17,] .           -0.16    -0.16 .         .         .         .         .
[18,]    -0.16 .         .           -0.16    -0.16    -0.16    -0.16 .
[19,] .           -0.16 .         .         .         .         .         .
[20,]    -0.16 .         .         .         .           -0.16 .           -0.16

 [1,]    -0.16 .         .           -0.16
 [2,] .        .         .         .
 [3,] .        .         .         .
 [4,] .        .         .         .
 [5,] .        .         .         .
 [6,] .        .         .           -0.16
 [7,] .           -0.16 .           -0.16
 [8,] .        .         .         .
 [9,] .           -0.16 .           -0.16
[10,]    -0.16 .           -0.16 .
[11,]    -0.16 .         .         .
[12,] .           -0.16 .         .
[13,] .           -0.16 .         .
[14,] .           -0.16 .           -0.16
[15,] .           -0.16 .         .
[16,] .        .         .           -0.16
[17,] .        .         .         .
[18,] .        .         .           -0.16
[19,] .        .         .         .
[20,] .           -0.16 .         .
```

2. Solve the Scaling Matrix We don't need to worry about any terms of $\delta_{\mathbf{B}} = \texttt{colsums}\left(\texttt{B\_o}\right) + \texttt{n}$ being 0:

```
(B   <- 1/(colSums(Bo)+n))
```

```
 [1] 0.05203951 0.05079631 0.05120406 0.05039501 0.05120406 0.05120406
 [7] 0.05203951 0.05120406 0.05203951 0.05161840 0.05161840 0.05120406
[13] 0.05246754 0.05120406 0.05203951 0.05039501 0.05120406 0.05290267
[19] 0.05039501 0.05290267
```

```
(B   <- 1/(colSums(B)))
```

```
 [1] 0.05203951 0.05079631 0.05120406 0.05039501 0.05120406 0.05120406
 [7] 0.05203951 0.05120406 0.05203951 0.05161840 0.05161840 0.05120406
[13] 0.05246754 0.05120406 0.05203951 0.05039501 0.05120406 0.05290267
[19] 0.05039501 0.05290267
```

3. Find the Transition Probability Matrix

```
  DB   <- diag(B)
## ** Create the Transition Probability Matrix
## Create the Trans Prob Mat using Power Walk
  T <- Bo %*% DB
```

4. Implement the Loop

```
## ** Implement the Power Walk
## *** Set Initial Values
  p_new <- rep(1/n, n) # Uniform
  p     <- rep(0, n)  # Zero
        <- 10^(-6)
## *** Implement the Loop
```

```
 while (sum(abs(p_new - p)) > ) {
    (p <- as.vector(p_new)) # P should remain a vector
    sum(p <- as.vector(p_new)) # P should remain a vector
     p_new <- T %*% p + rep(t (B) %*% p, n)
  }
## ** Report the Values
print(paste("The stationary point is"))
print(p)
```

```
[1] "The stationary point is"
 [1] 0.04947529 0.05068616 0.05028254 0.05108978 0.05028254 0.05028254
 [7] 0.04947529 0.05028254 0.04947529 0.04987892 0.04987892 0.05028253
[13] 0.04907167 0.05028253 0.04947529 0.05108978 0.05028254 0.04866804
[19] 0.05108978 0.04866805
```

5 Creating a Package

6 Relating the Power Walk to the Random Surfer

6.1 Introduction

These are notes relating to [26, §3.3]

So if a term in the Power Walk can be related to α in the random surfer, which is in turn ξ_2, I'll be able to understand it better. [10]

Consider the equation:

$$\begin{aligned}\mathbf{T} &= \mathbf{B}\mathbf{D}_{\mathbf{B}}^{-1} \\ &= (\mathbf{B} + \mathbf{O} - \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1}\end{aligned}$$

Break this into to terms so that we can simplify it a bit:

$$\mathbf{T} = \left[(\mathbf{B} - \mathbf{O})\,\mathbf{D}_{\mathbf{B}}^{-1}\right] + \left\{\mathbf{O}\mathbf{D}_{\mathbf{B}}^{-1}\right\}$$

6.2 Value of [1st Term]

Observe that for all $\forall i, j \in \mathbb{Z}^+$:

[10] Although I'm not quite sure why α is ξ_2 either

$$
\begin{aligned}
\mathbf{A}_{i,j} &\in \{0,1\} \\
&\implies \mathbf{B}^{\mathbf{A}_{i,j}} \in \left\{\beta^0, \beta^1\right\} \\
&\qquad\quad = \{1,\beta\} \\
\implies \beta\mathbf{A} &= \{1,\beta\}
\end{aligned}
$$

Using this property we get the following

$$
\begin{aligned}
\mathbf{B}_{i,j} - \mathbf{O}_{i,j} = \left(\beta^{\mathbf{A}_{i,j}} - 1\right) &= \begin{cases} 0, & \mathbf{A}_{i,j} = 0 \\ \beta - 1, & \mathbf{A}_{i,j} = 1 \end{cases} \\
(\beta - 1)\,\mathbf{A}_{i,j} &= \begin{cases} 0, & \mathbf{A}_{i,j} = 0 \\ \beta - 1, & \mathbf{A}_{i,j} = 1 \end{cases}
\end{aligned}
$$

This means we have

$$
\mathbf{A} \in \{0,1\}\,\forall i,j \implies \mathbf{B}_{i,j} - \mathbf{O}_{i,j} = (\beta - 1)\,\mathbf{A}_{i,j}
$$

$$
\begin{aligned}
\mathbf{B} &= (\mathbf{B} + \mathbf{O} - \mathbf{O}) \\
&= (\mathbf{B} - 1)
\end{aligned}
$$

6.3 Value of {2nd Term}

$$
\begin{aligned}
\mathbf{O}\mathbf{D}_{\mathbf{B}}^{-\mathbf{1}} &= \begin{pmatrix} 1 & 1 & 1 & \\ 1 & 1 & 1 & \cdots \\ 1 & 1 & 1 & \\ & \vdots & & \ddots \end{pmatrix} \begin{pmatrix} \frac{1}{\delta_1} & 1 & 1 & \\ 1 & \frac{1}{\delta_2} & 1 \cdots & \\ 1 & 1 & \frac{1}{\delta_3} & \\ & \vdots & & \ddots \end{pmatrix} \\
&= n \begin{pmatrix} \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \\ \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \cdots \\ \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \\ & \vdots & & \ddots \end{pmatrix} \begin{pmatrix} \frac{1}{\delta_1} & 1 & 1 & \\ 1 & \frac{1}{\delta_2} & 1 & \cdots \\ 1 & 1 & \frac{1}{\delta_3} & \\ & \vdots & & \ddots \end{pmatrix} \\
&= n\mathbf{E}\mathbf{D}_{\mathbf{B}}{}^{-1}
\end{aligned}
$$

where the following definitions hold ($\forall i,j \in \mathbb{Z}^+$):

- $\mathbf{E}_{i,j} = \frac{1}{n}$
- $\mathbf{D}_{\mathbf{B}}{}^{-1}_{k,k} = \frac{1}{\delta_k}$
- The value of δ is value that each term in a column must be divided by to become zero, in the case of the power walk that is just $\frac{1}{\texttt{colSums}(\mathbf{B})} = \vec{1}\mathbf{B}$, but if there were zeros in a column, it would be necessary to swap out the \$0\$s for \$1\$s and then sum in order to prevent a division by zero issue and because the 0s should be left.

- $\mathbf{A} \in \{0,1\}\, \forall i,j$ is the unweighted adjacency matrix of the relevant graph.

putting this all together we can do the following:

$$\begin{aligned}\mathbf{T} &= \mathbf{B}\mathbf{D}_{\mathbf{B}}^{-1} \\ &= (\mathbf{B} + \mathbf{O} - \mathbf{O})\, \mathbf{D}_{\mathbf{B}}^{-1} \\ &= (\mathbf{B} - \mathbf{O})\, \mathbf{D}_{B}^{-1} + \mathbf{O}\mathbf{D}_{\mathbf{B}}^{-1}\end{aligned}$$

From above:

$$\begin{aligned}&= (\beta - 1)\, \mathbf{A}_{i,j} + n\mathbf{E}\mathbf{D}_{\mathbf{B}}^{-1} \\ &= \mathbf{A}_{i,j}\, (\beta - 1) + n\mathbf{E}\mathbf{D}_{\mathbf{B}}^{-1}\end{aligned}$$

because $\mathbf{D}\mathbf{D}^{-1} = \mathbf{I}$ we can multiply one side through:

$$= \mathbf{D}_{\mathbf{A}}\mathbf{D}_{\mathbf{A}}^{-1}\mathbf{A}_{i,j}\, (\beta - 1) + n\mathbf{E}\mathbf{D}_{\mathbf{B}}^{-1}$$

But the next step requires showing that:

$$(\beta - 1)\, \mathbf{D}_{\mathbf{A}}\mathbf{D}_{\mathbf{B}}^{-1} = \mathbf{I} - n\mathbf{D}_{B}^{-1}$$

6.4 Equate the Power Walk to the Random Surfer

Define the matrix $\mathbf{D}_{\mathbf{M}}$:

$$\mathbf{D}_{\mathbf{M}} = \operatorname{diag}\left(\texttt{colSum}\left(\mathbf{M}\right)\right) = \operatorname{diag}\left(\vec{1}\mathbf{M}\right) \tag{47}$$

To scale each column of that matrix to 1, each column will need to be divieded by the column sum, unless the column is already zero, this needs to be done to turn an adjacency matrix into a matrix of probabilities:

$$\mathbf{D}_{\mathbf{A}}^{-1} : \left[\mathbf{D}_{\mathbf{A}}^{-1}\right]_i = \begin{cases} 0, & [\mathbf{D}_{\mathbf{A}}]_i = 0 \\ \left[\frac{1}{\mathbf{D}_{\mathbf{A}}}\right], & [\mathbf{D}_{\mathbf{A}}]_i \neq 0 \end{cases} \tag{48}$$

In the case of the power walk $\mathbf{B} = \beta^{\mathbf{A}} \neq 0$ so it is sufficient:

$$\mathbf{D}_{\mathbf{B}}^{-1} = \frac{1}{\operatorname{diag}\left(\vec{1}\left(\beta^{\mathbf{A}}\right)\right)} \tag{49}$$

Recall that the *power walk* gives a transition probability matrix:

Power Walk

$$\mathbf{T} = \boxed{\mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1}}\mathbf{D}_{\mathbf{A}}\left(\beta-1\right)\mathbf{D}_{\mathbf{B}}^{-1} + \boxed{\mathbf{E}}n\mathbf{D}_{\mathbf{B}}^{-1} \tag{50}$$

Random Surfer

$$\mathbf{T} = \alpha\boxed{\mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1}} + \left(1-\alpha\right)\boxed{\mathbf{E}} \tag{51}$$

So these are equivalent when:

$$\mathbf{D}_{\mathbf{A}}\left(\beta-1\right)\mathbf{D}_{\mathbf{B}^{-1}} = \mathbf{I}\alpha \tag{52}$$

$$\begin{aligned} \vec{1}\left(1-\alpha\right) &= -n\mathbf{D}_{\mathbf{B}}^{-1} \\ \implies \vec{1}\alpha &= \vec{1} - n\mathbf{D}_{\mathbf{B}}^{-1} \end{aligned} \tag{53}$$

Hence we have:

$$\mathbf{D}_{\mathbf{A}}\left(\beta-1\right)\mathbf{D}_{\mathbf{B}}^{-1} = \vec{1}\alpha = \mathbf{I} - n\mathbf{D}_{\mathbf{B}}^{-1} \tag{54}$$

Solving for β with (52) :

$$\beta = \frac{1-\Theta}{\Theta} \tag{55}$$

$$\tag{56}$$

where: [11]

- $\Theta = \mathbf{D}_{\mathbf{A}}\mathbf{D}_{\mathbf{B}}^{-1}$

but we can't really do this so instead:

$$\beta\mathbf{1}_{[n,n]} = \left(1-\Theta\right)\Theta^{-1}$$

If β is set accordingly then by (54):

$$\begin{aligned} \mathbf{A}\left(\beta-1\right)\mathbf{D}_{\mathbf{B}}^{-1} &= \alpha = \mathbf{I} - n\mathbf{D}_{\mathbf{B}}^{-1} \\ \implies \mathbf{A}\left(\beta-1\right)\mathbf{D}_{\mathbf{B}}^{-1} &= \mathbf{I} - n\mathbf{D}_{\mathbf{B}}^{-1} \end{aligned} \tag{57}$$

And setting $\Gamma = \mathbf{I} - n\mathbf{D}_{\mathbf{B}}^{-1}$ from (53) and putting in (50) we have:

[11] NOTE: Similar to a signmoid function, which is a solution to $p \propto p(1-p)$, I wonder if this provides a connection to the exponential nature of the power walk 'erdos.renyi'erdos.renyi"

$$\mathbf{T} = \boxed{\mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1}}\mathbf{D}_{\mathbf{A}}\left(\beta - 1\right)\mathbf{D}_{\mathbf{B}}^{-1} + \boxed{\mathbf{E}}n\mathbf{D}_{\mathbf{B}}^{-1}$$
$$\mathbf{T} = \Gamma\boxed{\mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1}} + \left(1 - \Gamma\right)\boxed{\mathbf{E}}$$

$$\mathbf{T} = \Gamma\mathbf{A}\mathbf{D}_{\mathbf{A}}^{-1} + \left(1 - \Gamma\right)\mathbf{E} \tag{58}$$

Where $\mathbf{E}$ is square matrix of $\frac{1}{n}$ as in (16) (23)

6.5 Conclusion

So when the adjacency matrix is stictly boolean, the power walk is equivalent to the random surfer.

6.6 The Second Eigenvalue

6.6.1 The Random Surfer

The Second eigenvalue ξ_2 of the Power Surfer is less than α (See 3.2; Stability and Concvergence, of proposal).

6.6.2 Power Walk

Because the Power Walk relates to the random surfer as demonstrated in section 6 , what can be said about ξ_2

Applying this to Power Walk Let $\Lambda_{(2)}\left(\mathbf{T}\right) = \lambda_2$ return the second value of a transition, probability Matrix, then observe that:

$$\Lambda_{(2)}\left(\mathbf{T}_{\text{RS}}\right) \leq \left|\alpha\right| \implies \Lambda_{(2)}\left(\mathbf{T}_{\text{PW}}\right) \leq \left|\frac{\alpha - \mathbf{D_a}\mathbf{D}_{\mathbf{B}}^{-1}}{\mathbf{D}_{\mathbf{A}}\mathbf{D}_{\mathbf{B}}^{-1}}\right| \tag{59}$$

where:

- $\lambda_{(2)}\left(\mathbf{T}\right)$ refers to the transition probability matrix of the power walk and random surfer approaces as indicated.

My attempt

$$\beta\mathbf{1}_{[n,n]} = \frac{1 - \Theta}{\Theta} \tag{60}$$

(61)

where:

- $\Theta = \mathbf{D}_{\mathbf{A}}\mathbf{D}_{\mathbf{B}}^{-1}$

So I thought maybe if I could find a value of β that satisfied (60) then I could show circumstances under which $|\xi_2| < \alpha$.

Seemingly it's only satisfied where $\beta = 1$ though, using this simulation:

```r
g1 <- igraph::erdos.renyi.game(n = 9, 0.2)
A <- igraph::get.adjacency(g1) # Row to column
A <- t(A)
# plot(g1)

## * Finding beta values to behave like Random Surfer
  beta <- 10
  B <- beta^A

  DA    <- PageRank::create_sparse_diag_sc_inv_mat(A)
  DB_inv <- PageRank::create_sparse_diag_scaling_mat(B)

 THETA <- DA %*% DB_inv

THETA <- function(A, beta) {
  B  <- beta^A
  DA    <- PageRank::create_sparse_diag_sc_inv_mat(A)
  DB_inv <- PageRank::create_sparse_diag_scaling_mat(B)
  return(DA %*% DB_inv)
}

THETA_inv <- function(A, beta) {
  B  <- beta^A
  DB    <- PageRank::create_sparse_diag_sc_inv_mat(B)
  DA_inv <- PageRank::create_sparse_diag_scaling_mat(A)
  return(DA %*% DB_inv)
}

beta_func <- function(A, beta) {
    return(1-THETA(A, beta^A) %*% THETA_inv(A, beta^A))
}

THETA(A, 10) %*% THETA_inv(A, 10)


eta <- 10^-6
beta <- 1.01
while (mean(beta*matrix(1, nrow(A), ncol(A)) - beta_func(A, beta)) > eta) {
    beta <- beta + 0.01
    print(beta)
    print(diag(beta_func(A, beta)))
    print(beta*matrix(1, nrow(A), ncol(A)))
    print(beta_func(A, beta))
#    Sys.sleep(0.1)
}

beta


diag(beta_func(A, beta))
beta


## * blah
```

7 Simulating the Structure of the Web

A graph of the internet is *scale free*, this means that the number of nodes of a graph (n), having j edges is given by [19, §10.7.2]:

$$n \propto j^{-k}, \quad \exists k \in \mathbb{R} \tag{62}$$

The *Erdos Renyi* game is a random network, a superior approach to model the web is to use a scale free networks [3] such as the Barabasi-Albert graph [4]

8 Investigating the Second EigenValue

Maybe I should look at the most appropriate way to simulate social network links, one possibility is this paper [29].

Actually there is a data set available [13], I should just analyse that, see how it was done in Visual Analytics as a reminder.

Using the Wikipedia ArtYeah I think that's right, thaicle compare density and Determinant.

Is the determinant easily calculated for a large matrix? It appears to diverge

Will the determinant diverge for large matrices? Will the prob of making edges in the game just be the density?

Look at comparing the determinant and the density of the wikipedia adjacency matrix.

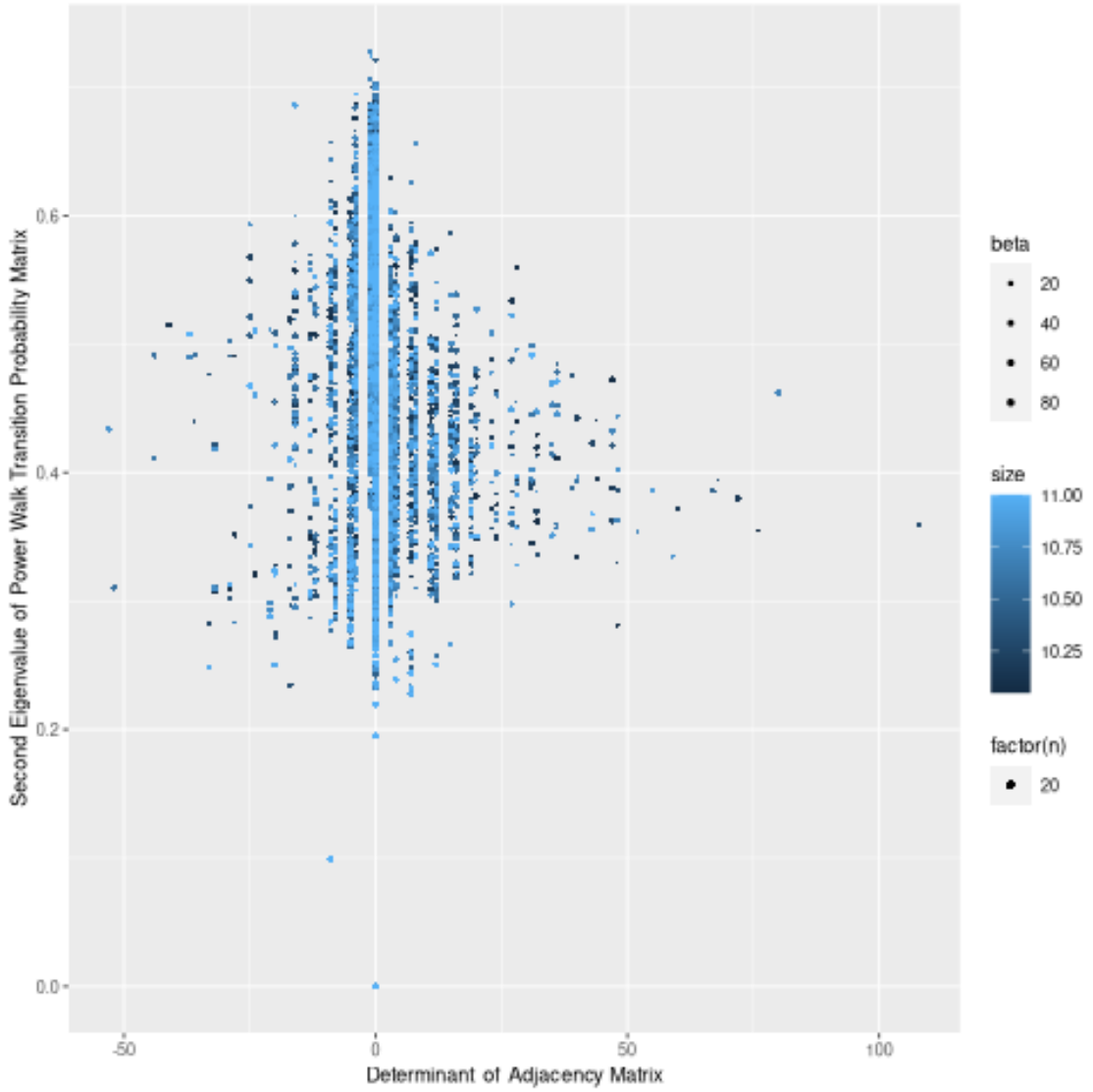
What are some ways that we can model the second eigenvalue?

8.1 Plotting Various Values

There is some relationship between the determinant and the density, check out the pairs plot:

```
  library(pacman)
  pacman::p_load(PageRank, devtools, Matrix, igraph, tidyverse)
n <- 20
p <- 1:n/n
beta <- 1:n/n
beta <- runif(n)*100
sz <- 1:n/n+10
input_var <- expand.grid("n" = n, "p" = p, "beta" = beta, "size" = sz)
input_var


random_graph <- function(n, p, beta, size) {
     g1 <- igraph::erdos.renyi.game(n = sz, p)
     A <- igraph::get.adjacency(g1) # Row to column
     A <- Matrix::t(A)

     A_dens <- mean(A)
     T      <- PageRank::power_walk_prob_trans(A)
     e2     <- eigen(T, only.values = TRUE)$values[2] # R orders by descending
         ↪ magnitude
     A_det <- det(A)
     return(c(abs(e2), A_det))
}
```

```
## TODO this should use pmap.
Y <- matrix(ncol = 2, nrow = nrow(input_var))
for (i in 1:nrow(input_var)) {
  X <- as.vector(input_var[i,])
  Y[i,] <- random_graph(X$n, X$p, X$beta, X$size)
}
if (sum(abs(Y) != abs(Re(Y))) == 0) {
  Y <- Re(Y)
}
nrow(input_var)
nrow(Y)
Y <- as.data.frame(Y); colnames(Y) <- c("eigenvalue2", "determinant")

data <- cbind(input_var, Y)

ggplot(data, aes(x = determinant, y = eigenvalue2, size = beta, color = size, shape
    ↪ = factor(n))) +
  geom_point() +
  labs(x = "Determinant of Adjacency Matrix", y = "Second Eigenvalue of Power Walk
      ↪ Transition Probability Matrix") +
  scale_size_continuous(range = c(0.1,1))
```

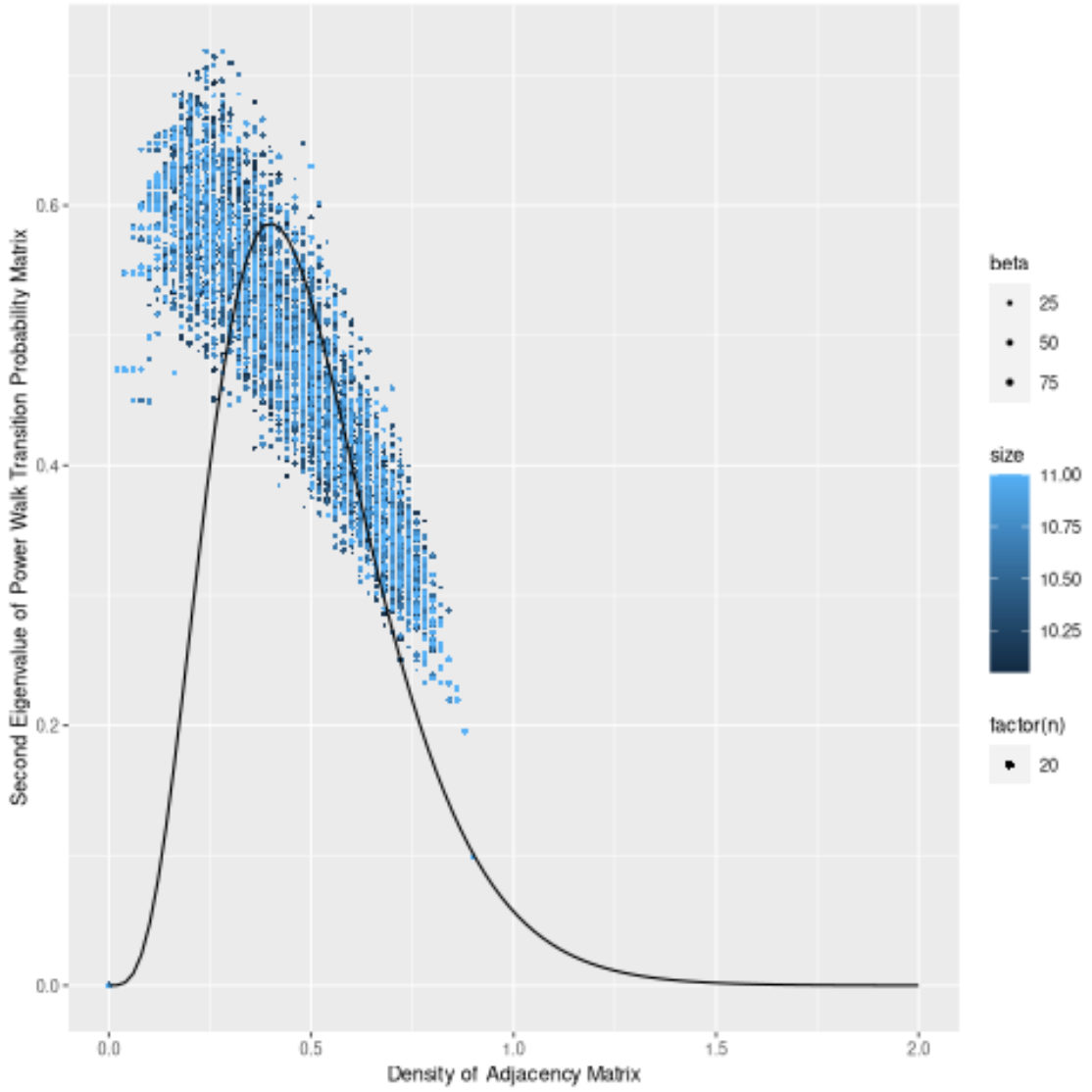



```
  library(pacman)
  pacman::p_load(PageRank, devtools, Matrix, igraph, tidyverse)
n <- 100
p <- 1:n/n
beta <- 1:n/n
beta <- runif(n)*100
sz <- 1:n/n+10
input_var <- expand.grid("n" = n, "p" = p, "beta" = beta, "size" = sz)
input_var


random_graph <- function(n, p, beta, size) {
     g1 <- igraph::erdos.renyi.game(n = sz, p)
     A <- igraph::get.adjacency(g1) # Row to column
     A <- Matrix::t(A)

     A_dens <- mean(A)
```

```
      T     <- PageRank::power_walk_prob_trans(A)
      e2    <- eigen(T, only.values = TRUE)$values[2] # R orders by descending
          ↪ magnitude
      A_det <- det(A)
      return(c(abs(e2), A_dens))
}

## TODO this should use pmap.
Y <- matrix(ncol = 2, nrow = nrow(input_var))
for (i in 1:nrow(input_var)) {
  X <- as.vector(input_var[i,])
  Y[i,] <- random_graph(X$n, X$p, X$beta, X$size)
}
if (sum(abs(Y) != abs(Re(Y))) == 0) {
  Y <- Re(Y)
}
nrow(input_var)
nrow(Y)
Y <- as.data.frame(Y); colnames(Y) <- c("eigenvalue2", "determinant")

data <- cbind(input_var, Y)

ggplot(data, aes(x = determinant, y = eigenvalue2, color = size, shape =
    ↪ factor(n))) +
  geom_point(base_size = 99, aes(size = beta)) +
  labs(x = "Density of Adjacency Matrix", y = "Second Eigenvalue of Power Walk
      ↪ Transition Probability Matrix") +
  scale_size_continuous(range = c(0.1,1))
```

Maybe this looks like a Chi distribution?

```
chival <- dchisq(seq(from = 0, to = 40, length.out = 100), df = 10)*6
index <- seq(from = 0, to = 2, length.out = 100)
chidata <- data.frame(index = index, chi = chival)
ggplot(data) +
  geom_point(mapping = aes(x = determinant, y = eigenvalue2, size = beta, color =
      ↪ size, shape = factor(n))) +
  geom_line(data = chidata, mapping = aes(x = index, y = chi)) +
  scale_size_continuous(range = c(0.1,1)) +
  labs(x = "Density of Adjacency Matrix", y = "Second Eigenvalue of Power Walk
      ↪ Transition Probability Matrix")
```



8.2 Model the log transformed data using a linear regression or log(-x) regression

$$\xi_2 = \left(1 - \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\mathbf{A}_{i,j}}{n^2}\right)^{0.6} \cdot e^{-0.48} \pm \Delta \tag{63}$$

8.2.1 Change the colour of each model by using $\text{pivot}_{\text{longer}}$

8.3 Could I get better performance by also considering the determinant?

No not really, it terms of accuracy

8.4 Is the determinant faster or slower?

Significantly slower for large matrices.

8.5 Import wikipedia data

- ~~Import the wikipedia data~~
- ~~Measure the density~~
- ~~Use the density to guess the p of the game~~
  - ~~Justify the witht the scatterplot matrix~~
- ~~Measure the affect of different β values on λ_2 for graphs ov various sizes given that p value.~~
  - ~~Or atleast a range within that prob~~
    use a *Barabassi-Albert* Random Graph through the ~igraph::

9 Cauchy Integral Formula

This is from section 54 of the book, isn't it nice that it more or less just works hey? [30]

$$f(a)\frac{1}{2\pi i}\oint\frac{f(z)}{z-a}\mathrm{d}z \tag{64}$$

In view of this equation then: [30]

$$\left|\int_C \frac{f(z)}{z-z_0}\mathrm{d}z - 2\pi i f(z_0)\right| < 2\pi\varepsilon$$

Some Images: [25]

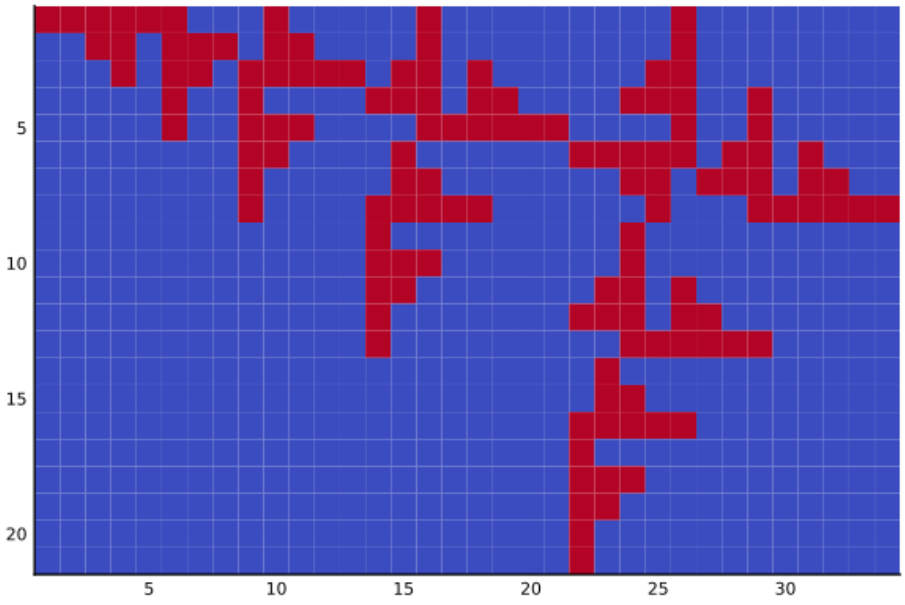


Figure 6: This image is for testing purposes [23]

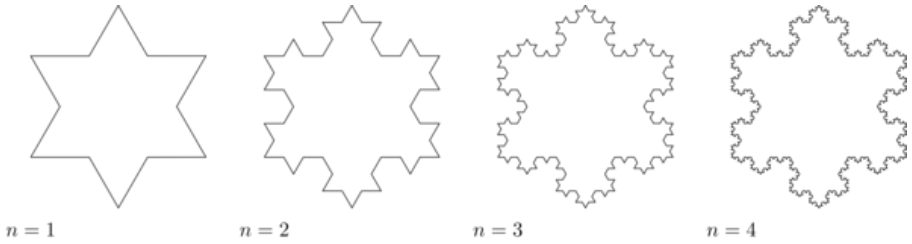
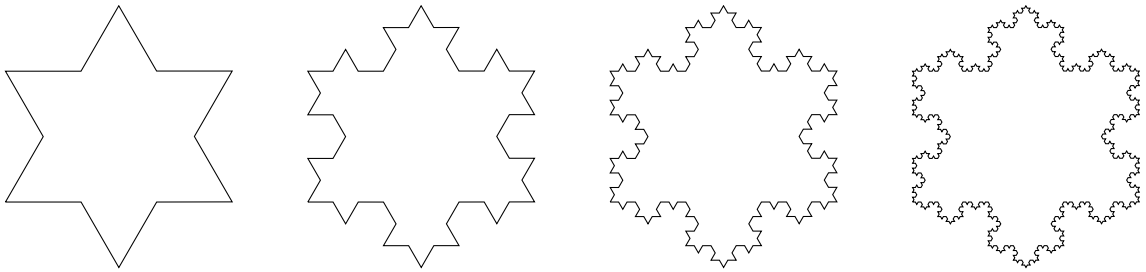


Figure 7: This is a tikz image inserted as a png from imagemagick



9.1 Heading 2

9.1.1 Heading 3

```
echo "Hello World"
```

Heading 4

Heading 5

1. Heading 6 Arbitrary Code:

```
n/bash

# Print Help
if [ "$1" == "-h" ]; then
    echo "Usage: `basename $0` <Format> <CSS>"
    style=~/Dropbox/profiles/Emacs/org-css/github-org.css
    exit 0
fi

# Make a working File from clipboard
filename=lkjdskjjalkjkj392jlkj
xclip -o -selection clipboard >> $filename
```

```
LocalFile=$filename.org

pandoc -s -f org -t gfm $filename -o $filename

echo "
This was converted from `org` to `md` using `pandoc -t gfm` at time:
$(date --utc +%FT%H-%M-%S)
" >> $filename

cat $filename | xclip -selection clipboard
rm $filename

nv & disown
echo "Conversion from Org Successful, MD is in Clipboard"

exit 0
```

10 Appendix

```
library(Matrix)
library(igraph)
n <- 200
m <- 5
power <- 1
g <- igraph::sample_pa(n = n, power = power, m = m, directed = FALSE)
plot(g)
A <- t(get.adjacency(g))
plot(A)
image(A)


# Create a Plotting Region
par(pty = "s", mai = c(0.1, 0.1, 0.4, 0.1))


# create the image

title=paste0("Undirected Barabassi Albert Graph with parameters:\n Power = ",
    ↪ power, "; size = ", n, "; Edges/step = ", round(m))
image(A, axes = FALSE, frame.plot = TRUE, main = title, xlab = "", ylab = "", )
```

Listing 7: ***R*** code to produce an image illustrating the density of a simulated Barabasi-Albert graph, the *Barabasi-Albert* graph is a good analouge for the link structure of the internet [19, 3, 4] see the output in figure 8

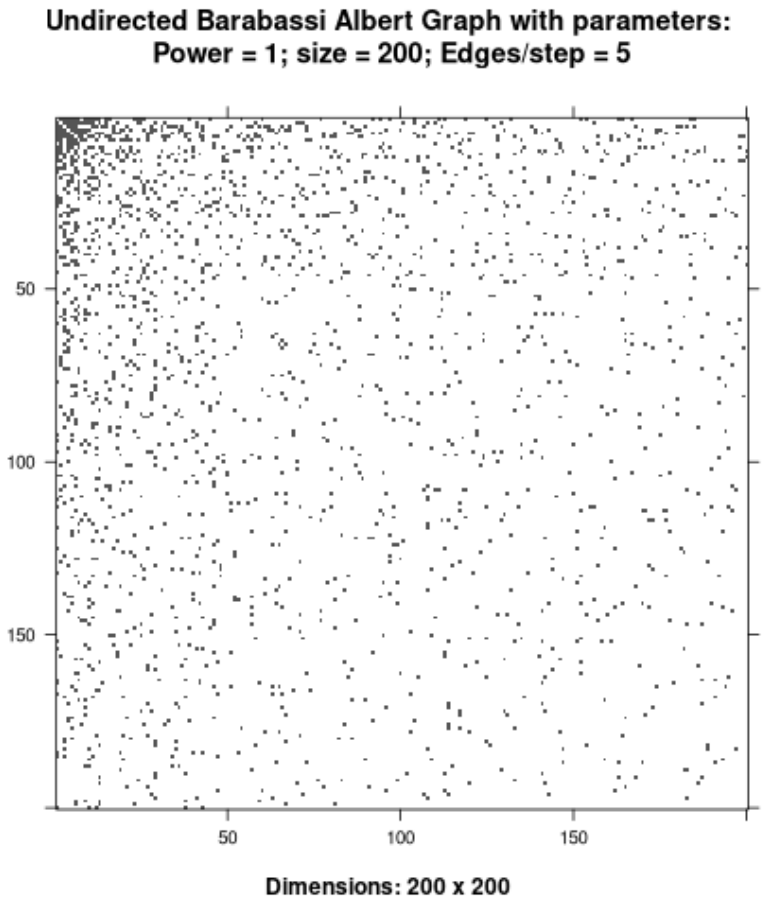


Figure 8: Plot of the adjacency matrix corresponding to a Barabassi-Albert (i.e. *Scale Free*) Graph produced by listing 7, observe the matrix is quite sparse.

11 Graph Diagrams

Graph Diagrams shown in 2.2.2 where produced using DOT (see [28, 9]).

12 Extensions to this Report

Accellerating the Computatoin of Page Rank [19]

13 Is the power Walk transition prob matrix a stochastic because it may contain negatives?

14 Look at the Trace of the Matrix as a comparison point

15 TODO Diamater

Diamater of the web sounds like a fun read [2]

16 Improving the Performance of Page Rank

This:

> Another approach involves involves reordering the problem and taking advantage of the fact that the transition probability matrix is sparse in order to produce a new algorithm which cannot perform worse than the *power method* but has been shown to improve the rate of convergence in certain cases. [18].

There was also a book that I downloaded that mentioned it

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This suggests an approach that uses structural network dynatims to provide an appropriate score distribution.
The method implemented is not something I have come yet to understand, but it could be very interesting to see:
- how it relates to the power walk method
- whether or not it could offer insightts into the convergence and stability of the power walk method
- Whether or not the method would be compatible with negatively weighted edges., pp. 3–33. ISSN: 1573-7594. DOI: 10.1007/s10626-017-0248-7. URL: https://doi.org/10.1007/s10626-017-0248-7 (visited on 08/19/2020) (cit. on p. 6).

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