1. Introduction

1.1 Context of the Problem

The evolution of information transfer represents one of the most crucial phases in the development of human history. Nowadays we are living in a world full of information. Therefore, it is necessary to explore the flow of information from the past to present.

The relationship between the flow of information and inherent value of information may differ from each other over periods, ranging from when newspapers were delivered by trains, stories were passed by telegraph and radios, and people watched televisions at homes to when we get access to information through Internet and phones. According to the statistic provided by Pew Research Center, an apparent trend can be visualized (Figure 1)[1].

![Where People Got News Yesterday](image)

Figure 1: The line chart of the research on Where People Got News Yesterday

In *An Introduction to Mass Communication*, the authors indicate that media innovations typically go through three stages. First is the novelty, or development stage, in which inventors and technicians try to solve a particular problem, such as...
making pictures move, transmitting messages from ship to shore, or sending mail electronically. Second is the entrepreneurial stage, in which inventors and investors determine a practical and marketable use for the new device. The third stage is the mass media stage. At this point, businesses figure out how to market the new device or medium as a consumer product. In the same way, Pentagon and government researchers helped develop early prototypes for the Internet, but commercial interests extended the Internet’s global reach and business potential.[2]

There are two influential models now. One is the Linear Model of Mass Communication in which mass communication is conceptualized as a linear process of producing and delivering messages to large audiences. The process can be shown in Figure 2 (M refers to Messages). The other is Cultural Model which recognizes that individuals bring diverse opinions to messages, given factors and differences such as gender, age, educational level, ethnicity, and occupation.[2]

1.2 The Task at Hand

Given the current increasing spread of information, it will be very critical to discover the trend of information flow so as to meet the requirements of comprehend the influence on our society. Our team aims to develop mathematical models that allow us to understand the information flow on different periods and predict the future trend. In addition, use the theory to reveal the truth of how public interest and opinion can change through information networks in today’s connected world.

1.3 Previous Work

Pioneering contributions to the modeling of social contagion processes, based on epidemiological models, date back to as early as 1953[3]. SIR epidemiological modeling has been used broadly, in which people are divided into three groups. They are denoted by susceptible (S), infected (I), and recovered (R). In a group of people, individuals transit from one compartment to another.

Besides, SIR models are usually extended, such as SI, SIS, SEIR (E refers to
exposed individuals) models. Because of the large similarities between information flow and virus passing in the spreading process, susceptible individuals can be potential message receivers, the infected one is whom has received messages and intends to spread them, and the recovers person is similar to whom has got messages and stops spreading them.

2. General Assumptions

1. Information can be spread freely without the resistance caused by non-human factors.
2. Individuals who have been turned off will not be interested in it anymore.
3. The total population is confirmed and unchangeable. The movement of population and other situations that bring about the decrease of population, such as birth and death, are not considered.
4. The probability given contact with individuals is confirmed and unchangeable.
5. The message spreading is done as soon as individuals contact with each other.
6. The infected individuals do not spread messages to each other in their compartment.
7. The sudden interruption of information flow is not included.
8. The bigger value and attraction of information are, the faster flow of information is.

3. The Models

It can be much difficult to talk about the information flow directly; therefore, we choose to use the transformation of different compartments, which is the population changes, to represent the information flow in society. As a result of this, our information model is based and developed on S-I-R model.

3.1 Basic Model: S-I-R Model

We divide the flow of information into three main stages: message-unknown stage, message-received-and-spread stage, and message-dead stage, which is similar to the original S-I-R Model. Thus, S-I-R Model becomes the basic model of our work.
At the beginning, some notations are defined \[\text{[4]}\]:

- $S(t)$ is the proportion of susceptible individuals at time $t$
- $I(t)$ is the proportion of infected individuals at time $t$
- $R(t)$ is the proportion of recovered individuals at time $t$
- $N$ is the total population size

$S + I + R = 1$

According the assumption of S-I-R Model, differential equations are set as follows\[4\].

\[
\begin{align*}
\frac{dS}{dt} &= -\beta S(t)I(t) \\
\frac{dI}{dt} &= (\beta S(t) - k)I(t) \\
\frac{dR}{dt} &= kI(t)
\end{align*}
\]

where $\beta$ is the average number of transmissions from an infected person in one day and $k$ is the recovery rate (with greater or equal to zero).

### 3.2 Notations

Table 1: Symbol table

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>The proportion of susceptible people</td>
</tr>
<tr>
<td>$I$</td>
<td>The proportion of information adopter</td>
</tr>
<tr>
<td>$R$</td>
<td>The proportion of information terminator</td>
</tr>
<tr>
<td>$Z$</td>
<td>The proportion of skeptics</td>
</tr>
<tr>
<td>$D$</td>
<td>The proportion of information delayed-spreading adopter</td>
</tr>
<tr>
<td>$C$</td>
<td>The proportion of chaos maker</td>
</tr>
<tr>
<td>$N$</td>
<td>Total population</td>
</tr>
</tbody>
</table>

Some symbols are defined as the corresponding ones in previous work. \[3\]

$s + i + r + z + d + c + n = 1$

### 3.3 Our Information Flow Model

Drawbacks of S-I-R Model when they are used to explore the information flow are that they cannot reflect the end of information flow and the changes of messages, which may be caused by media channels or chaos makers. Our information flow model tries to enrich it by adding new types of members.

We divided the population into six compartments. $S$ represents the proportion of those who has not known the information yet. $I$ represents the proportion of those who has accepted the information and will spread it immediately. $Z$ represents the proportion of those who will not accept the information and will not spread it any more. $D$ represents the proportion of those who delay spreading the information transferring to a part of Information adopters and a part of skeptics. $C$ represents the proportion of those who create chaos and continue spreading the false messages like rumors. $R$ represents the proportion of those who will not affect this model anymore,
including information adopters, skeptics and chaos makers, which is the end of the flow of information.

The parameters are defined as follows (Table 2).

**Table 2: Parameter definitions in our information flow model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>$S \rightarrow I$ contact rate</td>
</tr>
<tr>
<td>$b$</td>
<td>$S \rightarrow Z$ contact rate</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$D \rightarrow I$ contact rate</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$D \rightarrow C$ contact rate</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Incubation rate</td>
</tr>
<tr>
<td>$k$</td>
<td>Cure rate</td>
</tr>
<tr>
<td>$l$</td>
<td>$S \rightarrow Z$ Probability given contact with skeptics</td>
</tr>
<tr>
<td>$1-l$</td>
<td>$S \rightarrow D$ Probability given contact with adopters</td>
</tr>
<tr>
<td>$p$</td>
<td>$S \rightarrow I$ Probability given contact with adopters</td>
</tr>
<tr>
<td>$1-p$</td>
<td>$S \rightarrow D$ Probability given contact with adopters</td>
</tr>
</tbody>
</table>

As shown in Figure 4, information flow can be summarized as follow:

![Information flow model framework](image)

The model is defined by the following system of ordinary differential equations:

1. $\frac{dS}{dt} = -\beta SI - bSZ$  
2. $\frac{dD}{dt} = (1 - p)\beta SI + (1 - l)bSZ - \rho DI - \mu D - \lambda D$  
3. $\frac{dI}{dt} = p\beta SI + \rho DI + \mu D - kl$  
4. $\frac{dZ}{dt} = lbSZ - Z$  
5. $\frac{dC}{dt} = \lambda D - C$  
6. $\frac{dR}{dt} = kl + C + Z$
3.4 Limited Issues

During the adoption of our information flow model, some unknowns exist in the model. For example, we cannot know the transition probability when one type of individuals transfers to another, especially on the period when information spread slowly and imprecisely. Besides, we cannot quantify the proportion of each compartment precisely. Although the proportion of information adopters can be measured in some way, the other proportions are still unknown.

3.5 Parameter Identification

The initial proportions of every compartment, the information-free state proportion, are set:

\[
R(0) = C(0) = 0
\]
\[
S(0), I(0), Z(0), D(0)
\]

where each is greater than zero

\[
S(0) + I(0) + Z(0) + D(0) = 1
\]

At the beginning, some individuals have known the information, who may be the senders as Linear Model of Mass Communication [2]. These senders may vary in information adopters, skeptics, and information delayed-spreading adopters. Because the real spread does not start, the population of information terminators and chaos makers is zero.

Due to complexity of the system of ordinary differential equations, analytical solution cannot be gained. Thus, we solve it numerically ODE toolbox in MATLAB R2013b by setting the initial values by ourselves. The program is as follows. The simulated parameter values are in Table 3. Figure 5 displays the trend of different proportions.

```matlab
function y=information (t,x)
a=6; b=5; c=4; d=5; e=4; f=2; g=0.8; h=0.5;
y=[-a*x(1)*x(2)-b*x(1)*x(4),h*a*x(1)*x(2)+x(6)*x(5)*x(2)+e*x(5)-f*x(2),f*x(2)+x(6)+x(4),g*b*x(1)*x(4)-x(4),(1-h)*a*x(1)*x(2)+(1-g)*b*x(1)*x(4)-x(6)*x(5)*x(2)-e*x(5)-d*x(5),d*x(5)-x(6)];
ts=0:0.1:8;
% R(0) = C(0) = 0, S(0) = 0.7, I(0) = 0.1, Z(0) = 0.1, D(0) = 0.1
x0=[0.7,0.1,0.1,0.1,0.1,0.1];
[t,x]=ode45('ill',ts,x0);[t,x]
plot(t,x(:,1),t,x(:,2),t,x(:,3),t,x(:,4),t,x(:,5),t,x(:,6)),grid,pause
plot(x(:,6),x(:,5),x(:,4),x(:,3),x(:,2),x(:,1)),grid,
```

Table 3: Simulated parameter values
<table>
<thead>
<tr>
<th>$t$</th>
<th>$S$</th>
<th>$I$</th>
<th>$R$</th>
<th>$Z$</th>
<th>$D$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.7</td>
<td>0.1</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.3208</td>
<td>0.1554</td>
<td>0.2435</td>
<td>0.1646</td>
<td>0.0276</td>
<td>0.088</td>
</tr>
<tr>
<td>1</td>
<td>0.1433</td>
<td>0.103</td>
<td>0.5031</td>
<td>0.1541</td>
<td>0.0099</td>
<td>0.0868</td>
</tr>
<tr>
<td>1.5</td>
<td>0.0814</td>
<td>0.0518</td>
<td>0.684</td>
<td>0.1158</td>
<td>0.0032</td>
<td>0.0637</td>
</tr>
<tr>
<td>2</td>
<td>0.0573</td>
<td>0.0236</td>
<td>0.7951</td>
<td>0.0804</td>
<td>0.0012</td>
<td>0.0424</td>
</tr>
<tr>
<td>2.5</td>
<td>0.0462</td>
<td>0.0104</td>
<td>0.8616</td>
<td>0.054</td>
<td>0.0005</td>
<td>0.0273</td>
</tr>
<tr>
<td>3</td>
<td>0.0405</td>
<td>0.0045</td>
<td>0.9017</td>
<td>0.0357</td>
<td>0.0003</td>
<td>0.0173</td>
</tr>
<tr>
<td>3.5</td>
<td>0.0373</td>
<td>0.002</td>
<td>0.9263</td>
<td>0.0234</td>
<td>0.0001</td>
<td>0.0108</td>
</tr>
<tr>
<td>4</td>
<td>0.0354</td>
<td>0.0009</td>
<td>0.9415</td>
<td>0.0153</td>
<td>0.0001</td>
<td>0.0068</td>
</tr>
<tr>
<td>4.5</td>
<td>0.0343</td>
<td>0.0004</td>
<td>0.9511</td>
<td>0.0099</td>
<td>0</td>
<td>0.0042</td>
</tr>
<tr>
<td>5</td>
<td>0.0336</td>
<td>0.0002</td>
<td>0.9571</td>
<td>0.0064</td>
<td>0</td>
<td>0.0026</td>
</tr>
<tr>
<td>5.5</td>
<td>0.0331</td>
<td>0.0001</td>
<td>0.9609</td>
<td>0.0042</td>
<td>0</td>
<td>0.0016</td>
</tr>
<tr>
<td>6</td>
<td>0.0328</td>
<td>0.0001</td>
<td>0.9633</td>
<td>0.0027</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>6.5</td>
<td>0.0327</td>
<td>0</td>
<td>0.9649</td>
<td>0.0018</td>
<td>0</td>
<td>0.0006</td>
</tr>
<tr>
<td>7</td>
<td>0.0325</td>
<td>0</td>
<td>0.9659</td>
<td>0.0011</td>
<td>0</td>
<td>0.0004</td>
</tr>
<tr>
<td>7.5</td>
<td>0.0325</td>
<td>0</td>
<td>0.9665</td>
<td>0.0007</td>
<td>0</td>
<td>0.0003</td>
</tr>
<tr>
<td>8</td>
<td>0.0324</td>
<td>0</td>
<td>0.9669</td>
<td>0.0005</td>
<td>0</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

As shown in Figure 5, this threshold demonstrated to be numerically stable. At the end of information flow, proportions except $S$ and $R$ come to zero because $I$, $Z$, $D$, and $C$, as the middle state of spreading, will transfer to $R$ eventually. Furthermore, most people receive messages while some of the population has not even if the information flow comes to the end.
3.6 Model Application

3.6.1 Discussion on Different Periods

In the past, people gained information by newspaper and telegraph, and then radio and television. At present, the Internet and phones have become the main source from which individuals receive messages. Apparently, the biggest difference is the speed of information. Messages can be spread more quickly than before.

The speed of information spread corresponds to contact rate and probability of compartments transfer. The improvement of speed makes $\beta$, $b$, $\rho$, $\lambda$ rise. As the sources arise, incubation rate decreases while cure rate increases because it will be easier for people to acquire knowledge and make judgments.

Take a specific information flow as an example. In February 2015, “Is the dress white and gold or black and blue?” stormed social networks. We gained the data, indicating the search volume of the key word “dress”, from Google Trend [5]. To apply the data into our information flow model, we find the average number of Google searches for a month [6], and estimate the number per day. Then, we transfer the data into proportion. Next, a fitting experiment is done by MATLAB. The fitting curves and potential values are as follows in Figure 6, Figure 7, and Table 4.

![Figure 6: The fitting curve](image)

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$b$</th>
<th>$\rho$</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$k$</td>
<td>$l$</td>
<td>$p$</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

![Figure 7: Model fitting and residuals](image)

Table 3: Simulated parameter values
In this application, the curve of I is matched to the discrete dots. Furthermore, from the value of I and p is very high, which suggests that people tend to make judgments by themselves in the connected network. And 1-I and 1-p decrease, suggesting the speed of information flow is also very high without many information delayed-spreading adopters. In addition, the result indicates that it becomes easier for individuals to make a quick decision by their abundant knowledge structures.

At last, we use the data to make prediction. When $t=7$, the result of our model is 0.0089 while the real proportion is 0.007. Therefore, the reliability and prediction capability of information flow model are apparent.

3.6.2 News Filtering

News has two significant characteristics: temporary effectiveness and accuracy. Due to the temporary effectiveness, news is effective only for a short time, so we can generally ignore D; as for the accuracy, the truth of news is confirmed, so $C$ and $Z$ can be ignored as well.

As a result, the model of news is a simple S-I-R model. By using the equations mentioned in 3.1, we can figure out the fitting curve of news. After matching our fitting curve of information with this curve, we can preliminarily identify our information is qualified as news. Of course, we need to consider the inherent value of the information to make further confirmation.

![Figure 8: News model (S-I-R model)](image)

3.6.3 Prediction

In Network properties [7], the density $D$ of a network is defined as a ratio of the number of edges $E$ to the number of possible edges, giving

$$D = \frac{2E}{N(N-1)}$$

To distinguish variable $D$ here with the $D$ in our model, we change the notation here. $F$ refers to $D$ here, so the above equation becomes

$$F = \frac{2E}{N(N-1)}$$

Another definition is size, which refers to the number of nodes $N$ or, less
commonly, the number of edges $E$ which can range from $N-1$ to $E_{\text{max}}$. The definition of $N$ is as same as the total population in our information flow model. Logistic growth [https://en.wikipedia.org/wiki/Population_model], as a well-known population growth model, can be used in density equation. According to World Population Prospects: The 2000 Revision Volume III Analytical Report by UN [8], world population is predicted to be 9.3 billion with lower average annual growth rate than now. Thus, $N$ is getting greater and greater. The communication networks’ capacities will definitely increase. Besides, $E$ will increase as well. With the development of technology, it will be much quicker to communicate with each other. As the changes from 1870s to now, the speed is becoming higher and higher. Due to this trend, we predict that the rate:

$$\begin{align*}
\frac{dE}{dt} &= m \\
\text{where } m \text{ is greater than zero.}
\end{align*}$$

$$\begin{align*}
\frac{dE}{dt} &= n \\
\text{where } n \text{ is less than zero, according the prediction by UN. Thus, } F \text{ will be greater than now, resulting in the rise of } \beta, b, \rho, \lambda \text{ in equation (1) to (5). In other words, the communication networks’ relationships will be closer.}
\end{align*}$$

3.7 Public Interests and Opinions

We gather some Google Top 10 searches/news in US. From the diagram below, we can see the decrease of people’s interests in political information. Besides, the Years Top1 search items in USA table indicates the rise of people’s concern about international things. In earlier years, when people got information from newspapers or radios, information was limited by districts. People gain information about their local issues mostly. Compared with those years, people can get a great amount of information on the Internet nowadays. Our world is becoming smaller, and people are more closely connected.

How do information networks change public interest and opinion? It is both determined by information itself and connections between nodes. Before the description of our model, we will first introduce some concepts.
Figure 9: Google Top 10 search items in UK

Table 4: Years Top 1 search items in USA

<table>
<thead>
<tr>
<th>Year</th>
<th>Search Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Paris under attack</td>
</tr>
<tr>
<td>2014</td>
<td>Robin Williams</td>
</tr>
<tr>
<td>2013</td>
<td>Boston Marathon</td>
</tr>
<tr>
<td>2012</td>
<td>Whitney Houston</td>
</tr>
<tr>
<td>2011</td>
<td>Hurricane Irene</td>
</tr>
<tr>
<td>2009</td>
<td>Swine Flu</td>
</tr>
</tbody>
</table>

3.7.1 Basic Concepts [wiki]

1. **Degree** [9]: the degree of a vertex of a graph is the number of edges incident to the vertex, with loops counted twice.

2. **Diameter of a network** [7]

   As another means of measuring network graphs, we can define the diameter of a network as the longest of all the calculated shortest paths in a network. It is the shortest distance between the two most distant nodes in the network. In other words, once the shortest path length from every node to all other nodes is calculated, the diameter is the longest of all the calculated path lengths. The diameter is representative of the linear size of a network.

3. **Clustering coefficient** [7]

   The clustering coefficient is a measure of an "all-my-friends-know-each-other" property. This is sometimes described as the friends of my friends are my friends. The clustering coefficient for the entire network is the average of the clustering coefficients of all the nodes. A high clustering coefficient for a network is another indication of a small world.

3.7.2 Basic Models [7]

   Information network model is in different types as follows.

   Network models serve as a foundation to understand interactions within empirical complex networks. Various random graph generation models produce
network structures that may be used in comparison to real-world complex networks.

1. Erdős–Rényi Random Graph model
A random graph is obtained by starting with a set of \( n \) isolated vertices and adding successive edges between them at random. The Erdős–Rényi model is used for generating random graphs in which edges are set between nodes with equal probabilities.

2. Watts-Strogatz Small World model
The Watts and Strogatz model is a random graph generation model that produces graphs with small-world properties. As the Watts-Strogatz model begins as non-random lattice structure, it has a very high clustering coefficient along with high average path length.

3. BA Preferential Attachment model
The BA model is a random network model used to demonstrate a preferential attachment or a "rich-get-richer" effect. In this model, an edge is most likely to attach to nodes with higher degrees. The BA model is the first scale-free model.

3.7.3 Our Information Network Model

Information networks consist of both nodes and connections; thus, these two compartments both change public interests and opinions.

\begin{align*}
S &= \frac{\sum_{i=1}^{a} a}{M-1}
\end{align*}

(12)

where \( s \) is the proportion of adopters in the total nodes, \( a \) equals 1 if an individual becomes an adopter while \( a \) equals 0 if he has not, and \( M \) is the total amount of nodes of this network system. As one of those nodes is the starter of information flow, the number of potential receivers is \( M-1 \). Here adopters are the individuals who have received messages and take action, such as spreading the...
message to others continually or making some changes that may influence the whole system.

Now, we start to consider how individuals’ interests and opinions can be changed through the flow of information, which is presented by $s$.

We develop our model by adding a new parameter to equation (12). $P$ denotes the probability of which people prefer to choose an exact node as their next message receiver. At this time, the original model turns into as follow.

$$ s = \frac{p \sum_{i=1}^{n-1} a}{M-1} $$

(13)

This model is to reflect the situation that we always tend to choose our favorite listeners as the receivers of messages in our hands. For example, if you have a piece of good news, the first person you want to tell about the news may be your best friend, your family or someone that you want to share the happiness with. You may not just pick up a passer-by as your listener. That is the point of our model. Furthermore, $P$ can be any probability that can influence people’s choice. It can be gender factors, geographic factors, culture background factors, and so on. Thus, the concept of $P$ can be abstract.

To explore the relationships between people’s interests and opinions, we suppose other two situations.

The first situation is the trend in which a node with little degrees turns into a node with greater degrees. This study can be done by computer experiments and investigation among different network systems.

The second situation is the influential level when a node with the greatest degrees, which indicates that this individual has many ties between others, is taken out from networks. This change may cause the break of the whole network systems according the networking theory.

4. Conclusion

The information flow model can show the tendency of the number of every group people while the information network model indicates the influence of exact influencing factors. In fact, the second model is an enhanced model of the first model. We don’t consider what the factors are in the first model, but we can specifically figure out the influence of them in the second model.

The information network model can also be used in other fields because the model derives from graph theory which is widely used in things with complicated relationships.
5. Strength and Weakness

- **Strength**
  
  1. We extend S-I-R model and add a new group of people to represent chaos makers (C).
  2. With limited statistics, we have several as reliable results as possible.
  3. More completing link in information diffusion helps the results to be more accurate.
  4. Calculating, according to fraction, decrease the influence of the deviations in population. It also allows us to estimate when we know the general trend.
  5. We take the delay in information diffusion into consideration.
  6. In the process of creating model, we try our best to avoid complicated problem in daily life and avoid the effect from minor details.

- **Weakness**
  
  1. It is hard to collect our statistics, so there are some deviations in our model.
  2. We cannot do more simulation experiments in our condition, so the accuracy of our model is uncertain.
  3. For the lack of data, we set many assumptions to simplify our calculation. But those assumptions need to be incorporated into the model while doing a real experiment.
  4. It is difficult for us to notice all details in reality.
Reference


[5] Google Trend.[online]

[6] (August 2012)Google: 100 Billion Searches Per Month, Search To Integrate Gmail, Launching Enhanced Search App For iOS.[online]
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   https://en.wikipedia.org/wiki/Network_science


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