

Compactified Horizontal Visibility Graph for the Language Network

D.V. Lande^{1,2}, A.A.Snarskii^{1,2}

¹Institute for information recording, NAS Ukraine, Kiev, Ukraine

²National Technical University “Kiev Polytechnic Institute”, Kiev, Ukraine

A compactified horizontal visibility graph for the language network is proposed. It was found that the networks constructed in such way are scale free, and have a property that among the nodes with largest degrees there are words that determine not only a text structure communication, but also its informational structure.

Key words: language network, complex network, scale-free network, visibility graph.

Construction of networks with text elements, words, phrases or fragments of natural language as nodes in some cases allows to detect the structural elements of the text critical for its connected structure and find informationally significant elements, as well as words that are secondary for understanding of the text. Such networks may also be used to identify unconventional text components, such as collocations, supra-phrasal units [1], as well as for finding similar fragments in different texts [2].

There is a multitude of approaches to constructing networks from the texts (so-called language networks) and different ways of interpreting nodes and links, which causes, accordingly, different representation of such networks. Nodes are connected if corresponding words are either adjacent in the text [3, 4], or are in a single sentence [5], or are syntactically [6, 7] or semantically [8, 9] connected.

At the intersection of digital signal processing (DSP) theory and complex network theory there are several ways of constructing networks from the time series, among those are visibility graph construction methods (see survey [10]), namely the horizontal visibility graph (HVG) [11,12]. Based on these approaches, networks can also be constructed from texts in which numeric values are assigned in some manner to each word or phrase. The examples of functions assigning a number to a word are: ordinal number of a unique word in a text, length of the word, “weight” of the word in a text, e.g., generally accepted TFIDF metric (canonically, a product of the term frequency in a text fragment and a

binary logarithm of the inverse number of text fragments containing this word – inverse document frequency) or its modifications [13, 14] and other word weight estimates.

In this paper, the standard deviation estimate of word weight is used for constructing word networks [15]. If all the words in the text of N words are numbered in succession (let $n=1,\dots,N$ be the ordinal number of the word in a text, the word position), layout of a certain word A can be designated as $A_k(n)$, where $k=1,2,\dots,K$ denotes the number of occurrence of this word in a text, and n is a position of this word in a text. For example, $A_3(50)$ means that the third occurrence of the word A has position 50 in the text.

The distance between successive occurrences of the word in these terms would be $\Delta A_k = A_{k+1}(m) - A_k(n) = m - n$, where m and n are the positions of the $k+1$ -th k -th occurrences of the word A in the text, respectively.

Standard deviation estimate proposed in [15] is calculated as follows:

$$\sigma_A = \frac{\sqrt{\langle \Delta A^2 \rangle - \langle \Delta A \rangle^2}}{\langle \Delta A \rangle}, \quad (1)$$

where $\langle \Delta A \rangle$ is a mean value of the sequence $\Delta A_1, \Delta A_2, \dots, \Delta A_K$, $\langle \Delta A^2 \rangle$ is a mean value of $\Delta A_1^2, \Delta A_2^2, \dots, \Delta A_K^2$, and K is a number of occurrences of the word A in the text.

As opposed to other series examined in DSP theory, the series of numerical values assigned to words are transformed into horizontal visibility graphs (HVG), where each node not only has a corresponding numerical value, but also the corresponding word itself.

The process of constructing the language network using HVG consists of two stages. At the first stage, the traditional HVG is constructed [16]. To do that a series of nodes is put on the horizontal axis, where each node corresponds to a word in order of occurrence in the text, and standard deviation estimates are put on the vertical axis (visually a histogram, see fig. 1). There is a connection between nodes if they are in “line of sight” with each other, i.e., if they can be connected by a horizontal line that does not cross any other histogram bar. This

(geometric) criterion can be written down as follows, according to [10,11]: the two nodes (words), e.g., $B_3(n)$ and $C_7(m=n+5)$, are connected if (see fig. 1)

$$\sigma_n, \sigma_m > \sigma_p, \text{ for all } n < p < m. \quad (2)$$

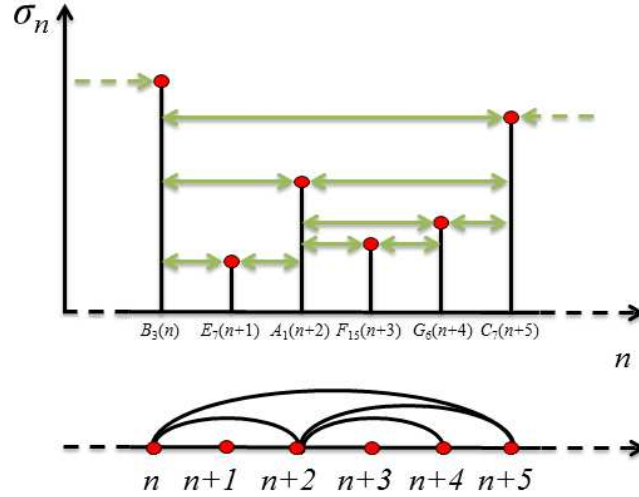


Figure 1. An example of HVG construction

The process of constructing can be algorithmized. For example, in figure 1 the word node $A_1(n+2)$ is considered incident (and is connected with edges) to the words $B_3(n)$ and $C_7(n+5)$, $B_3(n)$ being the closest word to the left of $A_1(n+2)$ with a standard deviation estimate $\sigma_n = \sigma_B$ greater than that of the word A : $\sigma_{n+2} = \sigma_A$, and $C_7(m=n+5)$ being the closest word to the right of $A_1(n+2)$, for which $\sigma_m > \sigma_A$.

At the second stage, the derived network is compactified. All the nodes corresponding to a single word, e.g., the word A , are combined into a single node (naturally, occurrence numbers and positions of the words are lost). The connections of these nodes are also combined. Note that there is no more than one edge left between any pair of nodes, multiple connections are removed (see fig. 2).

This means, in particular, that the degree (number of connections) of the node A does not exceed the sum of degrees $\sum_k A_k(n)$. As a result, the new network of words – *compactified horizontal visibility graph* (CHVG) – is constructed (fig. 2).

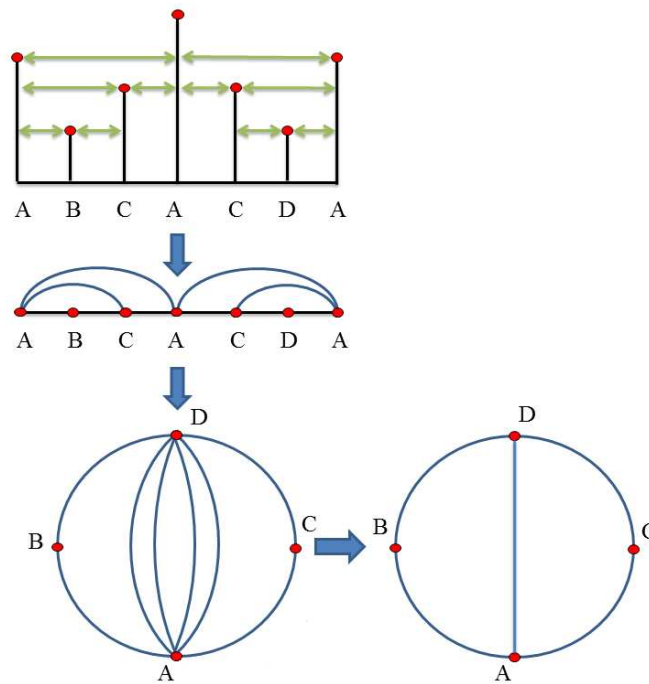


Figure 2. Two stages in construction of CHVG

Texts used for CHVG construction were the novels “The Master and Margarita” (original version) by Mikhail Bulgakov and “Moby-Dick; or, The Whale” by Herman Melville, as well as arrays of news information from the Web.

For all CHVG networks of words described here, the degree distribution is close to power law (fig. 3), i.e., these networks are scale free.

For comparison, was studied for the simplest language networks, where during the first stage of the network construction adjacent words were connected, and, at the second stage, the network was compactified. It is obvious that the weight of a node in such network corresponds to the word frequency, and the distribution of these weights follows the Zipf law [18]. The most connected are the nodes corresponding to the most frequently occurring words – conjunctions, prepositions, etc., which are very important for the text coherence, but are of little interest for the aspect of informational structure.

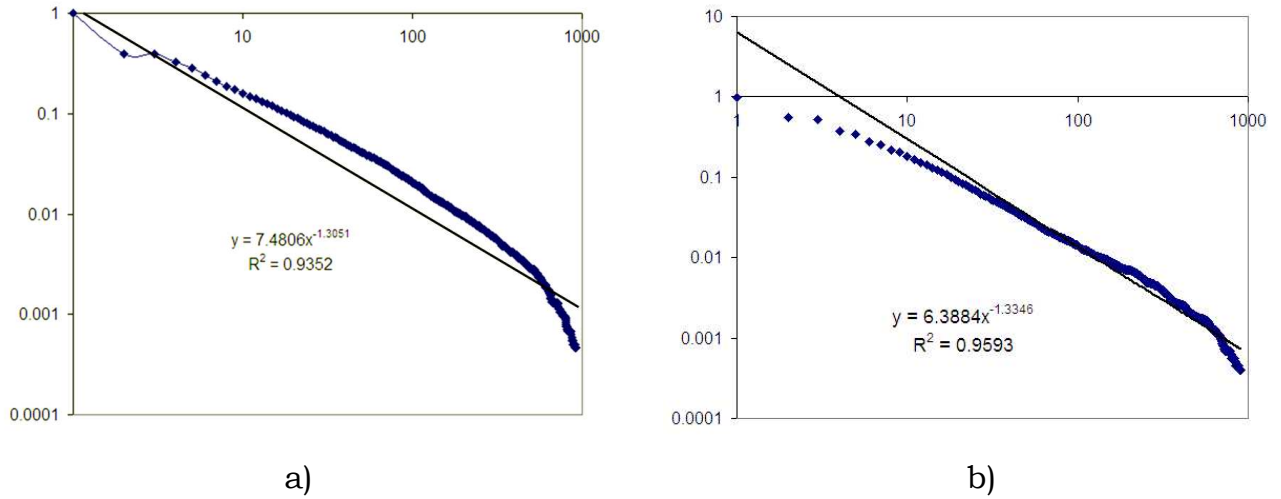


Figure 3. Node degree distribution (log-log scale) of CHVG constructed from “The Master and Margarita” (a) and “Moby-Dick; or, The Whale” (b). Horizontal axis contains node degrees k , vertical axis shows the values $1 - F(k)$, where $F(k)$ is a distribution function of node degrees

Among the nodes with largest degrees, alongside with personal pronouns and other function words (particles, prepositions, conjunctions, etc.), are the words, which determine the informational structure of the text [16, 17].

Let Ψ be a set of N different words (in our case $N = 100$) corresponding to the largest-weight nodes of the aforementioned simple language network, and let Λ be a set of words corresponding to the largest-weight nodes of the CHVG. Then the set $\Omega = \Lambda \setminus \Psi$ will contain informational words, which are also important for the text coherence. Appendix gives juxtaposition of the top 100 largest-weight nodes for the two types of language networks constructed from the novels “The Master and Margarita” by Michael Bulgakov and “Moby-Dick; or, The Whale” by Herman Melville.

In particular, the Ω set of the CHVG built from “Мастер и Маргарита” contains such words as Иван, Мастер, Варенуха, Берлиоз, Бегемот, Римский, профессор, Левий, Иешуа.

The following results were obtained from studying the language networks:

1. An algorithm compactified horizontal visibility graph (CHVG) was proposed.
2. Language networks were built from different texts based on series of standard deviation estimates and CHVG.

3. In CHVG obtained from literary works, among the largest-degree nodes there are words responsible not only for the coherence of the text, but also for its informational structure. They reflect the meaning of the mentioned texts.

References

1. *Dijk van T.A.* Text and Context: Explorations in the Semantics and Pragmatics of Discourse. – London: Longman. –357 p. (1977).
2. *Broder A.* Identifying and Filtering Near-Duplicate Documents, COM'00 // Proceedings of the 11th Annual Symposium on Combinatorial Pattern Matching. – P. 1-10 (2000).
3. *Ferrer-i-Cancho R., Sole R. V.* The small world of human language // Proc. R. Soc. Lond. – B 268, 2261 (2001).
4. *Dorogovtsev S.N., Mendes J. F. F.* Language as an evolving word web // Proc. R. Soc. Lond. – B 268, 2603 (2001).
5. *Caldeira S. M. G., Petit Lobao T. C., Andrade R. F. S., Neme A., Miranda J. G. V.* The network of concepts in written texts // Preprint physics/0508066 (2005).
6. *Ferrer-i-Cancho R., Sole R.V., Kohler R.* Patterns in syntactic dependency networks // Phys. Rev. E 69, 051915 (2004).
7. *Ferrer-i-Cancho R.* The variation of Zipf's law in human language. // Phys. Rev. E 70, 056135 (2005).
8. *Motter A. E., de Moura A. P. S., Lai Y.-C., Dasgupta P.* Topology of the conceptual network of language // Phys. Rev. E 65, 065102(R) (2002).
9. *Sigman M., Cecchi G. A.* Global Properties of the Wordnet Lexicon // Proc. Nat. Acad. Sci. USA, 99, 1742 (2002).
10. *Nunez A. M., Lacasa L., Gomez J. P., Luque B.* Visibility algorithms: A short review // New Frontiers in Graph Theory, Y. G. Zhang, Ed. Intech Press, ch. 6. – P. 119 – 152 (2012).
11. *Luque B., Lacasa L., Ballesteros F., Luque J.* Horizontal visibility graphs: Exact results for random time series // Physical Review E,– P. 046103-1–046103-11 (2009).
12. *Gutin G., Mansour T., Severini S.* A characterization of horizontal visibility graphs and combinatoris on words // Physica A, – 390 – P. 2421-2428 (2011).

13. *Jones K.S.* A statistical interpretation of term specificity and its application in retrieval // *Journal of Documentation*. – 28 (1). – P. 11–21 (1972).
14. *Salton G., McGill M. J.* Introduction to Modern Information Retrieval. – New York: McGraw-Hill. – 448 p. (1983).
15. *Ortuño M., Carpena P., Bernaola P., Muñoz E., Somoza A.M.* Keyword detection in natural languages and DNA // *Europhys. Lett*, – 57(5). – P. 759-764 (2002).
16. *Dijk van T.A.* Issues in Functional Discourse Analysis / In H. Pinkster (Ed.), *Liber Amicorum for Simon Dik* . – Dordrecht: Foris. – P. 27-46. (1990).
17. *Giora R.* Segmentation and Segment Cohesion: On the Thematic Organization of the Text // *Text. An Interdisciplinary Journal for the Study of Discourse* Amsterdam. – 3. – № 2. – P. 155-181 (1983).
18. *Zipf G.K.* Human Behavior and the Principle of Least Effort. – Cambridge, MA: Addison-Wesley Press. – 573 p. (1949).

Appendix

Table 1. Juxtaposition of the top 100 largest-weight nodes of the word networks constructed from Bulgakov's "The Master and Margarita"*

Simple network		CHVG	
Weight	Word	Weight	Word
5724	И	14724	И
3591	В	12880	В
2235	НА	8069	НЕ
1893	НЕ	7550	НА
1616	С	6511	ЧТО
1396	ЧТО	6050	ОН
1204	ОН	5225	ТО
1081	А	5224	Я
979	ЕГО	5105	С
936	ТО	4518	<i>МАРГАРИТА</i>
936	КАК	3642	ЕГО
899	НО	3396	А
809	К	3009	К
760	Я	2996	КАК
709	ИЗ	2848	ИВАН
680	ПО	2847	ОНА
634	ЗА	2562	ИЗ
555	ОТ	2509	ВЫ
553	У	2441	<i>ПРОКУРАТОР</i>
534	ЭТО	2317	ЗА
521	ВСЕ	2313	ПО
520	ЖЕ	2206	БЫЛО
514	ОНА	2076	ЭТО
484	МАРГАРИТА	2057	НО
460	ЕЕ	2000	У
409	БЫЛО	1989	О
403	ПОД	1940	ЕЕ
403	БЫЛ	1914	ВСЕ
400	ТАК	1904	<i>КОРОВЬЕВ</i>
382	ВЫ	1859	<i>ВОЛАНД</i>
379	УЖЕ	1815	БЫ
375	ЕМУ	1761	БЫЛ
333	БЫ	1721	<i>КОТ</i>
328	О	1696	ТАК
321	ТУТ	1693	<i>АЗАЗЕЛЛО</i>
313	ТОЛЬКО	1687	ЖЕ
307	ЕЩЕ	1602	ПОД
297	ТЫ	1568	ТЫ
297	МНЕ	1439	<i>ПИЛАТ</i>
281	НИ	1418	ОТ
281	МЕНЯ	1374	БЕРЛИОЗ
281	ДА	1337	НИ
277	ЭТОГО	1323	МНЕ
276	ИВАН	1321	МЕНЯ
258	ГДЕ	1315	ЕМУ
254	ЧТОБЫ	1208	ДА
254	ОЧЕНЬ	1179	ТУТ
250	КОГДА	1147	ВОТ
250	ДО	1095	НЕТ
241	НЕТ	1030	ТОЛЬКО

Simple network		CHVG	
Weight	Word	Weight	Word
237	ЭТОТ	1020	ЧЕЛОВЕК
222	КОТ	1007	ВАС
219	ПРОКУРАТОР	978	СКАЗАЛ
219	ГЛАЗА	961	ЭТОГО
215	СО	944	ГОСТЬ
213	ВАС	919	ГДЕ
212	ИЛИ	905	ВАРЕНУХА
210	ВОТ	886	МАСТЕР
209	СОВЕРШЕННО	871	НИКАНОР
207	ЧЕЛОВЕК	866	БУФЕТЧИК
206	ЛИ	861	УЖЕ
206	КОРОВЬЕВ	825	ТЕПЕРЬ
204	ТЕПЕРЬ	815	ЕЩЕ
199	АЗАЗЕЛЛО	807	ЧТОБЫ
197	ИХ	805	ИВАНОВИЧ
193	СКАЗАЛ	803	НУ
187	НАД	798	СТЕПА
184	ВАМ	790	НАД
183	СЕБЯ	766	ВАМ
183	ОНИ	761	ВО
183	КТО	740	РИМСКИЙ
182	БЫЛА	738	ОЧЕНЬ
177	ПЕРЕД	724	ОТВЕТИЛ
175	ТОТ	722	СО
172	ЧЕРЕЗ	720	КОГДА
171	БЫЛИ	719	НИЧЕГО
166	ВО	671	МАРГАРИТЕ
165	ВОЛАНД	663	ЛИЦО
165	НЕГО	657	ПРОФЕССОР
162	ТОГДА	656	ЛИ
157	ОТВЕТИЛ	652	ИВАНА
157	ЛИЦО	651	ЧЕРЕЗ
156	ДАЖЕ	649	МЫ
153	ВРЕМЯ	644	ВРЕМЯ
150	СЕЙЧАС	641	ДО
149	ЧЕМ	636	ОНИ
149	ПИЛАТ	633	НЕГО
147	ПРИ	623	ЭТОТ
147	ПОСЛЕ	619	ПОСЛЕ
147	ЕЙ	612	МАРГАРИТЫ
145	ОПЯТЬ	609	БЕГЕМОТ
144	НУ	607	ИХ
141	КАКОЙ	598	ЧЕМ
139	ЗДЕСЬ	590	ЕЙ
139	МЫ	588	ТОГО
138	НИЧЕГО	577	ЛЕВИЙ
138	КОНЕЧНО	575	СЕБЯ
137	ТАМ	575	АФРАНИЙ
137	БЕЗ	569	ИЕШУА
136	ТОГО	568	КАКОЙ

* The words present in the first one hundred of CHVG nodes but absent from the first one hundred of simple network nodes are in bold. The most informationally significant words from the CHVG top 100, which are also present in simple network top 100, are in italics.

Table 2. Juxtaposition of the top 100 largest-weight nodes of the word networks constructed from Melville's "Moby-Dick; or, The Whale"*

Simple network		CHVG	
Weight	Word	Weight	Word
6612	THE	41291	THE
5589	AND	23567	OF
4257	OF	17704	I
3083	A	16585	A
2862	TO	16577	AND
2730	IN	14853	HIS
2050	THAT	11976	IS
1915	HIS	11961	TO
1568	BUT	11582	HE
1524	IT	11431	WAS
1400	HE	10956	IN
1341	WITH	9883	WHALE
1301	FOR	9516	THAT
1281	I	9244	IT
1248	AS	7483	AS
1166	IS	7224	YOU
1152	WAS	6640	AHAB
1148	THIS	6457	HIM
1086	ALL	5727	BE
1008	BY	4867	BY
977	SO	4753	THIS
924	OR	4747	ALL
887	AT	4647	WITH
847	FROM	4578	ME
832	ON	4511	BUT
796	NOW	4403	HAD
784	NOT	4182	YE
733	WERE	4147	THEIR
721	THERE	4143	FROM
713	ONE	4038	FOR
703	HIM	3921	MY
697	THEIR	3645	WERE
694	YOU	3618	NOT
684	BE	3405	AT
671	LIKE	3352	BOAT
653	THEY	3289	<i>SHIP</i>
643	THEN	3276	ON
614	ARE	3238	ARE
609	MY	3113	THEY
597	HAD	3104	OR
596	WHICH	3077	<i>STUBB</i>
594	WHALE	3077	QUEEQUEG
581	SOME	3052	NOW
580	AN	3022	THERE
563	NO	2997	<i>CAPTAIN</i>
547	WHEN	2979	WE
511	UPON	2869	SO
502	HAVE	2635	WHICH
479	ME	2618	SEA
478	WHAT	2592	HER

Simple network		CHVG	
Weight	Word	Weight	Word
467	MORE	2591	OUT
458	OUT	2590	SPERM
451	WE	2575	HAVE
445	UP	2538	OLD
441	INTO	2482	THOU
433	THESE	2351	THEM
431	OLD	2317	WHALES
429	AHAB	2291	ONE
425	THEM	2259	ITS
425	ITS	2252	MAN
414	YE	2214	WHAT
397	YET	2187	STARBUCK
381	HER	2159	LIKE
380	WHO	2085	WHITE
369	OVER	2053	INTO
361	STILL	2010	MORE
360	THOUGH	1981	NO
360	ONLY	1944	THEN
353	MAN	1934	SOME
352	HERE	1903	UP
351	WILL	1891	AN
348	SEA	1872	UPON
343	SUCH	1846	THESE
343	LONG	1836	SUCH
339	VERY	1788	WHEN
338	WOULD	1694	BEEN
336	ABOUT	1665	PEQUOD
331	THOSE	1634	ABOUT
326	BEEN	1592	THOUGH
321	OTHER	1589	SEEMED
320	YOUR	1574	YOUR
318	THOU	1549	OVER
317	IF	1544	OUR
316	DOWN	1540	THOSE
310	ANY	1540	DECK
307	AFTER	1521	HAS
306	MOST	1496	HEAD
304	SHIP	1491	MEN
303	TWO	1459	MOST
301	THAN	1446	WILL
301	CHAPTER	1443	WOULD
300	BEFORE	1428	DOWN
295	GREAT	1419	DO
294	AGAIN	1415	US
283	SEEMED	1415	HERE
283	BEING	1399	GREAT
280	HOW	1385	YET
279	WHILE	1357	SAID
275	CAPTAIN	1342	VERY
268	STUBB	1335	ANY

* The words present in the first one hundred of CHVG nodes but absent from the first one hundred of simple network nodes are in bold. The most informationally significant words from the CHVG top 100, which are also present in simple network top 100, are in italics.