

The Difficulty of Path Traversal in Information Networks

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Keywords: Information Networks, Path Traversal, Wikipedia.

Abstract: This paper introduces a set of classification techniques for determining the difficulty — for a human — of path traversal in an information network. In order to ensure the generalizability of our approach, we do not use ontologies or concepts of expected semantic relatedness, but rather focus on local and global structural graph properties and measures to determine the difficulty of finding a certain path. Using a large corpus of over two million traversed paths on Wikipedia, we demonstrate how our techniques are able to accurately assess the human difficulty of finding a path between two articles within an information network.

1 INTRODUCTION

Searching and navigating through structured information such as Wikipedia, a social network or the web, has become an aspect of people's daily lives. In this paper we will analyze the way in which humans traverse structured data in search of a specific piece of information. The motivation for this work comes from the fact that understanding the difficulty of path traversal may lead to a better understanding of human search behavior in general (Hsieh-Yee, 2001), possibly improving the strategy of intelligent search algorithms. Understanding the aspects which complicate path traversal may also help to improve the structure of the linked data itself (Bizer et al., 2009).

Although search engines can often help to find the content within a structured dataset that the user is looking for, sometimes search engine performance does not exactly meet the user's needs (Teevan et al., 2004), for example because the required page is located within the so-called "Deep Web" (He et al., 2007). In such cases, the user will have to reach the correct article by traversing hyperlinks and forming a path towards the correct piece of information. We will study this type of path traversal by analyzing over two million paths traversed by (human) users of the well-known online encyclopedia *Wikipedia*. The path data was gathered from *The Wiki Game*, an online game in which the user is assigned the task of connecting two given random articles on Wikipedia by following the clickable links within the Wikipedia articles. In turns out that humans, especially after some practice, are often able to complete this task in less than

10 clicks. This is actually a quite remarkable accomplishment, because even though a standard backtracking algorithm is certainly able to match or even beat humans in terms of path length, a human instead does not use millions of backtracking steps, but rather relies on background knowledge in terms of expected semantic relatedness (Kentsch et al., 2011). However, incorporating such extensive knowledge into an algorithm for classifying path difficulty, for example via ontologies, may in large networks such as Wikipedia be too complex.

Instead, we will propose a range of local and global structural network properties and measures as indicators for the difficulty of connecting two articles. An advantage of considering structural features is that they capture the direct relationship between the concepts within the network, independent of which exact information network is studied, ensuring the generalizability of the approach. Also, structural properties are relatively easy to compute, and do not require prior knowledge about the dataset. Furthermore, while both the content as well as the linking structure of Wikipedia are subject to change, the classifiers that we propose will only be affected by the second type of change.

The rest of this paper is organized as follows. First, Section 2 describes some concepts, our datasets, and defines our main problem statement. Related work is discussed in Section 3. We analyze and compare the techniques for assessing the difficulty of path traversal, at a local as well as on a global scale, in Section 4 and 5, respectively. Section 6 concludes.

2 PRELIMINARIES

In this section we first discuss various concepts and definitions, after which we describe our two main datasets. Next we formulate our problem statement and verification approach.

2.1 Concepts & Definitions

Our structured data will be represented by a directed graph $G(V, E)$ with $n = |V|$ nodes and $m = |E|$ links. When we talk about a *path* between two nodes $u, v \in V$, we mean a sequence consisting of at least two nodes, starting at u and ending at v , where there is a link from each node to the next node in the sequence. A *shortest path* between two nodes $u, v \in V$ is a path of length $\ell \geq 1$ between u and v for which there is no other path from u to v of length smaller than ℓ . The length of such a shortest path, or in short the *distance*, is denoted by $d(u, v)$. If there is no (shortest) path, then $d(u, v) = \infty$, and of course there can be multiple (shortest) paths connecting two nodes. Because our graph is directed, it can happen that $d(u, v) \neq d(v, u)$. We define the indegree $\text{indeg}(v)$ of a node $v \in V$ as the number of links pointing to node v , and similarly, the outdegree $\text{outdeg}(v)$ as the number of links pointing from node v to some other node.

2.2 Wikipedia

Wikipedia (<http://www.wikipedia.org>) according to its own definition, “is a free, web-based, collaborative, multilingual encyclopedia project with over 3.9 million articles in English alone”. Considering solely the content of the articles and the links it contains, Wikipedia can be seen as a large directed graph, where each node represents an article, and each directed link a hyperlink within the source article pointing to the target article. In this study we will use the August 2011 English dataset of Wikipedia from DBpedia (Auer et al., 2007), from which we only consider the so-called “pagelinks” to other Wikipedia articles, so we exclude links to external websites or other special pages. After some pruning and cleaning, the Wikipedia graph has statistics as presented in Table 1.

We note that the edge-to-node ratio, diameter, the effective diameter (the 90-th percentile of the cumulative distribution of shortest path lengths), the average node-to-node distance (sampled over 10,000 node pairs) and the size of the largest (weakly) connected component (WCC) are consistent with that of other small world networks (Watts and Strogatz, 1998). We also confirmed the power-law node degree distribu-

Table 1: Wikipedia dataset.

Articles (n)	3,464,902
Directed links (m)	82,019,786
Largest WCC	99.9%
Average indegree	26
Average outdegree	22
Average distance (\bar{d})	4.81
Effective diameter	7
Diameter	11

tion for our Wikipedia dataset.

2.3 The Wiki Game

The *Wiki Game* (<http://thewikigame.com>) is an online game in which, starting from a certain source article, the main objective is to reach the goal article by repeatedly clicking links on the current article’s page. We will focus on the “speed-race”-games, in which the task is to connect two given random Wikipedia articles in as few steps as possible, as quickly as possible, with a time limit of 120 seconds. As an example of a path traversal task, consider the path from the Wikipedia article on MP3 to the article on Northern Ireland. An actual (computed) shortest path of length 3 runs subsequently via the articles on the United States and Ice Hockey (see Figure 1). Human users attempting to find a path tend to know that Northern Ireland is somewhere in Europe, so from the article on MP3 they first find their way to an article related to Europe, for example via the page on the Internet which is a direct link from the article on MP3. Next, they will for example navigate to the article on the United Kingdom, from where they find the article on Northern Ireland. Some users take another detour on the way, for example via the pages Republic of Ireland and Ireland (island).

Our dataset T consists of 407,268 games (or *tasks*) and a total of 2,278,986 user-generated paths. A task is essentially a (*start*, *goal*)-pair inbetween which a path has to be formed. For each of these tasks we have a list of paths generated by the (fully anonymized) users, of which little less than one third (28.0%) was successful. The data was filtered to exclude non-serious attempts (more than 40 clicks per task, or no clicks at all).

Figure 2 further clarifies the distribution of shortest and user-generated path lengths. We note that even though shortest paths of length greater than 6 exist within Wikipedia, none of these tasks were included in our database of attempted tasks. Most tasks have a shortest path length somewhere between 2 and 4 (red line, ∇). Figure 2 shows how the distribution of the successful user-generated paths (blue line, \diamond) has a fat tail and follows the same distribution as that

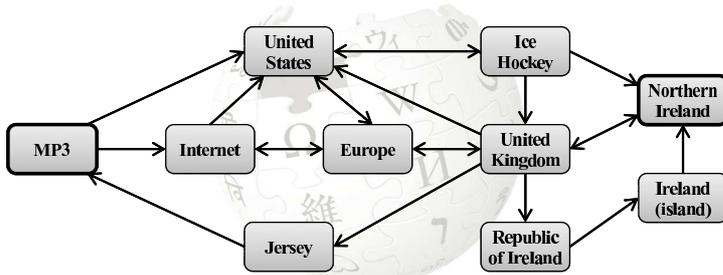


Figure 1: Sample of a fictive Wikipedia graph.

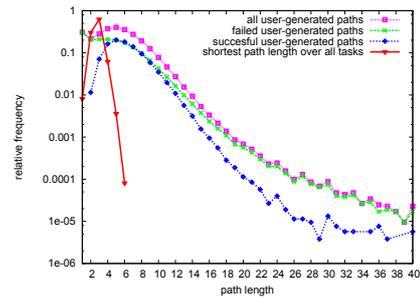


Figure 2: Path lengths (relative frequency).

of the shortest paths, but with an average path length that is roughly 2 times larger than the shortest path length (between 5 and 7). The distribution of the path length over all user-generated paths (purple line, \square) is clearly dominated by the failed paths (green line, \times) and follows a fat-tailed power law, indicating that people frequently “fail” early in the process.

2.4 Problem Definition

Our main goal is to assess the difficulty of finding a path between two nodes in a directed graph:

Problem 1. Given a directed graph $G(V,E)$ and nodes $u,v \in V$, can we assign a function value $f(u,v) \in [0;1]$ indicating the difficulty of finding a path from u to v ?

In this paper we will consider various approaches (or *difficulty classifiers*) of assigning such a function value. We evaluate the quality of an approach based on a comparison with the results obtained by the users on tasks from The Wiki Game.

For each of the user-generated paths of a certain task $t \in T$ we know whether or not the path was successfully formed, allowing us to define the average percentage of success $g(t) \in [0;1]$ for task t , which will serve as a ground truth for assessing the quality of our classifiers.

A classifier f can assign a function value $f(t)$ to all tasks $t \in T$, which allows us to create a partition $\{T_1, T_2, \dots, T_q\}$ of the set of tasks T . The partitioning is done in such a way that the tasks in each T_i have the same function value (range), so that the (average) function value of the tasks in T_i is always greater than the average function value of tasks in T_{i-1} , and where every T_i is maximal in size. The partitions can be used to define q difficulty levels for The Wiki Game.

The overall quality of a classification measure will be determined by computing both the *Pearson correlation coefficient* $c(f,g)$ as well as the *Spearman rank correlation coefficient* $rc(f,g)$ of f and g , defined as:

$$c(f,g) = \frac{q \sum_i \overline{f(i)} \overline{g(i)} - \sum_i \overline{f(i)} \sum_i \overline{g(i)}}{\sqrt{q \sum_i \overline{f(i)}^2 - (\sum_i \overline{f(i)})^2} \sqrt{q \sum_i \overline{g(i)}^2 - (\sum_i \overline{g(i)})^2}}$$

$$rc(f,g) = \frac{\sum_i (\overline{f(i)} - \overline{f})(\overline{g(i)} - \overline{g})}{\sqrt{\sum_i (\overline{f(i)} - \overline{f})^2} \sqrt{\sum_i (\overline{g(i)} - \overline{g})^2}}$$

Here, $\overline{f(i)}$ is equal to the average function value $f(t)$ of paths $t \in T_i$, $\overline{g(i)}$ is the average percentage of success of the paths in T_i , and \overline{f} and \overline{g} are equal to the average value over all i of $\overline{f(i)}$ and $\overline{g(i)}$, respectively. The correlation coefficient measures the extent to which the two attributes f and g are correlated. If we want a task at a certain difficulty level to always be harder than a task at the previous level, then we primarily aim for a high rank correlation coefficient, as it describes the extent to which the relation between the classifier output and path difficulty can be described using a monotonic function.

We call a measure correlated with path difficulty if it has a correlation larger than 0.8 or smaller than -0.8 . For simplicity, we denote the correlation and rank correlation coefficient by c and rc , respectively.

3 RELATED WORK

The structure behind Wikipedia has been analyzed in great detail, addressing tasks such as improving the linking structure (Milne and Witten, 2008) and automatic disambiguation of articles (Hu et al., 2009). Patterns within clickpaths have also been analyzed extensively, and have proven useful for tasks such as page prediction (Agarwal et al., 2010). These patterns are often found within clickstreams from the web, where there is a great deal of “noise”, by which we refer to duplicate, false or untrusted information. An advantage of studying paths on Wikipedia is that due to the active user base, there is much less noise. Using a dataset similar to ours, a comparison between automatic and human navigation in Wikipedia was made in (West and Leskovec, 2012a). An extensive analysis

of the path data was done and methods for predicting the target page were introduced (West and Leskovec, 2012b). To the best of our knowledge, the issue of path difficulty has so far been unaddressed.

4 LOCAL DIFFICULTY MEASURES

In this section we consider *local* difficulty measures that depend solely on a node and its neighborhood, in our case the Wikipedia article and its linked or linking articles.

4.1 Degree Measures

Having a large number of outgoing links for a certain node is likely to make it easier to directly reach a larger part of the graph from that particular node. Similarly, we expect that the number of incoming links of a node will probably make it relatively more easy to reach that node from any other node. We will verify the actual influence of these two measures by analyzing $q = 100$ ranges of goal article's indegrees and start article's outdegrees. The results are depicted in Figure 3, and a Bezier curve is drawn to get a better idea of the overall correlation. We observe no real significant correlation with the starting article's outdegree ($c = 0.637$ and $rc = 0.789$). However, a strong correlation ($c = 0.850$ and $rc = 0.960$) is noticeable with respect to the indegree of the goal article and the actual percentage of success. Apparently, the indegree of the goal article is of great influence to the difficulty of finding a certain path, whereas the outdegree of the starting node does not appear to play a very significant role. Because the graph is stored as an adjacency list, degree measures can be computed in $O(1)$.

4.2 Neighborhood Measures

Extending the degree measure, we define the ℓ -neighborhood $N_\ell(v)$ of a node $v \in V$ as the set of nodes with distance at most ℓ from v , more specifically: $N_\ell(v) = \{w \in V \mid d(v, w) \leq \ell\}$. Similarly, we can define $N'_\ell(v) = \{u \in V \mid d(u, v) \leq \ell\}$, the *reverse neighborhood*, which is the set of all articles u with distance at most ℓ to v . The ℓ -neighborhood size is the number of nodes in the neighborhood of v , denoted by $|N_\ell(v)|$, and similarly we can define the *reversed ℓ -neighborhood size* $|N'_\ell(v)|$. The functionality of this measure can be explained by looking at the example graph in Figure 1. There, the article on Ice Hockey

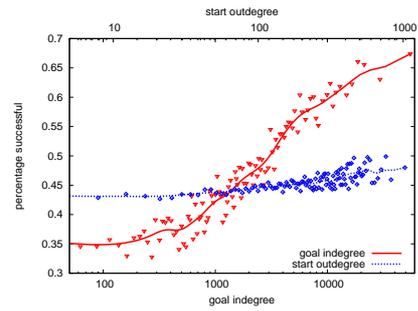


Figure 3: Start outdegree and goal indegree (horizontal axes, logarithmic) vs. percentage successful (vertical axis).

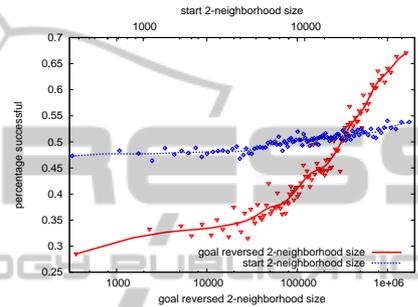


Figure 4: Start & goal 2-neighborhood measures (horizontal axes, logarithmic) vs. percentage successful (vertical axis).

and the article on Ireland (island) both have an indegree of 1, while intuitively, but also based on the degree of the neighbors, Ice Hockey seems much easier to reach than Ireland (island), which is nicely reflected by the reversed 2-neighborhood size, as $|N'_2(\text{Ireland (island)})| = 3$ and $|N'_2(\text{Ice Hockey})| = 6$.

Figure 4 shows $q = 100$ intervals of the goal article's reversed 2-neighborhood, again compared to the success percentage, and strong correlation coefficients ($c = 0.915$ and $rc = 0.978$) can be observed. We notice how for the hardest ($g(t) < 0.35$) tasks in the database, looking beyond the indegree apparently helps to increase the amount of monotonicity. Again, the starting node's 2-neighborhood did not appear to be relevant ($c = 0.397$ and $rc = 0.492$).

Even though in some graphs it makes sense to look at (reverse) neighborhoods larger than $\ell = 2$, in our dense Wikipedia graph, considering more than the 2-neighborhood will quickly yield the entire graph, and indeed, correlation coefficients lower than 0.5 are observed when considering larger neighborhoods. We note that the neighborhood measures discussed here can be computed in $O((m/n)^{\ell-1})$ time per task. The average node indegree (or outdegree), (m/n) , is between 20 and 30, still allowing for quick computation of this local measure, especially for $\ell = 2$.

Concluding this section on local measures, we can say that the reversed 2-neighborhood size is the best

indicator for path difficulty, whereas measures related to the starting article do not appear to be effective. This can be explained by considering the small-world property of the Wikipedia: with relatively few steps it is possible to reach a large portion of the graph via so-called hubs. The user will often find his way to a hub node very quickly, from where the actual search for the goal node starts, making the first part of the search of little influence in general.

5 GLOBAL DIFFICULTY MEASURES

In contrast with the previous section, we will now look at *global* properties of the nodes, meaning that we look at actual paths and global centrality measures, using knowledge about the entire graph. Though possibly better in terms of prediction strength, the computation time of global measures is longer, typically $O(m)$ per task.

5.1 Path Length

As mentioned in Section 2 and shown in Figure 2, the distribution of user-generated path lengths follows the same type of distribution as that of the actual shortest paths, suggesting a correlation between the two. Whereas we were able to aggregate our local measures from the previous section into $q = 100$ intervals, in case of shortest path length we only have 6 different values. In Figure 6, the solid line shows for each actual *distance* the percentage of successful human paths. This shows a strong correlation coefficient of $c = -0.957$ between the computed shortest path length and the percentage of successful paths, and an obvious rank correlation of $rc = -1.000$. A clear downside of this measure is the fact that we can only define $q = 6$ different difficulty levels.

5.2 Number of Shortest Paths

We may also choose to look at the *number* of shortest paths $\sigma(u, v)$ between the start and goal article u and v . Intuitively, if there is only one shortest path from the start node to the end node, the task will be much harder compared to when there would have been thousands of shortest paths. Luckily, computing actual shortest path lengths is easy, as $\sigma(u, u) = 1$ and $\sigma(u, v) = \sum_{w \in B(u, v)} \sigma(u, w)$ with $B(u, v) = \{w \in N_1'(v) : d(u, v) = d(u, w) + 1\}$ (Brandes, 2001). The number of shortest paths showed no significant correlation with path difficulty, which is understandable: a

path of length 2 with 20 possible shortest paths is expected to be much easier to find than a path of length 4 with 20 shortest paths. So we propose to combine the distance with the number of shortest paths:

$$dsp(u, v) = d(u, v) + \alpha \left(1 - \frac{\log \sigma(u, v)}{\max_{w, z \in V} (\log \sigma(w, z))} \right)$$

The reason why we take the log of $\sigma(u, v)$ is motivated by Figure 5, where the thick lines indicate how the distribution of the number of shortest paths for each shortest path length decreases logarithmically. The parameter $\alpha \geq 0$ essentially defines the amount of focus on the number of shortest paths. If this parameter is set to 1, then a path of length 4 with only 1 possible shortest path is assumed to be easier to find than a path of length 5 with 2000 different shortest paths. After some parameter tuning we obtained the best results for $\alpha = 1.5$, where we observe again a strong correlation of $c = -0.895$ and $rc = -0.876$ with path difficulty. The results are depicted in Figure 6.

5.3 Shortest Paths Uniqueness

To further refine the measure from the previous section, we propose to look at the number of *distinct nodes* that occur within these shortest paths. This measure is based on the intuition that shortest paths quickly overlap, and that the extent to which paths overlap may influence the difficulty of a path finding

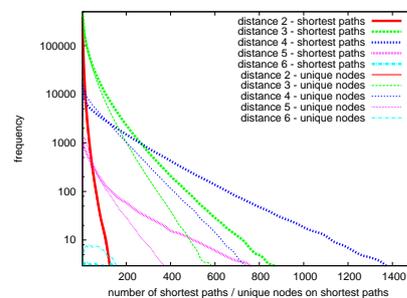


Figure 5: Distribution of number of shortest paths and number of unique nodes on these paths for each distance.

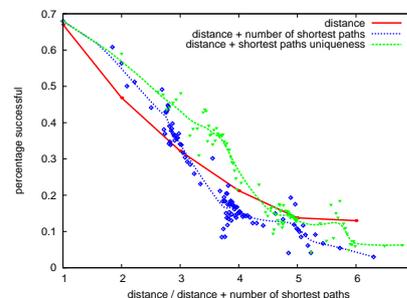


Figure 6: Various global measures (horizontal axis) vs. percentage successful (vertical axis).

task. For example, in Figure 1, the 3 shortest paths of length 3 from MP3 to United Kingdom run through a total of 4 different nodes: United States, Internet, Europe and Ice Hockey. The maximum number of unique nodes on 3 shortest paths of length 3 is 6 (3 times 2 unique intermediary nodes). Somewhat inspired by betweenness centrality, we propose to divide the number of nodes on the actual shortest paths by the maximum possible number of intermediary nodes, a measure which we will call *shortest paths uniqueness*. In our example this results in a score of $\frac{4}{6} \approx 0.67$. We will incorporate this measure along with the distance in the difficulty classifier defined as:

$$dsp(u, v) = d(u, v) + \beta \left(1 - \frac{\log(\psi(u, v))}{\log(d(u, v) \times \sigma(u, v))} \right)$$

Here, $\psi(u, v)$ is a function that returns the number of distinct nodes on the shortest paths between u and v . The used values are again logarithmic as a result of the distribution of the number of unique nodes on the shortest paths, depicted by the various thin lines in Figure 5. The parameter $\beta \geq 0$ indicates the amount of focus on the number of distinct nodes over all shortest paths, and best results were obtained for $\beta = 1.75$.

The performance of the measure is displayed by the dotted line in Figure 6, showing a correlation of $c = -0.924$ and $rc = -0.925$, demonstrating how shortest paths uniqueness is a good refinement of the global difficulty indicator based solely on distance.

6 CONCLUSIONS

Throughout this paper we have proposed and analyzed a range of techniques for classifying path traversal difficulty in information networks. The results are summarized in Table 2. Local measures related to the goal article, such as the reversed neighborhood size, appear to be most effective, whereas local properties of the source article appear to be of little influence to path difficulty. Apparently, a user tends to quickly find his way to a hub node, from where the actual search process starts. As for the global measures considered in this work, the distance between two articles, though limited in range, is a good measure of difficulty. Incorporating the percentage of unique nodes over all shortest paths results in a global classifier with slightly better performance, but due to the higher complexity of global measures, one may favor the local classifiers in a practical application such as The Wiki Game, where the difficulty classifiers could be used to allow users to select a difficulty level.

In future work we would like to include more article-specific information, such as the article's link

Table 2: Summary of correlation coefficients (c), rank correlation coefficients (rc) and complexity per task $t = (u, v)$ of the proposed difficulty classifiers for q difficulty classes.

Classifier	Complexity	q	c	rc
$indeg(v)$	$O(1)$	100	0.850	0.960
$outdeg(u)$	$O(1)$	100	0.637	0.789
$ N_2^i(v) $	$O(m/n)$	100	0.915	0.978
$ N_2(u) $	$O(m/n)$	100	0.397	0.492
$d(u, v)$	$O(m)$	6	-0.957	-1.000
$dsp(u, v)$	$O(m)$	100	-0.895	-0.876
$dusp(u, v)$	$O(m)$	100	-0.924	-0.925

density, which loosely represents the branching factor. We also want to analyze a user's frequent subpaths, which may help us to obtain a better understanding of the search process of a certain user or group of similar users, possibly allowing us to personalize the difficulty indicators.

ACKNOWLEDGEMENTS

This research is part of the NWO COMPASS project (#612.065.926). We thank A. Clemesha for the data.

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