

THE STRUCTURAL DIMENSION OF COOPERATION

Cooperation Networks as Cohesive Small Worlds

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Abstract

The last half of twentieth century has witnessed a key shift in the production process of knowledge: the most important discoveries and innovations in science and technology are not anymore the result of the work of very talented individuals working alone, but the result of cooperation and teamwork. The remarkable increase in scale of cooperation in knowledge intensive production processes has renewed the interest in analyzing the mechanisms by which large scale cooperation emerges and thrives.

The two main theoretical approaches to cooperation are, on the one hand, a micro approach that considers cooperation as an atomic process in which cooperation is produced between two individuals and, on the other hand, as a macro level phenomenon in which the center of analysis is the collectively or group. The aim of this research is to bridge the gap between macro level and micro level approaches to cooperation by focusing on meso level mechanisms, which until recently have received little attention in the theoretical debate. I argue that a meso level approach has to focus on the structural dimension of cooperation, that is, the patterns of relations between the individuals that participate in production processes, what I call cooperation networks. This perspective shows that between the dyadic interactions among individuals, and the shared goals and values that guide large organizations and groups, there are subgroups of individuals that play a key role in enabling the kind of large scale cooperation that we have witnessed during the last decades.

This research focuses on the case study of two large, mature, and successful Free and Open Source Software (FOSS) projects —the Debian operating system and the Python programming language— in order to build a structural theoretical framework that helps explain and understand how large scale cooperation works. I present a network model, that I name Cohesive Small World, which is based on two well established network models: the Small World model and the Structural Cohesion model. I propose that these two models are not mutually exclusive. The family of networks that fit in the intersection of both models exhibit consistent structural patterns. These patterns, I argue, provide the scaffolding for the emergence of collaborative communities, such as FOSS projects, and enable and foster effective large scale cooperation.

On the one hand, the generation of trust and congruent values among heterogeneous individuals are fostered by structurally cohesive groups in the connectivity hierarchy of cooperation networks because individuals embedded in these structures are able to compare independent perspectives on each other through a variety of paths that flow through distinct sets of intermediaries, which provides multiple independent sources of information about each other. Thus, the perception of an individual embedded in such structures of the other members of the group to whom she is not directly linked is filtered by the perception of a variety of others whom she trusts because is directly linked to them. This mediated perception of the group generates trust at a global scale. On the other hand, the existence of dense local clusters connected between them by relative short paths allows successful cooperation among heterogeneous individuals with common interests and, at the same time, fosters the flow of information between these clusters preventing the local clusters to be trapped in echo chambers of like minded collaborators.

I developed heuristics to compute the k -components structure, along with the average node connectivity for each k -component. These heuristics allow to compute the

approximate value of group cohesion for moderately large networks, along with all the hierarchical structure of connectivity levels, in a reasonable time frame. I show that these heuristics can be applied to networks at least one order of magnitude bigger than the ones manageable by the only algorithm available until now. I test empirically the new network model that I proposed to further our understanding how cooperation in collaborative communities works. I find that the model that I named “Cohesive Small World” is a good fit to describe the cooperation patterns of the two big and mature FOSS projects that I analyze in the empirical part of this thesis.

To further the empirical analysis, I explore the dynamic dimension of the connectivity hierarchies that emerge on the cooperation networks of the Python and Debian projects. I defined cooperation networks as the patterns of relations among developers established while contributing to the project. The dynamic analysis that I present is not only a longitudinal account of the changes in the hierarchy through time, but also the analysis of the pace of renewal of individuals in the positions defined by the hierarchy. I show that the Cohesive Small World model is a solid theoretical framework to define cohesive groups in cooperation networks. The nested structure of k -components nicely captures the hierarchy in the patterns of relations that individual contributors establish when working together. This hierarchy, on the one hand, reflects the empirically well established fact that in FOSS projects only a small fraction of the developers account for most of the contributions. And, on the other hand, refutes the naive views of early academic accounts that characterized FOSS projects as a flat hierarchy of peers in which every individual does more or less the same.

I also show that the position of individual developers in the connectivity hierarchy of the cooperation networks impacts significantly, on the one hand, on the volume of contributions that an individual does to the project. And, on the other hand, the median active life of developers in the project. I argue that the latter is a better way to analyze robustness of FOSS projects than the classical random and targeted attacks that has been used to assess robustness in other kinds of networks.

I argue that the connectivity structure of collaborative communities’ cooperation networks can be characterized as an open elite, where the top levels of this hierarchy are filled with new individuals at a high pace. This feature is key for understanding the mechanisms and dynamics that make FOSS communities able to develop long term projects, with high individual turnover, and yet achieve high impact and coherent results as a result of large scale cooperation. I conclude that cooperation in FOSS communities has a structural dimension because membership in cohesive groups that emerge from cooperation networks has an important and statistically significative impact on both the volume of individual contributions, and on the median active life of developers in the projects under analysis.

Resum

L'última meitat del segle XX ha estat testimoni d'un canvi fonamental en el procés de producció de coneixement: els descobriments més importants i les innovacions en ciència i tecnologia no són el resultat de la tasca de persones amb molt talent que treballen soles, sinó que són el resultat de processos de cooperació i de treball en equip. El notable augment de l'escala de la cooperació en els processos de producció intensius en coneixement ha renovat l'interès en l'anàlisi dels mecanismes pels quals emergeix i prospera la cooperació a gran escala.

Els dos principals enfocaments teòrics sobre la cooperació són, d'una banda, un enfocament micro que considera que la cooperació com un procés atòmic en el qual l'interès es centra en com es produceix cooperació entre dues persones i, d'altra banda, com un fenomen a nivell macro en el qual el centre de l'anàlisi és el grup com a col·lectivitat. L'objectiu d'aquesta recerca és acostar posicions entre l'enfoc macro i el micro sobre la cooperació tot centrant-se en els mecanismes a nivell meso, que fins fa poc han rebut poca atenció en el debat teòric. El meu argument és que un enfocament de nivell meso ha de centrar-se en la dimensió estructural de la cooperació, és a dir, en els patrons de relacions entre les persones que participen directament en els processos de producció, el que jo anomeno xarxes de cooperació. Aquesta perspectiva mostra que entre les interaccions diàdiques entre els individus, i els grans objectius i valors compartits que guien les grans organitzacions i grups, hi ha subgrups d'individus que tenen un paper fonamental en generar i fomentar la cooperació a gran escala de la que hem estat testimonis en les últimes dècades.

Aquesta recerca es centra en l'estudi de cas de dos projectes de programari lliure (FOSS en anglès) —el sistema operatiu Debian i el llenguatge de programació Python— per tal de construir un marc teòric estructural que ens ajudi a explicar i entendre com funciona la cooperació gran escala. En aquesta tesi presento un model de xarxa, que anomeno “Cohesive Small World”, que es basa en dos models teòrics ben establerts: el model “Small World” i el model de cohesió estructural. Proposo que aquests dos models no són mútuament excloents. La família de xarxes que s'ajusten a la intersecció de tots dos models mostren patrons estructurals consistents. Aquests patrons proporcionen els fonaments per al sorgiment de comunitats de col·laboració, com ara projectes de programari lliure, i tenen un paper clau en fomentar la cooperació a gran escala.

D'una banda, els grups estructuralment cohesius en la jerarquia de connectivitat de les xarxes de cooperació generen confiança i valors compartits entre individus heterogenis perquè els individus inclosos en aquestes estructures poden comparar perspectives independents sobre cadascun dels altres membres de la col·lectivitat a través de múltiples intermediaris, la qual cosa els proporciona múltiples fonts d'informació independents. Per tant, les persones incloses en aquests grups cohesius, tenen una percepció dels altres membres de la xarxa de cooperació amb qui no estan directament connectats que està filtrada per altres membres d'aquests grups cohesius amb qui confien perquè hi estan directament connectades. Aquesta percepció mediada pels grups cohesius genera confiança i valors compartits a escala global. D'altra banda, l'existència de *clusters* locals —grups de persones que treballen estretament entre elles— connectats per distàncies relativament curtes amb altres *clusters* de la xarxa de cooperació, permet la cooperació entre individus heterogenis amb interessos comuns i, al mateix temps, fomenta el flux d'informació entre

aquests *clusters* que impedeixen que aquests grups de persones que treballen estretament entre elles siguin atrapades en caixes de ressonància formades per col·laboradors afins amb les mateixes idees.

En la part metodològica de la tesi, he desenvolupat heurístiques per a calcular l'estructura de k -components de les xarxes de cooperació. Aquestes heurístiques permeten calcular en un temps raonable el valor aproximat de la cohesió dels grups en xarxes de cooperació moderadament grans, juntament amb tota l'estructura jeràrquica dels diferents nivells de connectivitat. En la tesi demostro com aquestes heurístiques poden ser aplicades a xarxes almenys un ordre de magnitud més grans que les que podia assumir l'únic algoritme disponible fins ara. Amb l'ajuda d'aquestes heurístiques poso a prova empíricament el nou model que proposo per tal de millorar la nostra comprensió de com funciona la cooperació en les comunitats de col·laboració. L'anàlisi empírica demostra que el model estructural que proposo en la part teòrica s'ajusta als patrons de cooperació que observem en els projectes de programari lliure analitzats en la part empírica de la tesi.

L'anàlisi empírica d'aquesta tesi explora la dimensió dinàmica de les jerarquies de connectivitat que sorgeixen en les xarxes de cooperació dels projectes de Python i Debian. Defineixo xarxes de cooperació com els patrons de relació entre les persones que participen en els processos productius dels projectes analitzats. L'anàlisi dinàmic que presento no és només una anàlisi longitudinal dels canvis en la jerarquia a través del temps, sinó també una anàlisi del ritme de renovació dels individus en les posicions definides per aquesta jerarquia. Demostro que el model estructural que proposo és un marc teòric sólid per tal de definir grups cohesius en les xarxes de cooperació. L'estructura d'aquests grups cohesius defineix la jerarquia de connectivitat dels patrons de relacions que estableixen els individuals al treballar conjuntament. Aquesta jerarquia, d'una banda, reflecteix el fet empíricament ben establert que en projectes de programari lliure només una petita part dels participants contribueix la major part de la feina feta en cada projecte. I, d'altra banda, refuta les opinions ingènues dels primers relats acadèmics que caracteritzen els projectes de programari lliure com una jerarquia plana de persones en la qual cada individu fa més o menys el mateix.

L'anàlisi empírica d'aquesta tesi també mostra que la posició dels desenvolupadors individuals en la jerarquia de connectivitat de les xarxes de cooperació impacta significativament, d'una banda, en el volum de les contribucions que cada persona fa al projecte. I, d'altra banda, en el temps de vida mitjana de les persones en el projecte, entesa com el temps que de mitjana una persona és participant activa en el projecte.

Finalment, argumento que l'estructura de connectivitat de xarxes de cooperació de les comunitats de col·laboració pot caracteritzar-se com una elit oberta, on els nivells més alts d'aquesta jerarquia es renoven constantment amb la incorporació de noves persones. Aquesta característica és clau per entendre els mecanismes i dinàmiques que fan que les comunitats de programari lliure siguin capaces de desenvolupar projectes a llarg termini, amb un alt volum de renovació individual, i no obstant això, aconsegueixin uns resultats coherents com a resultat de la cooperació a gran escala. Finalment conclo el que la cooperació en les comunitats de programari lliure té una dimensió estructural ja que la pertinença a grups cohesius que sorgeixen en les xarxes de cooperació té un impacte important i estadísticament significatiu tant en el volum de les contribucions individuals com en la vida activa mitjana de les persones que participen en els projectes analitzats en aquesta tesi.

Acknowledgments

This thesis is the result of many years of work, many more than the current standards prescribed by the Spanish law that regulates PhD studies. This has been both a blessing and a curse; a blessing because working on this thesis allowed me to explore many theoretical approaches and empirical analysis relevant to the main research question. This exploration expanded my abilities in fields, such as programming and statistical analysis, that were not prominent in my undergraduate and graduate studies. But it has been also a curse because I had to discard a lot of work and interesting approaches explored during these years in order to finish the thesis and obtain a coherent final product.

First of all I'd like to thank all the people that devote their work to produce Free Software, and especially to the people that contributes to the Debian Operating System and to the Python programming language. Those are the focus of the empirical part of this thesis, but more importantly, are the main tools —along with L^AT_EX, the Vim text editor, and the R programming language— with which I made this thesis. I installed Debian back in 2004 when I first had my own computer, and it opened the door to a wealth of free software that has helped me immensely in my research career. It was searching the Debian archive that I discovered NetworkX, a Python package for the analysis of the structure and dynamics of networks. I started contributing to NetworkX in 2008 and by doing so I learned to program and to perform sophisticated network analysis. The empirical part of this thesis uses Python extensively, and it helped me immensely in sharpening my analytical and programming skills.

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Part I

Introduction

Theoretical approaches to Cooperation

Robert Merton popularized Isaac Newton's quote "if I have seen further it is by standing on the shoulders of giants". This quote highlight, on the one hand, the cumulative nature of the scientific knowledge and, on the other hand, implies that the contribution to knowledge production by highly talented individuals —the giants— is far more important than the contribution of ordinary individuals. If we look at the history of science, the names of Archimedes, Galilei, Newton, Euler, Darwin, Einstein and a few others shine strongly. It is certainly true that without their contribution to knowledge, our understanding of the universe would be far less deep and sharp. But, nowadays, have giants such a key role in the production of knowledge?

The last half of twentieth century has witnessed a key shift in the production process of knowledge. Based on works on science and engineering, social sciences, arts and humanities and Patents, Wuchty, Jones, and Uzzi (2007) show that until 1950s the likelihood that an important —ie wildly cited— paper or invention was developed by a single author was bigger than it was developed by a team. But this trend has experimented a shift in the last four decades. The rising importance of collective research and cooperation is illustrated by the fact that top cited papers in all those disciplines are mostly created by teams in 2000s.

The fact that, in the twenty first century, the most important discoveries and innovations in science and technology are not anymore the result of the work of very talented individuals working alone but the result of cooperation is well established but untheorized. I argue that a key element of the social processes that helps explain this empirical evidence is the increase in scale of cooperation as a key social mechanism of socialization. The aim of this research is to propose a theoretical explanation of how large scale cooperation works in the context of knowledge intensive production processes.

I approach the concept socialization in this research drawing on the Marxian tradition. The common use of this concept in mainstream social science is somewhat different but related. As Paul Adler put it, "in recent Marxist writings as in political science more generally, socialization refers to the transfer of ownership from the private to the public sphere. In psychology, socialization is commonly construed as the process whereby people new to a culture internalize its knowledge, norms and values. Marx's use was broader than either and encompasses both." (Adler, 2007, 1320). Then Adler cite a relevant passage of Capital:

The social productive forces of labour, or the productive forces of directly social,

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socialized (i.e. collective) labour come into being through cooperation, division of labour within the workshop, the use of machinery, and in general, the transformation of production by the conscious use of the sciences, of mechanics, chemistry, etc. for specific ends, technology, etc. and similarly, through the enormous increase of scale corresponding to such developments (for it is only socialized labour that is capable of applying the general products of human development, such as mathematics, to the immediate process of production; and conversely, progress in these sciences presupposes a certain level of material production). (Marx, 1990, 1024)

Following Marx's argument, we could say that what was once only achievable by a gifted mind working alone is now within reach of ordinary minds through cooperation, division of labour, the use of machinery, and by the conscious use of the science and technology. The aim of this research is to focus on cooperation as a key social mechanism that allow organizations achieve high impact in the development of complex technology and in the production of knowledge.

1.1 A Meso Level Approach to Cooperation

The central topic of this thesis is to understand and explain under which conditions and through which social mechanisms large scale cooperation operates in an open organizational environment. Therefore, one of the main theoretical challenges is conceptualize the social process of cooperation. There are two main approaches to conceptualize cooperation in the literature: as an atomic process in which cooperation is produced between two individuals and, on the other hand, as a macro level phenomenon in which the center of analysis is the collective or group.

Karl Marx is a classical exponent of the latter approach. According to him, two key dimensions of cooperation are the shared goal that guide the social process and its collective nature: “[w]hen numerous workers work together side by side in accordance with a plan, whether in the same process, or in different but connected processes, this form of labour is called co-operation” (Marx, 1990, 443). Marx highlights that the principal characteristic of cooperation is that the final result of coordinated action is much more than the sum of the individual actions. In Marx words, “[...] the sum total of the mechanical forces exerted by isolated workers differs from the social force that is developed when many hands co-operate in the same undivided operation [...] [n]ot only do we have here an increase in the productive power of the individual, by means of co-operation, but the creation of a new productive power, which is intrinsically a collective one.” (Marx, 1990, 443). According to Marx, cooperation constitutes the starting point of capitalist production (Marx, 1990, 439), not only in historical terms, but also conceptually.

More recently, new macro approaches to cooperation have been developed in order to deal with the challenging problem of understanding and explaining how knowledge is produced and disseminated in the context of production processes that depend on effective innovation Adler (2015). Based on the Marxian tradition, (Adler and Heckscher, 2006) introduce the concept of collaborative communities to make sense of novel organizational forms —both in-

1.1. A Meso Level Approach to Cooperation

side and outside large capitalist corporations— strongly grounded on large scale cooperation which were defying the traditional dichotomy between hierarchy and market (Coase, 1937; Williamson, 1975) as coordinating mechanisms for production processes. Collaborative communities are characterized by conscious cooperation, high individual interdependence, trust, shared values and a value-rational basis for legitimate authority (Adler and Heckscher, 2006; Adler et al., 2008). Thus, this macro level approach to explain large scale cooperation focuses on values, norms, generalized trust, and authority forms as the key elements that enable large scale cooperation inside capitalist corporations, and on new emerging open organizational environments.

According to Adler (2015), recent literature in organization studies (O’Mahony and Lakhani, 2011) has highlighted the role of community (Tönnies, 1974) as a critical precondition for innovation in large scale production processes. Adler proposes an alternative reading of Marx’s theory of the capitalist production process where community—in the form of what Marx calls the “collective worker”— is an essential feature the labour process, even under antagonistic capitalist employment conditions (Adler, 2015, 446). The need to create use-values in the labour process makes large scale cooperation essential in complex production processes, but the need to obtain exchange-value in the valorization process of the Capital, that is, the capitalist firm’s profitability imperative, undermines and thwarts the full potential of large scale cooperation. Adler argues that the emergence of a new collaborative form of community in recent decades can be understood as communism developing in the heart of capitalist production processes.

On the other hand, there are the dyadic approaches to cooperation (Axelrod and Hamilton, 1981; Axelrod, 1997). Those approaches are based on the assumption that interactions between pairs of individuals occur on a probabilistic basis. From this standpoint, models are developed based on the concept of an evolutionary strategy on the context of an iterated Prisoner’s Dilemma game. Based on deductions from such a model and agent-based simulations, those approaches show how cooperation based on reciprocity can get started in an asocial world, can thrive while interacting with a wide range of other strategies, and can resist invasion once fully established (Axelrod and Hamilton, 1981).

Those approaches to cooperation are very useful to conceptualize cooperation in an evolutionary and interspecies scenario. On one hand, the payoffs of iterated Prisoner’s Dilemma are not assumed to be commensurable, and on the other hand, the players (i.e. organisms) do not need brain to employ a strategy. So this model can explain not only interactions between two bacteria and two primates (for example *homo sapiens*), but it can also explain interactions between a colony of bacteria and a primate serving as a host (Axelrod and Hamilton, 1981, 211). Thus, these models of cooperation explain the emergence of relevant mutualist biological relations as symbiosis.

The classical dyadic approach developed by Axelrod was the basis on which further refinements have been build. Watts, in his seminal book on small world networks (Watts, 1999b), tested the effects of the small world topology on dyadic interactions finding that the initial configuration of strategies of the nodes of networks are critical in the evolution of strategies—cooperation or defection— without been able to establish a strong relation between topology and cooperative strategy. In the same stream of research, the analysis of emergence of role differentiation in an hierarchical network environment, based upon Spatial Prisoner’s

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Dilemma, showed that leaders —nodes with a large payoff who are imitated by an important fraction of the population— play an essential role in sustaining a cooperative regime (Eguíluz, Zimmermann, Cela-Conde, and Miguel, 2005).

All those approaches have in common their dyadic nature, their grounding in agent-based simulations, and their reductionist approach. We can conceptualize reductionism in this context as the assumption that macro processes —such as mutualist biological relations or cooperation in knowledge intensive production process— must be understood only in terms of the actions and relations of the individuals involved in the process. I argue however that we must differentiate between cooperation strategies developed in a conscient level —such as production processes— and mutualist biological relations, where payoffs of iterated Prisoner's Dilemma are not assumed to be commensurable and the players do not even need a brain to employ a cooperation strategy. The reductionist approach to cooperation is extremely general and thus can highlight commonalities between social and biological cooperation processes, but this generality also hinders its power to successfully modeling all the nuances of complex social process, such as the knowledge intensive production processes that are the focus of this thesis.

The aim of this research is to bridge the gap between macro level and micro level approaches to cooperation by focusing on meso level mechanisms, which until recently have received little attention in the theoretical debate focused on the two extremes highlighted above. I argue that a meso level approach has to focus on the structural dimension of cooperation, that is, the patterns of relations between the individuals that participate in production processes. This perspective shows that between the atomic dyadic interactions among individuals, and the shared goals, values, and visions that guide large organizations and groups, there are sub-groups of individuals that play a key role in effectively enabling large scale cooperation to work, as we have witnessed during the last decades.

In order to conceptualize and clearly define how to analyze the patterns of relations that individual participants establish in knowledge intensive production processes, I use the concept of cooperation networks as a kind of social network. A social network is composed of social actors and their interactions. Social network literature (Wasserman and Faust, 1994; Scott and Carrington, 2011), and more generally what has been recently named network science (Newman, 2003; Newman, Barabási, and Watts, 2006; Newman, 2010; Easley and Kleinberg, 2010), provide methods for analyzing the structure of these networks along with the processes that are developed in, and by, these networks. In the concrete case of knowledge intensive production processes, the objects that are the result of the production process can also be included as part of the cooperation networks, as I will show in the empirical analysis part of this thesis. This approach allows for an in deep analysis of the different levels of individual contributions to the whole cooperation process, which has been one of the empirical puzzles that has driven the literature on cooperation in new open organizational forms.

This network approach to cooperation links with the micro approaches to cooperation in that it focuses on the dyadic interaction of actors, but instead of stopping at the dyadic level, I will analyze the groups that emerge from the global patterns of relations. That is, groups of actors that are more intensely interconnected among them than with the rest of the actors of the network. I argue that the formation and dissolution of these groups through time, and their individual composition and turn over are key elements to explain how large scale cooper-

ation works in practice. These meso level mechanisms link with the macro level approach to cooperation because they help explain how generalized trust, shared values, and non-despotic forms of authority can emerge and be maintained through time in large organizations and on informal groups and communities.

Obtaining detailed data about knowledge intensive production processes is a challenging endeavor, specially from big capitalist corporations, because there are no public records and their internal processes are implicitly considered a secret. However, in order to build a theoretical framework it is imperative to have detailed information on how the production processes actually work. This is the main reason I focus on open organizational environments, namely Free and Open Source Software communities, as a source of empirical data. The production processes in this context are developed mainly through the Internet, and the details and electronic records of these production processes are public and freely available.

1.2 Free and Open Source Software as a case study

Free Software, broadly defined, is computer software that allows users to run, copy, distribute, study, change and improve it. Thus, what defines Free Software is not its price but the freedoms that their users enjoy. Richard Stallman aptly summarizes it by saying that “to understand the concept, you should think of “free” as in “free speech”, not as in “free beer”.” (Stallman, 2002a, 3). In the late 1990s the term Open Source Software was used to refer to this same concept in a less ideological and more business friendly way. Though there are important philosophical differences between the two names used to refer to this kind of software (Stallman, 2002b, 75) for the objectives of this research can be used interchangeably. This is also the case for most research on the phenomenon, and a common practice in the literature is to refer to it as Free and Open Source Software (FOSS). I follow the same convention in this thesis.

The case studies that are the focus of the empirical analysis for this thesis are the Debian project, which releases a complete operating system, and the Python project, a general purpose programming language. The development of an open source project —such as Debian or Python— can be conceptualized as a social system build on the top of the complex technological system of Free and Open Source Software (FOSS). This technological system is composed of all the free software that is written and released.

FOSS has experimented an impressive increment of scale in the past two decades (Ghosh et al., 2006). Approximately two thirds of the existing free software is developed by individual programmers working collaboratively, 15% by for-profit companies and 20% other organizations (academic, social,...). According to the calculations presented in Ghosh et al. (2006), if capitalist companies wanted to reproduce internally the production of free software in use, it would cost approximately 12 billion euros¹ that would be used primarily to pay the workforce. The code base of free software has doubled every 18-24 months over the last years. According to estimates of the authors of this report, this trend will continue over the next few years. This code base can be quantified, at least, in 131,000 person-years of work. This work has been developed mainly by unpaid programmers.

¹We refer here to english billions, that is 12,000,000,000 euros.

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The impressive momentum gained by FOSS, exemplified by an outstanding increment of scale, is only possible by the emergence of complex social systems on top of it that, in turn, feed this increment of scale. The FOSS phenomenon have attracted some research efforts from different scientific fields during last years. The main focus have been in four related areas: a) its microfundaments or individual incentives, ie why individuals decide to involve in FOSS development despite the fact that only by narrow self-interest and instrumental rationality it should be better for them to free-ride other's efforts (Hars and Ou, 2002; Lerner and Tirole, 2002; Lakhani and Von Hippel, 2003; Hertel et al., 2003; Weber, 2004; Roberts et al., 2006; Bagozzi and Dholakia, 2006); b) innovation and intellectual property policy, ie how community managed or corporate sponsored FOSS projects are able to innovate in order to solve complex technical problems and freely reveal those innovations without appropriating private returns from selling the software (Moglen, 1999; Kogut and Metiu, 2001; Hippel, 2001; Von Hippel and Von Krogh, 2003; Von Krogh et al., 2003; O'Mahony, 2003; West, 2003; Lerner and Tirole, 2005; Hargrave and Van de Ven, 2006; West and O'Mahony, 2008); c) development methods, ie how FOSS communities manage coordination and complexity developing large software systems, this stream of research have been mainly addressed from a software engineering perspective (Godfrey and Tu, 2000; Feller and Fitzgerald, 2000; Mockus et al., 2002; Koch and Schneider, 2002; Weber, 2004; MacCormack et al., 2006); d) organization and governance, ie how communities producing public goods govern themselves, this stream of research addresses the classic problem of how individuals coordinate their actions in order to achieve collective outcomes (Ljungberg, 2000; O'Mahony and Ferraro, 2007b; West and O'Mahony, 2008).

Regarding area a) described above, that is, why talented individuals decide to work on FOSS projects even without direct economic compensation, the literature has proposed three main compatible responses to address the individual motivations of direct producers. First, work on solving problems whose solution is considered useful for the individual that is directly doing the work is a powerful motivation, Raymond (1999) aptly named this individual incentive “scratching an itch”. Second, given the public nature of the source code of FOSS projects, individual participants can build a reputation based on their work in FOSS projects which can help them advance in their professional career (Lerner and Tirole, 2002; Roberts et al., 2006; Bagozzi and Dholakia, 2006). And, finally, it has also been proposed that FOSS projects can be understood as a gift economy, where individual participation is boosted by shared ethical and moral standards (Coleman, 2004).

Regarding area b), that is, how FOSS projects can innovate and freely reveal those innovations without appropriating private returns from selling the software, Von Hippel and Von Krogh (2003) argue that the classical distinction between two models of innovation are not discrete states but two ends of a continuum, and that FOSS is an instance of a mixed model which they name “private-collective” innovation model, because the software is not released to the public domain but protected by copyright laws. The two classical models of innovation are the “private investment” model that assumes returns to the innovator from private goods that are protected by efficient regimes of intellectual property, and the “collective action” model that assumes that when the market fails to foster innovation the only option for innovators is to cooperate and to produce public goods. O'Mahony (2003) stresses that FOSS projects have indeed a sophisticated set of legal and normative tactics to protect their source

code from proprietary appropriation and to protect their collective identity and reputation. The software licenses used by FOSS projects ensure that free software remains a common good “to which anyone may add but from which no one may subtract.” (Moglen, 1999). Also, O’Mahony (2003, 17) argues that direct producers of FOSS pool their efforts in order to create collectively owned and managed resources, and thus they also apply well studied mechanisms to manage common pool resources, such as drawing on trust, reciprocity, and reputation to develop norms that ensure the fair use of those common pool resources (Ostrom, 1999).

This research will be centered in the intersection of areas c) and d) described above. The aim is to analyze the development methods of FOSS from the perspective of a knowledge based production process in order to address the classical sociological problem of social organization of production and its dependencies and relations with political organization and governance, in the sense of how individuals coordinate their actions in order to achieve collective outcomes. The major difference of this perspective from the works based on software engineering that previously addressed the development methods issue is that the empirical source —software development— is not an objective in itself; it is a proxy to analyze large scale cooperation in the context of new organizational forms, FOSS projects, that develop a complex knowledge based production process that do not rely mainly on market or hierarchy mechanisms in order to guide individual decisions and actions. I argue that focusing on the patterns of relations of direct producers —that is, focusing on cooperation networks— we can analyze the meso level mechanisms that enable and foster large scale cooperation.

The empirical part of this thesis is thus a case study, and its principal aim is to develop theoretical insights in order to build a framework that allows us to understand and explain both the new characteristics of this production process as well as the elements of continuity with capitalist production processes. Thus, this thesis will analyze cooperation in the Debian and Python projects in order to show that the social structure resulting from the cooperation among their individual participants is characterized by the formation and transformation of subgroups of actors more densely connected between them than with the rest of the actors. These subgroups form the structural scaffolding that enables and fosters large scale of cooperation. These meso level mechanisms are key to explain the impressive increase of scale of cooperation in knowledge intensive production processes that empirical research has reported in the last decades in the production of knowledge, in general, and the development of FOSS, in particular.

1.3 Objectives of this thesis

The main research question of this thesis can be succinctly stated as: Which meso level mechanisms are key to explain how large scale cooperation work in knowledge intensive and technically complex production processes developed in new organizational environments, such as FOSS projects, where loosely coupled individuals that rarely meet face to face have to coordinate through internet in order to produce world class software products.

In more detail, the objectives of this thesis can be classified as:

Methodological Contributions to the state of the art techniques of social network analysis.

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1. Design and implement a fast approximation algorithm for computing structural cohesion in order to be able to analyze large cooperation networks.
2. Design and implement a new visualization technique for structural cohesion analysis.

Theoretical Contributions to the sociological literature on structural cohesion, cooperation, and collaborative communities.

1. Extend theoretically the structural cohesion model by introducing the consideration of average node connectivity on top of the plain node connectivity.
2. Propose a new network model for modeling the patterns of relations between direct producers in collaborative communities, named “Cohesive Small World”, that is based on two well known network models: the Small World model and the Structural Cohesion model.
3. Explore the meso level mechanisms that are developed in the nested cohesive subgroups structure of cooperation networks and their impact in the diffusion of information, the convergence on common values and shared goals, and especially in how generalized trust is maintained between individuals that rarely meet face to face, and how this enables the resilience of the whole cooperation network to individual turnover.
4. Contribute to the collaborative communities literature from a structural perspective by showing the key role of meso level structures, such as subgroups of individuals in the connectivity hierarchy of cooperation networks, in their effectiveness in the production and diffusion of knowledge through large scale cooperation.

Empirical Contributions to the empirical analysis of FOSS projects.

1. The literature on FOSS, especially from software engineering and computer science, have stressed that only a small fraction of the developers is doing most of the work. I focus on who actually are these developers by analyzing the network structure that emerges from cooperation among participants in the community.
2. The empirical analysis presented in this thesis shows that the developers that contribute the most are in the higher levels of the connectivity hierarchy of cooperation networks.
3. The developers that are in the higher levels of the connectivity hierarchy of cooperation networks change significantly through the history of the project. This is an indication of an open elite dynamic, where new developers are able to access the top levels of the hierarchy.
4. This is an essential meso level mechanism that help explain, on the one hand, the long term survival of community based projects, and on the other hand, how large scale cooperation works in the face of high individual turn over in the context of new organizational forms.

Practical Contributions of general interest beyond academia.

1. Make widely available the implementation of the new approximation algorithm for structural cohesion presented on this thesis by contributing a suitable implementation to NetworkX (Hagberg et al., 2008), a popular Python Free Software project for the analysis of the structure and dynamics of complex networks.

Part II

Theory and Methods

Cohesive Groups: The Structural Cohesion Model

Group cohesion is a central concept that has a long and illustrious history in sociology and organization theory, although its precise characterization has remained elusive. Its use in most sociological research has been ambiguous at best. This is largely because, as Moody and White (2003) argued, it is often based on sloppy operationalization grounded mostly in intuition and common sense. Network analysis has provided a large number of solutions to this problem. From classical work in the graph-theoretic sociological tradition on cliques, clans, clubs, k -plexes, k -cores and lambda sets (Wasserman and Faust, 1994, chapter 8), to the more recent contribution of physicists and computer scientists on community analysis (Fortunato, 2010), network theorists have provided researchers with a wide range of measures of cohesion in social networks.

However, neither the classical approaches nor new developments in community analysis are well-enough suited to address many of the common uses of group cohesion in the sociological and organizational literature, for three key reasons. First, while most of these measures can help us identify cohesive subgroups, they do not provide insight into their robustness, which is a critical element to the theoretical conceptualization of cohesion. In most cases, the removal of only a few actors from the subgroups can lead to its fragmentation into smaller disconnected groups (White and Harary, 2001). Secondly, many cohesive subgroup measures do not allow for overlap among subgroups. Finally, even when they do allow for overlap, most measures cannot capture the hierarchical nature of nested social groups, where subgroups, like Russian dolls, are recursively nested in one another. As a result, hardly any of the existing measures capture the theoretical complexity of cohesion, and thus fall short of offering useful operationalizations for many empirical phenomena of sociological interest.

One model which provides a more fertile ground for sociological analysis is the structural cohesion model (White and Harary, 2001; Moody and White, 2003). This model is grounded on two common conceptualizations of group cohesion in the literature. A social group is considered cohesive to the extent that: a) it is resistant to being pulled apart by the removal of some of its members; and b) pairs of its members have multiple direct or indirect connections that pull it together (White and Harary, 2001, 309-310). Building on the concept of node connectivity from graph theory, the structural cohesion of a group is defined in this model as the

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minimal number of actors who need to be removed from the group to disconnect it. Despite its solid and elegant mathematical foundation, the structural cohesion model has not been widely used in empirical analysis because it is not possible to perform the required computations for networks with more than a few thousands nodes and edges in a reasonable time frame.

These computational challenges also hindered the development of an interesting feature of the structural cohesion model: its applicability to both bipartite and unipartite networks. While many social networks are essentially bipartite in nature (as people meet, interact, and cooperate around specific events and/or objects), most of our analytical tool-kit was developed to analyze one-mode networks (Latapy, Magnien, and Vecchio, 2008). Therefore it was common practice to conduct network analysis on one-mode projections only, but it is now clear that this practice leads to biased estimates of key measures, as recent work on the clustering coefficient has amply shown (Robins and Alexander, 2004; Lind et al., 2005; Latapy et al., 2008). The structural cohesion model, instead, can be applied without modification to both bipartite and unipartite networks (White, Owen-Smith, Moody, and Powell, 2004). That said, the original algorithm is prohibitively time-consuming to compute, especially with the exponential growth in the size of available network data.

In this chapter I extend the structural cohesion model by using the concept of average node connectivity, that is the *average number of actors who need to be removed from the group to disconnect an arbitrary pair of actors in the group*. I present a set of heuristics to compute structural cohesion based on the fast approximation to compute pairwise node independent paths (White and Newman, 2001). I implemented it in NetworkX (Hagberg et al., 2008), a Python Library for Complex Network Analysis¹. The heuristics presented here allow to compute the approximate value of group cohesion for moderately large networks, along with all the hierarchical structures of connectivity levels, one order of magnitude faster than implementations which are currently available. I also suggest a novel graphical representation of the results of the analysis that might help synthetically communicate results and spot differences across different networks (Moody, McFarland, and Bender-deMoll, 2005).

I used the implementation of the heuristics proposed in this chapter to analyze three large cooperation networks: the co-maintenance network of Debian packages, and the co-authorship networks in Nuclear Theory and High-Energy Theory. I ran the analysis in both one-mode and two-mode networks, and compare the networks in terms of their connectivity structure. Consistent with the literature on two-mode networks, I show that the complex hierarchy of cooperation captured in the two-mode analysis is a better representation of the connectivity structure of empirical networks than their one-mode counterparts.

The rest of the chapter is organized as follows: I start by laying out the notation used in the rest of the paper. Then I discuss the main features which a cohesive subgroup formalization should have from a sociological perspective, reviewing the most important formalizations of cohesive subgroups in the social network literature and discussing in depth the structural cohesion model. I then describe the exact algorithm proposed by Moody and White (2003) to compute the connectivity hierarchy of a given network. After that, I introduce the proposed heuristics, and describe their implementation and performance. I go on to report the

¹See appendix D for references and links to the actual implementation published as part of NetworkX version 1.10.

findings from applying the structural cohesion analysis to three large cooperation networks, as well as proposing a novel graphical representation of the connectivity structure using a three-dimensional scatter plot, which I use in the empirical part of this thesis. Finally I conclude this chapter with implications for future research.

2.1 Terminology and notation

An undirected graph $G = (V, E)$ consists of a set $V(G)$ of n nodes and a set $E(G)$ of m edges, each one linking a pair of nodes. The *order* of G is its number of nodes n and the *size* of G is its number of edges m . Two nodes are adjacent if there is an edge that links them, and this edge is said to be incident with the two nodes it links. A *subgraph* of G is a graph whose nodes and edges are all in G . An *induced subgraph* $G[U]$ is a subgraph defined by a subset of nodes $U \subseteq V(G)$ with all the edges in G that link nodes in U . A subgraph is *maximal* in respect to some property if the addition of more nodes to the subgraph will cause the loss of that property.

A *path* is an alternating sequence of distinct nodes and edges in which each edge is incident with its preceding and following nodes. The length of a path is the number of edges it contains. The *shortest path* between two nodes is a path with the minimum number of edges. The *distance* between any two nodes u and v of G , denoted $d_G(u, v)$, is the length of the shortest path between them. The *diameter* of a graph G , denoted $\text{diam}(G)$, is the length of the longest shortest path between any pair of nodes of G . *Node independent paths* are paths between two nodes that share no nodes in common other than their starting and ending nodes. A graph is connected if every pair of nodes is joined at least by one path. A *component* of a graph G is a maximal connected subgraph, which means that there is at least one path between any two nodes in that subgraph.

The *density* of a graph G , denoted $\varrho(G)$, measures how many edges are in set $E(G)$ compared to the maximum possible number of edges among nodes in $V(G)$. Thus, density is calculated as $\varrho(G) = \frac{2m}{n(n-1)}$. A *complete graph* is a graph in which all possible edges are present, so its density is 1. A *clique* is an induced subgraph $G[U]$ formed by a subset of nodes $U \subseteq V(G)$ if, and only if, the induced subgraph $G[U]$ is a complete graph. Thus, there is an edge that links each pair of nodes in a clique. The *degree* of a node v , denoted $\deg(v)$, is the number of edges that are incident with v . The minimum degree of a graph G is denoted $\delta(G)$ and it is the smallest degree of a node in G . A k -core of G is a maximal subgraph in which all nodes have degree greater or equal than k ; which means that a k -core is a maximal subgraph with the property $\delta \geq k$. The *core number* of a node is the largest value k of a k -core containing that node.

The removal of a node v from G results in a subgraph $G - v$ that does not contain v nor any of its incident edges. The *node connectivity* of a graph G is denoted $\kappa(G)$ and is defined as the minimum number of nodes that must be removed in order to disconnect the graph G . Those nodes that must be removed to disconnect G form a *node cut-set*. If it is only necessary to remove one node to disconnect G , this node is called an *articulation point*. We can also define the *local node connectivity* for two nodes u and v , denoted $\kappa_G(u, v)$, as the minimum number of nodes that must be removed in order to destroy all paths that join u and v in G .

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Then the *node connectivity* of G is equal to $\min\{\kappa_G(u, v) : u, v \in V(G)\}$. Similarly, the *edge connectivity* of a graph G is denoted $\lambda(G)$ and is defined as the minimum number of edges that must be removed in order to disconnect the graph G . The edges that must be removed to disconnect G form an *edge cut-set*.

The measures discussed above are defined as properties of whole graphs but they can also be applied to subgraphs. A *k-component* is a maximal subgraph of a graph G that has, at least, node connectivity k : we need to remove at least k nodes to break it into more components. The *component number* of a node is the largest value k of a k -component containing that node. Notice that k -components have an inherent hierarchical structure because they are nested in terms of connectivity: a connected graph can contain several 2-components, each of which can contain one or more tricomponents, and so forth.

2.2 Cohesion in social networks

Doreian and Fararo (1998) argue that group cohesion can be divided analytically into an *ideational* component, which is based on the members' identification with a collectivity, and a *relational* component, which is based on connections among members. These connections are, at least in part, observable, and thus the relational approach seems more appropriate for theory building and empirical research. But, despite its attractiveness, the relational component has received much less attention than the ideational component in sociological literature. Social network analysis has been the exception, and since the beginning, its proponents formalized group cohesion in relational terms, that is, they defined the boundaries of subgroups in a community starting from the patterns of relations among actors.

Unfortunately most of the existing formalizations of cohesive subgroups do not capture some key properties of the theoretical concept of cohesive groups. First, a cohesive subgroup should be *robust*, in the sense that its qualification as a group should not be dependent on the actions of a single individual, or any small set of individuals that belong to the group. This implies, on the one hand, that no actor, or small set of actors, should be able to dissolve the cohesive subgroup by abandoning it; while, on the other hand, all actors in a group should be related to all other actors by multiple direct or indirect connections in order to pull it together (White and Harary, 2001; Moody and White, 2003). Therefore, cohesive subgroups should also be relatively invariant to changes outside the group (Brandes and Erlebach, 2005, chapter 6).

Second, actual social groups tend to *overlap* in the sense that some actors are likely to be part of more than one cohesive subgroup. As Freeman (1992) notes, formalizations of subgroups that overlap a lot are not well suited to capturing the theoretical concept of groups because their sociological use is not focused on individuals but on contexts, such as productive relations, friendship relations, or family ties, to name a few. Thus if groups are defined around a highly specific context the overlap is likely to be small. Therefore the formalization of subgroups often assumed non-overlapping subgroups. Moreover, non-overlapping subgroups can be used to develop categorical variables for membership that could be used in regression analysis (Borgatti et al., 1990). However, there is always overlap among cohesive subgroups in actual social groups; and this overlap might be both empirically and theoretically relevant.

Third, following a typical distinction in the social network literature, cohesive groups have both a *structural* and a *positional* dimension. In the former, cohesive subgroups are defined in terms of the global patterns of relations, and the focus is on the groups and the network as a whole. In the latter, the focus is on the identification of actors who, because of their network position, obtain preferential access to information or resources that flow through the network. Cohesive subgroup formalizations should help address both structural and positional questions.

Last but by no means least, cohesive subgroups are likely to display a *hierarchical structure* in the sense that highly cohesive subgroups are nested inside less cohesive ones. This notion of hierarchy is grounded on Simon's definition: "a system that is composed of inter-related subsystems, each of the latter being, in turn, hierachic in structure until we reach some lowest level of elementary subsystem" (Simon, 1962, 468). A hierarchical conception of cohesive subgroups implies that there is a relevant organization at all scales of the network, and that cohesive groups are a meso level structure that is not reducible to either macro nor micro level phenomena and dynamics. This nested conception of cohesive subgroups provides a direct link with the structural dimension of the sociological concept of embeddedness (Granovetter, 1985). The nested nature of cohesive groups allows one to operationalize social relations that are, in direct contrast to arms length relations, structurally embedded in a social network.

In the following section I briefly review existing social network formalizations of subgroup cohesion. For each method, in table 2.1 I provide the definition, the underlying logic, the measure proposed, and evaluate them in terms of the four criteria just described. I will therefore consider whether they are robust, can allow for overlapping groups, provide information on both the structure and the position of nodes, and whether they capture the hierarchical structure of the groups.

Formalizations of cohesive subgroups

Historically, the first social networks approaches to subgroup cohesion formalization identified cohesive subgroups by considering only internal ties among the actors in the group. However, most recent formalizations define cohesive subgroups by considering both internal ties among its members and also external ties between each subgroup and the rest of the network (Wasserman and Faust, 1994). All the formalizations based on internal ties are based on the concept of clique, which were later generalized by relaxing some of the strict conditions of distance, degree or density that the clique concept imposes. The formalizations that consider both internal and external ties can be organized in two main categories depending on whether they use density or connectivity to measure internal and external ties.

The first formalization of cohesive subgroups was the concept of clique (Luce and Perry, 1949), which is a maximal subset of actors in which each actor is directly connected to every other actor in the subgroup. For small groups in some contexts, such as friendship networks, it makes sense to use the clique concept. However, in many contexts, especially in large and/or very sparse networks, it is unlikely that the existing cohesive subgroups will be formed by actors that have direct relations with all other actors in the subgroup. Cliques, however, intuitively capture the idea that a cohesive subgroup exists independently of the action of any

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individual in the group. Thus the group is robust because it cannot be disconnected by removing any individual actor. Cliques can overlap —and they usually do so a lot— but they do not display a hierarchical organization. Because of the limitations of the clique concept, some generalizations were developed; on the one hand, there emerged a family of generalizations based on relaxing distances among members of the subgroup — n -cliques , n -clans, and n -clubs (Mokken, 1979); and, on the other, generalizations based on relaxing the number of links between members of the subgroup — k -plex (Seidman and Foster, 1978), and k -cores (Seidman, 1983b).

All these generalizations except for k -core are quite arbitrary because the analyst has to set the parameters n or k depending on the concrete aim of the analysis at hand and its empirical setting. Thus, k -core is the only generalization of the clique concept with an inherent hierarchical structure: 3-cores are always nested inside 2-cores; and 4-cores inside 3-cores, and so forth. Thus, this formalization captures an important aspect of the sociological concept of cohesive groups. However, k -cores are not robust because the removal of a few actors could potentially disconnect them; in fact they don't even need to be connected at all to be a k -core (White and Harary, 2001). Furthermore, the definition of k -core only considers internal relations among actors within it, without considering relations with the rest of the network.

Another important subset of subgroup formalizations identifies cohesive subgroups by comparing the internal and external ties of subgroups members. The two key criteria to define groups in these categories are density and connectivity. The first formalization of this kind was the LS set (Luccio and Sami, 1969; Lawler, 1973): a set of nodes in which each of its proper subsets has more ties with the nodes outside that subset than the LS set itself. The main idea is that an LS set is a union of subsets of nodes. This union is better than any subset in terms of cohesion because it has fewer connections to the outside. Thus, actors in the LS set have more connections to other members than to outsiders. LS sets are robust to the removal of edges and they have an inherent hierarchical structure; however, due to their strict requirements, only very few LS sets are actually found in empirical social networks. Lambda sets (Borgatti et al., 1990) were introduced as a generalization of LS sets designed to capture only the edge-connectivity properties of the LS sets. Lambda sets are maximal subsets of nodes that have more edge independent paths between them than with nodes outside the subset. This generalization, however, does not capture important features of the sociological concept of group cohesiveness. On the one hand, they are not robust to the removal of nodes, and, on the other hand, the edge independent paths that link the members of a Lambda set can go through nodes that are not in the lambda set, thus there is no strict separation between the role of actors inside and outside a lambda set in respect to its internal cohesion.

	Based on	Criteria	Measure	Definition	Robust	Overlap	Positional	Hierarchical	Computational
Absolute: only internal	complete connectivity	$diam = \varrho = 1$ $\delta = \lambda = \kappa = n - 1$	clique	maximal subgraph of nodes all of which are adjacent to each other	Yes	Yes: clique percolation	Yes: structural folds	Yes: k -cliques	Slow
	relax distance	$\max\{d_G(u, v)\} \leq n$	n -clique	maximal subgraph in which the largest geodesic distance is no greater than n	No	No	No	No	Slow
		n -clique with $diam \leq n$	n -clan	n -clique that also have a diameter no greater than n	No	Yes	No	No	Slow
		$diam = n$	n -club	a maximal subgraph of diameter n	No	Yes	No	No	Slow
	relax degree	$\delta \geq n - k$	k -plex	maximal subgraph in which each node may be lacking ties to no more than k other nodes	No	Yes	No	No	Slow
		$\delta \geq k$	k -core	maximal subgraph in which all nodes have degree k or more	No	No	No	Yes	Very fast $O(m)$
relax density	$\varrho \geq \eta$	η -dense subgraph		subgraph with density greater than or equal to η , where $0 \leq \eta \leq 1$	No	No	No	No	Slow
Relative: Internal (+) External (-)	density	minimize edges to outside	LS sets	set of nodes in which each of its proper subsets has more ties with the nodes outside that subset than the LS set itself	Yes	No	Yes	Yes	Slow $O(n^4)$
		quality function of partitions	modularity	the fraction of the edges that fall within the given groups minus the expected such fraction if edges were distributed at random		No	No	No	Optimum: Slow Approx: Fast
	connectivity		conductance	weight of edge cut-sets among different subgroups					
	edge-connectivity	lambda sets	maximal subset of nodes that have more edge independent paths between them than with nodes outside the subset	Not as robust as LS sets	No	No	Yes	Slow $O(n^4)$	
	node-connectivity	k -components	maximal subgraph that has, at least, node connectivity k : we need to remove at least k nodes to break it into more components	Yes	Yes: $k - 1$ nodes	Yes	Yes	Exact: Slow $O(n^4)$ Approx: $\ll O(n^4)$	
	random walk based partition algorithms				No	No	No	Fast	

Table 2.1: Summary of cohesive subgroups formalizations from social network analysis literature (Luce and Perry, 1949; Luccio and Sami, 1969; Lawler, 1973; Seidman and Foster, 1978; Mokken, 1979; Seidman, 1983b,a; Borgatti et al., 1990; Wasserman and Faust, 1994; White and Harary, 2001; Moody and White, 2003; Brandes and Erlebach, 2005; Fortunato, 2010). Notation: $diam$ is diameter, ϱ is density, δ is minimum degree, λ is edge-connectivity, κ is node connectivity, n is the number of nodes, m is the number of edges, and $d_G(u, v)$ is the distance between nodes u and v in G .

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More recently, under the label community analysis, an interdisciplinary community of researchers interested in complex networks has proposed a novel family of subgroup measures and algorithms (Fortunato, 2010). Essentially their approach is to divide a network into subgroups by grouping nodes that are more densely connected among them than with the rest of the network. To objectively define how good a concrete partition of a network is, they define a quality function (Brandes and Erlebach, 2005; Fortunato, 2010). There are many different quality functions used in network literature, with most of them based on density, but also a few based on connectivity. The most popular quality function is modularity, which is computed as the fraction of the edges that fall within the given groups minus the expected value of the fraction if edges were distributed at random. However, the subgroups resulting from community analysis techniques are not hierarchically organized in the sociological sense discussed above because there is no natural nestedness among groups².

The first wave of community analysis focused on the analysis of non overlapping groups, but recent developments have explored overlapping community structures. The most interesting approach of this kind is the clique percolation method (Palla, Derényi, Farkas, and Vicsek, 2005) and their generalizations based on short cycles connectivity (Batagelj and Zaveršnik, 2007). A k -clique is a complete subgraph formed by k members. Two k -cliques are considered adjacent if they share $k - 1$ actors. A k -clique community is the largest connected subgraph obtained by the union of all adjacent k -cliques. k -clique communities can share nodes, so overlapping is possible. The clique percolation approach has proven to be a fertile ground over which to build theoretical developments on the positional dimension of cohesion. The concept of inter-cohesion based on the structural fold network topology (Vedres and Stark, 2010) is the most prominent example. Actors at structural folds are insiders in multiple cohesive subgroups (k -clique communities). Thus they have access to diverse resources and information from each subgroup without being isolated and limited to only one group of neighbors. Vedres and Stark show that this distinctive structural position helps to explain innovation and entrepreneurial dynamics in the context of firm networks.

However these new developments on community analysis are not well suited to address many of the common uses of group cohesion in the sociological literature. The clique percolation method assumes that the network under analysis has a large number of cliques, so it may fail to deliver meaningful results for networks with few cliques; also, if there are too many cliques, it may yield trivial results, such as considering the whole network a cohesive group without internal divisions. Moreover, this method is focused on finding subgraphs that contain many k -cliques inside, which is not exactly the same as subgraphs more densely connected internally than externally, because a k -clique community could be formed by chains of k -cliques with low edge density among non adjacent k -cliques. This implies that k -clique communities are not necessarily robust to node removal.

²However, some of those methods are called hierarchical because they use hierarchical clustering to organize partitions in each step of the partition algorithm, which is commonly represented by a dendrogram. Thus, researchers need to introduce an arbitrary criteria to identify relevant partitions –that is, the level at which we cut the dendrogram.

The structural cohesion model

The structural cohesion approach to subgroup cohesion (White and Harary, 2001; Moody and White, 2003) is grounded on two mathematically equivalent definitions of cohesion that are based on commonly used concepts of cohesion in the sociological literature. On the one hand, the ability of a collectivity to hold together independently of the will of any individual. As set out by the formal definition, “a group’s structural cohesion is equal to the minimum number of actors who, if removed from the group, would disconnect the group” (Moody and White, 2003, 109). Yet, on the other hand, a cohesive group has multiple independent relational paths among all pairs of members. According to the formal definition “a group’s structural cohesion is equal to the minimum number of independent paths linking each pair of actors in the group” (Moody and White, 2003, 109). These two definitions are mathematically equivalent in terms of the graph theoretic concept of connectivity as defined by Menger’s Theorem (White and Harary, 2001, 330), which can be formulated locally: “The minimum node cut set $\kappa(u, v)$ separating a nonadjacent u, v pair of nodes equals the maximum number of node-independent $u - v$ paths”; and globally: “A graph is k -connected if and only if any pair of nodes u, v is joined by at least k node-independent $u - v$ paths”. Thus Menger’s theorem links with an equivalence relation a structural property of graphs —connectivity based on cut sets— with how graphs are traversed —the number of node independent paths among pairs of different nodes. This equivalence relation has a deep sociological meaning because it allows for the definition of structural cohesion in terms of the difficulty to pull a group apart by removing actors and, at the same time, in terms of multiple relations between actors that keep a group together.

The starting point of cohesion in a social group is a state where every actor can reach every other actor through at least one relational path. The emergence of a giant component —a large set of nodes in a network that have at least one path that links any two nodes— is a minimal condition for the development of group cohesion and social solidarity. Moody and White (2003) argue that, in this situation, the removal of only one node can affect the flow of knowledge, information and resources in a network because there is only one single path that links some parts of the network. Thus, if a network has actors who are articulation points, their role in keeping the network together is critical; and by extension the network can be disconnected by removing them. Moody and White (2003) convincingly argue that biconnectivity provides a baseline threshold for strong structural cohesion in a network because its cohesion does not depend on the presence of any individual actor and the flow of information or resources does not need to pass through a single point to reach any part of the network. Therefore, the concept of robustness is at the core of the structural cohesion approach to subgroup cohesion.

Note that the bicomponent structure of a graph is an exact partition of its edges, which means that each edge belongs to one, and only one, bicomponent; but this is not the case for nodes because k -components can overlap in $k - 1$ nodes. In the case of bicomponents, articulation points belong to all bicomponents that they separate. Thus, this formalization of subgroup cohesion allows limited horizontal overlapping over k -components of the same k . On the other hand, the k -component structure of a network is inherently hierarchical because k -components are nested in terms of connectivity: a connected graph can contain several 2-components, each of which can contain one or more tricomponents, and so forth. This is one

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of the bases over which the structural cohesion model is built and it is specially useful for operationalizing the hierarchical conception of nested social groups.

However, one shortcoming of classifying cohesive subgroups only in terms of node connectivity is that k -components of the same k are always considered equally cohesive despite the fact that one of them might be very close to the next connectivity level, while the other might barely qualify as a component of level k (i.e. removing a few edges could reduce the connectivity level to $k - 1$). White and Harary (2001) propose to complement node connectivity with the measure of conditional density. If a subgroup has node connectivity k , then its internal density can only vary within a limited range if the subgroup maintains that same level of connectivity. Thus, they propose to combine node connectivity and conditional density to have a continuous measure of cohesion. But connectivity is a better measure than density for measuring cohesion because there is no guarantee that a denser subgroup is more robust to node removal than a sparser one, given that both have the same node connectivity k .

Building on this insight, I propose using another connectivity-based metric to obtain a continuous and more granular measure of cohesion: the average node connectivity. Node connectivity is a measure based on a worst-case scenario in the sense that to actually break apart a k connected graph by only removing k nodes we have to carefully choose which nodes to remove. Recent work on network robustness and reliability (Albert, Jeong, and Barabási, 2000; Dodds, Watts, and Sabel, 2003) use as the main benchmark for robustness the tolerance to the random or targeted removal of nodes by degree; it is unlikely that by using either of these attack tactics we could disconnect a k connected graph by only removing k nodes. Thus node connectivity does not reflect the typical impact of removing nodes in the global connectivity of a graph G . Beineke, Oellermann, and Pippert (2002) propose the measure of *average node connectivity* of G , denoted $\bar{\kappa}(G)$, defined as the sum of local node connectivity between all pairs of different nodes of G divided by the number of distinct pairs of nodes. Or put more formally:

$$\bar{\kappa}(G) = \frac{\sum_{u,v} \kappa_G(u, v)}{\binom{n}{2}} \quad (2.1)$$

Where n is the number of nodes of G . In contrast to node connectivity κ , which is the minimum number of nodes whose removal disconnects some pairs of nodes, the average connectivity $\bar{\kappa}(G)$ is the expected minimal number of nodes that must be removed in order to disconnect an arbitrary pair of nodes of G . For any graph G it holds that $\bar{\kappa}(G) \geq \kappa(G)$. As Beineke et al. show, average connectivity does not increase only with the increase in the number of edges: graphs with the same number of nodes and edges, and the same degree for each node can have different average connectivity (Beineke et al., 2002, figure 2, 33). Thus, this continuous measure of cohesion doesn't have the shortcomings of conditional density to measure the robustness of the cohesive subgroups.

The relation between node connectivity and average node connectivity is analog to the relation between diameter and average distance. The diameter of a graph G is the maximum distance between any two nodes of G , and like node connectivity, it is a worst-case scenario. It does not reflect the typical distance that separates most pairs of nodes in G . When modeling distances between actors in networks, it is better to use the average path length (L) because it

2.3. Existing algorithms for computing k -component structure

is close to the typical case: if we choose at random two nodes from a network, it is more likely that their distance is closer to the average than to the maximum distance. Taking into account the average connectivity of each one of the k -components of a network allows a more fine grained conception of structural cohesion because, in addition to considering the minimum number of nodes that must be removed in order to disconnect a subgroup, I also consider the number of nodes that, on average, have to be removed to actually disconnect an arbitrary pair of nodes of the subgroup. The latter is a better measure of subgroup robustness than the departure of key individuals from the network.

Structural cohesion is a powerful explanatory factor for a wide variety of interesting empirical social phenomena. It can be used to explain, for instance: the likelihood of building alliances and partnerships among biotech firms (Powell et al., 2005); how positions in the connectivity structure of the Indian inter-organizational ownership network are associated with demographic features (age and industry); and differences in the extent to which firms engage in multiplex and high-value exchanges (Mani and Moody, 2014). Social cohesion can also help us understand degrees of school attachment and academic performance in young people, as well as the tendency of firms to enroll in similar political activity behaviors (Moody and White, 2003). It offers insight, also, into emerging trust relations among neighborhood residents or the hiring relations among top level US graduate programs (Grannis, 2009). In addition to social solidarity and group cohesion, the model can equally fit many relevant theoretical issues, such as conceptualizing structural differences among fields and organizations (White et al., 2004), operationalizing the structural component of social embeddedness (Granovetter, 1985; Moody, 2004), explaining the role of highly connected subgroups in boosting diffusion in social networks without a high rate of decay (Moody, 2004; White and Harary, 2001), or highlighting the complexity and diversity of the structure of real world markets beyond stylized one-dimensional characterizations of the market (Mani and Moody, 2014).

Despite all its merits, the structural cohesion model has not been widely applied to empirical analysis because it is not practical to compute it for networks with more than a few thousands nodes and edges due to its computational complexity. What's more, it is not implemented in most popular network analysis software packages. In the next section, I will review the existing algorithm to compute the k -component structure for a given network, before introducing the heuristics to speed up the computation.

2.3 Existing algorithms for computing k -component structure

Moody and White (2003, appendix A) provide an algorithm for identifying k -components in a network, which is based on the Kanevsky (1993) algorithm for finding all minimum-size node cut-sets of a graph; i.e. the set (or sets) of nodes of cardinality k that, if removed, would break the network into more connected components. The algorithm consists of 4 steps:

1. Identify the node connectivity, k , of the input graph using flow-based connectivity algorithms (Brandes and Erlebach, 2005, chapter 7).

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2. Identify all k -cutsets at the current level of connectivity using the Kanevsky (1993) algorithm.
3. Generate new graph components based on the removal of these cutsets (nodes in the cutset belong to both sides of the induced cut).
4. If the graph is neither complete nor trivial, return to 1; otherwise end.

As the authors note, one of the main strengths of the structural cohesion approach is that it is theoretically applicable to both small and large groups, which contrasts with the historical focus of the literature on small groups when dealing with cohesion. But the fact that this concept and the algorithm proposed by the authors, are theoretically applicable to large groups does not mean that this would be a practical approach for analyzing the structural cohesion on large social networks³.

The equivalence relation established by Menger's theorem between node cut sets and node independent paths can be useful to compute connectivity in practical cases but both measures are almost equally hard to compute if we want an exact solution. However, White and Newman (2001) proposed a fast approximation algorithm for finding good lower bounds of the number of node independent paths between two nodes. This smart algorithm is based on the idea of searching paths between two nodes, marking the nodes of the path as “used” and searching for more paths that do not include nodes already marked. But instead of trying all possible paths without order, this algorithm considers only the shortest paths: it finds node independent paths between two nodes by computing their shortest path, marking the nodes of the path found as “used” and then searching other shortest paths excluding the nodes marked as “used” until no more paths exist. Because finding the shortest paths is faster than finding other kinds of paths, this algorithm runs quite fast, but is not exact because a shortest path could use nodes that, if the path were longer, may belong to two different node independent paths (White and Newman, 2001, section III). Therefore a condition for the use of this approximation algorithm would be that the networks analyzed should be sparse; this will reduce its inaccuracy because it will be less likely that a shorter path uses nodes that could belong to two or more longer node independent paths.

White and Newman suggest that this algorithm could be used to find k -components. First one should compute the node independent paths between all pairs of different nodes of the graph. Then build an auxiliary graph in which two nodes are linked if they have at least k node independent paths connecting them. The induced subgraph of all nodes of each connected component of the auxiliary graph form an extra-cohesive block of level k (like a k -component but with the difference that not all node independent paths run entirely inside the subgraph). Finally, we could approximate the k -component structure of a graph by successive iterations of this procedure.

However, there are a few problems with this approach. First, a k -component is defined as a maximal subgraph in which all pairs of different nodes have, at least, k node independent paths between them. If we rely on the connected components of the auxiliary graph as

³The fastest implementation of this algorithm runs in $O(N^4)$ time (Csárdi and Nepusz, 2006) which is impractical for moderately large networks.

proposed by White and Newman (2001) we will include in a given k -component all nodes that have at least k node independent paths with *only one* other node of the subgraph. Thus, the cohesive subgraphs detected won't have to be k -components as defined in graph theory. Second, k -components can overlap in $k - 1$ nodes. If we only consider connected components (i.e. 1-components) in the auxiliary graph, we will not be able to distinguish overlapping k -components. Finally, the approach proposed by White and Newman is not practical in computational terms for large networks because of its recursive nature and because it needs to compute node independent paths for all pairs of different nodes in the network as starting point.

2.4 Heuristics for computing k -components and their average connectivity

The logic of the algorithm presented here is based on repeatedly applying fast algorithms for k -cores (Batagelj and Zaveršnik, 2011) and biconnected components (Tarjan, 1972) in order to narrow down the number of pairs of different nodes over which we have to compute their local node connectivity for building the auxiliary graph in which two nodes are linked if they have at least k node independent paths connecting them. I follow the classical insight that, “ k -cores can be regarded as seedbeds, within which we can expect highly cohesive subsets to be found” Seidman (1983b, 281). More formally, my approach is based on Whitney's theorem (White and Harary, 2001, 328), which states an inclusion relation among node connectivity $\kappa(G)$, edge connectivity $\lambda(G)$ and minimum degree $\delta(G)$ for any graph G :

$$\kappa(G) \leq \lambda(G) \leq \delta(G) \quad (2.2)$$

This theorem implies that every k -component is nested inside a k -edge-component, which in turn, is contained in a k -core. This approach, unlike the proposal of White and Newman (2001), does not require computing node independent paths for all pairs of different nodes as a starting point, thus saving an important amount of computation. Moreover it does not require recursively applying the same procedure over each subgraph. With this approach I only have to compute node independent paths among pairs of different nodes in each biconnected part of each k -core, and repeat this procedure for each k from 3 to the maximal core number of a node in the input network.

The aim of the heuristics presented here is to provide a fast and reasonably accurate way of analyzing the cohesive structure of empirical networks of thousands of nodes and edges. As we have seen, k -components are the cornerstone of structural cohesion analysis. But they are very expensive to compute. My approach consists of computing extra-cohesive blocks of level k for each biconnected component of a k -core. Extra-cohesive blocks are a relaxation of the k -component concept in which not all node independent paths among pairs of different nodes have to run entirely inside the subgraph. Thus, there is no guarantee that an extra-cohesive block of level k actually has node connectivity k . I introduce an additional constraint to the extra-cohesive block concept in order to approximate k -components: the algorithm computes extra-cohesive blocks of level k that are also k -cores by themselves in G . Based on

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several tests with synthetic and empirical networks presented below, I show that usually extra-cohesive blocks detected by this algorithm have indeed node connectivity k . Furthermore, extra-cohesive blocks maintain high requirements in terms of multiconnectivity and robustness, thus conserving the most interesting properties from a sociological perspective on the structure of social groups.

Combining this logic with three observations about the auxiliary graph H allows me to design a new algorithm for finding extra-cohesive blocks in each biconnected component of a k -core, that can either be exact but slow —using flow-based algorithms for local node connectivity (Brandes and Erlebach, 2005, Chapter 7)— or fast and approximate, giving a lower bound with certificate of the composition and the connectivity of extra-cohesive blocks —using White and Newman (2001) approximation for local node connectivity. Once we have a fast way to compute extra-cohesive blocks, we can approximate k -components by imposing that the induced subgraph of the nodes that form an extra-cohesive block of G have to also be a k -core in G .

Let H be the auxiliary graph in which two nodes are linked if they have at least k node independent paths connecting them in each of the biconnected components of the core of level k of original graph G (for $k > 2$). The first observation is that complete subgraphs in H (H_{clique}) have a one to one correspondence with subgraphs of G in which each node is connected to every other node in the subgraph for at least k node independent paths. Thus, we have to search for cliques in H in order to discover extra-cohesive blocks in G .

The second observation is that an H_{clique} of order n is also a core of level $n - 1$ (all nodes have core number $n - 1$), and the degree of all nodes is also $n - 1$. The auxiliary graph H is usually very dense, because we build a different H for each biconnected part of the core subgraph of level k of the input graph G . In this kind of network big clusters of almost fully connected nodes are very common. Thus, in order to search for cliques in H we can do the following:

1. For each core number value c_{value} in each biconnected component of H :
2. Build a subgraph $H_{candidate}$ of H induced by the nodes that have *exactly* core number c_{value} . Note that this is different than building a k -core, which is a subgraph induced by all nodes with core number *greater or equal than* c_{value} .
3. If $H_{candidate}$ has order $c_{value} + 1$ then it is a clique and all nodes will have degree $n - 1$. Return the clique and continue with the following candidate.
4. If this is not the case, then some nodes will have degree $< n - 1$. Remove all nodes with minimum degree from $H_{candidate}$.
5. If the graph is trivial or empty, continue with the following candidate. Or otherwise recompute the core number for each node and go to 3.

Finally, the third observation is that if two k -components of different order overlap, the nodes that overlap belong to both cliques in H and will have core numbers equal to all other nodes in the bigger clique. Thus, I can account for possible overlap when building subgraphs

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$H_{candidate}$ (induced by the nodes that have *exactly* core number c_{value}) by also adding to the candidate subgraph the nodes in H that are connected to all nodes that have *exactly* core number c_{value} . Also, if we sort the subgraphs $H_{candidate}$ in reverse order (starting from the biggest), we can skip checking for possible overlap for the biggest.

Based on these three observations, the heuristics for approximating the cohesive structure of a network and the average connectivity of each individual block, consists of:

Let G be the input graph. Compute the core number of each node in G . For each k from 3 to the maximum core number build a k -core subgraph G_{k-core} with all nodes in G with core level $\geq k$.

For each biconnected component of G_{k-core} :

1. Compute local node connectivity $\kappa(u, v)$ between all pairs of different nodes. Optionally store the result for each pair. Either use a flow-based algorithm (exact but slow) or White and Newman's approximation for local node connectivity (approximate but a lot faster).
2. Build an auxiliary graph H with all nodes in this bicomponent of G_{k-core} with edges between two nodes if $\kappa(u, v) \geq k$. For each biconnected component of H :
3. Compute the core number of each node in $H_{bicomponent}$, sort the values in reverse order (biggest first), and for each value c_{value} :
 - a) Build a subgraph $H_{candidate}$ induced by nodes with core number *exactly* equal to c_{value} plus nodes in H that are connected with all nodes with core number equal to c_{value} .
 - i. If $H_{candidate}$ has order $c_{value} + 1$ then it is a clique and all nodes will have degree $n - 1$. Build a core subgraph $G_{candidate}$ of level k of G induced by all nodes in $H_{candidate}$ that have core number $\geq k$ in G .
 - ii. If this is not the case, then some nodes will have degree $< n - 1$. Remove all nodes with minimum degree from $H_{candidate}$. Build a core subgraph $G_{candidate}$ of level k of G induced by the remaining nodes of $H_{candidate}$ that have core number $\geq k$ in G .
 - A. If the resultant graph is trivial or empty, continue with the following candidate.
 - B. Else recompute the core number for each node in the new $H_{candidate}$ and go to (i).
 - b) The nodes of each biconnected component of $G_{candidate}$ are assumed to be a k -component of the input graph if the number of nodes is greater than k .
 - c) Compute the average connectivity of each detected k -component. Either use the value of $\kappa(u, v)$ computed in step 1 or recalculate $\kappa(u, v)$ in the induced subgraph of candidate nodes.

Notice that because this approach is based on computing node independent paths between pairs of different nodes, I'm able to use these computations to calculate both the cohesive

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structure and the average node connectivity of each detected k -component. Of course, computing average connectivity comes with a cost: either more space to store $\kappa(u, v)$ in step 1, or more computation time in step 3.c if we did not store $\kappa(u, v)$. This is not possible when applying the exact algorithm for k -components proposed by Moody and White (2003) because it is based on repeatedly finding k -cutsets and removing them, thus it does not consider node independent paths at all.

The output of these heuristics is an approximation to k -components based on extra-cohesive blocks. It finds extra-cohesive blocks and not k -components because it only builds the auxiliary graph H one time on each biconnected component of a core subgraph of level k from the input graph G . Local node connectivity is computed in a subgraph that might be larger than the final $G_{candidate}$ and thus some node independent paths that shouldn't could end up being counted.

Accuracy can be improved by rebuilding H from the pairwise node connectivity in $G_{candidate}$ and following the remaining steps of the heuristics at the cost of slowing down the computation. There is a trade-off between speed and accuracy. After some tests I decided to compute H only once and lean towards the speed pole of the trade-off. The goal is to have an usable procedure for analyzing networks of thousands of nodes and edges. Following this goal, the use of White and Newman (2001) approximation algorithm for local node connectivity in step 3.b is key. It is almost on order of magnitude faster than the exact flow-based algorithms. As usual, speed comes with a cost in accuracy: White and Newman (2001) algorithm provides a strict lower bound for the local node connectivity. Thus, by using it I can miss an edge in H that should be there. Therefore, a node belonging to a k -component could be excluded by the algorithm if White and Newman (2001) approximation was used in step 3.b. This is a source of false negatives in the process of approximating the k -component structure of a network. However, as I discussed above, the inaccuracy of this algorithm for sparse networks is reduced because in those networks the probability that a short node independent path uses nodes that could belong to two or more longer node independent paths is low.

The tests reveal that the use of White and Newman (2001) approximation does indeed underestimate the order of some k -components, particularly in not very sparse networks. One approach to mitigate this problem is to relax the strict cohesion requirement of $H_{candidate}$ being a clique. Following the network literature on cliques, we can relax its cohesion requirements in terms of degree, coreness and density. I did some experiments and found that a good relaxation criteria is to set a density threshold of 0.95 for $H_{candidate}$; it doesn't increase false positives and does decrease the false negatives derived from the underestimation of local node connectivity of White and Newman (2001) algorithm. Other possible criteria that has given good results in my tests is permitting a variation in degree of 2 in $H_{candidate}$ —that is, that the absolute difference of the maximum and the minimum degree in $H_{candidate}$ is at most 2. The former relaxation criteria is used for all analysis presented below and in the appendix.

This algorithm can be easily generalized so as to be applicable to directed networks provided that the implementation of White and Newman's approximation for pairwise node independent paths supports directed paths (which is the case in my implementation of this algorithm on top of NetworkX library). The only change needed then is to use strongly connected components instead of bicomponents. And, in step 3, to start with core number 2 instead of 3.

In appendix B.1 I present an illustration of the heuristics using a convenient small syn-

thetic network. In appendix B.2 I present an analysis of the performance of the heuristics compared to the performance of the exact algorithm for finding k -components (Moody and White, 2003). In appendix B.3 I discuss the implementation details of the heuristics; and in appendix B.4 I present the python code of my implementation of the heuristics. I also contributed an implementation of the heuristics to a popular Python software package for the analysis of complex networks: NetworkX (Hagberg et al., 2008). See appendix D for the documentation and source code published as part of NetworkX version 1.10.

2.5 Structural cohesion in cooperation networks

The structural cohesion model can be used to analyze cooperation in different kinds of cooperation networks; for instance, coauthorship networks (Moody, 2004; White et al., 2004) and cooperation among biotech firms (Powell et al., 2005). Most cooperation networks are bipartite because the cooperation of individuals has as a result —or, at least, as a relevant byproduct— some kind of object or event to which its authors are related. All these papers follow the usual practice to deal with two-mode networks: focus the analysis only on one-mode projections. As such, we don't know how much information about their cohesive structure we lose by ignoring the underlying bipartite networks. Recent literature on two-mode networks strongly suggests that it is necessary to analyze two-mode networks directly to get an accurate picture of their structure. For instance, in small world networks, we do know that focusing only on projections overestimates the smallworldiness of the network (Uzzi et al., 2007). We also know that generalizing clustering coefficients to bipartite networks can offer key information that is lost in the projection (Robins and Alexander, 2004; Lind et al., 2005; Opsahl, 2011). Finally, the loss of information is also critical in many other common network measures: degree distributions, density, and assortativity (Latapy et al., 2008). I show that this is also the case for the k -component structure of cooperation networks.

Structural cohesion analysis based on the k -component structure of bipartite networks has been conducted very rarely and only on very small networks (White et al., 2004). The limited diffusion of these studies can be readily explained by the fact that bipartite networks are usually quite a lot bigger than their one-mode counterparts, and the computational requirements, once again, stifled empirical research in this direction. Other measures have been developed to deal with cohesion in large bipartite networks, such as (p, q) -cores or 4-ring islands (Ahmed et al., 2007). However, the former is a bipartite version of k -cores and thus it has the same limitations for subgroup identification; while the latter is very useful to determine subgraphs in large networks that are more strongly connected internally than with the rest of the network, but also lacks some of the key elements of the definition for groups in the sociological literature, such as being hierarchical and allowing for overlaps.

The heuristics for structural cohesion presented here allows us to compute connectivity-based measures on large networks (up to tens of thousands of nodes and edges) quickly enough to be able to build suitable null models. Furthermore I will be able to compare the results for bipartite networks with their one-mode projections. To illustrate those points I use data on cooperation among software developers in one organization (the Debian project) and scientists publishing papers in the arXiv.org electronic repository in two different scientific fields:

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Network	Bipartite				Unipartite			
	# nodes	# edges	Av. degree	Time(s)	# nodes	# edges	Av. degree	Time(s)
Debian Lenny	13121	20220	3.08	1105.2	1383	5216	7.54	204.7
High Energy (theory)	26590	37566	2.81	3105.7	9767	19331	3.97	7136.0
Nuclear Theory	10371	15969	3.08	1205.2	4827	14488	6.00	3934.1

Table 2.2: cooperation networks analyzed from science and from software development. See text for details on their content. Time refers to the execution of the heuristics on each network expressed in seconds.

High Energy Theory and Nuclear Theory. I built the Debian cooperation network by linking each software developer with the packages (i.e. programs) that she uploaded to the package repository of the Debian Operating System during a complete release cycle. I analyze the Debian Operating System version 5.0, codenamed ‘‘Lenny’’, which was developed from April 8, 2007, to February 1, 2009. Scientific networks are built using all the papers uploaded to the arXiv.org pre-print repository from January 1, 2006, to December 31, 2010, for two well established scientific fields: High Energy Physics Theory and Nuclear Theory. In these networks each author is linked to the papers that she has authored during the time period analyzed. One-mode projections are always on the human side: scientists linked together if they have coauthored a paper, and developers linked together if they have worked on the same program. Table 2.2 presents some details on those networks.

In the remaining part of this section I perform three kinds of analysis to demonstrate the loss of information we incur when focusing only on one-mode projections when dealing with bipartite networks. First, I present a tree representation of the k -component structure —the cohesive blocks structure (White and Harary, 2001; Moody and White, 2003; White et al., 2004; Mani and Moody, 2014)— for the bipartite networks and their one-mode projections, both for actual networks and for their random counterparts. Second, I present a comparison among actual and random networks (both for one and two-mode) on the k -number frequencies of nodes. Finally, I present a novel graphic representation of the structural cohesion of a network, based on three-dimensional scatter plot, using average node connectivity as a synthetic and more informative measure of cohesion of each k -component.

For the first two analyses it is necessary to generate null models in order to discount the possibility that the observed structure of actual networks is just the result of randomly mixing papers and scientists or packages and developers. The null models used in this chapter are based on a bipartite configuration model (Newman, 2003), which consists of generating networks by randomly assigning papers/programs to scientists/developers but maintaining constant the distribution of papers per scientists and scientists by paper observed in the actual networks, that is the bipartite degree distribution. For one-mode projections, I generated bipartite random networks based on their original bipartite degree distribution, and then performed the one-mode projection. This is a common technique for avoiding overestimating the local clustering of one-mode projections (Uzzi et al., 2007). As the configuration model can generate some multiple edges and self-loops, I followed the usual practice of deleting them before the analysis in order to guarantee that random networks are simple, like actual networks.

So let's start with the tree representation of the cohesive blocks structure. As proposed by White et al. (2004), we can represent the k -component structure of a network by drawing a tree whose nodes are k -components; two nodes are linked if the k -component of higher level is nested inside the k -component of lower level (see Mani and Moody (2014, 1643,1651) for this kind of analysis on the Indian interorganizational ownership network). This representation of the connectivity structure can be built during the run time of the exact algorithm. However, because the heuristics are based on finding node independent paths, I have to compute first the k -components hierarchy, and then construct the tree that represents the connectivity structure of the network.

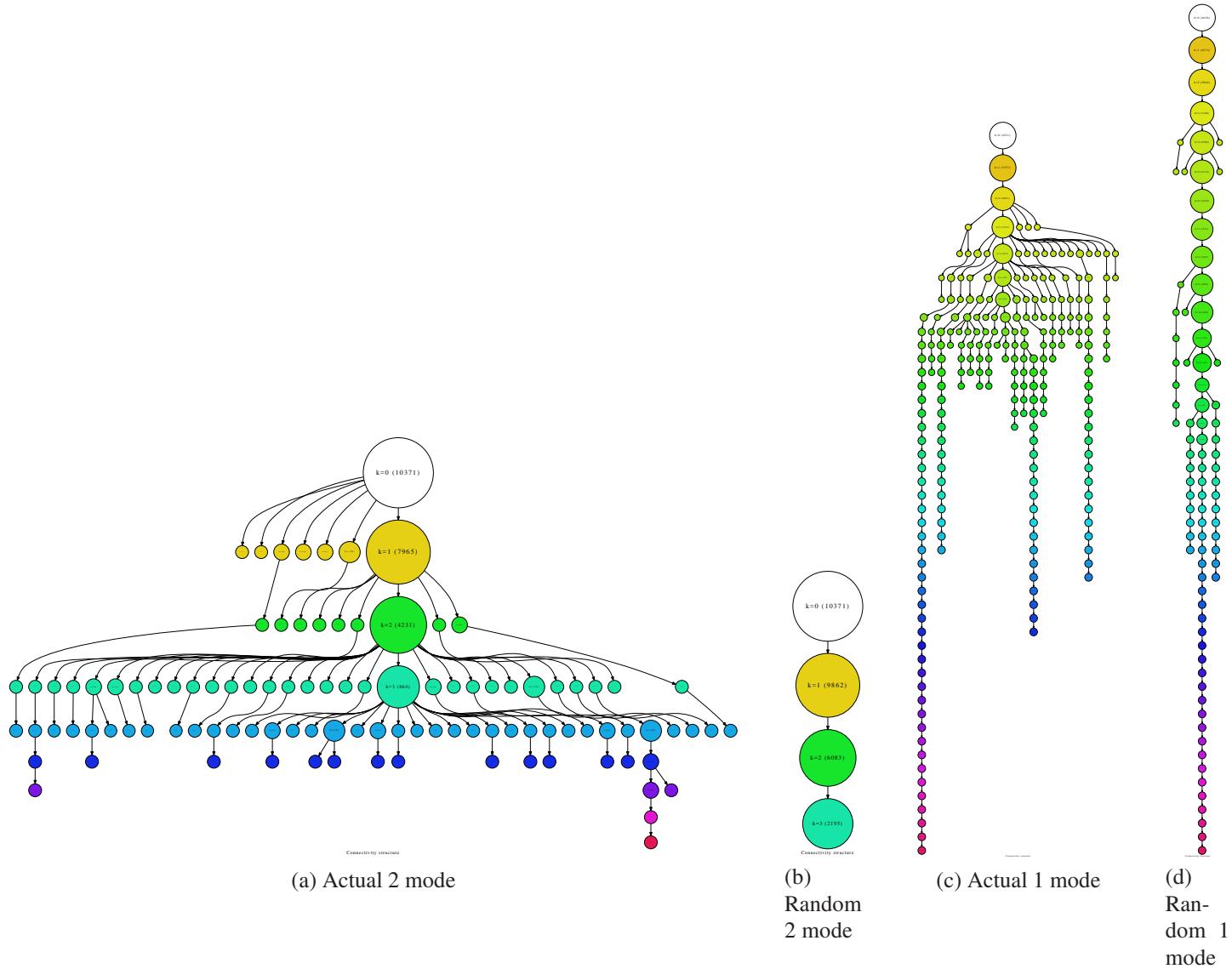


Figure 2.1: Cohesive blocks for two-mode and one-mode Nuclear Theory cooperation networks, and for their random counterparts. Random networks were generated using a bipartite configuration model. I built 1000 random networks and chose one randomly, see text for details. For lower connectivity levels I have removed some small k -components to improve the readability: I do not show 1-components with less than 20 nodes, 2-components with less than 15 nodes, or tricomponents with less than 10 nodes.

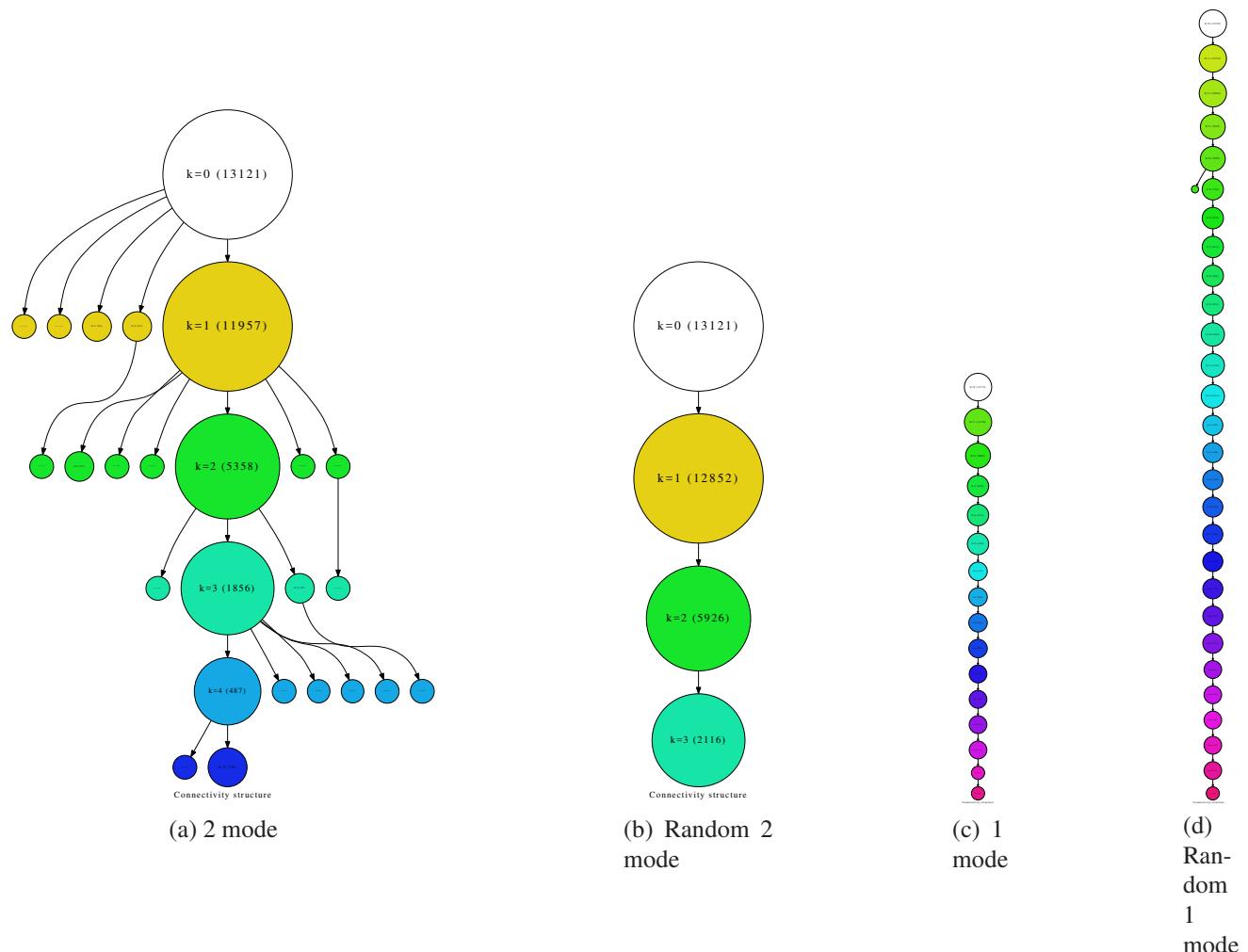


Figure 2.2: Cohesive blocks for two-mode and one-mode Debian cooperation networks, and for their random counterparts. Random networks were generated using a bipartite configuration model. I built 1000 random networks and chose one randomly, see text for details. For lower connectivity levels I have removed some small k -components to improve the readability: I do not show 1-components with less than 20 nodes, 2-components with less than 15 nodes, or tricomponents with fewer than 10 nodes.

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Figures 2.1a and 2.1c show the connectivity structure of Nuclear Theory cooperation networks represented as a tree, the former for the two-mode network and the latter for one-mode ones. As we can see, both networks display non-trivial structure. The two-mode network has up to an 8-component, but most nodes are in k -components with $k < 6$. Up to $k = 3$ most nodes are in giant k -components, but for $k = \{4, 5\}$ there are many k -components of similar order. Figure 2.1c, which corresponds to the one-mode projection, has a lot more connectivity levels—a byproduct of the mathematical transformation from two-mode to one-mode. In this network, the maximum connectivity level is 46; the four long legs of the plot correspond to 4 cliques with 47, 31, 27 and 25 nodes. Notice that each one of these 4 cliques are already a separated k -component at $k = 7$. It is at this level of connectivity ($k = \{7, 8\}$) where the giant k -components start to dissolve and many smaller k -components emerge.

In order to be able to assess the significance of the results obtained, I have to compare the connectivity structure of actual networks with the connectivity structure of a random network that maintains the observed bipartite degree distribution. In this case, I compare actual networks with only one random network. I obtained it by generating 1000 random networks and choosing one randomly. Figures 2.1b and 2.1d show the connectivity structure of the random counterparts for Nuclear Theory cooperation networks. For the two-mode network, instead of the differentiated connectivity structure displayed by the actual bipartite network, there is a flatter connectivity structure, where the higher level k -component is a tricomponent. Moreover, instead of many small k -components at high connectivity levels, the random bipartite network has only giant k -components where all nodes with component number k are. In this case, the one-mode network is also quite different from its random counterpart. There are only giant k -components up until $k = 15$, where the four cliques observed in the actual network separate from each other to form distinct k -components.

The hierarchy of the connectivity structure displayed in these plots allows us to do meaningful comparisons between networks in terms of their connectivity structure. For instance, figures 2.2a and 2.2c show the connectivity structure of Debian cooperation networks. The former displays the bipartite connectivity structure, which is quite different from two-mode Nuclear Theory structure discussed above. Although there are some small k -components for each connectivity level, most of the nodes with k -number k are in a giant k -component that encompasses most of the nodes of that level. Even at the top level of connectivity ($k = 5$), 80 percent of the 88 nodes with k -number 5 are in the same 5-component. Figure 2.2c displays the cohesive block structure for its one-mode projection. It consists of a monotonous linear succession of increasingly smaller k -components nested inside each other.

Figures 2.2b and 2.2d show the connectivity structure of the random counterparts of Debian cooperation networks. The random one-mode projection has the same structure than its actual counterpart, a single long chain of k -components nested inside each other. However, the random two-mode structure is quite different from its actual counterpart: it consists of a chain of single cohesive blocks. At lower connectivity levels, up to $k = 3$, the random network have more nodes in those giant k -components than its actual counterpart; but the actual Debian two-mode network has a bigger 4-component and also 2 5-components that are not present in its random counterpart. Thus, in terms of their connectivity structure, two-mode networks are farther apart from their random counterparts than their one-mode projections.

Note that, so far, the comparison of actual networks with their random counterparts has

focused on a single random network. But, a single random network is not a sound null model. I do need to generate a large enough set of them and perform the connectivity analysis to have an accurate picture of possible connectivity structures generated solely by chance given the observed bipartite degree distribution. A good way to evaluate the differences between the actual network and the set of random networks is comparing the frequencies of k -numbers of their nodes. A node's k -number, or component number, is the value k of the highest order k -component in which it is embedded. In the barplots displayed in figure 2.3, each bar represents the number of nodes that have k -number k . Green bars represent k -number frequencies for the actual networks and blue bars represent the average value of 64 random networks that maintain the degree distribution of the original two-mode network. I analyzed 64 random networks to keep computation time reasonable, but I generated ten times more random networks and I have randomly selected one of each ten to perform the actual analysis.

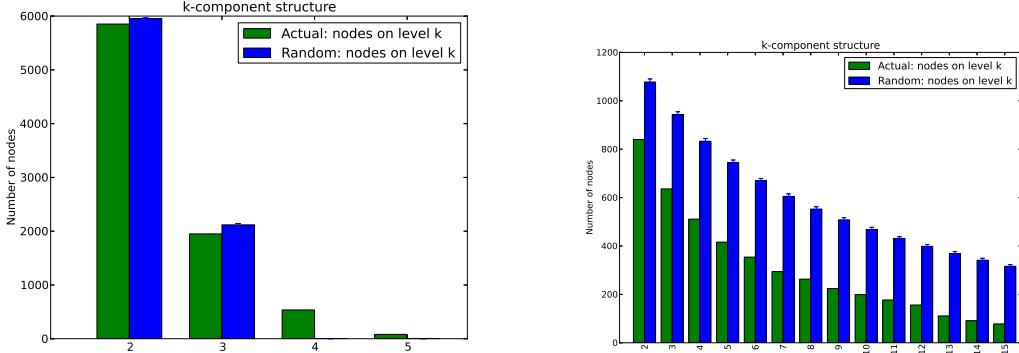
Figure 2.3 shows that two-mode and one-mode projections of the same network yield quite different results in terms of k -number distribution among nodes when compared with their random counterparts. Bipartite cooperation networks have slightly fewer nodes with low component number (2 and sometimes 3) than their random counterparts. However, they have a lot more nodes in higher levels of connectivity. This means that, in bipartite random networks, the edges are more evenly distributed among all nodes. Thus more nodes are embedded in bicomponents, and in some cases, tricomponents; but also for this same reason, random networks have a lot fewer nodes in k -components of higher order (4, 5 or 6) than actual networks. Therefore, I can conclude that bipartite cooperation networks are significantly more hierarchical in connectivity terms than their random counterparts. As this hierarchy cannot be explained in terms of random mixing papers/programs with scientists/developers, it must be the result of an underlying organization principle that shapes the structure of these cooperation networks.

Going one step beyond classical structural cohesion analysis, as proposed above, I can deepen this analysis by also considering the average connectivity of the k -components of these networks. By analogy with the k -component number of each node, which is the maximum value k of the deepest k -component in which that node is embedded, the average k -component number of each node is the value of average connectivity of the deepest k -component in which that node is embedded. Notice that, unlike plain node connectivity, average node connectivity is a continuous measure of cohesion. Thus it provides a more granular measure of cohesion because it allows to rank k -components with the same k according to their average node connectivity.

Figure 2.4 graphically represents the three networks with three-dimensional scatter plots⁴. In these graphs, each dot corresponds to a node of the network, for two-mode networks nodes represent both scientists/developers and papers/programs. The Z axis (the vertical one) is the average k -component number of each node, and the X and Y axis are the result of a 2 dimensional force-based layout algorithm implemented by the `neato` program of Graphviz (Ellson et al., 2002). The two dimensional layout is computed by constructing a virtual physical model and then using an iterative solver procedure to obtain a low-energy configuration. Following Kamada and Kawai (1989), an ideal spring is placed between each pair of nodes (even if they are not connected in the network). The length of each spring corresponds to the

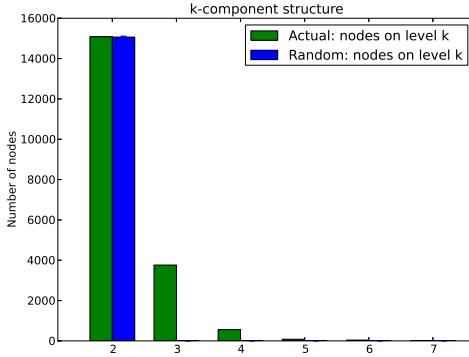
⁴These plots are produced with the powerful Matplotlib python library (Hunter, 2007).

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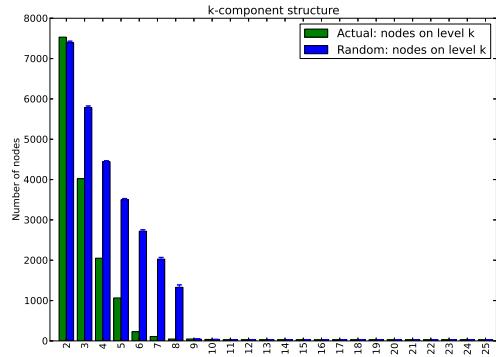


(a) Bipartite network formed by developers and packages during 2 years of cooperation (from 2007 to 2009) on the release codenamed Lenny of the Debian operating system

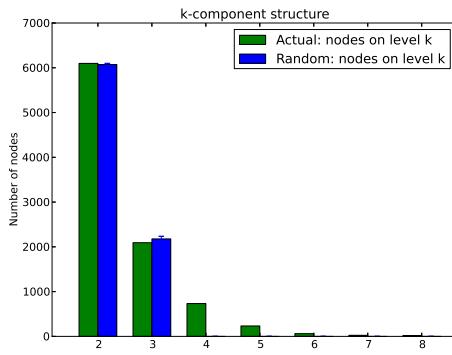
(b) Unipartite network formed by developers during 2 years of cooperation (from 2007 to 2009) on the release codenamed Lenny of the Debian operating system



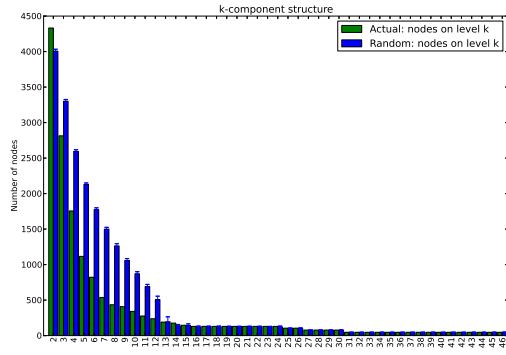
(c) Bipartite network formed by scientists and preprints during 5 years (2006-2010) in the high energy physics (theory) section of arXiv.org



(d) Unipartite network formed by scientists during 5 years (2006-2010) in the high energy physics (theory) section of arXiv.org



(e) Bipartite network formed by scientists and preprints during 5 years (2006-2010) in the nuclear physics (theory) section of arXiv.org



(f) Unipartite network formed by scientists during 5 years (2006-2010) in the nuclear theory section of arXiv.org

Figure 2.3: Barplots of k -number frequencies for two-mode and one-mode cooperation networks and their random counterparts. Green bars represent the actual k -number frequencies and blue bars represent the average k -number frequencies for 64 random networks that maintain the degree distribution of the original two-mode network.

geodesic distance between the pair of nodes that it links. The final node positioning in the layout approximates the path distance among pairs of nodes in the network.

This novel graphic representation of cohesion structure is inspired by the approximation technique developed by Moody (2004) for plotting the approximate cohesion contour of large networks to which is not practical to apply Moody and White's exact algorithm for k -components 2003. Moody's technique is based on the fact that force-based layouts algorithms tend to draw nodes within highly cohesive subgroups near each other. Then it is necessary to divide the surface of the two-dimensional plane in squares of equal areas and compute node independent paths on a sample of pairs of nodes inside each square so as to obtain an approximation for the node connectivity in that square. Then it is possible to draw a surface plot using a smoothing probability density function. However, in order to obtain a nice smooth surface plot, it is necessary to use heavy smoothing in the probability density function, and carefully choose the area of the squares (mostly by trial and error). Moreover, this technique strongly relies on the force-based layout algorithm to put nodes in highly cohesive subgroups near each other —something which is not guaranteed because they are usually based in path distance and not directly on node connectivity. Because I'm able to compute the k -component structure with the heuristics for large networks, the three-dimensional scatter plot only relies on the layout algorithm for setting the X and Y positions of the nodes, while the Z position (average node connectivity) is computed directly from the network. Moreover, I don't have to use a smoothed surface plot because there is actually a value of average connectivity for each node, and thus I can plot each node as a dot on the plot. This gives a more accurate picture of the actual cohesive structure of a network.

This synthetic representation of their cohesive structures can help researchers visualize the presence of different organizational mechanisms in different kinds of cooperation networks. The difference between the Debian and the scientific cooperation networks is striking. Figure 2.4a shows the scatter plot for a Debian bipartite network. There is a clear vertical separation among nodes in different connectivity levels. This is because almost all nodes in each connectivity level are in a giant k -component and thus they have the same average connectivity. In other words, developers in Debian show different levels of engagement and contribution, with a core group of developers deeply nested at the core of the community. This pattern is the result of formal and informal rules of cooperation that evolved over the years (O'Mahony and Ferraro, 2007a) into a homogeneous hierarchical structure, where there is only one core of highly productive individuals at the center. Not surprisingly, perhaps, the Debian project has been particularly resilient to developers' turnover and splintering factions.

Scientific cooperation networks show a rather different structure of cooperation. The two-mode science cooperation networks (figures 2.4c and 2.4e) display a continuous hierarchical structure in which there are nodes at different levels of average connectivity for each discrete plain connectivity level. This is because science cooperation networks have a complex cohesive block structure where there are a lot of independent k -components in each plain connectivity level, for $k \geq 3$. Each small cohesive block has a different order, size and average connectivity; thus, when I display them in this three-dimensional scatter plot there is a continuous hierarchical structure that contrasts with the almost discrete structure of Debian cooperation networks.

One explanation why we observe this heterogeneous connectivity structure is that sci-

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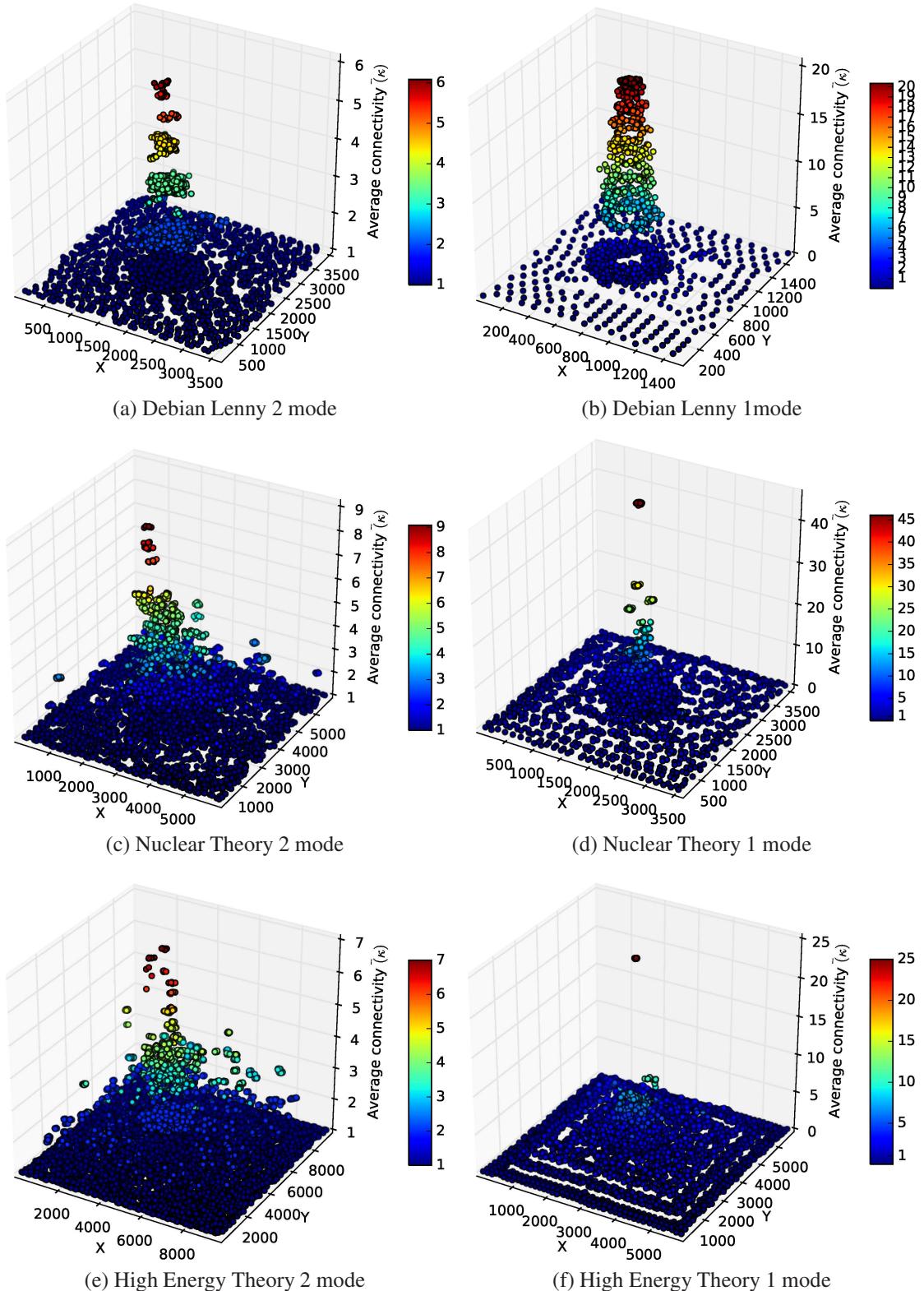


Figure 2.4: Average connectivity three-dimensional scatter plots. X and Y are the positions determined by the Kamada-Kawai layout algorithm. The vertical dimension is average connectivity. Each dot is a node of the network and two-mode networks contain both papers/programs and scientists/developers.

tific cooperation clusters around a variety of different aims, methods, projects, and institutional environments. Therefore as the most productive scientists collaborate with each other, hierarchies naturally emerge. However, we are less likely to observe one single hierarchical order as we did in the Debian network, as more than one core of highly productive scientists is likely to emerge. In a way this visualization captures the structure of the “invisible college” of the scientific discipline.

If we compare the bipartite networks with their one-mode projections using this graphical representation (see figures 2.4b, 2.4d, and 2.4f) we can see that, again, they look quite different. While bipartite average connectivity structure for the Debian network is characterized by clearly defined and almost discrete hierarchical levels, its one-mode counterpart shows a continuous hierarchical structure. However, this is not caused by the presence of many small k -components at the same level k , as in the case of bipartite science networks discussed above, but by the close succession of hierarchy levels with almost the same number of nodes in a chain-like structure (as depicted in figure 2.2c).

For cooperation science networks, the three-dimensional scatter plots of one-mode projections are also quite different than their original bipartite networks. They have a lot more hierarchy levels than bipartite networks but most nodes are at lower connectivity levels. Only a few nodes are at top levels of connectivity, and they all form part of some clique, which are the groups in the long “legs” of the cohesive block structure depicted in figure 2.1c. Thus, the complex hierarchical connectivity structure of bipartite cooperation networks gets blurred when the one-mode projection is performed. An important consequence of the projection is that only a few nodes embedded in big cliques appear at top connectivity levels and all other nodes are way down in the connectivity structure. This could lead the risk of overestimating the importance of those nodes in big cliques and to underestimate the importance of nodes that, despite being at high levels of the bipartite connectivity structure, appear only at lower levels of the unipartite connectivity structure.

2.6 Summary of Contributions

This chapter contributes to our understanding of structural cohesion in a number of ways.

First, I extended theoretically the structural cohesion model by considering not only plain node connectivity, which is the minimum number of nodes that must be removed in order to disconnect a network, but also the average node connectivity of networks and its cohesive groups, which is the number of nodes that, on average, must be removed to disconnect an arbitrary pair of nodes in the network. Taking into account average connectivity allows a more granular conception of structural cohesion, and I show in the empirical analysis of cooperation networks how this approach leads to useful implications in empirical research.

Second, I developed new heuristics to compute the k -component structure of networks, along with the average node connectivity for each k -component. Instead of directly identifying k -cutsets using standard flow algorithms, this approach is based on computing pair-wise connectivity within biconnected parts of k -cores. These heuristics allow for computing the approximate value of group cohesion for moderately large networks, along with all the hierarchical structure of connectivity levels, in a reasonable time frame. I showed that these

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heuristics can be applied to networks at least one order of magnitude bigger than the ones manageable by the exact algorithm proposed by Moody and White (2003). To ensure reproducibility and to facilitate diffusion of these heuristics, I provided a very detailed description of the implementation, along with a fully functional implementation contributed to the NetworkX⁵ free software python package for the analysis of complex networks.

One limitation of this approach is that it can potentially identify groups that are not internally k -connected when using White and Newman (2001)'s approximation for pair-wise node connectivity, because some node independent paths can go through nodes that are not part of the group. I discuss this limitation and analyze its impact on practical empirical analysis in appendix B.5.

Finally, I used the heuristics proposed in this chapter to analyze three large cooperation networks. With this analysis, I showed that the heuristics and the novel visualization technique for cohesive network structure help us capture important differences in the way cooperation is structured. Obviously a detailed comparative analysis of the institutional and organizational structures and the differences between science and FOSS cooperation structure and dynamics is beyond the scope and aims of this chapter. But future research could leverage the tools I provide to systematically analyze cooperation networks from different fields. For instance, sociologists of science often compare scientific disciplines in terms of their collaborative structures (Moody, 2004) and their level of controversies (Shwed and Bearman, 2010). The measures and the visualization technique I proposed could nicely capture these features and compare them across scientific disciplines. This would make it possible to further our understanding of the social structure of science, and its impact in terms of productivity, novelty and impact. Social network researchers interested in organizational robustness would also benefit from leveraging the structural cohesion measures to detect sub-groups that are more critical to the organization's resilience, and thus prevent factionalization. Exploring the consequences of different forms of cohesive structures will eventually help us further our theoretical understanding of cooperation and the role that cohesive groups play in linking micro level dynamics with macro level social structures.

⁵ Available in NetworkX version 1.10 released on August 2015 <https://pypi.python.org/pypi/networkx/>. See also appendix B.4 for illustrative code and appendix D for references to NetworkX code and documentation that I contributed.

The Network Structure of Collaborative Communities

The organization of knowledge production and diffusion has been a challenging problem for economists, sociologists and organization theorists. The increasing importance of knowledge-intensive sectors of the economy, and the inadequacies of markets and hierarchy as coordinating principles for knowledge production and diffusion, has prompted some scholars to suggest that these activities might be better organized through an alternative organizing principle: community (Adler, 2001). It is suggested that a new form of community, qualitatively different from the traditional *Gemeinschaft* and the modern *Gesellschaft* (Tönnies, 1974), has emerged. Examples of collaborative communities are large scientific projects, novel forms of professional work organization (Adler, Kwon, and Heckscher, 2008), open source software communities, and knowledge-intensive production processes in corporations (Adler and Heckscher, 2006).

These collaborative communities are characterized by conscious cooperation, high interdependence, trust, shared values and a value-rational basis for legitimate authority (Adler and Heckscher, 2006; Adler et al., 2008). While all these dimensions matter for a proper characterization of collaborative communities, it is clear that trust plays a more critical role as the key social mechanism of this form. But how does trust develop in these loosely coupled social forms? Adler and Heckscher (2006) suggest that dense local interactions facilitate the emergence of trust, and common values facilitate the development of collective identity. Scarce attention is given to the structural features of cooperation in these communities. Given the sizable literature on the social structure that facilitate (or inhibit) the emergence of trust in society (Granovetter, 1985; Coleman, 1988; Moody and White, 2003), I believe that an important question to further our understanding of collaborative communities is to explore the network structure that lead to their emergence and effectiveness in the production and diffusion of knowledge.

In this chapter therefore I suggest that a unique social network structure undergirds collaborative communities, and facilitate the development of trust and increase their robustness to turnover. Building on the literature on small world and cohesive groups, I identify the key structural feature of these networks which I call cohesive small worlds.

3.1 Collaborative communities

The concept of collaborative communities was introduced to make sense of novel organizational forms which were defying the traditional dichotomy between hierarchy and market (Coase, 1937; Williamson, 1975). Ouchi (1980) was one of the first social theorist to include community/trust in the principles of social organization; he referred to these principles as clan, but he conceptualized the relation between market, hierarchy and community as a three-way trade-off. Likewise Powell (1990) introduced networks as an alternative principle to hierarchy and markets. Instead, Adler (2001) considers these three principles —Hierarchy, Market and Community— as ideal-types which concrete organizations mix in hybrid forms. Each one of these principles is based on a coordination mechanism. Authority is the main mechanism used in hierarchy to coordinate horizontal and vertical division of labour. Price is the mechanism through which market coordinates competing and anonymous suppliers and buyers. And trust, generated by shared values and norms, is the main mechanism of community principle (Adler, 2001).

This three-dimensional space allows a fine gained classification of organizations and institutions, considering the effects of the mixture of different organization principles. Adler and Heckscher (2006) argue that, on the one hand, neither market nor hierarchy can actually function without at least some underpinning of community and, on the other hand, that the form of community differs depending on its relation to the other two principles of social organization: “When the dominant principle is hierarchy, community takes the form of *Gemeinschaft*. When the dominant principle shifts to market, community mutates from *Gemeinschaft* into *Gesellschaft*. We postulate that when community itself becomes the dominant organizing principle, it will take a form quite different from either *Gemeinschaft* or *Gesellschaft*” (Adler and Heckscher, 2006, 16).

This new form of community can be called collaborative community and it is based on contribution-based trust as its primary social mechanism: “The basis of trust is the degree to which members of the community believe that others have contributions to make towards this shared [end]” (Adler and Heckscher, 2006, 21). This form of community seems especially well suited to deal with the challenges of knowledge-based production processes because, hierarchy and market have proved ineffective, at best, at managing knowledge. On the hierarchy side, knowledge is treated as scarce resource and therefore centralized at the higher levels of the organization where key decisions are taken; this rigid scheme prevents the necessary flexibility to deal with unanticipated problems —very common in non-routine tasks— and to foster innovation and generation of new knowledge (Adler, 2001, 216).

On the market side, the price mechanism fails to optimize the production and allocation of knowledge (Arrow, 1962; Stiglitz, 1996). The fact that knowledge is a public good that grow rather than diminish with use poses serious problems to the effectiveness of price mechanism. There is a trade-off between production and allocation: “On one hand, production of knowledge would be optimized by establishing strong intellectual property rights that create incentives to create knowledge. On the other hand, not only are such rights difficult to enforce, but more fundamentally, they block socially optimal allocation. Allocation of knowledge would be optimized by allowing free access because the marginal cost of supplying another costumer with the same knowledge is close to zero” (Adler, 2001, 217).

In conclusion: “neither markets nor hierarchies [...] nor any intermediate forms [...] can simultaneously optimize incentives to produce knowledge and to disseminate it” (Adler and Heckscher, 2006, 29). But community can effectively deal with knowledge production and distribution by “reduc[ing] both transaction costs –replacing contracts with handshakes— and agency risks —replacing the fear of shirking and misrepresentation with mutual confidence. Community can thus greatly mitigate coordination difficulties created by knowledge’s public good character” (Adler and Heckscher, 2006, 30). The community principle of coordination allows to combine different people with different sets of knowledge and expertise in order to solve complex problems while in the process they benefit each other and their common goal.

The strengths of community and trust at managing complex knowledge-based production processes should not blind us about its potential downsides: exclusivism and elitism is a potential problem of communities based in shared norms or familiarity (Adler, 2001, 226). The ideas and practices that come from a trusted peer can be evaluated less critically than best ones coming from an outsider, therefore inertia and complacency are a threat to a dynamical and innovative environment based mainly on community/trust. Thus it can degenerate in a closed community where traditionalism, autocracy and nepotism become its main characteristics, not very different than the *Gemeinschaft* form discussed above.

According to Adler and Heckscher (2006, 59-61), effective authority is essential to counter balance those downsides of the community principle of social organization. The keys of success are specifically the need of authority in three central processes: to define direction, to allocate resources and to resolve internal disputes. Authority under the shadow of community should be consistent with the values and norms of the collective, thus authority has to be seen as essential in order to achieve the collective goals of the community. Consistently with the theoretical model presented above, the three organizing principles of social action coexist in actual organizations and the predominant principle —community in this case— shapes the subordinate —authority—. The authors offer a couple of illustrative examples: complex science projects and open source software development (they cite specifically Linux and Apache).

Authority and power are two central concepts in sociological and organizational theory. Max Weber is one of the key theorist in this area; his formulations have shaped a powerful theoretical stream and have centered an important part of discussions and disputes around the conceptualization of power in society and in organizations. The classical theoretical approach to collectivist organizations —which is a key antecedent of the Collaborative Communities theoretical approach— draws on the weberian formulation of authority, or more concretely, on what is missing in his formulation. Weber built a typology of social action consisting in four ideal types: affectual, traditional, legal-rational and value-rational. According to Weber, three of this four ideal types of social action —affectual, traditional and legal-rational— have its own form of authority associated which implies a particular type of organization to implement its aims. Therefore there is a missing type of authority based on value-rational social action.

This “missing type” has been the starting point of an interesting theoretical conceptualization on governance systems in professions and collectivist organizations (Wilier, 1967; Satow, 1975; Rothschild-Whitt, 1979). Table 3.1 summarizes the situation. The fact that Weber did not formulate the counterpart authority type of value-rationality social action was not a neglect; he intended to do a comprehensive typology of authority forms. However

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he acknowledged that there is a tension between substantive or value-rational and formal or instrumentally-rational social action. According to Rothschild-Whitt (1979, 510), Weber thought that the conflict between formal and substantive rationality has no ultimate solution; he established his conceptualization of bureaucracy —the main locus of formal-rationality—as if it could eliminate all substantive considerations in the exercise of power. The progressive dominance of bureaucracies in modern society, that he saw as an inevitable trend, is what he referred as the “iron cage”.

Social Action	Legitimacy	Authority
Traditional	Traditional	Traditional
Affectual	Affectual	Affectual-Charismatic
Purposive-Rational	Legal	Rational-legal
Value-Rational	Value-Rational	<i>missing type</i>

Table 3.1: Weber’s typology of social action, legitimacy and authority (Satow, 1975, 526).

The dark fears of Weber’s “iron cage” produced an important influence in twentieth century’s social science: in the sixties and seventies, there was an important consensus between main stream economist and organizational theorist in the prognosis that large bureaucratic organizations will expand until encompass a large portion of economic landscape (Adler, 2001, 215). Following Weber, it was thought that a large firm bureaucratically organized will outperform in the market all competing organizational forms. This prognosis has revealed wrong; the last decades have witnessed an important shift in the size of corporative organizations (Brynjolfsson et al., 1994). As we discussed above, the role of community and trust in the production and dissemination of knowledge and, on the other hand, the socialization tendency of complex knowledge-based labour processes are key factors to understand this shift. Those changes partially explain why collectivist organizations—and particularly free software communities—have received growing attention from sociologists and organizational theorists in the last decade (Kogut and Metiu, 2001; Von Hippel and Von Krogh, 2003; Weber, 2004; O’Mahony and Ferraro, 2007b), contrasting with theoretical work in the twentieth century, that have been centered mostly in bureaucratic organizations driven by formal rationality (Thompson, 2003), although with important exceptions (Johnson and Whyte, 1977; Rothschild-Whitt, 1979; Rothschild and Whitt, 1989).

The classic theoretical approach to collectivist organizations (Rothschild-Whitt, 1979; Rothschild and Whitt, 1989) stresses the differences between the bureaucratic and the collectivist models of organization assessing that the latter is a *sui-generis* form of organization premised on the logic of substantive rationality, not a failure to achieve bureaucratic standards (Rothschild-Whitt, 1979, 509). This approach has postulated that main characteristics of the collectivist organization are: authority based on consensus and open to negotiation, minimal stipulated rules with primacy of *ad hoc* decisions, social controls based on moral appeals and selection of homogeneous personnel (without relaying in direct supervision and standardized

3.1. Collaborative communities

rules), minimal division of labour and holistic roles stressing the autonomy of the worker/participant (Rothschild-Whitt, 1979, 519).

It is assumed that the collectivistic approach to production is less efficient and effective than the bureaucratic one, although this has not to be seen as a failure but as an outcome of implementation of a different set of goals. This theoretical stream was developed in the seventies and eighties of the twentieth century. Its approach was to generate an ideal type based on empirical evidence gathered from collectivist organizations that thrive in that age as schools, newspapers, clinics, foods co-ops, etc. All this empirical sources involved productive processes characterized by low socialization and developed in small organizations.

The turn of the century has witnessed the birth and development of a wide range of collectivist organizations with complex and sophisticated governance systems, highly developed sets of rules concerning activities of the organization and high degree of interdependence between the members. Those communities have shown that they can be, at least, as productive as hierarchical bureaucracies, for instance FOSS communities compete effectively with some of the larger capitalist corporations in the world. The main focus of the new analysis on collectivist organizations or communities is their governance system. Based on the tradition of organizational science, this new approach tries to explain how communities producing collective goods govern themselves. In the case of Debian project, we do know that members tend to develop a shared basis of formal authority limited with democratic mechanisms that enabled experimentation with shifting conceptions of authority over time (O'Mahony and Ferararo, 2007b).

But little is known about how those communities are able to develop large scale cooperation in complex knowledge intensive production processes to the point that allows them to produce and innovate at a similar level than capitalist corporations. The aim of this research is to overcome this research gap, explaining and theorizing the mechanisms that enable large scale cooperation by focusing on the patterns of relations that direct producers establish in the production process, that is, their cooperation networks. I would like to stress that the technological revolution of information and communication technologies is an important change that had a huge impact in all kinds of productive processes. Internet and the World Wide Web have changed some of the constraints faced by collectivist organizations, enabling them to scale up and to disperse geographically at an extend unthinkable before the digital era. But these technological changes are not an explanation by themselves, they are a necessary but not sufficient condition to enable large scale cooperation in Collaborative Communities.

In summary, the Collaborative Communities theoretical approach to the organization of knowledge intensive production processes has helped us understand puzzling empirical cases, but few theoretical puzzles need to be addressed. Given the central role that trust play in enabling large scale cooperation in Collaborative Communities, it seems essential to explore the conditions in which trust can thrive. Adler and Heckscher (2006) suggest that individuals in Collaborative Communities will develop higher trust because given the high interdependence of their work, they need to collaborate to achieve their common goal. Furthermore they suggest a common value orientation facilitate the development of common identities. This approach, while based on decades of literature on trust and traditional communities, is problematic for two reasons. First of all, it is not clear how trust and value congruence emerge. Both these characteristics are neither easy to find, nor to maintain, and it is theoretically crit-

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ical to ask ourselves if there are factors that can explain both. Moreover, it is not clear how trust and shared values can be maintained in large heterogeneous geographically distributed communities where membership exhibits high turnover.

I argue that the current characterization of collaborative community can be fruitfully enriched with the growing literature on social networks, in order to identify the structural conditions that enable trust, value congruence, and large scale cooperation. A structural approach to collaborative communities is not inconsistent with what has been done so far, but will help (1) refine the current characterization of communities in social network terms, (2) provide a methodology to unobtrusively identify Collaborative Communities in the wild, and (3) a contribution to the existing tool-kit to design Collaborative Communities. I explore existing models of network of knowledge production, compare them, and suggest that there is a consistent set of structural features of the patterns of relations between direct producers —topological properties in network terms— that characterize Collaborative Communities.

3.2 A network approach to collaborative communities

A network approach to collaborative communities should start from the basic building block of collaborative activity: team work. There is evidence of a trend towards more cooperative activity, often associated with the increasing complexity and interdependence of knowledge production and creative activity more generally (Guimerà, Uzzi, Spiro, and Amaral, 2005; Uzzi and Spiro, 2005; Wuchty, Jones, and Uzzi, 2007; Jones, Wuchty, and Uzzi, 2008). Based on works in science, engineering, social sciences, arts, humanities and patents, Wuchty et al. (2007) show that until the 1950s solo-authored academic articles and inventions were more likely to receive a large number of citations than articles and inventions developed by teams. This is not true anymore, and the trend towards collective research and teamwork is illustrated by the fact that in the last decade the top cited papers in all the disciplines studied were mostly created by teams.

The study of science as collaborative creative work, and scientific communities as collaborative communities has contributed to our understanding of the properties of the networks created by these collaborations. For instance, Guimerà et al. (2005) suggest that three simple mechanisms of team assembly (number of team members, probability of team members being and incumbent, and propensity to repeat collaborations) determine the topological properties of the network structure that emerge and are correlated with the performance of the teams. They study the evolution of cooperation networks in Social Psychology, Economics, Ecology and Astronomy, and show how the network evolve from a structure characterized by isolated clusters of scientists towards one in which a large portion of them are connected (in networks terms, they all belonged to the same component: all nodes that can be connected to each other by at least one path). In all cases more than half the scientists belonged to the largest connected component of the network. The relative size of the giant component was also associated with performance (publishing in journals with high impact factor) in social psychology and ecology (but not in economics and astronomy). Guimerà et al. (2005) argue that a large connected component in a field would be an evidence of the existence of an invisible college (de Solla Price, 1986; Merton, 1979): a network of social and professional relations linking

scientists across universities, which forms a repository of resources and knowledge developed in the past collaborations of the members of the filed. The emergence of a giant component, therefore, seems like a necessary, but clearly not sufficient feature of the network of a collaborative community.

Networks of knowledge production: small world model

One of the key properties of the network structure of a collaborative community should be facilitating an efficient flow of information and ideas among collaborators. The class of network models that most likely fit these requirements is the small-world model (Watts and Strogatz, 1998). Small World networks are characterized by a high level of local density of social ties and short average distances among nodes in the network. More formally, Watts and Strogatz (1998) postulated than 2 measures can be used in order to quantify small world model: average path length (L) and clustering coefficient (CC). L measures the average number of intermediaries between any two nodes of the network, which theoretically means that it is a measurement of how close resources, people and knowledge are in a concrete network. CC is the mean probability that two nodes that are neighbors of the same other node will themselves be neighbors. This measure has been used as proxy for cohesion or closure of networks. The smallworldiness of a network is usually measured with the small world index Q (see appendix A for a formal definition).

Since the publication of Watts and Strogatz's seminal paper, an important stream of empirical studies have analyzed a wide variety of networks, spanning multiple levels of analysis, with the theoretical apparatus of the small world model. For instance, Uzzi and Spiro (2005) analyzed the network of artists who made Broadway musicals from 1945 to 1989. They found a non-linear association between smallworldiness and the financial and artistic performance of the musicals they produced: at low levels of Q the network consists of many unconnected teams, which inhibits the circulation of new ideas and hinders creativity; as Q increase there are more links among teams and those links are more local cohesive which foster creativity and exchange of ideas. But if Q continues to rise beyond a threshold: "the network increases in connectivity and cohesion to a point at which connectivity homogenizes the pool of creative material while cohesive ties promote common information exchanges, limiting the diversity of the pool of creative material and trapping artists in echo chambers of like minded collaborators" (Uzzi et al., 2007, 87).

Studies conducted on other types of networks have not consistently replicated these findings (for a recent review see Uzzi, Amaral, and Reed-Tsochas, 2007). The inconsistency of the relation between small world structure and performance could be explained by the wide differences in the activities actors were engaged in, by the different measures of performance used, or by the different time frames of the analysis and to differences in the measurement of performance. In addition to these explanations, I would like to stress the fact that the small world model is based on a purely local measure of cohesion (CC). Therefore a high clustering coefficient only means that local teams are highly cohesive, but these teams might not be connected by anything more than a few random connections, and therefore we cannot say anything about the global connectivity of the network. As I will show in the next section, the global connectivity, and the presence of multiple redundant paths among actors, might play a role in

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explaining the differences in performance between small world structures in different settings. A network can have high global cohesion and connectivity without too much local cohesion, which is what Uzzi argues “traps artists in echo chambers of like minded collaborators”.

Another interesting empirical result of studies of scientific cooperation networks, points to the role of specific actors in keeping the network together. Goyal, Van Der Leij, and Moraga-González (2006) show that the global patterns of cooperation among economists from 1970 to 1999 can be modeled as a small world. They also found that a core of interlinked star authors spanned the network shortening otherwise long path lengths. If those brokers were removed from the network, the average path length would rise sharply and the size of the giant connected component will shrink significantly. In the field of sociology Moody (2004) shows that the global patterns of cooperation among authors does not follow a small world model. Furthermore he showed that the cohesion between sub-fields in sociology does not depend on a core of brokers, and the network did not fragment until all scholars with 10 collaborators were removed from the network.

In addition to facilitating the diffusion of ideas and the combination of diverse skills and pieces of knowledge, teams can also generate common social norms and trust —another essential feature of Collaborative Communities. To explain how trust can operate beyond the confine of each team it is necessary to explore its structural antecedents.

Trust and social solidarity in networks: the structural cohesion model

Cohesion and social solidarity are central features for collaborative communities, and distinguish them from both ideal-typical hierarchies and markets. These concepts have a long and illustrious history in sociology (Durkheim, 2008) but their precise characterization has been elusive. Much more attention has been focused on its ideational component, which is based on the members' identification with a collectivity, than on its relational component (Doreian and Fararo, 1998), that is the structure of social relations among members of the group that facilitate the emergence of cohesion. Indeed, even the collaborative community literature focus almost solely on the ideational community, stressing the importance of collective identification.

As discussed in chapter 2, White and Harary (2001) and Moody and White (2003) developed a robust operationalization of the relational dimension of social solidarity based on the graph-theoretic property of connectivity (Harary, 1969). They propose two equivalent definitions of structural cohesion: “a group's structural cohesion is equal to the minimum number of actors who, if removed from the group, would disconnect the group” and “a group's structural cohesion is equal to the minimum number of independent paths linking each pair of actors in the group” (Moody and White, 2003, 109). These two definitions are equivalent because of Menger's theorem¹.

The starting point of the social cohesion in a group is a state where every actor can reach every other actor through at least one relational path. The formalization of this state in a con-

¹A cutset is a set of nodes that, if removed, would break the component into two or more pieces. A graph is k -connected —has node connectivity k — and it is called a k -component if it has no cutset of fewer than k nodes. Menger's theorem states that a k -connected graph also has at least k node-independent paths connecting every pair of nodes.

3.2. A network approach to collaborative communities

crete group is the size of the largest connected component. The emergence of a giant component, therefore, does not just provide the opportunity to access the invisible college (Guimerà et al., 2005), but is also a minimal condition for the development of cohesion. Moody and White (2003) argue that the removal of a few key nodes can affect the flow of knowledge, information and resources in the network. In network terms, a graph is k -connected and is called a k -component if you need to remove at least k nodes to break it into more components. A 2-component, or biconnected is a component that requires at least 2 nodes to be removed to break down connectivity. Therefore Moody and White (2003) convincingly argue that a biconnected component provides a baseline threshold for strong structural cohesion.

The cohesive structure of a network can be conceptualized as increasingly cohesive groups —called cohesive blocks— nested inside each other. As an example we can think of a group with an highly cohesive core surrounded by a less cohesive periphery (Borgatti and Everett, 2000). A common structural pattern in large networks is an hierarchical nesting of increasingly cohesive groups at low connectivity levels and non-overlapping highly cohesive groups at higher connectivity levels (Moody and White, 2003, 112). Those highly cohesive groups play a key role in the diffusion of the consequences of social interactions among actors in networks (White and Harary, 2001, 355-356). It is usually assumed that the transmission through the network of knowledge, influence and resources generated by social interactions is limited to people 2 or 3 steps away from the initiator of such interactions. In graph theoretic terms, this means that social interactions have a high rate of decay. However, strongly cohesive blocks allow repetition of information and reinforcement of influence because they are characterized by multiple independent pathways that compensate the decay effects of the transmission of knowledge, influence and resources.

This key feature of cohesive groups provides a plausible social mechanism for the emergence and development of trust in Collaborative Communities. Actors in strongly cohesive groups are able to compare independent perspectives on each other through a variety of paths that flow through distinct sets of intermediaries, which provides multiple independent sources of information about other's characteristics or identity (White and Harary, 2001, 320). Thus, the perception of an individual embedded in such structures of the other members of the group to whom he is not directly linked is filtered by the perception of a variety of others whom he trusts because is directly linked to them. This mediated perception of the group generates trust at a global scale.

Collaborative Communities Networks: Cohesive Small Worlds

The two models of network topology discussed above provide a solid theoretical starting point in order to analyze the characteristic network structure of collaborative communities, which, I argue, is a key element to understand trust generation and value congruence between highly heterogeneous and interdependent producers in knowledge-based production processes. Table 3.2 summarizes the key dimensions along which I am comparing small world and structural cohesion, and the features I argue are critical for enabling large scale cooperation in Collaborative Communities.

I want to highlight that the structural cohesion model and the small world model are not mutually exclusive. A strongly cohesive network could have an average path length com-

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	Structural cohesion model	Small world model	Cohesive small world
Cohesion	Global cohesion: focus on cohesive groups formed by nodes linked by node-independent paths	Local Cohesion: Focus on cohesive clusters linked by few edges	Both global and local cohesion
Role of stars	Connectedness and cohesion are not dependent on stars	Connectedness might be highly dependent on stars	Not dependent on stars
Robustness	Resiliency in front of random and targeted removal of nodes	Resiliency on random removal but not necessary on targeted removal of nodes with high degree	Resiliency in front of random and targeted removal of nodes
Trust	Global trust among all nodes of strong cohesive groups	Local trust only among cohesive local neighborhoods	Both local and global trust
Source of trust	Node-independent paths between nodes	Direct links within dense local clusters	Both
Average path length (L)	Implicit: strong cohesive groups must have relative low L	Explicit inclusion of L in the model	Explicit inclusion of L in the model
Diffusion of social interaction	Cohesive groups as amplifiers of signals in networks	No clear mechanism; it is assumed that low L is enough	Cohesive groups as amplifiers

Table 3.2: Comparison of network models for collaborative communities.

parable with its random counterpart while its clustering coefficient is significantly higher. Therefore, there are networks that fit in the intersection between the two models. In order to illustrate this fact, figure 3.1 depicts examples—with toy graphs of 25 nodes—of a network that is structural cohesive but not small world (figure 3.1a), a network that is small world but not structurally cohesive (figure 3.1c) and a network that is both structurally cohesive and small world (figure 3.1b). On the lower row of figure 3.1 there are plots of the robustness of each model in front of the deletion of nodes. Those plots depict the size of the giant component divided by the total number of nodes minus the nodes removed in the preceding steps in log scale. Red dots represent targeted removal of nodes, that is, removing nodes starting with nodes of high degree. Blue marks represent random removal of nodes, in each step I chose a node at random and remove it, error bars represent the standard deviation over 100 runs of random removal of nodes.

The example of a pure structurally cohesive network (figure 3.1a) consists in a 2 dimension grid where all nodes of the network form a giant bicomponent but its average path length is significantly higher than a random network with the same number of nodes and edges, and its clustering coefficient is 0 because there are no triangles. Therefore, this network is not a small world. This kind of network is very robust in front of targeted removal of nodes because high

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degree nodes are in the middle of the grid; after removing all nodes with degree 4 we still have a cycle formed by the outer edges of the original grid.

The example of a pure small world network (figure 3.1c) is inspired in the caveman network proposed by Watts (1999b). It consists in a fully connected core with 20% of the nodes; where each node in this core is connected to a node of a fully connected subgraph of 4 nodes. Thus, the clustering coefficient of this example is significantly higher than its random counterpart but its average path length is almost the same. But, in terms of structural cohesion, the giant biconnected component is formed only by the 20% of the nodes in the core. It should be noticed that despite the fact that this kind of network has more edges than the pure structural cohesive example, its robustness in front of targeted removal of nodes is much lower. As we can see in the robustness plot depicted in figure 3.1f, if we start removing nodes with high degree, the relative size of the giant component shrinks quickly because high degree nodes are in the core of the network, and every node deleted in the core means that the fully connected subgraph of four nodes linked to it will be outside of the giant connected component. Thus, in this example, connectedness is highly dependent on stars (ie high degree nodes).

The example of a cohesive small world network (figure 3.1b) is generated algorithmically. I start with a seed formed by a cycle network containing all the nodes in order to make sure that, in the final network, all the nodes will be in a giant biconnected component. Then I randomly link pairs of nodes until we reach the number of edges contained in a 2 dimension grid with the same number of nodes². Then I compute the small world index (Q) of the resultant network —see appendix A for a formal definition— and if it is lower than an arbitrary threshold I start again from the beginning until the resultant network has a small world index greater than this arbitrary threshold. For the example in figure 3.1b, I have chosen a threshold of 1.5, but any network can be characterized as a small world if $Q > 1$.

Thus, the cohesive small world example has all its nodes in a giant biconnected component —like the pure structural cohesive example— but it also has almost the same average path length than its random counterpart and a clustering coefficient significantly higher —like the pure small world example—. Figure 3.1e depicts its robustness in front of targeted removal of nodes. As we can see, it is in between of the other two examples. We need to remove an important percentage of the nodes with high degree in order to shrink the size of the giant component significantly. Despite the fact that the cohesive small world example has less edges than the pure small world example, its connectedness is much less dependent on stars. Moreover, we need to remove more than 10% of all nodes in order to be able to distinguish the effects of random and targeted removal of nodes in the relative size of the giant component. While in the pure small world example, the effects of targeted and random removal are quite different from the beginning of the removal process.

Therefore, I can conclude that the two models are not mutually exclusive. The family of networks that fit in the intersection of both models —what I call Cohesive Small Worlds— exhibit consistent topological patterns, that is, they have the same structure. These patterns,

²I have chosen to limit the number of edges of the cohesive small world model to the number of edges contained in a 2 dimension grid with the same number of nodes in order to highlight that the density is not the main determinant of the robustness of a network: it is its structure. Thus, a 2 dimension grid is more robust than the cohesive small world model with the same number of edges, and the cohesive small world model is more robust than the pure small world example despite the fact that the latter has more edges

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I argue, provide the scaffolding for the emergence of Collaborative Communities and enable large scale cooperation. On the one hand, the generation of trust and congruent values among heterogeneous individuals are fostered by structurally cohesive groups in the connectivity hierarchy of cooperation networks because individuals embedded in these structures are able to compare independent perspectives on each other through a variety of paths that flow through distinct sets of intermediaries, which provides multiple independent sources of information about each other. Thus, the perception of an individual embedded in such structures of the other members of the group to whom she is not directly linked is filtered by the perception of a variety of others whom she trusts because is directly linked to them. This mediated perception of the group generates trust at a global scale. On the other hand, the existence of dense local clusters connected between them by relative short paths allows successful cooperation among heterogeneous individuals with common interests and, at the same time, fosters the flow of information between these clusters.

As I will show in the next chapters, the cooperation networks of the FOSS projects under analysis in this thesis —Debian and Python— conform to the structural patterns of the Cohesive Small World model described here.

3.2. A network approach to collaborative communities

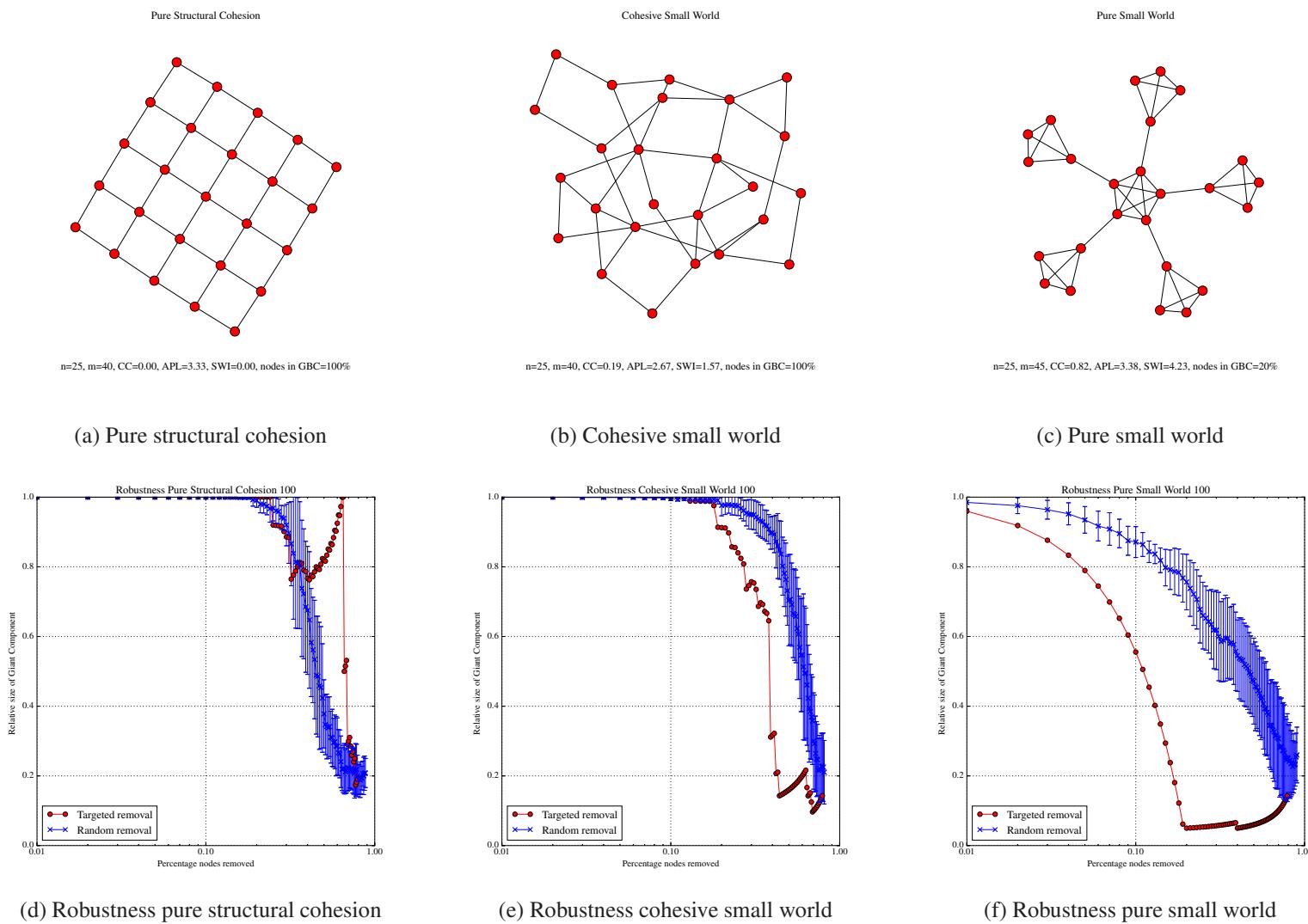


Figure 3.1: Models of network structure and their robustness. The plots of the example networks (figures 3.1a, 3.1b and 3.1c) contain 25 nodes in order to facilitate the perception of their structure. The robustness plots (figures 3.1d, 3.1e and 3.1f) are generated by toy networks of 100 nodes because the robustness pattern is clearer than in the 25 nodes examples. I also tested the robustness of all the models with 400 and 2500 nodes and the patterns are the same.

Part III

Empirical analysis

Historical Background on Free and Open Source Software

The software is the logic part of a computer system, while the hardware is the physical part. Loosely speaking we could say that computer programs are written in different programming languages, the set of instructions forming a program is called source code. This source code is compiled in order to translate it to a language that can be executed by the hardware; the result is the binary code —a sequence of 0 and 1—. Based only in the binary code of a program no human can understand how the program develops the task for which it was designed. It is like a black box that receives some *inputs* and returns some *outputs*.

There are two types of software programs according to their function within a computer system: application software are programs that develop specific tasks useful to the user, such as a word processor or a web browser. System software are programs that conform the operating system, according to Tanenbaum and Woodhull the two main functions of an operating system are, on the one hand, being an abstraction layer that provides to applications — and to developers who write applications— a set of simple operations that hide the complexity of hardware. On the other hand, the operating system is responsible for managing system resources —RAM, processor, disk space ,...— between different programs competing for them when they run in the system (Tanenbaum and Woodhull, 1996, 3-5). From a more practical but less rigorous point of view, we can conceive an operating system as the minimal set of programs that allow a computer to do useful things. Because what is considered useful has evolved along time, operating systems have also evolved.

At the beginnings of computer science, there was no clear distinction between software and hardware and between developer and user. There were only people who gave precise instructions to computers about what they should do. In 1952 IBM commercialized the first computer and during this decade began to spread their use (Weber, 2004, 21). One of the key events that marked the evolution of software at this time was the decision of the US Department of Justice that Western Electric and American Telephone and Telegraph (AT&T) could not join to work together beyond the field telecommunications. This decision, taken in 1956 under anti-trust legislation, lead AT&T to promote software licenses to a nominal cost and to release in the public domain the output of research developed at Bell Labs, in order to not violate anti-trust laws (Roca, 2007, 20).

4.1 UNIX and the C language

In the 1960s, computers were very expensive facilities that were only available to government centers, some large companies, and universities. The study, design, and implementation of operating systems largely focused research efforts in those years. A major project was the result of collaboration between MIT researchers and staff of Bell Labs, the goal was to build an operating system called MULTICS (*Multiplexed Information and Computing Service*). The results of those efforts did not succeed; in 1969 AT&T withdrew from the project. But two researchers who had participated in the work on MULTICS, Ken Thompson and Dennis Ritchie, developed on their own a new operating system, based in part on their work in MULTICS, which was called UNIX. The first implementation was made entirely by Thompson in a month during the summer of 1969 and consisted in a *kernel*, a shell, a text editor and an assembly language (Weber, 2004, 26).

Assembly languages are tightly linked to each hardware platform, that is, each kind of computer has its own assembly language, which is incompatible with other assembly languages. Thus it was not possible to run software written for a computer in any other computer. In the early 1970s, Dennis Ritchie invented C, a general-purpose programming language, which allowed to write the source code of software once, and was able to run in a wide range of hardware thanks to a compiler, that translated the common C source code to the particular hardware instructions for each kind of computer. Until the early 1980s, although compilers existed for a variety of hardware, the C language was almost exclusively associated with UNIX; more recently, its use has spread much more widely, and today it is among the programming languages most commonly used (Ritchie, 1993).

The first impulse to the spread of UNIX operating system was a computer science symposium in which Thompson and Ritchie presented a paper about UNIX. The authors offered to send a copy of UNIX to whom were interested, petitions exceeded by far initial expectations of the authors. The interest grew when they rewrote UNIX with the C programming language, so it could work on any hardware that had a C compiler. Given this growing interest, AT&T —constrained by anti-trust legislation— decided to license UNIX, at first, under minimal conditions: the software was provided without warranty ('*as-is*') and without support or correction of errors by the company; paying a fee of several hundred of dollars AT&T sent a copy of the source code of UNIX (Weber, 2004, 28-29).

The UNIX operating System became popular as a teaching and research tool in computer science departments in universities around the world, especially at US. The availability of source code enabled experimentation, modification and improvement of the UNIX system. AT&T did not offer support or maintenance, so system users had a strong incentive to share solutions to bugs and improvements with the user community. Users of computers at that time were not like today, they were in large part, college students, scientists or engineers with extensive technical training. UNIX was one of the first experiences of collaboration and knowledge exchange on a large scale in the field of software.

One of the main actors in the development of UNIX was the University of Berkeley, which began its own distribution of UNIX called BSD (*Berkeley Software Distribution*) in the 1970s. This distribution was started based on the UNIX source code of the company AT&T, but they added significant improvements. In 1976 Thompson joined the Berkeley team. The

authorship of the contributions to the source code were collected in the same source, following the practice established by Thompson and Ritchie (Weber, 2004, 27). In 1983 Berkeley's team published the 4.2 version of BSD UNIX which had major improvements, the most notable of which was an implementation of the TCP/IP stack —the communication protocol of Internet—, this version of BSD UNIX is one of the foundations of the Internet as we know it today (Weber, 2004, 35). The 4.2 version of BSD UNIX directly competed with a version of the company AT&T but it was far superior technically. The liberal license terms of BSD UNIX allow to build proprietary implementations on top of BSD UNIX, this allowed the emergence of new companies that commercialized modified versions of UNIX.

Requests for licenses from UNIX in the late seventies and early eighties increased considerably, mainly from large companies, military institutions, universities, and research centers. AT&T and Bell Labs had to be separated by court order in 1984. As a result, Bell Labs began trading for the price of hundreds of thousands of dollars for new licenses of UNIX, which restricted drastically the number of institutions that could afford it. They also began a series of lawsuits in order to prevent the free dissemination of the various implementations of UNIX, particularly the implementation of Berkeley (Roca, 2007, 22). The dynamics of litigation lasted until the 1990s. This fact jeopardized the development of UNIX BSD; the future legal viability of the system was not clear. This uncertainty prompted the emergence of alternatives that, in its infancy, were technically inferior.

4.2 GNU and Linux

Richard Stallman started working in the Laboratory of Artificial Intelligence (AI) of MIT in 1971. In his own words, he joined a community that have shared the software for many years. Stallman says poetically that the act of sharing software is as old as computers, just as sharing recipes is as old as cooking (Stallman, 1998). At that time, the source code was accessible to all users and the act of sharing modifications involving improvements with the rest of the community was the norm. According to Stallman, this situation changed in the early eighties of the twentieth century when the community of MIT hackers collapsed. One spin-off of the MIT AI lab hired almost all the people working there. The contract contained a non-disclosure agreement forcing people to not disclose their work and therefore prevented them to publish or share their work. In addition, in 1982, the MIT AI lab changed its hardware and a proprietary operating system were installed on them.

According to Stallman, those events led him to abandon his work at the MIT AI lab because, on the one hand, ethically he could not continue working with proprietary software and, on the other hand, the community in which he worked was dismantled. But rather than stop using software and engage in other activities, he decided to promote the construction of a new community within which they could restore the practice of sharing software. Stallman explained that he thought that the first step to restore the community was building a free operating system, because it is the essential tool in order to make a computer work. Thus was born the GNU project (*GNU is Not UNIX*) which aimed to create a general-purpose operating system that was a completely free reimplementation of UNIX (Stallman, 1985).

Stallman devise a set of formal rules, which revolve around the concept of copyleft. This

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new concept is supported in the legislation about copyright. In Stallman's words, the idea of copyleft is that the author of a program gives everyone, without exception, permission to execute, copy, modify and distribute modified versions of the program. Stallman argues that in order to be effective, copyleft requires that derivative works of a program must also be free (Stallman, 1998). In this way privatization by software companies can be avoided, unlike free licenses that are permissive with private ownership, as the BSD license which allows a company to make changes to a free program and commercialize it in a binary format without providing any changes in source code form. The concrete implementation of these formal rules is the GNU/GPL License.

To articulate the process of building this new free operating system, Stallman founded in 1985 the Free Software Foundation (FSF), a nonprofit foundation with the objective of supporting the free software movement and give them legal cover. A relatively small group of people joined the efforts of Stallman, which was, in part, responsible for strategic planning in the early years of GNU. Hackers of the FSF created many free programs, some of them proved to be the best in their field. In the early nineties, the GNU project had a wide range of software but lacked a kernel —the program that interacts directly with the hardware—to have a complete operating system.

In this context, Andrew Tanenbaum created the first version of Minix in 1987. Minix is an operating system written from scratch by Tanenbaum and their students. The main objective was to allow his students to learn by analyzing how it is made and how it works an actual operating system. The Minix's source code is supplied as part of Tanenbaum and Woodhull (1996) book on operating systems. Linus Torvalds was a student at the University of Helsinki when he developed the first version of the Linux kernel. His aim was to write a new implementation of Minix for the popular and cheap i386 computer architecture. One of the key factors for the success of Linux was that Linus Torvalds decided to license it under the GNU/GPL license because the tools he used to develop Linux came from the GNU project. He released the source code on-line and asked everyone who wanted to collaborate with the project to submit improvement proposals.

Eric Raymond, a hacker from the old school, exposed the Linux development model in a work that has had a significant influence in the field of software development: *The Cathedral & the Bazaar* (Raymond, 1999). He starts by explaining the perplexity he felt when he became interested in Linux. Since the mid 80's had worked with the FSF by writing free software and always followed a development model that, metaphorically, can be compared with building a cathedral. A small group of architects design the program, implement it and test it for a long time. When it successfully pass all the tests it is released. He was surprised both with Linux and its development model, which consisted in releasing the program very often, even if it had known error that had not been solved. The main idea is to rely on all the people who devote their free time to test and improve Linux, collect all the proposals, and implement the best.

Raymond qualifies metaphorically this production model as a bazaar, where anyone can contribute code to the project and each project is responsible for integrating the proposals that seem useful to the source code of the program. It is fair to say that further studies on the actual dynamics of larger projects and relevant software —like Apache and Mozilla— have shown that the cathedral model is not entirely abandoned, rather the actual model is an hybrid; a combination of the two models where a significant portion of the program development is

provided by a relatively small group of people, but there are an extensive variety of people, who more or less sporadically, contribute to the project (Mockus et al., 2002).

We must consider that in the 1990s starts a massive deployment of Internet in some countries. Internet is the infrastructure that makes possible to weave a network of peer collaboration that characterize this production model. This development model was not invented by Linus Torvalds, is not difficult to recognize the principle of peer review of scientific practice in it. In fact other software projects, such as BSD UNIX, had adopted a model that closely resembles the practices of scientific communities. It must be said that it was quite difficult that a contribution that came from an outsider of the Berkeley team was accepted in BSD UNIX; in this sense, the classical model of development of UNIX established at Berkeley was more elitist than the Linux model, which was more open and transparent but less rigorous. The key to understand the success of the Linux model is that it was contemporary to the spread of access to global digital networks in some countries.

In the early nineties, the GNU system was almost complete, just lacked the kernel; the gap was important because the kernel is the software that allows the system to operate autonomously on the hardware. Linux filled the void that was missing, the sum of the Linux kernel and GNU applications resulted in a general purpose operating system completely free: the GNU/Linux system. But the fact that all the pieces of the operating system were available did not mean that putting them to work together was an easy thing. In the first half of the nineties, installing a GNU/Linux system required a great deal of expertise and considerable time to devote to it. In this context appear and develop different distributions of the GNU/Linux operating system, among which is the Debian project, which is the subject of empirical analysis of this research.

4.3 The Debian Project

In the early nineties of the twentieth century the most powerful free operating system was BSD UNIX. But as I said, the litigation that was submitted by the companies who hold the copyrights of UNIX threatened its future viability. This led to the emergence of alternatives, although initially were technically inferior, were substantially improved in the late nineties and early twenty-first century. These alternatives were the GNU project and the Linux kernel, the combination of which allowed to build a completely free general purpose operating system. But combining these pieces of software was not, nor is, a trivial task. Linux was in its early stages of development, many people made contributions to the source code and new versions of Linux were released on a daily basis. Therefore, it was required a great effort to have GNU/Linux system running, and even more, keep them updated. Especially for people who wanted to work *with* the GNU/Linux system to develop different tasks and not *in* the system (Krafft, 2005, 30).

In 1993 Ian Murdock, a student at Purdue University at Indiana took the initiative of creating the Debian Project¹ with the goal of building a distribution of GNU/Linux system. The Debian Project's initial proposals were included in the *Debian manifesto* (Murdock, 1994). Two of the main features of the Debian project are listed in this manifesto. First, define a

¹The name Debian is the contraction of the names Debra —Murdock's wife— and Ian.

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new type of distribution of GNU/Linux, instead of being developed by a person or a closed group, the aim was to develop the system following an open and decentralized model inspired by Linux. Secondly, Debian was defined as a non-commercial project and focused on technical excellence instead of economic profits, but without sacrificing the aim to compete in excellence with commercial options, whether free or proprietary.

In the Debian manifesto Murdock notes that distributions are essential for the future of GNU/Linux systems, because they eliminate the need for the user to search, download, compile, install and integrate a large number of programs that are the basic components of a functional system. Murdock notes that despite the importance of the distributions, they have not received much attention by free software developers. To maintain a well integrated, error-free, and reasonably updated distribution of GNU/Linux system is not an easy nor glamorous task, it requires a great amount of work and coordination to manage complexity. Many distributions of GNU/Linux system at the time —the most popular of which was Softlanding Linux System (SLS)— started with a technically acceptable level, but as time passed were degenerating because they did not solve the problems that arise nor updated versions of programs distributed. Thus, it was relatively easy to start a distribution of GNU/Linux system but it was very difficult to keep it operational and functional for significant periods of time.

The Debian project, thus, does not produce all the software that distributes; their main task is software integration. The source code of the programs that compose the Debian operating system is published originally under some kind of free license by authors that typically aren't involved in the project. The aim of Debian is to integrate useful programs and package them so that an average user —without deep knowledge of software engineering— can install or upgrade many programs in an easy and automated way. One of the main features of the production process of Debian is modularity, that is, dividing the project into semi-independent modules, designed to work together but that can be developed relatively independently. This feature allows people with different expertise, skills, and motivation to participate in the development of the system at different levels and with different intensity.

The availability of data derived of the open nature of the project and the recent interest by community forms of organizing have triggered an interesting stream of research about the Debian project in the last years (O'Mahony, 2003; Coleman, 2005; O'Mahony and Ferraro, 2007b; Ferraro and O'Mahony, 2010). Those research efforts have focused mainly in the governance system, the membership process, and the ethical motivations of developers. Thus we have a good understanding of the political and individual dynamics of the project but we lack a detailed analysis of its production related dynamics. My aim is to fill this gap providing a longitudinal analysis of the global patterns of relations among developers in the production process. This allows to illustrate the relevance of a structural approach in order to understand the actual production process of the Debian operating system.

4.4 The Python Language

In the late 1980s, Guido van Rossum —a dutch computer scientist working at the *Centrum Wiskunde & Informatica*²— invented the Python programming language. A commonly cited

²Which translates in English to National Research Institute for Mathematics and Computer Science

account of the invention of Python by his author is the foreword to one of the first books on the Python programming language (Lutz, 1996):

Over six years ago, in December 1989, I was looking for a “hobby” programming project that would keep me occupied during the week around Christmas. My office ... would be closed, but I had a home computer, and not much else on my hands. I decided to write an interpreter for the new scripting language I had been thinking about lately: a descendant of ABC³ that would appeal to Unix/C hackers. I chose Python as a working title for the project, being in a slightly irreverent mood (and a big fan of Monty Python’s Flying Circus).

The Python programming language, according to the nice definition that Wikipedia provides⁴, is a high-level, general-purpose, interpreted, dynamic programming language. Its design philosophy emphasizes code readability, and its syntax allows programmers to express concepts in fewer lines of code than possible in other widely used programming languages. Python provides constructs intended to enable writing clear programs on both a small and large scale.

It is necessary to distinguish between the specification of a programming language and its concrete implementation. A specification or technical standard is a set of grammatical, syntactic, and semantic rules and conventions that define how to write programs, and what those programs should do. A concrete implementation is what actual computers execute. There are several different implementations of the Python language, but the reference implementation—that is the standard concrete form that implements the language specification—is written in the C programming language and is named CPython to reflect this fact. The development of Python’s reference implementation is lead by Guido van Rossum and has a community-based development model: a non-profit organization, the Python Software Foundation, acts as a legal umbrella to sponsor and direct the development of the Python language.

The analysis of the production process of Python presented in the following chapters focuses on the development of the CPython reference implementation of the Python programming language, but I’ll refer to it as just the Python project henceforth for the sake of brevity.

The governance model of the Python project is based on public debates and discussions taking place in mailing lists and public meetings such as the language summits held each year in the annual Python conferences, where some Python developers meet face to face and discuss key issues in order to make decisions. The inventor of Python has however a lead role in settling disputes or arguments when the community of developers don’t reach consensus. He has the power of making final decisions when there is no consensus. This is why he has the somewhat irreverent title of “Benevolent Dictator For Life (BDFL)” in the python community.

In the beginning, the Python project started as an individual effort of Guido van Rossum, and has become one of the mainstream computer languages in the XXI century. Until 2000 it was almost an individual effort of van Rossum with few close collaborators. From 2000 the

³ABC was a teaching language that van Rossum helped develop in the early eighties at *Centrum Wiskunde & Informatica*. It was a language aimed at non-professional programmers.

⁴[https://en.wikipedia.org/wiki/Python_\(programming_language\)](https://en.wikipedia.org/wiki/Python_(programming_language)) accessed November 2016

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project gained popularity and several developers joined the project. In 2014, 172 individuals contributed at least one line of source code to Python project in all its history.

Nowadays, the Python language is widely used in several key areas of computing and software development. Some of the biggest websites of the World Wide Web (WWW) are powered by Python, such as youtube.com or reddit.com. Another main area where Python is very prominent is scientific computing and data processing and analysis. For instance, a big part of the data coming from the big telescopes on —and around— our planet are processed using tools written completely or partially in Python.

Finally, it is worth saying that most of the data processing, analysis, and graphical representations presented in this thesis are also written Python. The only other programming language used is the R language which is a programming language that focus on statistical computing.

FOSS projects as Cohesive Small Worlds

As discussed in chapter 3, “Cohesive Small World” is the network model that I propose in order to theoretically understand the structural dimension of cooperation of FOSS projects. I argued that the family of networks that fit in the intersection of small world networks and structural cohesion networks exhibit consistent structural patterns. These patterns, I argue, provide the scaffolding for the emergence of collaborative communities and enable effective large scale cooperation.

On the one hand, the generation of trust and congruent values among heterogeneous individuals are fostered by structurally cohesive groups in the connectivity hierarchy of cooperation networks because individuals embedded in these structures are able to compare independent perspectives on each other through a variety of relations that flow through distinct sets of intermediaries, which provides multiple independent sources of information about each other. Thus, the perception of an individual embedded in such structures of the other members of the group to whom she is not directly linked is filtered by the perception of a variety of others whom she trusts because is directly linked to them. This mediated perception of the group generates trust at a global scale. On the other hand, the existence of dense local clusters connected between them by relative short paths allows successful cooperation among heterogeneous individuals with common interests and, at the same time, fosters the flow of information between these clusters preventing the local clusters to be trapped in echo chambers of like minded collaborators.

This chapter focus on the empirical analysis of the network structure of two mature and well established FOSS projects: the CPython reference implementation of the Python programming language and the Debian Operating System. These two projects, as outlined in the previous chapter, are quite different despite being both successful FOSS projects. The Debian project has approximately ten times more participants than Python. Debian, being a complete Operating system, has many parts which are only lightly related between them because it contains programs that do very different tasks (eg the developers working on packaging software for music editing do not need to pay close attention to what debian developers focused on packaging word processors do). On the other hand, the Python programming language is a much more integrated software project, and thus developers working on different parts of the

language implementation have to play attention, and work very closely, with other developers.

This has a strong impact in the structure of the patterns of relations that emerge between developers in the two projects. The analysis presented here has two parts: first I will compute the small world metrics for the two projects, as described in chapter 3, and then I will compute the structural cohesion metrics as described in the chapter 2. However first it is necessary to define how I will build the cooperation networks for this two projects as a formalization of the patterns of cooperation between the individuals in these projects.

5.1 Modeling patterns of cooperation as networks

My modeling strategy to capture the patterns of relations among developers in these two projects is to focus on the actual contributions of each developer to the project. I model the cooperation patterns between individuals as affiliation networks (Wasserman and Faust, 1994, chapter 8). This kind of networks contain two types of nodes: N actors each of which belongs to one or more groups M . Such networks are bipartite or 2-mode because they contain two types of nodes and there are no edges between nodes of same type.

The two sets of nodes in the networks analyzed here are, on the one hand, human developers and, on the other hand, entities that conform the product that is released by the FOSS project. In the case of Debian, these entities are software packages, and in the case of Python, they are source code files. Note that the collaboration network is based on individual contribution but it not only captures the total amount of contribution that a given individual does, but also to which part of the project the contributions are focused, and who else in the project is also working on the same entities. This is why I name these bipartite graphs collaboration or cooperation networks.

One feature of most large software projects is modularity, that could be defined as the division of a software project into semi-independent parts, designed to work together but that can be developed relatively independently. In the case of an operating system, such as the Debian project, modularity is more prominent than in other software projects, such as Python. An operating system comprises a comprehensive set of software packages with varying importance, from those responsible for interacting with the hardware to others that provide certain features that are only useful in very specific and specialized configurations. On the other hand, an implementation of a programming language, such as Python, is also modular but their parts are much more closely related and have to be tightly integrated in order to function as a coherent whole.

This modeling approach captures mostly the informal patterns of relations that individuals establish when contributing to the project. FOSS projects have a wide range of formal organizational forms, and in this respect, they can be quite different. The definition of the leadership position in the two projects in which this thesis is focused nicely capture these differences in formal organization: Debian has a very developed formal bureaucracy, the project elects its leader each year through a secret vote of all its members after a electoral campaign where the candidates discuss among them and try to gain supports; Python instead has its original author —Guido van Rossum— in a permanent position of leadership, the people in the project refer to him, and his position of leadership, as “Benevolent Dictator For Life” (BDFL).

Despite these differences in the formal organization, if the focus is placed on the patterns of relations among developers in the productive process, what I call the cooperation network, we can analyze the contribution dynamics, analyze hierarchical positions defined by these patterns, assess the pace of renewal in these positions, and determine the impact of being in a concrete hierarchical position in the median active life of a developer in the project.

For the case of the Debian project, I define that each package of source code is a module of the system or, in terms of network affiliation, a group or team. The main data source is the Ultimate Debian Database (UDD)¹ (Nussbaum and Zacchiroli, 2010). The UDD contains information related to the work of each individual in the project which allow me to build the developers-packages affiliation network. One developer is linked to every package she has uploaded in the archive in a period of one year. Therefore, the result is a 2-mode network with developers —the actors— and packages —the groups— as the two types of nodes.

For the case of the Python project, I define that each source code file that forms the reference implementation of the programming language is a module of the system or, in terms of network affiliation, a group or team. Thus, contributions are lines of source code added or deleted from one of the source code files of Python’s code base. The main data source is the Python source code repository², which is under version control. That means that each change to any source code file is recorded and attributed to a person.

These cooperation relations are only part of the whole patterns of cooperative relations established among developers in both projects. I cannot obtain more accurate data of the frequent interactions between developers related to the production process that take place in a large variety of on-line or face-to-face settings. However, the subset of cooperation relations captured by this approach are significative and serve my purpose to analyze the global patterns of relations among direct producers because the result of the productive process is, in fact, the archive of packages that form the Debian operating system or the set of source code files that form the implementation of the Python programming language. Therefore, I base the analysis of cooperation on the registered contribution of each developer to the final product of the productive process delivered to end users.

Moreover, two important advantages of this approach are, on the one hand, that there is public data on all uploads —in the case of Debian— or all the modifications of source code files —for the Python project—, thus I do not need to worry about sample bias because there is accurate data of all the work performed in the period under analysis. On the other hand, having a strict definition of what cooperation means allows me to analyze the evolution of cooperation patterns throughout the history of the two projects. Therefore, I can make meaningful comparisons between years in the same project, and between projects.

Null models

Both kinds of analysis presented in this chapter have in common the use of null models. In empirical analysis of networks we need to be able to compare the statistical measures obtained from the actual networks with a suitable null model in order to assert that what we observe is

¹<http://udd.debian.org/> [accessed November 2016]

²<https://hg.python.org/cpython> [accessed November 2016]

not the result of pure chance. That is, we have to make sure that the metrics observed in the actual networks are significantly different to the patterns of relations that we might expect if the relation between developers and packages, or developers and files in the case of Python, were produced uniformly at random.

To this end, the canonical approach is to compare the measures of actual networks with measures taken from random networks that maintain some constraints of the original network, such as the degree distribution. Newman (2003); Newman, Strogatz, and Watts (2001) provided a configuration model in order to generate random graphs with arbitrary degree distributions. In the analysis presented here I have used the configuration model for 2-mode networks to generate 100 random null models for each year. The configuration model assigns at random developers to packages, or developers to source code files, maintaining the concrete skewed distribution of packages by developer and files by developer observed in the actual networks.

In order to compute the small world metrics reported in the next section, I've used the mean of the relevant statistics from ten random networks selected uniformly at random from a pool of one hundred random networks —generated using the configuration models described above. I did some test increasing one order of magnitude these figures —that is, selecting one hundred random networks from a pool of one thousand— and the results were the same up to the second decimal of the relevant statistics.

For the case of structural cohesion null models, it's not possible to use the mean because what we have to compute is the whole connectivity structure, and it's graphical representation requires to use only one network. Thus I've used only one random configuration model network, selected uniformly at random from a pool of one hundred random networks, as a null model for the structural cohesion analysis.

5.2 Small World Metrics

As I discussed in chapter 3, a network fits the small world model if it is more locally clustered (CC) than its random network counterpart but has approximately the same average distance (L) between nodes. In unipartite or 1-mode networks, CC is the mean probability that two nodes that are neighbors of the same other node will themselves be neighbors. Thus, this measure is computed as the ratio of triangles —a fully connected graph of 3 nodes— over two-stars —three nodes connected by two edges—. But, in bipartite or 2-mode networks there can be no triangles because, by definition, edges can only link nodes of different type. Following Robins and Alexander (2004), Lind et al. (2005) and Latapy et al. (2008), local cohesion in 2-mode networks can be measured with the notion of cluster coefficient based on squares (CC_4). CC_4 is the ratio between the number of squares (C_4) —composed by two nodes of each type linked by four edges— over the number of three-paths (L_3) —composed by two nodes of each type linked by three edges— (See appendix A for a formal definition of CC_4). Like CC , CC_4 applied to bipartite networks is a measurement of local cohesion.

The Small World Index (Q) is a summary indicator of the smallworldiness of a network and accounts for both the relation of the clustering coefficients of actual networks compared to their random counterparts, and the relation of average path length (a global measure of the average distance between nodes in a network) of actual networks compared to their random

5.2. Small World Metrics

counterparts. Networks with the Small World Index (Q) bigger than 1 are considered small world networks (see appendix A for details). I compute the Small World Index using the following formulas:

$$Q = \frac{CC_{ratio}}{L_{ratio}} \quad (5.1)$$

Where:

$$CC_{ratio} = \frac{CC_{actual}}{CC_{random}} \quad L_{ratio} = \frac{L_{actual}}{L_{random}} \quad (5.2)$$

In the tables below, CC_{actual} is column 6, CC_{random} is column 7, L_{actual} or average path length (APL) is column 8, L_{random} is column 9, and the Small World Index Q is column 10.

In the first place I compute small world metrics for Debian networks. The results are shown in table 5.1.

Years	Nodes	Developers	Packages	Edges	CC	random CC	APL	random APL	SWI (Q)
1999	3,259	392	2,867	3,253	0.128	0.002	9.4	8.6	73.8
2000	3,593	524	3,069	3,501	0.134	0.001	9.4	8.9	97.0
2001	5,943	777	5,166	6,241	0.049	0.002	8.4	7.8	28.1
2002	6,857	858	5,999	7,215	0.081	0.001	9.2	7.8	47.6
2003	7,276	914	6,362	7,892	0.101	0.001	9.1	7.6	57.9
2004	7,984	995	6,989	9,543	0.158	0.002	8.0	6.5	52.6
2005	8,328	1,048	7,280	10,373	0.166	0.003	7.5	6.2	43.5
2006	9,599	1,162	8,437	13,081	0.171	0.005	6.7	5.6	30.4
2007	9,471	1,181	8,290	13,023	0.148	0.005	6.8	5.6	26.2
2008	10,662	1,269	9,393	14,531	0.187	0.005	7.2	5.6	31.8
2009	11,336	1,343	9,993	15,842	0.227	0.006	7.0	5.3	28.6
2010	10,515	1,387	9,128	14,063	0.277	0.005	7.7	5.5	40.0
2011	12,362	1,430	10,932	16,265	0.143	0.005	7.5	5.5	21.4
2012	11,904	1,435	10,469	15,356	0.190	0.004	7.6	5.6	31.4

Table 5.1: Small world metrics for debian networks.

As we can see, the Debian project cooperation networks for all years analyzed are indeed small world networks. Their Small World Index (Q) is quite bigger than 1, ranging from 21.4 in 2011 to 97 in year 2000. This large value of Q is driven by the fact that the clustering coefficient—the measure of local cohesion—of the observed networks is approximately a hundred times higher than in their random counterparts. However the average distance between nodes in the actual networks is slightly higher than the distance in their random counterparts, which

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reduces the value of the small world index. Therefore I can conclude that Debian cooperation networks fit nicely the small world model.

Note that the Small World Index (Q) is quite stable compared with the huge increment of the number of developers involved in the Debian project and the number of software packages uploaded to the Debian repository. The number of developers grows quickly the first years under analysis, but tends to stabilize in the 2010s. There were 392 active developers in 1999 who uploaded 2,867 software packages that year; in 2012 there were 1,435 active developers who uploaded 10,469 packages. That is a bit more than a three fold increment.

The high value of the Small World Index in the Debian project compared to its value in the Python project—which I discuss below—is because Debian as an Operating System is more modular than Python as a programming language. Thus it's much more common in Debian to have subgroups of developers that work only in a small set of packages independently of other subgroups of developers.

For the Python project, the results for the small world metrics are presented in table 5.2.

Years	Nodes	Developers	Files	Edges	CC	random CC	APL	random APL	SWI (Q)
1999	1,146	9	1,137	1,236	0.102	0.039	3.1	3.5	3.0
2000	2,172	31	2,141	3,720	0.214	0.135	3.3	3.5	1.7
2001	2,511	33	2,478	4,507	0.205	0.129	3.4	3.6	1.7
2002	2,317	38	2,279	4,502	0.204	0.129	3.6	3.6	1.6
2003	1,805	42	1,763	3,192	0.153	0.112	3.5	3.6	1.4
2004	1,850	49	1,801	3,163	0.113	0.093	3.4	3.6	1.3
2005	1,007	44	963	1,759	0.129	0.079	3.7	3.7	1.7
2006	2,632	52	2,580	6,794	0.235	0.156	2.8	3.2	1.7
2007	3,359	51	3,308	7,790	0.223	0.177	2.9	3.3	1.4
2008	2,951	59	2,892	7,833	0.231	0.175	3.0	3.3	1.5
2009	2,219	58	2,161	4,708	0.228	0.142	3.1	3.4	1.7
2010	2,930	63	2,867	6,504	0.175	0.128	3.4	3.5	1.4
2011	2,174	63	2,111	4,459	0.145	0.114	3.5	3.6	1.3
2012	2,444	65	2,379	4,843	0.124	0.087	3.7	3.8	1.4
2013	2,285	63	2,222	4,743	0.147	0.099	3.6	3.7	1.5
2014	2,134	62	2,072	4,149	0.138	0.095	3.6	3.7	1.5

Table 5.2: Small world metrics for python networks.

In the case of the Python project, the Small World Index (Q) is still greater than one in all years analyzed, ranging from 3 in 1999 to 1.3 in 2004 and 2011. The value of Q in this case is driven by the small average distance between nodes in the cooperation networks. Most years Python networks have an average path length L slightly smaller than their random networks counterparts, while their clustering coefficient CC is bigger than their null models, but not by much. I can still confidently conclude that the Python project cooperation networks also fit the small world model.

In this case, the Small World Index (Q) is remarkably stable during all years under analysis. In 1999, when only 9 developers edited 1,137 source code files, the value of Q was 3. The following years its value stabilized around 1.5 despite the fact that the number of developers participating actively in the project increased steadily until reaching approximately 60 developers in 2010, and maintaining this number from 2010 to 2014. Thus on the period analyzed the developers actively editing source code files in the project multiplied by seven.

The low value of the Small World Index (Q) in the Python project, compared with the values of Q in the Debian project, can be attributed to the lower modularity of Python as a programming language compared with the inherent modularity of the Debian project as an operating system. The need of tight integration between parts of the same programming language make more difficult for subgroups of developers to work in subsets of source code files independently of other developers.

5.3 Structural Cohesion Analysis

As discussed in chapter 2 my approach to the analysis of structural cohesion of cooperation networks is based on the work of White and Harary (2001) and Moody and White (2003). The cohesive structure of a network can be conceptualized as increasingly cohesive groups nested inside each other. A common structural pattern in large networks is an hierarchical nesting of increasingly cohesive groups at low connectivity levels and non-overlapping highly cohesive groups at higher connectivity levels (Moody and White, 2003, 112). Those highly cohesive groups play a key role in the diffusion of the consequences of social interactions among actors in networks (White and Harary, 2001, 355-356). It is usually assumed that the transmission through the network of knowledge, influence and resources generated by social interactions is limited to people 2 or 3 steps away from the initiator of such interactions. In graph theoretic terms, this means that social interactions have a high rate of decay. However, strongly cohesive blocks allow repetition of information and reinforcement of influence because they are characterized by multiple independent pathways that compensate the decay effects of the transmission of knowledge, influence and resources.

This key feature of cohesive groups provides a plausible social mechanism for the emergence and development of trust in collaborative communities. Actors in strongly cohesive groups are able to compare independent perspectives on each other through a variety of paths that flow through distinct sets of intermediaries, which provides multiple independent sources of information about other's characteristics or identity (White and Harary, 2001, 320). Thus, the perception of an individual embedded in such structures of the other members of the group to whom she is not directly linked is filtered by the perception of a variety of others whom she trusts because is directly linked to them. This mediated perception of the group generates trust at a global scale, which according to Adler and Heckscher (2006) is the key mechanism for the development of collaborative communities, as discussed in chapter 3.

The analysis presented in this section are only possible thanks to the heuristics that I developed in order to be able to deal with networks of tens of thousands of nodes and edges as described at length in chapter 2 and appendix B.

Table 5.3 presents the first step of the analysis for the Python cooperation networks.

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Years	Nodes	GC	Random GC	GBC	Random GBC	maximum k	Random max k
1999	1146	66.0%	100.0%	6.7%	6.5%	3 (1.0%)	2 (6.5%)
2000	2172	96.5%	100.0%	33.4%	31.4%	8 (1.2%)	5 (3.1%)
2001	2511	97.3%	99.8%	34.1%	33.0%	9 (1.2%)	6 (2.4%)
2002	2317	100.0%	99.8%	38.1%	36.9%	9 (2.6%)	7 (1.9%)
2003	1805	100.0%	99.2%	34.8%	33.1%	7 (3.3%)	6 (2.4%)
2004	1850	99.8%	100.0%	39.7%	37.1%	7 (1.8%)	5 (2.5%)
2005	1007	99.8%	100.0%	45.7%	44.2%	5 (5.8%)	4 (7.6%)
2006	2632	100.0%	100.0%	74.2%	69.8%	9 (1.5%)	6 (3.9%)
2007	3359	100.0%	100.0%	58.6%	55.2%	9 (2.0%)	6 (2.2%)
2008	2951	100.0%	99.9%	64.5%	61.7%	10 (2.2%)	7 (2.5%)
2009	2219	100.0%	99.9%	51.0%	48.5%	7 (2.8%)	5 (5.6%)
2010	2930	100.0%	99.9%	48.7%	47.0%	9 (2.7%)	7 (2.4%)
2011	2174	100.0%	99.8%	47.7%	45.9%	8 (2.9%)	7 (1.7%)
2012	2444	99.8%	99.8%	41.1%	40.3%	8 (3.4%)	7 (3.4%)
2013	2285	99.9%	99.9%	51.6%	49.8%	7 (4.2%)	6 (4.0%)
2014	2134	100.0%	99.8%	44.6%	43.4%	7 (2.6%)	6 (3.1%)

Table 5.3: Structural Cohesion metrics for python networks.

This table contains the total number of nodes of the cooperation network for each year analyzed on the column named “Nodes”. The column labeled “GC” contains the percentage of the total nodes that are part of the giant component of the cooperation network, and the column labeled “GC random” is this same percentage but for a random configuration model network which I use as a null model. This metric is important because the starting point of the social cohesion in a network is a state where every actor can reach every other actor through at least one relational path. The formalization of this state in a concrete network is the size of the largest connected component which is what these columns report.

The column labeled “GBC” contains the percentage of nodes that are part of the giant biconnected component of the cooperation network, and the column labeled “GBC random” is the same percentage for their random network counterpart. Moody and White (2003) argue that the removal of a few key nodes can affect the flow of knowledge, information and resources in a connected component because it only has at least one relational path between any two nodes. In network terms, a graph is k -connected and is called a k -component if you need to remove at least k nodes to break it into more components. A 2-component, or biconnected component is a component that requires at least 2 nodes to be removed to break down connectivity, and thus the cohesion of this group doesn’t depend in only one node. Therefore Moody and White (2003) convincingly argue that a biconnected component provides a baseline threshold for strong structural cohesion. This is what these columns report.

Regarding the comparison of both giant component and giant biconnected component with their counterparts in random networks, as Moody (2004, 229-230) points out, the random model is an upper bound of component size because under random mixing conditions the components at low levels of connectivity —that is $k = 1$ and $k = 2$ — tend to cover the entire network,

given a minimum density threshold. Therefore, the meaningful comparison consist in how much closer to the random configuration model the actual networks get.

Finally the column “maximum k ” reports the k value of the most cohesive k -component found in the cooperation network, and in parenthesis there is the percentage of nodes that are part of this k -component observed in the actual cooperation network. The column labeled “random max k ” contain the same metrics for their random network counterparts.

For the case of the Python project, as reported in table 5.3, we can see that in all years but 1999 —when only 9 developers were modifying source code files— the percentage of nodes in the giant component of the actual cooperation network is practically the same than in their random counterpart. Thus, at this level of connectivity — $k = 1$ — there is no significative difference between the null model and the actual network. This is important because as stated above, at low connectivity levels, the random null model is an upper bound.

For the case of the giant biconnected—that is for the largest subgroup with connectivity level $k = 2$ — in Python cooperation networks are slightly higher than their random counterparts in all years under analysis. The year in which the giant biconnected of the actual network is much higher than its random counterpart is 2006, where 74.2% of nodes in the actual network were part of the giant biconnected but only 69.8% of nodes in its random counterpart. This year also marks an inflection point for the size of the giant biconnected in Python cooperation networks, in previous years its size was around the lower thirties percent, after that high point in history it decreases again but it does not go below the 40% mark.

Finally the last two columns of table 5.3 clearly show that the actual cooperation networks have higher connectivity levels at the top of the connectivity hierarchy than their random counterparts. From 2000 to 2010 —excluding again 1999— the difference is between two and three hierarchy levels but in the last years. For instance, in 2008 the actual cooperation network has a subgroup with 2.2% percent of nodes that forms a 10-component, which means that we need to remove 10 nodes from that group in order to disconnect it —or equivalently, we have to remove 10 nodes to destroy all relational paths between any two nodes in that group. The random network used as a null model for that year has only one subgroup that has connectivity 7.

These high connectivity k -components only have a very small percentage of all the nodes in the cooperation network (between 1 and 5.8% of all nodes), but as I will show in the next chapter, they play a key role in terms of their contribution to the project measured in the number of source code lines added to the files that form the code base of the Python language. Also, at a theoretical level, these subgroups with high connectivity play a key role, on the one hand, in generating trust and congruent values among the individual developers of the project, and on the other hand, in compensating the decay effects of the transmission of knowledge, influence and resources through social interactions.

As discussed in chapter 2, it’s useful to visualize the k -component hierarchy of the cooperation networks in order to gain a better understanding of their structure and to be able to easily compare between the actual networks and their random counterparts. Figure 5.1 shows Python cooperation networks for years 2000, 2004 and 2013 along with their random counterparts using the novel visualization technique that I presented in chapter 2 and on the publication (Torrents and Ferraro, 2015).

Using this novel visualization technique it’s easy to see the differences in the hierarchy

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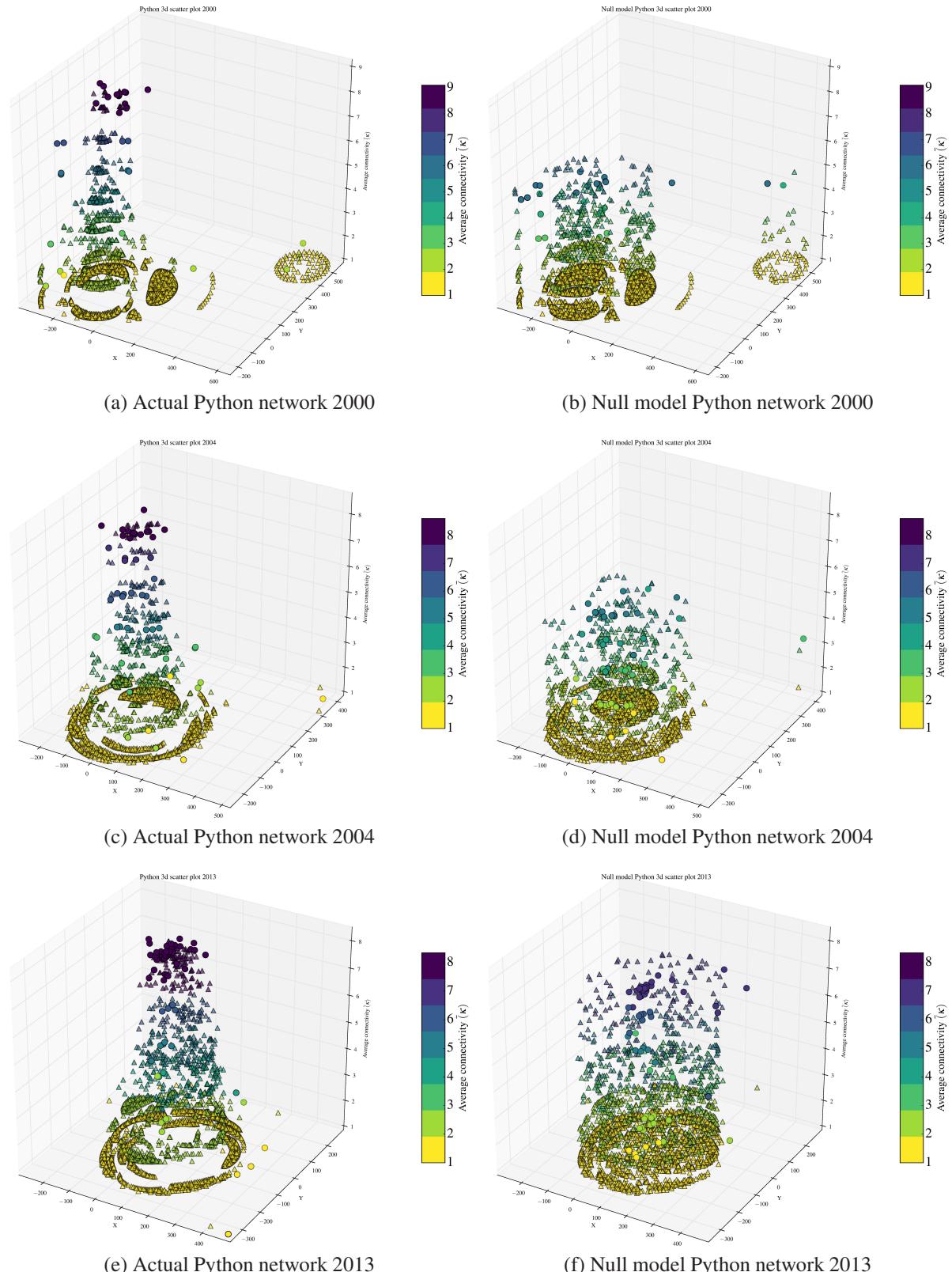


Figure 5.1: Python average connectivity three-dimensional scatter plots for actual networks and their random null models counterparts. X and Y are the positions determined by the Kamada-Kawai layout algorithm. The vertical dimension is average connectivity. Each mark is a node of the network as two-mode networks they contain both programs (triangles) and developers (circles).

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structure between the actual cooperation networks and their random counterparts. Actual networks not only have a higher connectivity levels at the top but their hierarchical structure of connectivity levels is more steep than in their random counterparts, which tend to have nodes more evenly distributed between connectivity levels and thus tend to be flatter connectivity hierarchies precisely because edges in random network are also more evenly distributed among nodes than in their actual counterparts.

After examining the tables and the figures for the Python cooperation networks I can conclude that the cooperation networks of the Python project fit nicely with the structural cohesion model. And, as explained above, also fit well the small world model. This allows to assess that they indeed fit the model what I named the Cohesive Small World.

Years	Nodes	GC	Random GC	GBC	Random GBC	maximum k	Random max k
1999	3,259	66.6%	83.4%	9.4%	11.4%	3 (0.2%)	2 (11.4%)
2000	3,593	52.5%	77.8%	7.0%	10.7%	3 (0.2%)	2 (10.7%)
2001	5,943	71.6%	86.4%	13.9%	17.5%	3 (0.1%)	2 (17.5%)
2002	6,857	72.4%	88.1%	12.7%	17.0%	4 (0.2%)	2 (17.0%)
2003	7,276	75.6%	89.5%	14.8%	20.2%	5 (0.2%)	2 (20.2%)
2004	7,984	78.4%	94.4%	22.1%	27.7%	5 (0.2%)	2 (27.7%)
2005	8,328	83.8%	94.4%	26.1%	31.3%	4 (0.5%)	3 (4.5%)
2006	9,599	84.2%	96.7%	33.7%	39.0%	4 (0.6%)	3 (8.4%)
2007	9,471	86.5%	96.1%	35.6%	40.7%	4 (0.2%)	3 (8.6%)
2008	10,662	87.2%	96.4%	34.3%	40.3%	4 (0.6%)	3 (7.5%)
2009	11,336	89.4%	96.1%	35.7%	42.3%	5 (0.4%)	3 (8.2%)
2010	10,515	86.9%	95.5%	32.7%	39.8%	5 (0.2%)	3 (5.1%)
2011	12,362	87.7%	95.0%	30.6%	36.0%	5 (0.3%)	3 (5.3%)
2012	11,904	87.1%	95.0%	31.0%	36.7%	4 (0.1%)	3 (2.3%)

Table 5.4: Structural Cohesion metrics for debian networks.

Regarding the Debian project, table 5.4, reports the structural cohesion analysis of their connectivity structure. As we can see the percentage of nodes of cooperation networks that form the giant component is smaller than the percentage in their random counterparts in all years under analysis. As explained above, for low connectivity levels the size for the giant components and bicomponents are an upper bound for the actual networks (Moody, 2004). In that sense, Python cooperation networks examined above are exceptional in that they equal or even surpass their random counterparts for low connectivity levels.

In the case of Debian networks we see an steady increase of the relative size of the giant component from 1999 to 2005, where the percentage stabilizes around eighty percent of the total nodes. However their random network counterparts grow similarly but there are approximately fifteen percent more nodes in the random giant components than in actual networks, stabilizing around 95% of the total nodes after 2005. For the case of giant bicomponents (column “GBC”), we see a similar picture than with the giant components: an steady increment of the relative size of bicomponents until 2006, where their relative size stabilizes around 30%

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of the nodes of the network with a peak of 35.7% in 2009. During all the period analyzed the random configuration model networks have a relative size of their giant bicomponent approximately 7% higher than their actual counterparts, also peaking in 2009 with 42.3% of the nodes.

For the higher connectivity levels, reported in the last two columns of the table, we can see that the actual cooperation networks have higher connectivity levels not present in the random configuration models used as null models. The difference in connectivity levels tends to increase in the later part of the period analyzed, where actual cooperation networks have 5-components—that is subgroups from which we have to remove five nodes in order to disconnect them— while random networks in all period analyzed have only 3-components as their higher connectivity level.

The number of nodes in the high connectivity subgroups in the actual cooperation networks is very low: less than 1% of all nodes. Note however that because of the total number of nodes in the Debian cooperation networks is quite big these subgroups are formed between 20 and 60 nodes.

In order to gain a better understanding of the shape of the hierarchical structure of these cooperation networks, and to compare them to their random counterparts we have to look at figure 5.2 where three dimensional scatter plots are shown for Debian cooperation networks for years 2000, 2004, and 2011, along with their random counterparts. Similarly to the Python cooperation networks, actual networks have a more steep connectivity hierarchy than their random counterparts because, on the one hand, they have nodes in higher connectivity levels that are not present in the random configuration models and, on the other hand, nodes in actual cooperation networks are less evenly distributed between connectivity levels. Thus I can conclude that Debian cooperation networks also correctly fit the structural cohesion model. And therefore they also conform to the model that I named Cohesive Small World.

The analysis presented in this chapter shows that the cooperation networks of both Debian and Python projects can be modeled using the proposed Cohesive Small World model. It is interesting to note that they also show significative differences because Debian cooperation networks lean more towards the small world end of the model, while Python cooperation networks lean more towards the structural cohesion end of the model. As discussed above, their difference in terms of modularity of the product that they are building—an Operating System versus a Programming language—impacts their respective production processes. Debian’s subgroups tend to work more independently from each other than Python’s subgroups, as shown by the fact that Debian cooperation networks exhibit a higher degree of smallworldiness; while Python’s networks are more structurally cohesive as shown by their sharper and steep connectivity hierarchy.

The next step in my analysis is to analyze the contribution levels of developers in both projects in the different levels of the connectivity hierarchy in order to assess the actual impact of this hierarchy of the respective cooperation networks in the production process of both projects. This is the focus of the next chapter.

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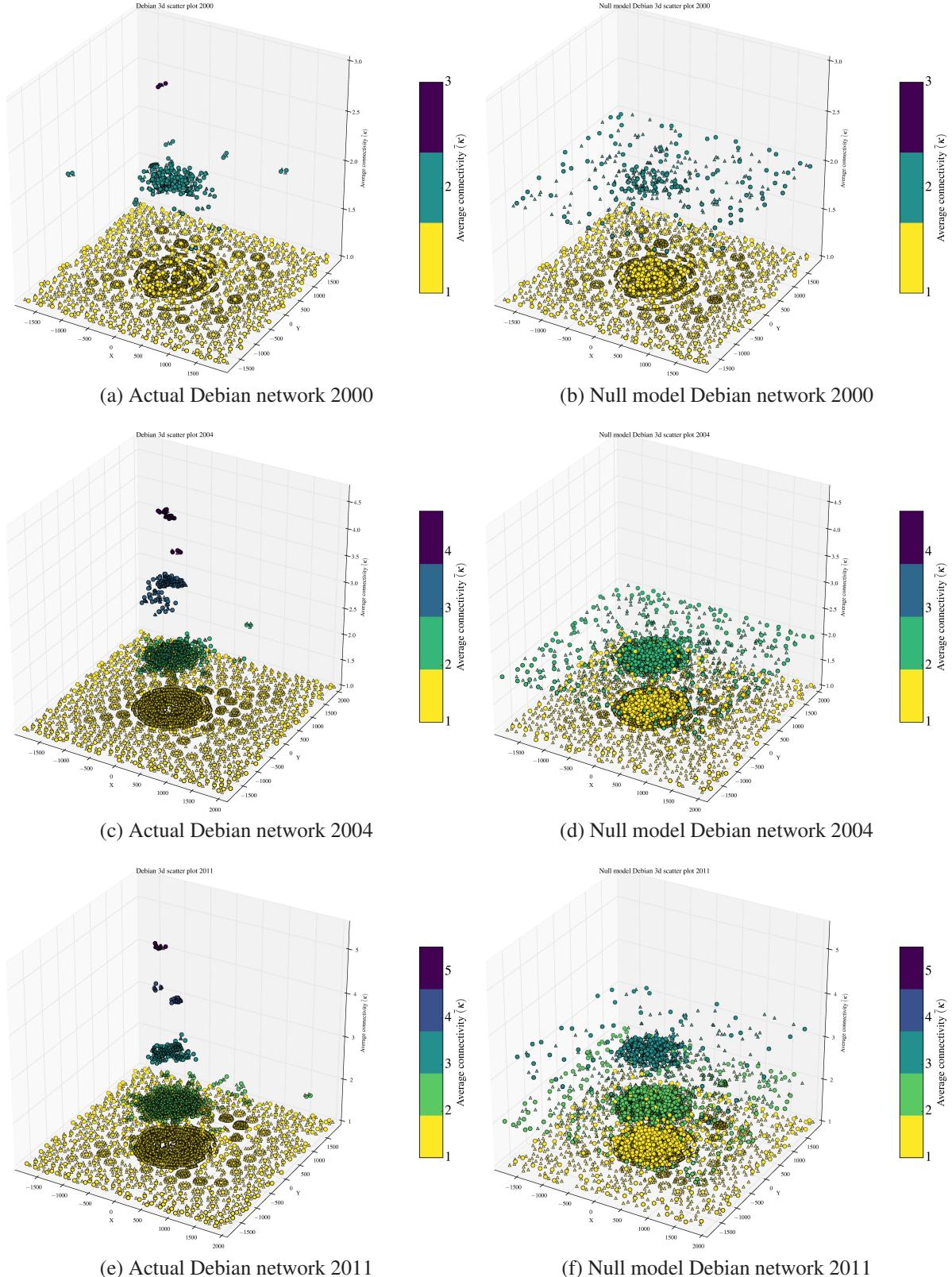


Figure 5.2: Debian average connectivity three-dimensional scatter plots for actual networks and their random null models counterparts. X and Y are the positions determined by the Kamada-Kawai layout algorithm. The vertical dimension is average connectivity. Each mark is a node of the network as two-mode networks they contain both programs (triangles) and developers (circles).

Connectivity Hierarchy and Individual Contributions

6.1 Cooperation networks' connectivity hierarchies as open elites

The analysis of the hierarchical structure of organizations has been a central topic on organizational research in the last decades. This analysis has been mainly static in the sense that the focus of interest has been, among others, the distinctions between formal hierarchies and informal patterns of relations (Krackhardt and Hanson, 1993; McFarland, 2001), the comparative analysis of the shape of the hierarchy (Blau and Scott, 1962; Blau, 1964), the impact of different kinds of hierarchical structures in the outcomes of the organizations' activities, the potential contradictions among the internal hierarchical structure of organization and its goals towards a more egalitarian society (Michels, 1915; Selznick, 1949), to cite only a few key issues.

Despite the huge amount of work devoted to the analysis of hierarchy in organizations, the dynamic dimension of the hierarchy has received a lot less attention. The work on the dynamic dimension has focused on the evolution of hierarchical structures of organizations through time (Blau, 1969). There is however another possible definition of dynamic dimension in the analysis of hierarchy in organizations: the ratio of renewal of the individuals in the positions defined by that hierarchy. This important element of the dynamic dimension of hierarchy has been partially approached from the perspective of vacancy chains (White, 1970; Stewman and Konda, 1983). However this approach has focused mostly on the career paths of individuals inside organizations instead of focusing on the pace of renewal of individuals in the hierarchical structure of organizations.

My approach to analyze the structure and impact on individual contributions of connectivity hierarchies in cooperation networks follows the concept of open elite, first suggested by John Padgett in his statistical analysis of marriage patterns, family structure and elite reproduction in Florence between 1282 and 1494 (Padgett, 2010). In this work, Padgett suggests that despite a tendency to maintain an elite structure through marriages, the existence of three contending dimension of status —age of lineage, wealth and, political faction— led higher-

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status families to reach out and marry middle-tier ones, thus contributing unintentionally to social mobility. This approach leads to a “reconceptualization of the concept of elite, more as a fluidly reproduced ideal than as a stable demographic reality” (Padgett, 2010, 360).

This reconceptualization was further developed in a study of the emergence of commercial biotechnology in the United States, where Powell et al. (2005) identified an “open elite” network structure among dedicated biotech firms, pharmaceutical companies, venture capitalists, government agencies and universities which “allowed for extensive crosstalk among a diverse set of organizations, melding practices and resources from multiple sources. Precisely because these organizations did not follow a common set of evaluative criteria, its heterogeneous, multiple affiliations made responsiveness to challenges possible.” Powell et al. (2005, 467).

I propose that hierarchical structures can be classified in a continuum, the two extreme points of which are, on the one hand, a static hierarchy —where when an individual is appointed in a position of the hierarchy, this position is for life— and, on the other hand, a dynamic hierarchy —where the individuals occupying positions defined by the hierarchy have a very high pace of renewal. Notice that, in this context, the hierarchy can refer to both the formal and informal patterns of relations. An example of static hierarchy is the catholic church, where an appointment —even far from the top level— will typically last for life. On the other hand, dynamic hierarchies are a lot less common, especially before the last years of the twentieth century.

Since then we have witnessed the emergence of new organizational forms, mainly around Free and Open Source Software projects (FOSS). I propose that one of the central characteristics of these new organizational forms is precisely their high ratio of turnover in key hierarchical positions, both in the formal and informal internal organization. I do think that this dynamic dimension has not been taken into account in the analysis of those new organizational forms, and only by considering and analyzing it we can deepen our understanding, not only of the new emerging organizational forms, but also further our understanding of organizations and the challenges that they face.

In this chapter, I will start from this reconceptualization of an open elite in a dynamic hierarchy, and suggest that in FOSS projects there is a structural elite, identified as subgroups in the connectivity structure of their cooperation network that guarantee continuity and cohesion, but that these positions experience high membership turnover, and thus that this elite can be characterized as an open elite.

The dynamism of hierarchies in FOSS cooperation networks

Free and Open Source Software (FOSS) communities have attracted a lot of attention from researchers of different fields since the late nineties of the past century. The first academic accounts of this phenomenon were mainly descriptive; their main focus was to just describe the organization of FOSS communities, the individual motivations of the people that form these communities, and the quality of the products that they produced (Benkler, Shaw, and Hill, Benkler et al.). Most of the interest was derived from the fact that FOSS communities do not conform to the accounts of collective dynamics and individual motivations established by the dominant neoclassical economic theories.

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Academic efforts took mainly two directions. On the one hand, some authors tried to reconcile the dynamics of FOSS communities with neoclassical economic accounts. This effort was mainly focused on the individual motivations of the participants in those communities. They tried to explain these motivations in terms of rational self-interested individuals, as prescribed by dominant economic theories. On the other hand, other authors saw the emergence of FOSS communities as a new organizational form that provided a more democratic way of enabling collective production without the constraints imposed by the markets and/or bureaucratic organizational forms (Benkler, 2002, 2006; Castells, 2013).

The later accounts of FOSS communities were initially uncritically celebratory of the phenomenon. They were heavily influenced by practitioners and advocates of the FOSS phenomenon which emphasized the technical superiority of the products developed by FOSS communities, while maintaining an ethical stand that valued more cooperation and reciprocity than competition and self-interest. One of the most influential early accounts from practitioners was Raymond (1999) that proposed, among other things, that the technical superiority of FOSS software products was due to the “Linus law”, which states that “given enough eyeballs, all bugs are shallow”, suggesting that given a large enough developer and user community with access to the source code, all software errors (ie “bugs”) will be detected quickly and the solution will be obvious at least to someone.

Thus “Linus law” suggests that FOSS communities are composed by a large set of individuals loosely organized with a very flat or nonexistent hierarchy among them, and that all individuals might contribute more or less the same: a pair of eyes that should look at the source code in order to improve it. This somewhat naive account of the dynamics of FOSS production process was accepted uncritically by many academics that were sympathetic with the arguments of the FOSS practitioners. Some critical voices, coming mostly from Computer Science, challenged this claim with sound empirical arguments; for instance Glass (2002) correctly noted that if “Linus Law” was right then the number of bugs found in a software project should increase linearly with the number of people looking at their source code. No such thing have been proved empirically. Also, “Linus Law” not only treats each pair of eyes (ie individuals) as equally important, it also implicitly assumes that all bugs are similar, which is very implausible.

Other early empirical research, coming mostly from Computer Science, has pointed out that even in big, mature and widely used FOSS projects, only few of the participants account for the lion's share of the work done. For instance, Mockus et al. (2002) show that less than 20 developers of the Apache project¹ contributed more than 80% of the code base. This core of developers is embedded in a larger set of participants, that mainly help reporting and fixing errors, answering questions about the software in public forums, and writing documentation. Later empirical research has confirmed that the distribution of contributions in FOSS projects is right-skewed and heavy tailed, meaning that most participants make very small contributions, and only few individuals make almost all relevant contributions.

Recent empirical research on peer production projects (concretely user edited wikis) has also shown that these projects exhibit deep contribution inequalities (Shaw and Hill, 2014).

¹ Apache is one of the most successful FOSS projects, its flagship product is the Apache web server which powers more than 50% of the web sites that form the WWW.

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The authors suggest that these projects may conform to Michels (1915) “iron law of oligarchy” which states that organizations tend towards oligarchy as they grow, even if democracy and participation are part of the core goals of the organization. Therefore, there is ample empirical evidence that confirms that there is an important differentiation of roles and functions among participants on FOSS communities. This fact does not fit well with the picture of a flat hierarchy of peers portrayed by early accounts of the phenomenon.

I do think that the narrative of a flat hierarchy of peers was so successful because the formal organization of most FOSS projects is usually quite fuzzy, and very different of the formal structure of other kinds of organizations. However, the informal structure emerging from the patterns of cooperation among individuals in a FOSS project is quite hierarchical because reflects the fact that only few individuals are responsible for most contributions to the project. I propose that the way to advance our theoretical understanding of the FOSS phenomenon is by analyzing their social structure. The social structure of a community are the patterns of relations established among individual participants in the process of building the software packages (or any other product, such as on on-line encyclopedia) that they release. The public nature of FOSS communities implies that most of the data generated in the production process is available, and thus an important source of empirical data that we can use to test competing theoretical accounts of the phenomenon.

In this chapter I show that the developers that contribute the most to the projects analyzed are in the higher levels of the connectivity structure of the project’s cooperation networks. Moreover, by analyzing the composition of individuals on these key topological positions I’m able to assess to which extend there is turn over of individuals at the top of the connectivity structure. My analysis shows that the ratio of renewal of individuals at this structural position is quite fast, which characterizes FOSS communities as dynamic hierarchies and open elites. Thus, if we analyze cross-sectionally (ie in a concrete point of time) a FOSS project, a very small fraction of the participants are the ones that actually do the lion’s share of contributions, as previous empirical research has shown. However if we analyze the evolution of contributions longitudinally, we find that the persons that contribute the most change through time. This continuous renewal of the people that does most of the work —what I call dynamic hierarchy— is a key mechanism to explain how FOSS projects, which are mostly voluntary based, geographically distributed, and mostly operated from the Internet, can thrive and evolve to a point where they are key pieces of the infrastructure that enables the Internet and other essential Information technologies.

The focus on the rotation of individuals at the top levels of the connectivity structure brings us to the issue of the robustness of the FOSS communities. From a pure network perspective, it is usual to analyze robustness by removing nodes and measuring how this affects the size of the giant connected component in the network (Albert et al., 2000). Nodes are removed following different mechanisms; either at random —to simulate failure— or removing nodes according to their degree —to simulate a deliberate attack. However these mechanisms are best suited for analyzing the robustness of physical networks, such as the Internet. They clearly fall short for analyzing the robustness of FOSS communities, because not random failures nor targeted attacks are the main mechanisms through which the persons that work on FOSS communities turn over.

My approach here is to analyze the median active life of developers in a FOSS project as a

better way of assessing the robustness of a FOSS community. I also apply the well established survival analysis techniques (Miller Jr, 2011) in order to describe and model the flux of people throughout the history of a FOSS community. I found that the position of an individual in the connectivity structure of the collaboration network also impacts significantly in the median active life of a developer in the project.

6.2 Methods

In this chapter I analyze the role of the connectivity structure of the cooperation networks in shaping individual contributions to Debian and Python projects. I focus on the structural positions in which the most active contributors are, and the median active life of individual contributions on the project. My main empirical interest is about the volume of contribution of each individual to the project, and the role of contributions—as independent variable—in relevant elements of a FOSS project, such as the median active life of individual contributors to the project.

My modeling strategy to capture the patterns of relations among developers in these two projects is to focus on the actual contributions of each developer to the project. Following the approach in the previous chapter, I model cooperation networks as bipartite graphs, where the two sets of nodes are, on the one hand, human developers and, on the other hand, entities that conform the product that is released by the FOSS project. In the case of Debian, these entities are software packages, and in the case of Python, they are source code files. Note that the cooperation network is based on individual contribution but it not only captures the total amount of contribution that a given individual does, but also to which part of the project the contributions are focused, and who else in the project is also working on the same entities. This is why I name these bipartite graphs cooperation networks.

This modeling approach captures mostly the informal patterns of relations that individuals establish when contributing to the project. FOSS projects have a wide range of formal organizational forms, and in this respect, they can be quite different. The definition of the leadership position in the two projects in which I focus this thesis nicely capture these differences in formal organization: Debian has a very developed formal bureaucracy, the project elects its leader each year through a secret vote of all its members after a electoral campaign where the candidates discuss among them and try to gain supports; Python instead has its original author—Guido van Rossum—in a permanent position of leadership, the people in the project refer to him, and his position of leadership, as “Benevolent Dictator For Life” (BDFL). Decisions in the Python project are usually made by consensus, but when consensus is not reached after collective deliberation, the leader of the project makes the decision.

Despite these differences in the formal organization, if we focus on the patterns of relations among developers in the productive process, what I call the cooperation network, we can analyze the contribution dynamics, analyze hierarchical positions defined by these patterns, assess the pace of renewal in these positions, and determine the impact in the median active life of a developer of being in a concrete hierarchical position.

One of the challenges that I faced, that is both theoretical and methodological, is how to define cohesive groups in cooperation networks. There are many ways of defining a cohesive

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group given a cooperation network. My aim was to define groups in cooperation networks in a way that is theoretically sound from a sociological point of view. Network science is nowadays quite interdisciplinary, and a lot of physicist have recently proposed a bunch of techniques, under the label of community detection algorithms (Fortunato, 2010), that determine groups in networks based on the patterns of relations among the entities of the network.

However, these techniques are suboptimal from a sociological theory point of view because the four key elements that a sociologically sound group classification should have are not present in most, if not all, most used community detection algorithms, as discussed in chapter 2 (and published at (Torrents and Ferraro, 2015)). The four key dimensions are: robustness (the groups should not depend on only one or few individuals to be a group), overlap (persons usually are part of more than one cohesive group), positional dimension (some actors, because of their position in the global patterns of relations, obtain preferential access to information or resources that flow through the network), and hierarchy (cooperation networks have *hierarchical structure* in the sense that highly cohesive subgroups are nested inside less cohesive ones).

As discussed in previous chapters, I model cooperation networks using the proposed Cohesive Small World model, which is partially based on the structural cohesion model, developed by White, Moody and Harary (White and Harary, 2001; Moody and White, 2003). This model is based on the graph theoretic measure of node connectivity, and defines cohesive groups as k -components, that is, groups of nodes in which k nodes have to be removed in order to disconnect the group. K -components form the connectivity structure of the network, and aptly capture the central elements of a sociological definition of cohesive group (Torrents and Ferraro, 2015) as discussed at length in chapter 2.

However, there are some important practical difficulties related to the computation of the measures that characterize the structural cohesion model. Their time complexity is super quadratic, approximately of the order of the forth power of the size of the input network. This makes non practical the exact computation of the k -component structure in networks bigger than several hundreds of nodes. I use here some useful heuristics that allow to approximately compute the connectivity structure of large sparse networks in a reasonable time frame, as I have shown in chapter 2.

Once I built the cooperation networks for the two projects, and determined their connectivity structure, I perform a descriptive analysis of the percentage of total contributions by connectivity level. This simple descriptive analysis shows that there is a strong correlation between the position of a developer in the connectivity structure of the cooperation network and her total amount of contribution to the project.

I then deepen the analysis by modeling individual contributions to the project using different regression models in order to asses the relation of the structural positions that individuals occupy with their level of contribution to the project. For the case of the Debian project, contributions are uploads of packages to the central repository of the project, thus contributions in this context have to be modeled as a discrete variable. For this case I used a negative binomial regression model to deal with the over-dispersed count data from the values of the discrete contributions variable.

For the case of the Python project, contributions are lines of source code added or deleted from one of the source code files of Python's code base. I modeled contributions using a panel

regression with individual fixed effects. This design allows us to account for unobserved variability among the individual developers, such as cultural background or coding expertise, and disentangle if the position of a developer in the connectivity hierarchy has an effect in her level of contribution to the project.

Finally, I'm also interested in the impact of the position than an individual occupies in the cooperation network with her long term involvement with the project. To that end I applied Cox proportional-hazards regression for survival data to both Debian and Python projects. In its origin, survival analysis, was focused on modeling lifespans of individuals and is still widely used in medicine. However, this kind of analysis can also be used to model any kind of duration. I model the active life of a developer in a FOSS project as the period that this developer is doing at least one contribution. I consider a developer “dead” when she no longer contributes.

6.3 Regression modeling and mobility analysis

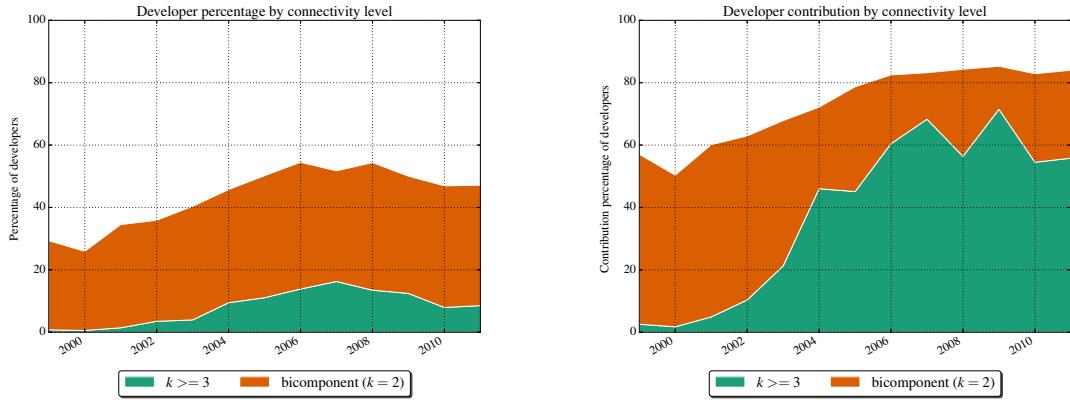
Modeling individual contributions

As discussed in the previous section, the empirical work on FOSS communities has already established that it is only a small fraction of all participants in a project who are responsible for most contributions. As a first step for the analysis, I analyze the topological position of the individuals that contribute the most in the patterns of relations —the social structure— among individuals in that project. Following the proposed cohesive small world model (see chapter 3), and one of its fundaments: the structural cohesion model (Moody and White, 2003) (see chapter 2), I found that these individuals are part of the top connectivity levels of the cooperation network, that is, they are members of k -components of high k which represent cohesive subgroups nested inside each other in the network that emerges from the patterns of relation among developers in the productive process.

Figure 6.1a displays the evolution of the percentage of developers by connectivity level in the period under analysis for the Debian project. The green surface represents the developers in the top connectivity levels, that is developers that are part of a k -component with k greater or equal than 3. The orange surface represents developers in bicomponents, that is k -components with $k = 2$. Note that all developers in the top connectivity levels are also part of the bicomponents. In the period under analysis, there is a significant increment of the hierarchy of connectivity levels, as I have shown in the previous chapter, which peaks in 2007 with 17% of the developers in connectivity levels with $k \geq 3$. The percentage of developers in bicomponents, goes from 26% in 2002 to 50% in 2005 and peaks at almost 54% of developers at 2006 and 2008. From 2005 to the end of the period under analysis the percentage stabilizes between 45% and 54%. The percentage of developers in higher connectivity levels also experiments an important increment, it goes from less than 1% in 1999 and 2000 to 8% in 2011, and peaks around 16% in 2007.

Figure 6.1b displays the percentage of contributions by developers by connectivity level. We can see that, although there are few developers in high connectivity levels, they are responsible for a big fraction of the total contribution in terms of packages uploaded to the Debian

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(a) Evolution of the percentage of developers by connectivity level for the Debian project.

(b) Evolution of the percentage of contributions by developers by connectivity levels for the Debian project.

Figure 6.1: Evolution of the percentage of developers in each connectivity level (left) and evolution of the percentage of contributions by developers by connectivity levels (right) for the Debian project. The green surface represents the developers in the top connectivity levels, that is developers that are part of a k -component with k greater or equal than 3. The orange surface represents developers in bicomponents, that is k -components with $k = 2$.

archive. For instance, in 2004 the developers in the top connectivity levels were less than 10% of all developers, but they contributed 46% of all uploads to the Debian repository that year. That same year, 45% of the developers were embedded in a bicomponent and contributed 72% of all uploads. In 2009, 12.5% of the developers that were part of the top connectivity levels were responsible for 71% of all contributions, while developers in k -components with $k \geq 2$ contributed 85% of all uploads while being only 50% of all developers that uploaded at least one package to the Debian archive that year.

Therefore, it is clear that there is a strong correlation between the connectivity level of a developer and her contribution to the project. To further the analysis, I modeled the contributions—which in this case are uploads of new versions of packages to the Debian archive—using a negative binomial regression. Which is well suited for the count nature of the dependent variable (# of uploads) and its over dispersion. I cannot use a zero inflated model in this case because by design there is no zeros in the dataset as I only considered developers that have at least uploaded one package. This regression model is not for all the period analyzed on the previous analysis (1999-2012) because the scale of the Debian system—in terms of the number of packages—has grown too much in this period and thus the later years would have been over-represented. I opted for analyzing the development time of a complete version of the Debian system. Concretely I analyzed the period from 2011-02-06 to 2013-05-04 corresponding to the development cycle of the Debian release 7.0 codename Wheezy.

I controlled the contributions of each developer, on the one hand, by several key variables related to the technical side of the production process, such as the size ($\log(\text{Package size})$) and the dependencies of each package (# of package dependencies), the bugs reported for each package (# of bugs reported), or the time that the developer has been active in the project

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(*Developer tenure (years)*). And, on the other hand, I also controlled for centrality measures including degree centrality (*Degree centrality*) and closeness (*Closeness*), and a local cohesion metric (*Square Clustering*). As can be seen in table 6.1, the connectivity level in which a developer is embedded (*k-component number*) has a positive and significative impact on her contributions to the project.

Table 6.1: Negative binomial model for Debian uploads

	<i>Dependent variable:</i>			
	Number of uploads by developer			
	(1)	(2)	(3)	(4)
Intercept	−0.647*	−0.545**	−0.837***	−1.453***
	(0.262)	(0.199)	(0.200)	(0.191)
log(Package size)	0.309***	0.229***	0.240***	0.203***
	(0.021)	(0.016)	(0.016)	(0.015)
# of bugs reported	−0.007***	0.002	0.002	0.001
	(0.002)	(0.001)	(0.001)	(0.001)
# of package dependencies	−0.020**	−0.016**	−0.017**	−0.021***
	(0.008)	(0.006)	(0.006)	(0.005)
Developer tenure (years)	0.105***	0.071***	0.077***	0.083***
	(0.008)	(0.006)	(0.006)	(0.006)
Degree centrality		47.333***	47.318***	27.174***
		(0.695)	(0.691)	(0.742)
Closeness		−0.304	−0.142	0.651***
		(0.179)	(0.180)	(0.175)
Square clustering			0.421***	0.055
			(0.077)	(0.077)
k-component number				0.690***
				(0.032)
Observations	1,750	1,750	1,750	1,750
Log Likelihood	−8,235.163	−7,541.388	−7,528.735	−7,393.372
Akaike Inf. Crit.	16,480.330	15,096.770	15,073.470	14,804.740

Note:

*p<0.05; **p<0.01; ***p<0.001

Tables C.1 and C.2 on appendix C show the descriptive statistics and the correlation matrix of the variables used in this model. In terms of the importance of the variables in the model, the independent variable *k*-number (the value *k* of the connectivity level in which the developer is embedded in the connectivity hierarchy) is the second most important only after degree centrality. I measure variable importance here as normalized magnitude by dividing the coefficient in the model by its standard deviation.

The fact that the quantification of contributions in the Debian project is a discrete variable —number of package uploads to the Debian repository— restricts the options of regression

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modeling available. The over dispersed negative binomial regression is clear in that the connectivity level in the cooperation network has a positive and significant impact on the level of contribution of each developer. However it does not allow to take into account unobserved individual differences among developers that might explain their level of contribution.

Another source of concern with this model it's the potential endogeneity of the relation between the dependent variable and the network metrics, which include the independent variable. Given that the cooperation network is build precisely based on uploads to the Debian archive, which is the dependent variable in this model. I will refine the analysis to deal with endogeneity problems using data from the Python project.

As discussed above, the data from Python project allows us to measure contributions as lines of source code added by each developer. This variable can be safely considered continuous and therefore I can model it as a panel regression with individual and time fixed effects. This modeling approach, on one hand, solves the problem of unobserved differences between developers that might have an effect of the volume of their contributions, and on the other hand, also allows to account for changes in system through time that I was not able to model in the negative binomial regression of table 6.1.

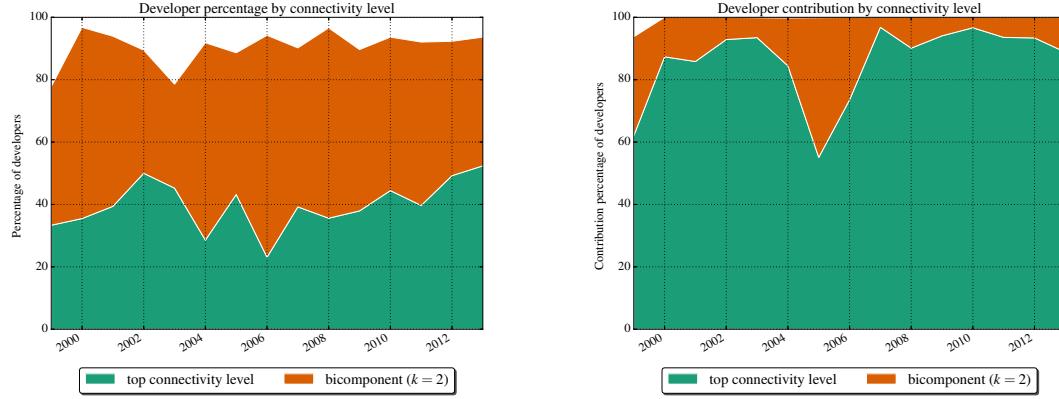
Let's first take a look at the descriptive data on percentage of contributions by the top connectivity level (the developers that are in the k -component with the highest k) in the Python project. Figure 6.2a displays the evolution of percentage of developers that are at the top connectivity level throughout the history of Python project. The orange surface shows the percentage of developers that are included in the giant biconnected component, and the green surface represents the percentage of developers in the top connectivity level, that is the k -component of maximum k in the cooperation network of that year.

We can see that around 40% of the developers that have contributed some code are in the top level of the connectivity hierarchy, and this percentage is quite stable through time. Note that the actual k value of the top level varies in time, depending on how the patterns of relations among developers and source code files have evolved each concrete year. The node connectivity of the k -component in the top of the connectivity hierarchy is almost all years between 7 and 10, with a minimum of 6 in 2005, as I have shown in the previous chapter.

Figure 6.2b shows the evolution of the contributions of the developers by connectivity level, measured in terms of lines of source code added to the project. Note that k -components are nested inside each other, like Russian dolls, thus the contributions of developers in the giant biconnected components also include the contributions of the developers in the top connectivity level. As we can see, developers in the giant biconnected component are the authors of almost all contributions, but they are also between 80% and 97% of all developers.

However developers in the top connectivity level are only between 40% and 55% of all developers on the project, but they are the authors, the latter years of the period under analysis, of around 90% of the source code contributions. Some years their percentage of contributions is lower (a bit less than 60%) but this is mostly before 2001, when the community was much smaller than in the following years, or in 2005. Therefore only a small fraction of the developers are responsible of the lion's share of the work done in the project. Note however that the contributions to source code files, what is measured here as contributions, does not include all the work done that is important to the project, such as managing the infrastructure for distributing Python, helping users in the mailing list, maintaining the websites of the project, etc

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(a) Evolution of the percentage of developers by connectivity level for the Python project. (b) Evolution of the percentage of contributions by developers by connectivity levels for the Python project.

Figure 6.2: Evolution of the percentage of developers by connectivity level (left) and evolution of the percentage of contributions by developers by connectivity levels (right) in the Python project. The green surface represents the developers in the top connectivity level, that is developers that are part of a k -component with maximum k . The orange surface represents developers in bicomponents, that is k -components with $k = 2$.

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For modeling individual contributions to the Python project, I used a panel regression with individual and year fixed effects. This design allows us to account for unobserved variability among the individual developers, such as cultural background or coding expertise, and disentangle if the position of a developer in the connectivity hierarchy has an effect in her level of contribution to the project. As we can see in the table, being in the top connectivity level has a positive and significant impact in the level of contribution of each developer. Note also that considering the k -number of the developer (ie, the level k of the highest k -component in which the developer is embedded) adds explanation power on the model and suggest that the impact of the connectivity hierarchy on the productivity of developers operates at all connectivity levels, not only at the top.

The model also includes control variables for the centrality of each developer in the co-operation network (Degree centrality and Closeness), the number of direct collaborators of each developer (collaborators), the tenure of each developer (measured as the number of years since their first contribution) and the value of square clustering which is a measure of local cohesion. Tables C.3 and C.4 on appendix C show the descriptive statistics and the correlation matrix of the variables used in this model.

This regression modeling of Python contributions by connectivity level complements and confirms the negative binomial regression results applied to the Debian project. The k -components of the cooperation network define groups of developers that are the core of the project and are responsible for most of the contributions, both in Debian and in Python project. These groups are central in a structural sense as they are at the top of the connectivity hierarchy that emerges from the patterns of cooperation among individual developers. The models presented thus far

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Table 6.2: Contributions Fixed Effects Panel Regression Results

	<i>Dependent variable:</i>			
	Lines of Source Code			
	(1)	(2)	(3)	(4)
Degree Centrality	7.053*** (0.887)	7.040*** (0.891)	5.779*** (0.797)	5.997*** (0.642)
Collaborators	0.086*** (0.006)	0.086*** (0.006)	0.072*** (0.006)	0.038*** (0.006)
Tenure (years)	-0.260*** (0.030)	-0.262*** (0.030)	-0.199*** (0.029)	-0.131*** (0.032)
Closeness	-0.709 (0.809)	-0.725 (0.815)	0.140 (0.828)	-0.465 (0.973)
Square clustering		-0.092 (0.364)	0.211 (0.336)	0.580 (0.299)
Top connectivity level			1.202*** (0.186)	0.579** (0.177)
k-component number				0.330*** (0.047)
Observations	816	816	816	816
Adjusted R ²	0.388	0.387	0.420	0.464

Note:

*p<0.05; **p<0.01; ***p<0.001

point out that these developers are also the ones responsible for the lion's share of the contributions, and thus the hierarchical structure of the cooperation network shapes the volume of contribution of individual developers.

However the fixed effects panel regression also has a potential problem of endogeneity as the cooperation network form which I computed the connectivity hierarchy is based on individual contributions and this was the dependent variable in both this regression model and the negative binomial model I explored before for the case of the Debian project. Note that despite this potential problem, if we look at the correlation tables for these models at appendix C, we can see that the correlations between the independent and dependent variables is not high enough —0.488 for the negative binomial and 0.211 for the fixed effects panel regression—to create collinearity problems in the models.

To deal with this potential endogeneity problem I now use a new dependent variable that captures contributions to the Python project but that is not directly related with the number of lines of source code contributed by each developer. This new variables is the number of PEPs (Python Enhancement Proposals) approved. PEPs² are design documents providing information to the Python community, or describing a new feature for Python or its processes or

²<https://www.python.org/dev/peps/> accessed November 2016

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Table 6.3: Zero Inflated negative binomial model for PEPs

	<i>Dependent variable:</i>			
	Total number of accepted PEPs authored			
	(1)	(2)	(3)	(4)
log(# of lines of code authored)	0.070 (0.037)	0.011 (0.038)	0.026 (0.043)	0.009 (0.042)
Degree Centrality	1.507* (0.728)	1.135 (0.662)	1.655* (0.724)	1.151 (0.673)
Tenure (years)	0.177*** (0.012)	0.180*** (0.011)	0.176*** (0.012)	0.180*** (0.011)
Collaborators	0.018* (0.008)	0.011 (0.007)	0.011 (0.008)	0.011 (0.008)
Closeness	-5.688* (2.574)	-4.661* (2.240)	-5.433* (2.540)	-4.659* (2.240)
Square clustering	-0.416 (0.266)	-0.108 (0.268)	-0.239 (0.278)	-0.103 (0.274)
Top connectivity level		0.683*** (0.163)		0.675*** (0.181)
k-component number			0.093* (0.047)	0.006 (0.051)
Constant	0.878 (0.921)	0.589 (0.835)	0.611 (0.921)	0.579 (0.842)
Year dummies:	Yes	Yes	Yes	Yes
Observations	773	773	773	773
Log Likelihood	-1,083.697	-1,073.610	-1,081.423	-1,073.576

Note:

*p<0.05; **p<0.01; ***p<0.001

environment. The PEP provide a concise technical specification of the feature and a rationale for the feature. PEPs are the primary mechanisms for proposing major new features, for collecting community input on an issue, and for documenting the design decisions that have gone into Python. The PEP author is responsible for building consensus within the community and documenting dissenting opinions.

Thus, PEPs are a key mechanism of innovation and evolution of the Python project, and the developers that successfully propose a PEP are the ones designing the technical future of the Python project, and thus we can consider them to be in a leadership position. By using the number of accepted PEPs for each developer as a dependent variable in the regression modeling I sort out the endogeneity problem of the plain number of lines of source code added to the project. For modeling PEPs contributions I used a zero inflated negative binomial model for count data, as the number of PEPs each developer authored is a discrete variable.

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The fact that many developers did not author any PEP requires us to use the zero inflated version of the negative binomial model.

I tested the model assumptions and compared it with alternative models such as a Poisson model, a plain negative binomial, and Hurdle model and found that the zero inflated negative binomial model is the one that better fits the number of accepted PEPs as a dependent variable. A good way to test the fit of the model is to see the number of zero observations that each model predicts. Zero observations are developers that either have not proposed any PEP or the PEPs that they proposed have not been accepted for each year (thus actual observations are pairs developer – year). The actual number of zeros in the Python PEP dataset is 449: the Poisson model predicts 322 zeros, the plain negative binomial predicts 434, and the zero inflated negative binomial model predicts 450 zeros, which is very close to the actual number of observed zeros.

Table 6.3 presents the results of the zero inflated negative binomial model. Tables C.5 and C.6 on appendix C show the descriptive statistics and the correlation matrix of the variables used in this model. This model shows that there is a positive and statistically significant effect of being part of the top connectivity level on the number of accepted PEPs authored by each developer. In this case however, if I include both being at the top to the connectivity hierarchy and the k -component number, only the former is significative. This model also shows that tenure in the project (the number of years since a developer made her first contribution to Python) has also a positive and statistically significant effect on the number of accepted PEPs authored. The tenure variable is the one that has a stronger impact on the dependent variable, but the second strongest is the variable that reflects if a developer is at the top of the connectivity hierarchy in the cooperation network. Note that I also included the individual developer contribution in terms of lines of source coded added as a control variable, which is not significative in this model.

Given that PEPs are not source code contributions, there is no potential endogeneity in this model, and I can assert that the connectivity hierarchy that emerges from the patterns of relations established by developers while contributing to the project —the cooperation network— shapes the contribution dynamics of individuals in the project. Also PEPs define the evolution of the Python language, thus the people that write them are effectively leading its development and evolution. This demonstrates that cooperation has an important structural dimension which cannot be neglected if we want to understand the mechanisms that shape individual contributions to the project.

Developer mobility in the connectivity hierarchy through time

The next step is to determine if the developers on the top connectivity level are always the same people, or if there is rotation and turn over. Table 6.4 shows, for each year under analysis, the number of developers in the top connectivity level of the cooperation network and the percentage that they represent of the total number of developers, the number of new developers that enter the top connectivity level and the percentage that they represent of the developers in the top connectivity level, the number of developers that get out of the top connectivity level and the percentage that they represent, and the number of developers that get back in the top

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connectivity level; that is, developers that have been in the top connectivity level other years than the previous year and they get back in it.

Table 6.4: Developer mobility in the top connectivity level for the Python project.

Years	Top Developers	New Developers	Developers Out	Developers back
1999	3 (33.3%)	3 (100.0%)	0 (0.0%)	0 (0.0%)
2000	11 (35.5%)	8 (72.7%)	1 (9.1%)	0 (0.0%)
2001	13 (39.4%)	4 (30.8%)	1 (7.7%)	0 (0.0%)
2002	19 (50.0%)	8 (42.1%)	1 (5.3%)	0 (0.0%)
2003	19 (45.2%)	3 (15.8%)	5 (26.3%)	0 (0.0%)
2004	14 (28.6%)	3 (21.4%)	1 (7.1%)	0 (0.0%)
2005	19 (43.2%)	1 (5.3%)	4 (21.1%)	5 (26.3%)
2006	12 (23.1%)	0 (0.0%)	4 (33.3%)	1 (8.3%)
2007	20 (39.2%)	10 (50.0%)	7 (35.0%)	3 (15.0%)
2008	21 (35.6%)	6 (28.6%)	6 (28.6%)	3 (14.3%)
2009	22 (37.9%)	9 (40.9%)	3 (13.6%)	1 (4.5%)
2010	28 (44.4%)	9 (32.1%)	7 (25.0%)	2 (7.1%)
2011	25 (39.7%)	7 (28.0%)	2 (8.0%)	1 (4.0%)
2012	32 (49.2%)	8 (25.0%)	12 (37.5%)	4 (12.5%)
2013	33 (52.4%)	8 (24.2%)	16 (48.5%)	5 (15.2%)
2014	20 (32.3%)	3 (15.0%)	0 (0.0%)	0 (0.0%)

As we can see, there is a constant flow of developers in and out of the top connectivity level throughout the history of Python project, especially when the community is consolidated after year 2000. Some years, such as 2000, 2002, 2007, and 2009, more than 40% of the developers on the top connectivity level are developers that have never been in that position before. If I also consider the developers that came back to the top connectivity level after being outside for more than one year as new developers, many other years see a significative renewal of the developers in the top position of the connectivity hierarchy.

The constant flow in and out of the top level of the connectivity hierarchy of the cooperation network is a key element to understand the dynamics of individual contributions to the project because even though a very big part of the contributions come from a small set of developers (the ones in the top connectivity level), these developers are not the same people throughout the history of the project. This fact sheds light over the findings of recent empirical analysis of contributions from collaborative communities (Shaw and Hill, 2014), where the authors find that only a small fraction of participants are the ones that contribute most of its contents, and they thus propose that some form of the “iron law of oligarchy” might be in play. They however do not analyze longitudinally if these people are the same throughout the history of the project. I suspect that they might not be the same people, and thus that a constant renewal of the people that contribute the most, such the one described here for the Python project, might also be in play in those projects.

6. CONNECTIVITY HIERARCHY AND INDIVIDUAL CONTRIBUTIONS

I argue that the constant flow in and out of the top level of the connectivity hierarchy of the cooperation network is what defines this hierarchy as an open elite, where the positions defined by it —the connectivity subgroups in the cooperation network in this concrete analysis— have a very high rate of turn over and renewal. Thus, in a community where most of their participants do not obtain their means of subsistence from the work that they do in the community, the rapid turn over of individuals that contribute the most is a key mechanism for ensuring the long term viability of the project beyond its original founders. Thus, this is a key mechanism that explains how large scale cooperation works, at least in FOSS projects.

A nice way to visualize the constant flow of developers to the top connectivity level is figure 6.3, which shows a Sankey diagram where each piece of the diagram represents the number of developers in the top connectivity level for a given year; the arrows that come from the top represent the number of developers who in year $y - 1$ were not at the top connectivity level but are in the top level at year y , the arrows on the bottom represent the number of developers that are in the top connectivity level at year y but not anymore in year $y + 1$. The horizontal arrow represents the number of developers that at year y are in the top connectivity level, and continue to be there at year $y + 1$. Note that in this figure I do not draw the developers that came back to the top connectivity level after being part of it other years than the immediately previous years (these numbers are reported in table 6.4).

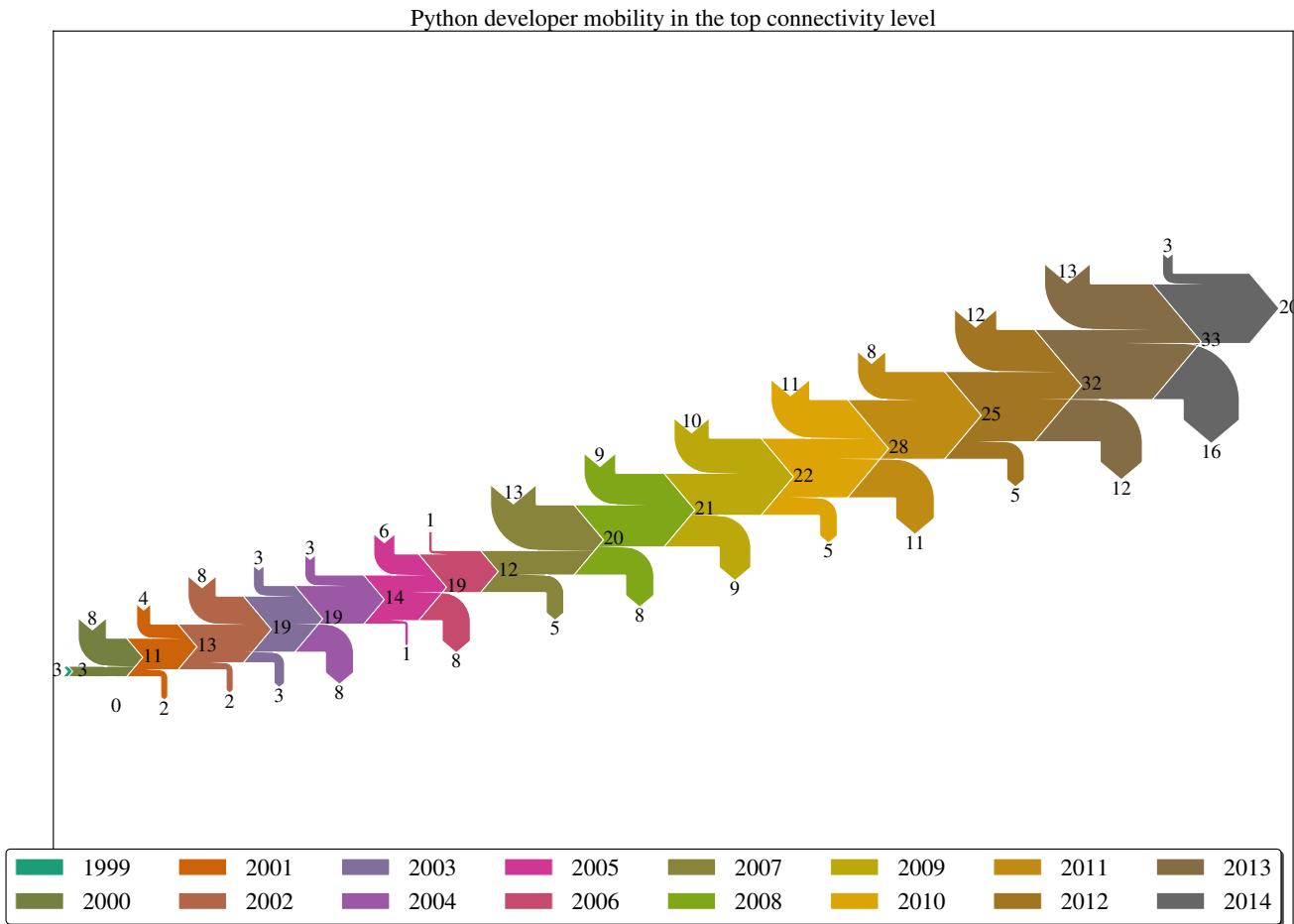


Figure 6.3: Sankey diagram of Python developer mobility in the top connectivity level. The numbers at the top are the number of new developers entering the top connectivity level, numbers inside are the number of developers at the top connectivity level, number below are the number of developers leaving the top connectivity level.

Modeling robustness as median active life of individuals in the project

In the network literature, robustness of networks is usually measured with simulations of failures (removing nodes at random) and attacks (removing nodes incrementally starting for the ones with higher degree) (Albert et al., 2000). However this is not a good way to model the evolution of participation in a FOSS project.

I use here the survival analysis approach (Miller Jr, 2011), that according to my knowledge, is the first time that is applied to model the turn over in FOSS communities. In its origin, survival analysis, was focused on modeling lifespans of individuals and is still widely used in medicine. However, this kind of analysis can also be used to model any kind of duration. Thus I model the active life of a developer in the Python project as the period that this developer is contributing at least one line of source code. I consider a developer “dead” when she no longer contributes to the project.

To estimate the survival function from the empirical data we used the Kaplan-Meier estimator (Kaplan and Meier, 1958) defined as:

$$\hat{S}(t) = \prod_{t_i < t} \frac{n_i - d_i}{n_i}$$

where d_i are the number of “death events” at time t and n_i is the number of subjects at risk of death at time t . If I compute the Kaplan-Meier estimator for all developers (figure 6.4a) we can see that the median survival time of a developer on the community, defined as the point in time where on average half of the population has abandoned the community, is 6 years. But if I consider separately the developers in the top level of the connectivity hierarchy (figure 6.4b), their median survival time is 12 years; but only 3 years for the developers that are not on the top of the connectivity hierarchy.

Although it is clear that the two survival functions depicted in figure 6.4b are different, I performed the log rank test, a common statistical test in survival analysis that compares two event series’ generators. The test confirms that that the two series have different generator mechanisms and are significantly different. The Kaplan-Meier estimator analysis and plots are performed using the lifelines python package (Davidson-Pilon, 2016).

Finally, given that we observe an important flow of new developers towards the top levels of the connectivity hierarchy; and also having established that the contributions of the developers in these top levels is significantly higher than other developers, it is interesting to analyze the personal trajectories of developers in the project. I model the active life of developers in the Python project using a Cox proportional hazards model with time-dependent covariates and right-censoring (Fox, 2002, appendix on survival analysis).

6.3. Regression modeling and mobility analysis

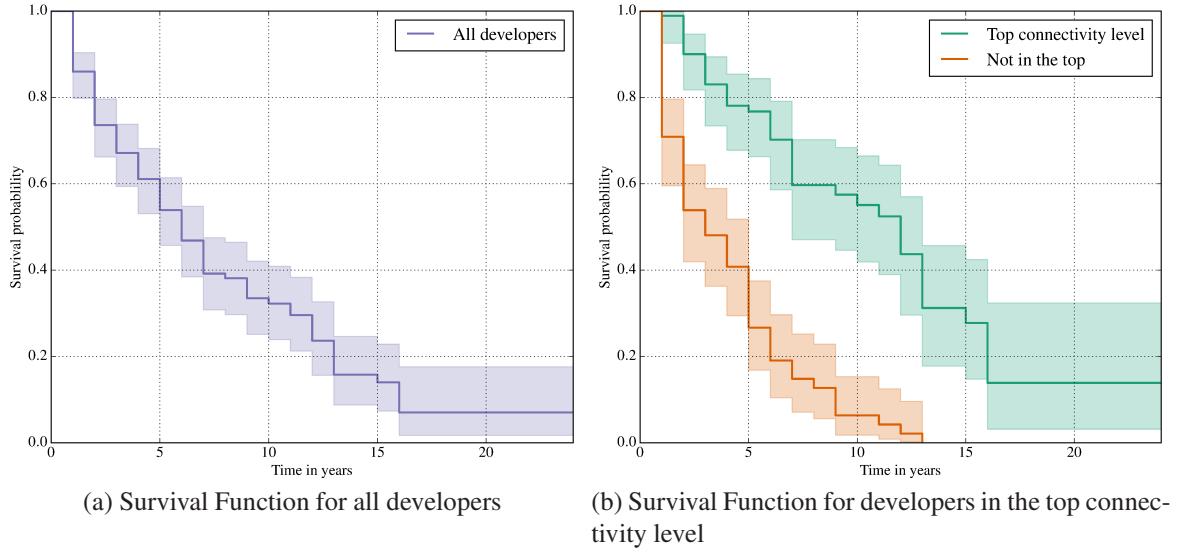


Figure 6.4: Estimation of the survival function using the Kaplan-Meier estimate. The median survival time of a developer in the community, defined as the point in time where on average half of the population has abandoned the community, is 6 years if I consider all developers (left). But if I consider separately the developers in the top level of the connectivity hierarchy (right), their median survival time is 12 years; but only 3 years for the developers that are not on the top of the connectivity hierarchy.

I'm interested in assessing the impact of being in the higher levels of the connectivity structure in terms of the expected active life of a developer in the project. The covariates in the model are: the number of accepted PEPs authored by each developer, the contributions of each developer to the Python project, measured as number of source code lines, the number of collaborators (ie second order neighbors in network terms) that each developer has in the cooperation network, the degree centrality and closeness of each developer in the cooperation network, the highest k of a k -component in which the developer is embedded, and the *Top connectivity level* dummy variable that equals to 1 if the developer is in the k -component of highest k in the cooperation network for that time period, and 0 otherwise.

In order to fit the model, I divided the data in “strata” based on the value of “tenure” covariate which reflects the time a developer has been active in the project measured in years. Each stratum is permitted to have a different baseline hazard function, while the coefficients of the remaining covariates are assumed to be constant across strata. Stratification is most natural when a covariate takes on only a few distinct values, and when the effect of the stratifying variable is not of direct interest.

Finally the estimations of the variance and standard errors of the coefficients of the covariates of interest are robust, and clustered for each developer. This is necessary because in a proportional hazards model with time-dependent covariates, each individual has more than one row in the database. Concretely, each individual has a row for each period of one year in which he or she has been an active contributor to the source code of the Python project. Tables C.7 and C.8 on appendix C show the descriptive statistics and the correlation matrix of the variables used in this model.

6. CONNECTIVITY HIERARCHY AND INDIVIDUAL CONTRIBUTIONS

Table 6.5: Survival Analysis: Cox proportional hazards regression model

	<i>Dependent variable:</i> Time active in the project			
	(1)	(2)	(3)	(4)
Total accepted PEPs	-0.118 (0.111)	-0.105 (0.114)	-0.113 (0.118)	-0.103 (0.118)
Contributions	-0.00003 (0.00003)	-0.00002 (0.00003)	-0.00003 (0.00003)	-0.00002 (0.00003)
Collaborators	-0.015 (0.008)	0.005 (0.010)	-0.012 (0.008)	0.004 (0.009)
Degree Centrality	-50.770** (15.834)	-13.886 (12.770)	-25.344 (15.175)	-6.944 (12.282)
Closeness	7.894 (5.052)	0.930 (4.741)	5.212 (4.562)	1.015 (4.353)
k-component number		-0.376*** (0.097)		-0.295** (0.101)
Top connectivity level			-1.885** (0.617)	-1.467* (0.657)
Observations	754	754	754	754
R ²	0.118	0.135	0.132	0.142
Max. Possible R ²	0.396	0.396	0.396	0.396
Log Likelihood	-142.808	-135.379	-136.915	-132.501

Note:

*p<0.05; **p<0.01; ***p<0.001

As we can see in table 6.5, the effect of being part of the top connectivity level is significant and negative with a coefficient of -1.467, meaning that it decreases the yearly hazard of leaving the project by a factor of $e^b = e^{-1.467} = 0.23$, that is, 77%. This interpretation holds assuming that all other covariates remain constant. The coefficient for k -number —the highest k of a k -component in which the developer is embedded— is also significative and negative with a coefficient of -0.295, which means that an increment of one connectivity level decreases the yearly hazard of leaving the project by a factor of $e^b = e^{-0.295} = 0.74$, that is, 26%.

It is relevant that both measures of cohesion are significative and negative when included in the same model, although the k -component number it's significative at $p < 0.01$ and being part of the top component at $p < 0.05$. When these two variables are included in the model none of the control variables is significative. I can conclude that not only being at the top connectivity level has a relevant impact on the active life of a developer in a project, but also smaller increments in cohesion of the groups in which a developer is embedded have a significant impact on their active life in the project.

6.4 Summary

In this chapter I explored the dynamic dimension of the connectivity hierarchies that emerge on the cooperation networks of the Python and Debian projects. I defined cooperation networks as the patterns of relations among developers established while contributing to the project. The dynamic analysis, in this case, is not only a longitudinal account of the changes in the hierarchy through time, but also the analysis of the pace of renewal of individuals in the positions defined by the hierarchy. I propose that organizations —and not only FOSS projects— can be classified in a continuum depending on the pace of renewal of the individuals that occupy top positions in the hierarchy.

I showed that the cohesive small world model (see chapter 3), which is partially grounded on the structural cohesion model (White and Harary, 2001; Moody and White, 2003) is a solid theoretical framework to define cohesive groups — k -components— in cooperation networks. The nested structure of k -components nicely captures the hierarchy in the patterns of relations that individual contributors establish when working together. This hierarchy, on the one hand, reflects the empirically well established fact that in FOSS projects only a small fraction of the developers account for most of the contributions. And, on the other hand, refutes the naive views of early academic accounts that characterized FOSS projects as a flat hierarchy of peers in which every individual does more or less the same.

I also showed that the position of individual developers in the connectivity hierarchy of the cooperation networks impacts significantly, on the one hand, on the volume of contributions that an individual does to the project. And, on the other hand, the median active life of developers in the project. I argue that the latter is a better way to analyze robustness of FOSS projects than the classical random and targeted attacks that has been used to asses robustness in other kinds of networks.

My main conclusion is that the connectivity structure of collaborative communities' cooperation networks can be characterized as a open elite, where the top levels of this hierarchy are filled with new individuals at a high pace. This feature is key for understanding the mechanisms and dynamics that make FOSS communities able to develop long term projects, with high individual turnover, and yet achieve high impact and coherent results. Thus, the renewal of individuals at the top levels of the connectivity hierarchy of cooperation networks is a key mechanism for enabling large scale cooperation. Therefore I can conclude that cooperation in FOSS communities has a structural dimension because membership in cohesive groups that emerge from the cooperation networks —the repeated patterns of relations that the direct producers establish in the production process— has an important and statistically significant impact on both the volume of individual contributions, and on the median active life of developers in the projects under analysis.

Part IV

Conclusion and Future Work

Conclusion and Future Work

The main objective of this thesis was to develop a theoretical framework in order to further our understanding on how large scale cooperation works in knowledge intensive production processes in the context of new organizational forms, such as FOSS projects. The central approach that guided this theory building effort on large scale cooperation is to focus on meso level social processes in order to bridge the gap between that most common approaches to cooperation in the literature: a more classical macro level approach focused on collective visions, shared values, and authority forms; and a micro level approach focused on the dynamics of individual dyadic cooperative interactions. This meso level approach is focused on the structural dimension of cooperation in the actual production processes, that is, the focus is on the patterns of relations that direct producers establish between them in knowledge intensive production processes.

Focusing on these patterns of relations, I proposed that the subgroups of individuals that are formed in cooperation networks —groups of producers that are more densely connected between them than with the rest of the network— are a key element to understand and explain how coordination problems are managed in large scale cooperation in knowledge intensive production processes with high individual turn over. The formation and dissolution of these subgroups, their high level of turnover in their individual composition, their role in shaping individual contributions to the whole production process, and their role in maintaining individuals attached to the project, are some of the elements explored in this thesis that enabled me to build a theoretical framework that bridges the gap between macro and micro levels theoretical approaches to cooperation.

I centered the development of this new theoretical framework on what I named the Cohesive Small World model. A network model grounded on two well established theoretical network models: the Small World model (Watts and Strogatz, 1998) and the Structural Cohesion model (White and Harary, 2001; Moody and White, 2003). These two models are not mutually exclusive. The family of networks that fit in the intersection of both models —what I call Cohesive Small Worlds— exhibit consistent topological patterns, that is, they have common structural patterns. These patterns, I argue, provide the scaffolding for the emergence of collaborative communities (Adler and Heckscher, 2006) and enable effective large scale cooperation.

7. CONCLUSION AND FUTURE WORK

On the one hand, the generation of trust and congruent values among heterogeneous individuals are fostered by structurally cohesive groups in the connectivity hierarchy of cooperation networks because individuals embedded in these structures are able to compare independent perspectives on each other through a variety of paths that flow through distinct sets of intermediaries, which provides multiple independent sources of information about each other. Thus, the perception of an individual embedded in such structures of the other members of the group to whom she is not directly linked is filtered by the perception of a variety of others whom she trusts because is directly linked to them. This mediated perception of the group generates trust at a global scale. On the other hand, the existence of dense local clusters connected between them by relative short paths allows successful cooperation among heterogeneous individuals with common interests and, at the same time, fosters the flow of information between these clusters preventing the local clusters to be trapped in echo chambers of like minded collaborators.

The structural approach to cooperation, and to any social process, is for me synonym of a network approach because, at its core, the network approach is a relational approach that allows a quantitative rigorous way to model patterns of relation among individuals, that is, to model social structures. And thus enables our theories and accounts of social processes to go beyond the reductionist approach to understand social interactions as pure dyadic and atomic interactions between individuals without losing the quantitative rigor usually associated with the methodological individualism approach to social interactions.

An important part of the research effort developed for this thesis has focused on the problem of how to determine cohesive subgroups in social networks as prescribed by the structural cohesion model. The problem is not new, and a lot of work has been done in this direction, but as usual in the social sciences, the methods available to researchers are far behind the theoretical insights when we want to exploit the increasing availability of data that should support the empirical work associated with the theories that we develop.

I extended theoretically the structural cohesion model by considering not only plain node connectivity, which is the minimum number of nodes that must be removed in order to disconnect a network, but also the average node connectivity of networks and its cohesive groups, which is the number of nodes that, on average, must be removed to disconnect an arbitrary pair of nodes in the network. Taking into account average connectivity allows a more granular conception of structural cohesion, and I show in the empirical analysis of cooperation networks how this approach leads to useful implications in empirical research.

I also developed heuristics to compute the k -components structure, along with the average node connectivity for each k -component, based on the fast approximation to compute node independent paths (White and Newman, 2001). These heuristics allow for the computing of the approximate value of group cohesion for moderately large networks, along with all the hierarchical structure of connectivity levels, in a reasonable time frame. I showed that these heuristics can be applied to networks at least one order of magnitude bigger than the ones manageable by the exact algorithm proposed by Moody and White (2003). To ensure reproducibility and facilitate diffusion of these heuristics I contributed an implementation of these heuristics to a popular Python software package for the analysis of complex networks: NetworkX (Hagberg et al., 2008). See appendix D for the documentation and source code at NetworkX github repository. I believe that providing detailed implementation is critical to en-

sure reproducibility, but often these details are black-boxed, some times because of proprietary software restrictions or authors' reluctance to share their work.

All these methodological efforts have paid out in theoretical terms, as I was able to test empirically the new network model that I proposed to further our understanding of how large scale cooperation works in the context of Collaborative Communities. The model that I named “Cohesive Small World” is a good fit to describe the cooperation networks —that is, the patterns of relations between direct producers— of the two big and mature FOSS projects that I have analyzed in the empirical part of this thesis: the CPython reference implementation of the Python programming language, and the Debian operating system.

The analysis presented in chapter 5 shows that the cooperation networks of both Debian and Python projects can be modeled using the proposed Cohesive Small World model. It is interesting to note that they also show significative differences because Debian cooperation networks lean more to the Small World end of the model, while Python cooperation networks lean more towards the Structural Cohesion end of the model. The difference in terms of modularity of the product that they are building—an Operating System versus a Programming language—impacts their respective production processes. Debian’s subgroups tend to work more independently from each other than Python’s subgroups, as shown by the fact that Debian cooperation networks exhibit a higher degree of smallworldiness; while Python’s networks are more structurally cohesive as shown by their sharper and steep connectivity hierarchy.

It’s necessary to note that the structural analysis presented in this thesis does not cover all the important elements needed for an in depth analysis of what enables successful cooperation in general. Things like the individual characteristics of the people that cooperate, the complementarity of their skills in relation to the task at hand, the emergence of leadership in the context of teams, are indeed also important for enabling successful cooperation. But the point that I tried to make in this thesis is that the structural dimension of cooperation is at least equally important and has been a lot less explored by theoretical accounts of cooperation.

To further the empirical analysis of this thesis, in chapter 6 I explored the dynamic dimension of the connectivity hierarchies that emerge on the cooperation networks of the Python and Debian projects. I defined cooperation networks as the patterns of relations among developers established while contributing to the project. The dynamic analysis, in this case, is not only a longitudinal account of the changes in the connectivity hierarchy through time, but also the analysis of the pace of renewal of individuals in the positions defined by this hierarchy.

I show that the Cohesive Small World model is a solid theoretical framework to define cohesive groups in cooperation networks. The nested structure of k -components nicely captures the hierarchy in the patterns of relations that individual contributors establish when working together. This hierarchy, on the one hand, reflects the empirically well established fact that in FOSS projects only a small fraction of the developers account for most of the contributions. And, on the other hand, refutes the naive views of early academic accounts that characterized FOSS projects as a flat hierarchy of peers in which every individual does more or less the same.

I also show that the position of individual developers in the connectivity hierarchy of the cooperation networks impacts significantly, on the one hand, on the volume of contributions that an individual does to the project. And, on the other hand, the median active life of an individual in the project. I argue that the latter is a better way to analyze robustness of FOSS

7. CONCLUSION AND FUTURE WORK

projects than the classical random and targeted attacks that has been used to asses robustness in other kinds of networks and that it's the standard approach to assess robustness in the network literature (Albert et al., 2000).

I argue that the connectivity structure of collaborative communities' cooperation networks can be characterized as an open elite, where the top levels of this hierarchy are filled with new individuals at a high pace. This feature is key for understanding the mechanisms and dynamics that make FOSS communities able to develop long term projects, with high individual turnover, and yet achieve high impact and coherent results as a result of large scale cooperation. Therefore, I can conclude that cooperation in FOSS communities has a structural dimension because membership in cohesive groups that emerge from the cooperation networks —the repeated patterns of relations that the direct producers establish in the production process— has an important and statistically significative impact on both the volume of individual contributions, and on the median active life of developers in the projects under analysis.

It is worth noting that the high rate of turn over in the top positions of the connectivity hierarchy of cooperation networks —which I argue is a key meso level mechanism for enabling large scale cooperation— is only possible assuming that the knowledge necessary to perform the tasks in the FOSS project is highly socialized. As I pointed out in the introduction, the concept of socialization of the production used by Marx refers to the process of replacing tacit knowledge generated by small groups in local contexts by knowledge that is explicitly codified and disseminated at a global level. In Marx's own words “only socialized labour [...] is capable of applying the general products of human development, such as mathematics, to the immediate process of production” (Marx, 1990, 1024). Therefore large scale cooperation is only possible in highly socialized production processes.

It is easier to analyze this kind of highly socialized production processes in FOSS projects than in capitalist corporations because the latter have to balance the need of enhancing large scale cooperation through knowledge socialization with the pressures of the profit imperative. In Marxian terms we could say that in FOSS projects there is no contradiction between the progressive socialization of the production and the private appropriation of the result of the production process typical of capitalist production relations. This is because the result of the production process in FOSS projects is Free Software, which as a common good is in many senses is quite similar to mathematics, and thus can be considered a general product of human development, as Marx puts it in the previous quote.

The empirical analysis presented in this thesis also sheds light over the findings of recent empirical analysis of individual contributions in Collaborative Communities (Shaw and Hill, 2014), where the authors find that only a small fraction of participants are the ones that contribute most of its contents, and they thus propose that some form of the “iron law of oligarchy” (Michels, 1915) might be in play. They however do not analyze longitudinally if these people are the same throughout the history of the project. I suspect that they might not be the same people, and thus that a constant renewal of the people that contribute the most, such the one described here for the Python project, might also be in play in those projects.

However, it is not clear that the theoretical model that I proposed fits all cooperation networks of Collaborative Communities, or even cooperation networks of all FOSS projects. Because the empirical analysis presented in this thesis was a case study of two successful

projects aimed to develop a theoretical framework, I cannot determine if other FOSS projects also fit nicely in it. Thus what I presented is more an existence proof than a empirical test of my proposed theoretical model.

The next steps in my research agenda will be to expand the kind of empirical analysis that I presented in this thesis to include both successful and unsuccessful large scale cooperation production process in order to assess up to which point the Cohesive Small World model can explain the achievements and continuity in time of FOSS projects and other Collaborative Communities.

Thus, it is necessary to include in the empirical analysis of the Cohesive Small World model other knowledge intensive production processes beyond FOSS projects in order to make sure that this model is a solid theoretical framework to explain and understand how large scale cooperation works in knowledge intensive production processes.

I'm especially interested in analyzing cooperation among scientists, but I feel that the Cohesive Small World model can also be useful to analyze any kind of large scale knowledge intensive production process with a high degree of cooperation, such as the ones that are developed inside big capitalist corporations, and on state sponsored large scale scientific and technical endeavors, such as Space exploration.

Part V

Appendices

Small worlds and affiliation networks

In order to assert that an actual network is a small-world network we should compare it against a null model. This null model is a random network with the same number of nodes and edges, but the edges assigned uniformly at random between the nodes. A small world network should be more highly clustered than its random counterpart and it should have similar short average path length. Building in this definition of smallworldiness, we can define the small world index (Q) as the division of the CC_{ratio} by the L_{ratio} (Watts, 1999a; Davis et al., 2003; Uzzi and Spiro, 2005; Uzzi et al., 2007). If $Q > 1$ we can assert that the actual network under analysis is a small world network.

$$Q = \frac{CC_{ratio}}{L_{ratio}} \quad (\text{A.1})$$

Where:

$$CC_{ratio} = \frac{CC_{actual}}{CC_{random}} \quad L_{ratio} = \frac{L_{actual}}{L_{random}} \quad (\text{A.2})$$

Affiliation networks contain two types of nodes: N actors each of which belongs to one or more groups M . Such networks are bipartite or 2-mode because they contain two types of nodes and there are no edges between nodes of same type. We can obtain an unipartite or 1-mode network—with only one type of nodes—projecting the bipartite network on the actors’ side or on the groups’ side. This projection assumes that the actors are connected if they belong to the same group and that groups are connected if they share some actor, respectively.

Their statistical properties differ from unipartite networks. As Uzzi et al. (2007, 83) point out, affiliation networks, on the one hand, have higher clustering than unipartite networks because each actor’s membership in a team makes them a fully connected clique in the one-mode projection, therefore an important part of the clustering is not due to “the friends of an actor are friends themselves” but to team topography. On the other hand, affiliation networks tend to have shorter average path lengths as the number of overlapping members between teams increase.

A. SMALL WORLDS AND AFFILIATION NETWORKS

Although a common practice, it is well documented in the literature that there is an important loss of information when we perform a 1-mode projection from a 2-mode network (Wasserman and Faust, 1994, 324-325). Our approach to analyze the structure of the production process of the FOSS projects is to focus on the topology and the connectivity of 2-mode networks. Robins and Alexander (2004) redefined clustering coefficient in order to analyze 2-mode networks of directors and firms. Their approach is based in the analysis of network configurations or motifs.



Figure A.1: Relevant motifs in two mode network in order to calculate CC_4 (Robins and Alexander, 2004, 78)

Figure A.1 depicts the two relevant motifs or configurations in order to compute the bipartite clustering coefficient (CC_4). Three-paths (L_3) are composed by four nodes —two of each type in the 2-mode network— linked by three edges. Robins and Alexander argue that the number of L_3 in 2-mode network is information lost in the 1-mode projection, they stress their importance: “three-paths are important to connectivity, potentially providing short geodesics between directors and companies of which they are *not* members. Long paths across the network of course must comprise several of these short three-paths, so we argue that the three-paths are precursors of global connectivity” (Robins and Alexander, 2004, 77-78).

Squares (C_4) are composed by four nodes —two of each type— linked by four edges. Squares are the simplest form of cycle in 2-mode networks and provide redundancy: when we perform the 1-mode projection, those four edges are represented by only one edge between the two nodes of the same type¹. Robins and Alexander (2004, 79) propose compute the bipartite clustering coefficient as depicted in equation A.3.

$$CC_4 = \frac{4 \times C_4}{L_3} \quad (\text{A.3})$$

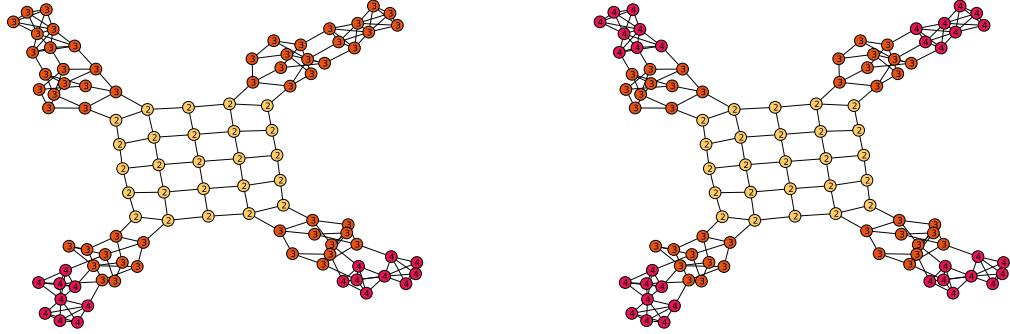
Robins and Alexander (2004, 79) argue that “high bipartite clustering indicates localized closeness and redundancy, just as is the case with triangles in 1-mode networks. [...] If the bipartite clustering coefficient is high, then many L_3 patterns are redundant. They do not provide new paths of connectivity across the bipartite graph. So for two bipartite graphs of similar size, the graph with the higher bipartite clustering ratio will show lower levels of connectivity”.

¹If the projection is weighted the value of the edge will be 2, acknowledging that the two nodes are linked to two groups in the 2-mode network.

Cohesive Subgroups: Illustration, Implementation and Accuracy

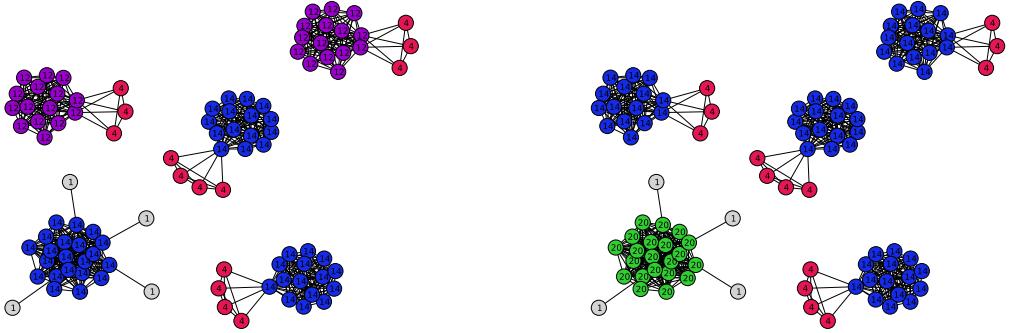
B.1 Illustration of the heuristics

In order to illustrate how the proposed heuristics works, we will use a convenient synthetic network with 99 nodes and 200 edges where $\kappa \neq \delta$. This network is based on a two dimensional grid of 5 by 5 nodes. In each corner of the grid we attach a Petersen graph (P), linked by two edges to the grid. Thus the only four nodes of the grid with degree 2 are linked to a Petersen graph. All nodes of the grid are therefore part of a 3-core. Each P is linked to two complete graphs with 5 nodes (K_5); in two cases those two K_5 overlap in only one node and in the other two cases, they overlap in two nodes. The Petersen graph is linked by three edges to one of the K_5 , thus making one of each K_5 part of a tricomponent along with P . In the case of the two K_5 that overlap only on one node, the outer K_5 has also one edge linking one of its nodes with one node of P nodes, in order to make the whole graph biconnected (see figure B.1). Petersen graphs have node connectivity 3 and complete graphs with 5 nodes have node connectivity 4. Notice that the whole example graph is biconnected and a 3-core, but it has three levels of node connectivity: 2 for the grid, 3 for the Petersen graphs (P) and 4 for the complete graphs of 5 nodes (K_5).

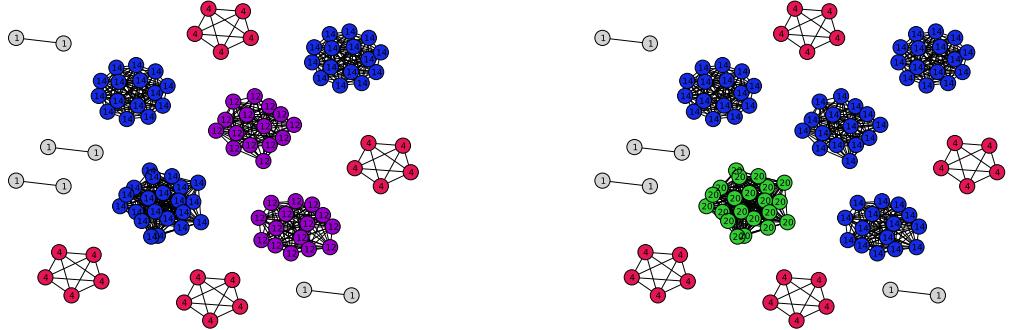


(a) Nodes colored by component number according to our algorithm. Note the error when two K_5 overlap in two nodes
 (b) Nodes colored by component number according to Moody & White algorithm.

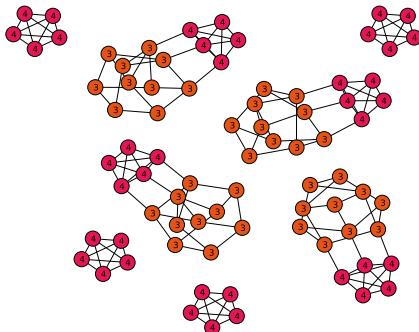
Figure B.1: Synthetic graph composed of a two dimensional grid of 25 nodes, four Petersen graphs (P) with ten nodes each (with $\kappa = 3$) linked by two edges to the grid, and eight complete graphs K_5 (with $\kappa = 4$) linked by three edges to each Petersen graph. In two cases K_5 overlap in 1 node and in the other two cases they overlap in 2 nodes. The whole graph is biconnected and also a tricore. Notice that our algorithm fails to classify the two K_5 that overlap in two nodes as 4-components. See text and figure figure B.3 for details.



(a) Auxiliary graph H for $k = 3$ computed using White & Newman's approximation algorithm for local node connectivity.
 (b) Auxiliary graph H for $k = 3$ computed using flow-based connectivity algorithm for local node connectivity.

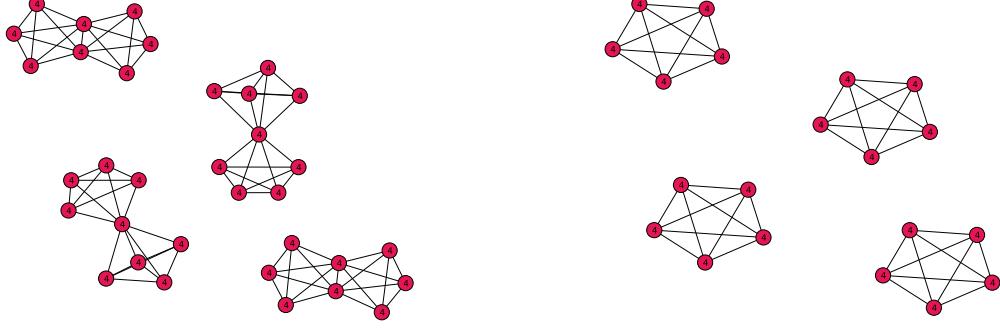


(c) All subgraphs $H_{candidate}$ from H_3 computed using White & Newman's approximation algorithm for local node connectivity.
 (d) All subgraphs $H_{candidate}$ from H_3 computed using flow-based connectivity algorithm for local node connectivity.



(e) Detected tri-components using the heuristics with the relaxation criteria of density ≥ 0.95 in $H_{candidate}$.

Figure B.2: Auxiliary graph H_3 for $k = 3$. Note that when using White and Newman's approximation algorithm for local node connectivity (subfigure a), some node independent paths are not detected: the P subgraphs linked to the two K_5 that overlap in two nodes should have core number 14 (blue) as in subfigure b, but they have core number 12. Thus to correctly detect all tricomponents we have to set a relaxation criteria for $H_{candidate}$, in this example setting density at 0.95 or allowing a variation of 2 in the degree of all nodes of $H_{candidate}$, allows the algorithm to correctly detect all tricomponents.



(a) Auxiliary graph H for $k = 4$ computed using White and Newman's approximation.

(b) Detected 4-components using our heuristics. Note that there should be four more K_5 , the ones that overlap in two nodes are not detected as 4-components. See text for an explanation.

Figure B.3: Auxiliary graph H_4 for $k = 4$. In this case both White and Newman's approximation algorithm, and the exact flow-based algorithm for local node connectivity yield equal results. Note that there should be four more K_5 in subfigure b, the ones that overlap in two nodes are not detected as 4-components. This is because, as can be seen in subfigure a, the nodes in these $H_{candidate}$ subgraphs have all the same core number, but their density is 0.67 and the difference in degree is 3. Thus, in order to detect them we would have to relax the clique criteria for $H_{candidate}$ too much, and even then we would classify both K_5 as a single 4-component, which is obviously wrong.

As discussed above, a k -core is a maximal subgraph that contains nodes of degree k or more. The core number of a node is the largest value k of a k -core containing that node. On the other hand, a k -component is a maximal subgraph that cannot be disconnected by removing less than k nodes. The component number of a node is the largest value k of a k -component containing that node.

The graph of figure B.1 is a biconnected 3-core, which means that it is a graph with minimum degree = 3 that cannot be disconnected by removing less than 2 nodes. Our algorithm starts by considering the whole graph the step 2, but in k -core subgraphs with more than one bicomponent, the following steps are performed for each bicomponent of the k -core. We will only compute up until $k = 4$ because the largest core number of a node in G is 4.

For $k = 3$ we create an auxiliary graph with all biconnected nodes with core number ≥ 3 (see figure B.2). In this case all nodes have a core number greater than or equal to 3. Thus the auxiliary graph H for $k = 3$ contains all 99 nodes. We then link two nodes in H_3 if we can find k or more node independent paths between them. As we can see, the result are five connected components, four of which correspond to each Petersen graph plus the two K_5 , while the last one corresponds to the nodes that form the grid. The later has 4 nodes that are linked by 3 node independent paths to only one node, these four nodes are the four corner nodes of the grid.

Notice that when using White and Newman's approximation algorithm for local node connectivity (subfigure B.2a), some node independent paths that actually exist are not detected:

the P subgraphs linked to the two K_5 that overlap in two nodes should have a core number of 14 (blue) because there are 3 node independent paths linking each pair of different nodes in the subgraph formed by the P and the K_5 to which it is linked through three edges, as in subfigure B.2b, which was computed using the exact flow-based algorithm for local node connectivity. Notice also that the grid has core number 14 in B.2a but actually should be core number 20 as shown in B.2b. This illustrates the importance of computing biconnected components of H (step 3.c) before building the subgraphs $H_{candidate}$ (step 3.d).

Figures B.2c and B.2d depict $H_{candidate}$ subgraphs, the former using White and Newman's approximation algorithm and the latter using an exact flow-based algorithm for local node connectivity. The subgraphs $H_{candidate}$ are composed by nodes that are in the same biconnected component of H and have *exactly* the same core number. Notice that in figure B.2c the P graphs linked to the two K_5 that overlap in two nodes have core number $< n - 1$ (the magenta clusters), thus they are not complete (density=0.96) and the degree of their nodes is not homogeneous: two nodes have degree 12, four have degree 13, and nine have degree 14. Therefore, if we enforce the clique criteria for $H_{candidate}$ we would not detect all tricomponents because, following the algorithm, we would have to start removing nodes with the lowest degree and check if at some point we find a complete subgraph. In order to correctly detect all tricomponents in this illustrative example, we have to first establish a relaxation for the clique criteria for $H_{candidate}$. In this case, setting density at 0.95 or allowing a variation of 2 in the degree of all nodes of $H_{candidate}$, allows the algorithm to correctly detect all tricomponents as shown in figure B.2e.

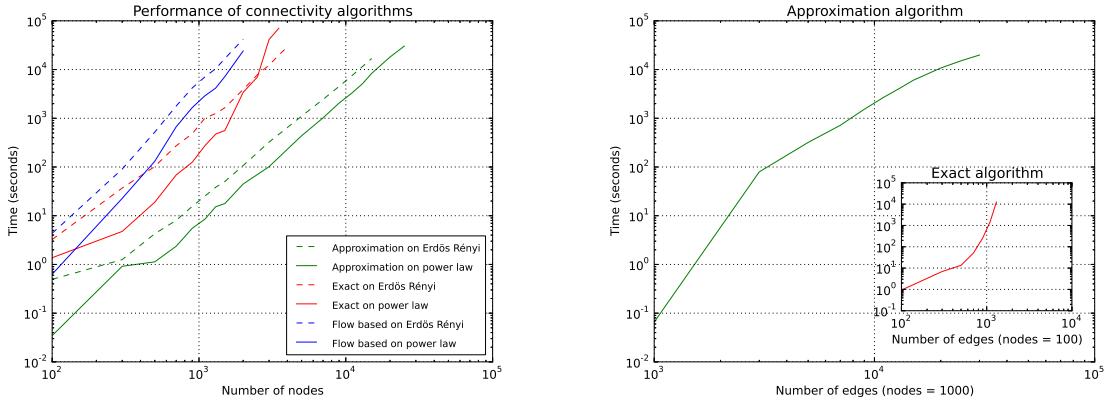
For $k = 4$, the auxiliary graph H_4 is composed of 4 connected components which correspond to the pairs of K_5 that share one node and the pairs of K_5 that share 2 nodes (see figure B.3a). In terms of biconnectivity, there are six bicomponents, with the two K_5 that overlap in two nodes as a single bicomponent. Inside these six bicomponents there are eight 4-components, but only four of them were detected (see figure B.3b). This is because when we build the $H_{candidate}$ subgraphs with all nodes in each biconnected component of H_4 that have exactly the same core number, in the case of the two K_5 that overlap in two nodes, all their nodes have the same core number (4), but their density is 0.67 and the difference in degree is 3. Thus, in order to detect them we would have to relax the clique criteria for $H_{candidate}$ too much, and even then, we would classify both K_5 overlapping in two nodes as a single 4-component, which is obviously wrong because they have node connectivity 2.

Note that this kind of false negative only happens when two k -components of the same level of connectivity and the same order overlap. If instead of two K_5 they were k -components with different order but the same connectivity, our algorithm would be able to separate them because they would have a different core number and thus they would be part of a different $H_{candidate}$ subgraph.

B.2 Performance analysis

The heuristics presented here are implemented on top of NetworkX (Hagberg et al., 2008), a library for the analysis of complex networks, using the Python programming language (Van Rossum, 1995). We have chosen Python because it is a language with high readability and flexibility that allows you to easily apply the well known principle of writing software for people to read and, only incidentally, for machines to execute (Abelson et al., 1985). To ensure reproducibility and accessibility we have used only free software to build and run all analyses presented in this paper.

The implementation of the heuristics presented here is not trivial; a careful implementation is needed to ensure that it has a reasonable memory footprint and that it runs in a reasonable time. Appendix C contains a detailed discussion of the implementation details and appendix D contains the python code of a simplified implementation for illustrative purposes.



(a) Performance of connectivity algorithms when adding nodes maintaining constant the average degree (Erdős-Rényi) or the exponent of the power law governing the degree distribution ($\alpha = 2$). Logarithmic scale.
 (b) Performance of the heuristics when adding edges and maintaining nodes constant (1000 nodes). Inset: performance of the exact algorithm with one order of magnitude fewer nodes (100 nodes). Both in logarithmic scale.

Figure B.4: Log-log plots for comparing between the heuristics and the exact algorithm to compute k -component structure. In this comparison, the heuristics do not compute the average node connectivity, only plain node connectivity, which is what is calculated by the exact algorithm. We have also implemented the exact algorithm in order to be able to compare both algorithms using the same language and infrastructure. All figures presented here were obtained running PyPy (Bolz et al., 2009). Using the heuristics proposed in this paper, we are able to handle networks almost one order of magnitude bigger than with the exact algorithm.

Figure B.4 presents the performance of the heuristics (green) compared with two variants of the exact algorithm: the Moody & White algorithm based on k -cutsets (red) and our algorithm using exact flow-based node connectivity for building the auxiliary graph. The tests were performed, on the one hand, on random graphs with fixed average degree (Erdős-Renyi model) and fixed power law exponent (Power law model) of several different orders. And, on the other hand, for graphs with a fixed number of nodes (1000 for the heuristics and 100 for

the exact) where we increase the number of edges. Random networks built using the Erdős-Renyi model have a flat hierarchical structure because edges are evenly distributed across all nodes of the network. The Erdős-Renyi graphs used in this benchmark have a big tricomponent and no higher connectivity levels. Random networks built using a power law based degree distribution have a steep hierarchical structure, the networks used in the benchmark have hierarchy levels of up to 20. Both the heuristics and the exact algorithms perform better in sparse networks with a steep hierarchical structure.

As we can see in figure B.4 the heuristics runs in polynomial time. It is fast enough to be practically applicable to networks with a few tens of thousands of nodes and edges. This is one order of magnitude better than the exact algorithm proposed by Moody and White (2003), and also an order of magnitude faster than using flow-based algorithms for building the auxiliary graph. Notice that the k -cutset based algorithm proposed by Moody & White (or at least our implementation) is faster than the exact flow-based local node connectivity variant of our algorithm.

The implementation that we provide in this paper only considers the exact solution for biconnected components. The heuristics presented here uses biconnectivity, but can be improved by using a triconnectivity algorithm. It would be: a) faster because there is a linear algorithm to compute triconnected components (Hopcroft and Tarjan, 1974; Gutwenger and Mutzel, 2001); and, b) more accurate, because we compute the exact solution up to $k = 3$. But, as far as we know, there is no publicly available implementation of triconnected components. An optimal implementation of the heuristics presented here would have to incorporate the triconnectivity algorithm to improve its accuracy and to allow it to run in reasonable time on somewhat larger networks.

B.3 Implementation details

The implementation of the heuristics proposed here was done by the first author listed on the NetworkX python library (Hagberg et al., 2008), a Python package for the study of the structure and dynamics of complex networks. Other parts of the powerful Python (Van Rossum, 1995) scientific computing stack (Jones et al., 2001; Pérez and Granger, 2007; Hunter, 2007) were also essential. The main requirement was that the whole software stack must be free software in order to avoid the black box effect of software solutions that do not release their source code. We believe that this is a necessary condition for ensuring the reproducibility of scientific research. Appendix B contains python code for the main part of the algorithm.

The implementation of the heuristics is not trivial. There are a few questions that need to be addressed in order to obtain a performance —both in terms of computation time and memory consumption— that will allow for these heuristics to be applied to large networks. The authors are in-debted to Aric Hagberg and Dan Schult (developers of the NetworkX package) for their help in this implementation.

The second step of the heuristics (compute the biconnected components of the input graph and use them as a baseline for k -components with $k > 2$) is faster than using the logic of the heuristics for $k = 2$. Biconnected components computation runs in linear time in respect to the number of nodes and edges (Tarjan, 1972). Besides in large networks, bicomponents are formed by an important part of the nodes of the network. Thus if we use the approximation logic to compute them, the memory footprint for large networks is too large to be practical. The implementation provided with this paper only computes the exact solution for bicomponents but there is also a linear algorithm to compute triconnected components (Hopcroft and Tarjan, 1974; Gutwenger and Mutzel, 2001). The heuristics would be even faster if we applied the approach used for bicomponents to that of tricomponents. But the implementation of triconnectivity is quite challenging and, to our knowledge, there is no implementation of triconnected components in free network analysis software packages.

The auxiliary graph H is usually very dense in real world networks because a large part of nodes that are in a biconnected part of a k -core are actually part of a k -component. The memory footprint of creating this dense auxiliary graph prevents a naive implementation of the heuristics in order to be practical for large networks. Our solution for this problem is to use a complement graph data structure that only stores information on the edges that are *not* present in the actual auxiliary graph. When applying algorithms to this complement graph data structure, it behaves as if it were the dense version. This is the only way to have a memory footprint that will allow for the application of the heuristics presented in this paper to large networks.

B.4 Python code

We provide a git repository with all the data, code, results, and other materials related to this paper at https://github.com/jtorrents/structural_cohesion.

We also contributed our implementation of the exact algorithm for finding k -components, and the heuristics that we propose here, to NetworkX a free software Python package for the analysis of complex networks. The relevant code and documentation can be found at:

- Kanevsky's algorithm for finding all minimum-size node cut-sets:

docs: http://networkx.readthedocs.org/en/latest/reference/generated/networkx.algorithms.connectivity.kcutsets.all_node_cuts.html

code: <https://github.com/networkx/networkx/blob/master/networkx/algorithms/connectivity/kcutsets.py>

- Moody and White exact algorithm:

docs: http://networkx.readthedocs.org/en/latest/reference/generated/networkx.algorithms.connectivity.kcomponents.k_components.html

code: <https://github.com/networkx/networkx/blob/master/networkx/algorithms/connectivity/kcomponents.py>

- White and Newman approximation for node connectivity:

docs: http://networkx.readthedocs.org/en/latest/reference/generated/networkx.algorithms.approximation.connectivity.node_connectivity.html

code: <https://github.com/networkx/networkx/blob/master/networkx/algorithms/approximation/connectivity.py>

- Our heuristics for computing k -components:

docs: http://networkx.readthedocs.org/en/latest/reference/generated/networkx.algorithms.approximation.kcomponents.k_components.html

code: <https://github.com/networkx/networkx/blob/master/networkx/algorithms/approximation/kcomponents.py>

We also add here a simplified implementation of the heuristics for illustrative purposes.

```

1 # Standard python libraries
2 import itertools
3 import collections
4 # NetworkX library for network analysis
5 import networkx as nx
6 # AntiGraph data structure
7 # see https://github.com/networkx/networkx/blob/master/examples/subclass/antigraph.py
8
9 def k_components(G, average=True, exact=False, min_density=0.95):
10     # Dictionary with connectivity level (k) as keys and a list of
11     # sets of nodes that form a k-component as values
12     k_components = collections.defaultdict(list)
13     # make a few functions local for speed
14     node_connectivity = local_node_connectivity
15     k_core = nx.k_core
16     core_number = nx.core_number
17     biconnected_components = nx.biconnected_components
18     density = nx.density
19     combinations = itertools.combinations
20     # Exact solution for k = {1,2}
21     # There is a linear time algorithm for triconnectivity, if we had an
22     # implementation available we could start from k = 4.
23     for component in nx.connected_components(G):
24         # isolated nodes have connectivity 0
25         comp = set(component)
26         if len(comp) > 1:
27             k_components[1].append(comp)
28     for bicomponent in nx.biconnected_components(G):
29         # avoid considering dyads as bicomponents
30         bicomp = set(bicomponent)
31         if len(bicomp) > 2:
32             k_components[2].append(bicomp)
33     # There is no k-component of k > maximum core number
34     # \kappa(G) <= \lambda(G) <= \delta(G)
35     g_cnumber = core_number(G)
36     max_core = max(g_cnumber.values())
37     for k in range(3, max_core + 1):
38         C = k_core(G, k, core_number=g_cnumber)
39         for nodes in biconnected_components(C):
40             # Build a subgraph SG induced by the nodes that are part of
41             # each biconnected component of the k-core subgraph C.
42             if len(nodes) < k:
43                 continue
44             SG = G.subgraph(nodes)
45             # Build auxiliary graph
46             H = _AntiGraph()
47             H.add_nodes_from(SG.nodes())
48             for u,v in combinations(SG, 2):
49                 K = node_connectivity(SG, u, v, cutoff=k)
50                 if k > K:
51                     H.add_edge(u,v)
52             for h_nodes in biconnected_components(H):
53                 if len(h_nodes) <= k:
54                     continue
55                 SH = H.subgraph(h_nodes)
56                 for Gc in _cliques_heuristic(SG, SH, k, min_density):
57                     for k_nodes in biconnected_components(Gc):
58                         Gk = nx.k_core(SG.subgraph(k_nodes), k)
59                         if len(Gk) <= k:
60                             continue
61                         k_components[k].append(set(Gk))
62
63     return k_components

```

```

64
65 def _cliques_heuristic(G, H, k, min_density):
66     h_cnumber = nx.core_number(H)
67     for i, c_value in enumerate(sorted(set(h_cnumber.values()), reverse=True)):
68         cands = set(n for n, c in h_cnumber.items() if c == c_value)
69         # Skip checking for overlap for the highest core value
70         if i == 0:
71             overlap = False
72         else:
73             overlap = set.intersection(*[
74                 set(x for x in H[n] if x not in cands)
75                 for n in cands])
76         if overlap and len(overlap) < k:
77             SH = H.subgraph(cands | overlap)
78         else:
79             SH = H.subgraph(cands)
80             sh_cnumber = nx.core_number(SH)
81             SG = nx.k_core(G.subgraph(SH), k)
82             while not (_same(sh_cnumber) and nx.density(SH) >= min_density):
83                 SH = H.subgraph(SG)
84                 if len(SH) <= k:
85                     break
86                 sh_cnumber = nx.core_number(SH)
87                 sh_deg = dict(SH.degree())
88                 min_deg = min(sh_deg.values())
89                 SH.remove_nodes_from(n for n, d in sh_deg.items() if d == min_deg)
90                 SG = nx.k_core(G.subgraph(SH), k)
91             else:
92                 yield SG

```

B.5 Accuracy and limitations of the heuristics

Figure B.5 shows the accuracy of connectivity structure detected by the heuristics for all empirical networks. In the subfigures, green bars are k -components with node connectivity $\geq k$ and red bars represent k -components with node connectivity $< k$. Note that, once we have an approximate structure of k -components, we can check—in a reasonable time frame—if the resulting k -components actually have node connectivity k using flow based connectivity algorithms (Brandes and Erlebach, 2005, chapter 7). For the candidate k -components that turned out to have node connectivity lower than k , we used the exact algorithm proposed by Moody and White (2003) to find out the order and size of the actual k -components inside the candidate k -component detected using our heuristics.

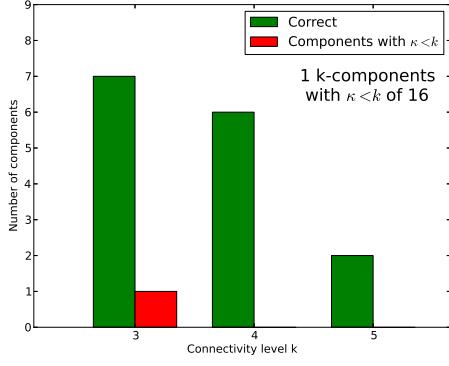
The output of our heuristics is an approximation to k -components based on computing extra-cohesive blocks for each biconnected component of all core levels of the network. Recall that in k -components all k node independent paths go through nodes that belong to the k -component, but in extra-cohesive blocks some of the node independent paths may go through external nodes. Thus, there is no guarantee that the extra-cohesive blocks, even those that also form a k -core subgraph in G , have node connectivity $\kappa = k$. This is a source of false positives for the approximation of the k -component structure of a network. However, the results shown in figure B.5 suggest that the heuristics yield a good approximation for the actual — k -component based— cohesion structure of empirical networks.

If we consider all components of all sizes, as in figure B.5, only a few of the extra-cohesive blocks detected by the heuristics have node connectivity of less than k , ranging from 6.5% (a single component) in the case of Debian to 1.2% of the components in the case of two-mode Nuclear Theory network. However, the extra-cohesive blocks that do not have the sufficient connectivity to be considered a k -component are, in the empirical networks analyzed, big components of levels {3,4}. This is because, in such big- and low-level components, a few node independent paths going through nodes that are part of the biconnected component of a k -core but not part of the k -component can yield false positives by including nodes that shouldn't be part of the k -component.

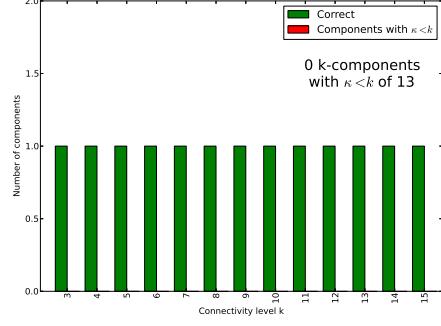
However, these false positives are actually part of an extra-cohesive block, which maintains most of those properties—in terms of robustness, hierarchy and overlap—which make k -component such a good measure of structural cohesion. This relaxed definition of connectivity might be sufficient in many cases; for instance, if we are interested in comparing the structural cohesion of a large network with a suitable null model, we may not need the exact k -component structure because we can meaningfully compare the relaxed connectivity structure of the actual network with its random counterparts. However, imagine we are interested in the exact k -component structure of a particular network because, say, we want to statistically analyze the impact of the connectivity level with the performance of different actors in a network. In this case, we would need to apply some cutting procedure on the extra-cohesive blocks that actually have a node connectivity of less than k .

It is more difficult to assess the impact of false negatives—that is, nodes that should be part of a k -component but are excluded—because computing exact k -components for big networks is not practical, and thus we cannot compare. False negatives are derived from the underestimation of local node connectivity of the White and Newman (2001) algorithm, which

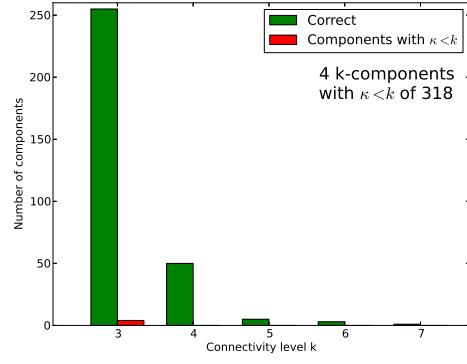
B.5. Accuracy and limitations of the heuristics



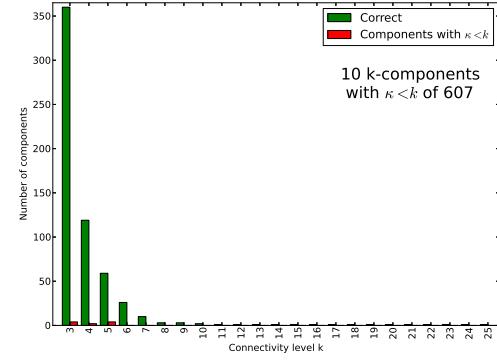
(a) Bipartite network formed by developers and packages over 2 years of collaboration (from 2007 to 2009) on the release codenamed Lenny of the Debian operating system



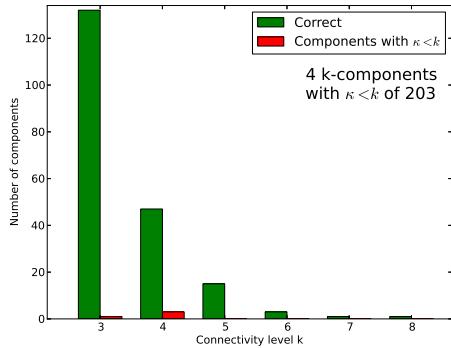
(b) Unipartite network formed by developers over 2 years of collaboration (from 2007 to 2009) on the release codenamed Lenny of the Debian operating system



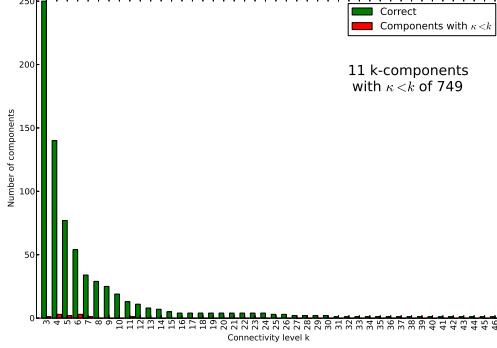
(c) Bipartite network formed by scientists and preprints during a five-year period (2006-2010) in the high energy physics (theory) section of arXiv.org



(d) Unipartite network formed by scientists during a five-year period (2006-2010) in the high energy physics (theory) section of arXiv.org



(e) Bipartite network formed by scientists and preprints during a five-year period (2006-2010) in the high energy physics (theory) section of arXiv.org



(f) Unipartite network formed by scientists during a five-year period (2006-2010) in the nuclear theory section of arXiv.org

Figure B.5: Accuracy barplots. Green bars are k -components with node connectivity $\geq k$ and red bars represent k -components with node connectivity $< k$.

provides a strict lower bound for the local node connectivity. Thus, by using it we can miss an edge in the auxiliary graph H that should be there. Therefore, a node belonging to a k -component could be excluded by the algorithm. Recall that in order to address this problem, we relaxed the clique criteria by setting a density threshold of 0.95 in $H_{candidate}$. Whilst this value has worked well in our analysis but careful experimentation should be performed to set this parameter in other types of networks.

Support Tables for Regression Models

C.1 Negative Binomial Regression support tables

Table C.1: Descriptive statistics for negative binomial regression for Debian

	Observations	Mean	Std. Dev.	Minimum	Maximum
(1) # of uploads	1,754	57.70	148.27	1	2,793
(2) Package Size	1,750	13.52	1.83	7.88	18.57
(3) # bugs reported	1,754	7.60	18.66	0	519.25
(4) # of package dependencies	1,754	6.44	4.87	0	52
(5) Developer tenure (years)	1,754	5.02	4.34	0	14
(6) Degree centrality	1,754	0.01	0.04	0	1
(7) Closeness	1,754	0.14	0.15	0.04	0.58
(8) Square clustering	1,754	0.19	0.33	0	1
(9) k-component number	1,754	1.77	0.91	1	6

C. SUPPORT TABLES FOR REGRESSION MODELS

Table C.2: Correlation matrix for negative binomial regression for Debian

	1	2	3	4	5	6	7	8
(1) # of uploads	—	—	—	—	—	—	—	—
(2) Package Size	0.138	—	—	—	—	—	—	—
(3) # bugs reported	0.000	0.204	—	—	—	—	—	—
(4) # of package dependencies	0.046	0.416	0.223	—	—	—	—	—
(5) Developer tenure (years)	0.161	0.148	0.114	-0.018	—	—	—	—
(6) Degree centrality	0.865	0.074	-0.029	0.012	0.096	—	—	—
(7) Closeness	-0.034	-0.027	-0.024	-0.092	0.401	-0.047	—	—
(8) Square clustering	-0.006	-0.027	-0.062	-0.022	-0.164	0.020	-0.209	—
(9) k-component number	0.488	0.204	0.031	0.108	0.047	0.479	-0.259	0.309

C.2 Contributions Panel Regression support tables

Table C.3: Descriptive statistics for contributions panel regression for Python.

	Observations	Mean	Std. Dev.	Minimum	Maximum
(1) # of lines of code authored	816	20816.20	69885.12	4	1,362,829
(2) Degree Centrality	816	0.07	0.15	0	1
(3) Tenure (years)	816	4.80	3.91	1	23
(4) Collaborators	816	34.02	19.28	0	61
(5) Closeness	816	0.31	0.11	0.11	1
(6) Square clustering	816	0.30	0.27	0	1
(7) Top connectivity level	816	0.41	0.49	0	1
(8) k-component number	816	5.43	2.63	1	10

C.3. Accepted PEPs zero inflated negative binomial support tables

Table C.4: Correlation matrix for contributions panel regression for Python.

	1	2	3	4	5	6	7
(1) # of lines of code authored	–	–	–	–	–	–	–
(2) Degree Centrality	0.563	–	–	–	–	–	–
(3) Tenure (years)	0.048	0.050	–	–	–	–	–
(4) Collaborators	0.107	0.005	0.210	–	–	–	–
(5) Closeness	0.287	0.459	-0.016	-0.033	–	–	–
(6) Square clustering	-0.053	-0.006	-0.091	-0.227	0.046	–	–
(7) Top connectivity level	0.269	0.446	0.014	0.347	0.120	-0.192	–
(8) k-component number	0.211	0.236	0.059	0.636	0.158	-0.262	0.653

C.3 Accepted PEPs zero inflated negative binomial support tables

Table C.5: Descriptive statistics for accepted PEPs from Python developers.

	Observations	Mean	Std. Dev.	Minimum	Maximum
(1) Total accepted PEPs	816	1.64	3.83	0	28
(2) # of lines of code authored	816	20816.20	69885.12	4	1,362,829
(3) Degree Centrality	816	0.07	0.15	0	1
(4) Tenure (years)	816	4.80	3.91	1	23
(5) Collaborators	816	34.02	19.28	0	61
(6) Closeness	816	0.31	0.11	0.11	1
(7) Square clustering	816	0.30	0.27	0	1
(8) Top connectivity level	816	0.41	0.49	0	1
(9) k-component number	816	5.43	2.63	1	10

C. SUPPORT TABLES FOR REGRESSION MODELS

Table C.6: Correlation matrix for accepted PEPs from Python developers.

	1	2	3	4	5	6	7	8
(1) Total accepted PEPs	—	—	—	—	—	—	—	—
(2) # of lines of code authored	0.064	—	—	—	—	—	—	—
(3) Degree Centrality	0.087	0.563	—	—	—	—	—	—
(4) Tenure (years)	0.592	0.048	0.050	—	—	—	—	—
(5) Collaborators	0.199	0.107	0.005	0.210	—	—	—	—
(6) Closeness	0.019	0.287	0.459	-0.016	-0.033	—	—	—
(7) Square clustering	-0.084	-0.053	-0.006	-0.091	-0.227	0.046	—	—
(8) Top connectivity level	0.143	0.269	0.446	0.014	0.347	0.120	-0.192	—
(9) k-component number	0.177	0.211	0.236	0.059	0.636	0.158	-0.262	0.653

C.4 Survival Regression support tables

Table C.7: Descriptive statistics for survival regression for the Python project.

	Observations	Mean	Std. Dev.	Minimum	Maximum
(1) Total accepted PEPs	754	1.58	3.72	0	27
(2) # of lines of code authored	754	21643.42	72362.51	4	1,362,829
(3) Tenure (years)	754	4.71	3.86	1	23
(4) Degree centrality	754	0.07	0.15	0	1
(5) Collaborators	754	32.84	19.12	0	61
(6) Closeness	754	0.10	0.22	0	1
(7) Square clustering	754	0.30	0.27	0	1
(8) k-component number	754	5.46	2.68	1	10
(9) Top connectivity level	754	0.42	0.49	0	1

C.4. Survival Regression support tables

Table C.8: Correlation matrix for survival regression for the Python project.

	1	2	3	4	5	6	7	8
(1) Total accepted PEPs	–	–	–	–	–	–	–	–
(2) # of lines of code authored	0.069	–	–	–	–	–	–	–
(3) Tenure (years)	0.589	0.060	–	–	–	–	–	–
(4) Degree centrality	0.095	0.561	0.082	–	–	–	–	–
(5) Collaborators	0.196	0.118	0.196	0.013	–	–	–	–
(6) Closeness	0.097	0.535	0.101	0.852	0.134	–	–	–
(7) Square clustering	-0.082	-0.051	-0.099	0.003	-0.247	-0.104	–	–
(8) k-component number	0.182	0.208	0.063	0.228	0.665	0.221	-0.251	–
(9) Top connectivity level	0.149	0.270	0.033	0.444	0.368	0.459	-0.178	0.651

Publications derived from my work on this thesis

Brief overview of the outcomes published from this thesis.

D.1 Algorithms and heuristics for graph connectivity as Free Software

The implementation of node and edge connectivity algorithms, and the design and implementation of heuristics for approximation to node connectivity and k -component structure that I developed during these years, have turned out to be a central part of my thesis. All these implementations are now part of the official NetworkX (Hagberg et al., 2008), a popular free Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks. They were published in NetworkX version 1.10, released August, 2nd 2015.

The algorithms and heuristics that I developed as part of my thesis that are now included in NetworkX are:

Exact node and edge connectivity Maximum flow based implementation of node and edge connectivity:

- http://networkx.readthedocs.io/en/stable/reference/generated/networkx.algorithms.connectivity.connectivity.node_connectivity.html
- http://networkx.readthedocs.io/en/stable/reference/generated/networkx.algorithms.connectivity.connectivity.edge_connectivity.html

Exact all minimum size k -cutsets Kanevsky's algorithm for finding all minimum-size node cut-sets of an undirected graph G (Kanevsky, 1993):

- http://networkx.readthedocs.io/en/stable/reference/generated/networkx.algorithms.connectivity.kcutsets.all_node_cuts.html

Exact k -component structure Moody and White exact algorithm for k -components (Moody and White, 2003):

- http://networkx.readthedocs.io/en/stable/reference/generated/networkx.algorithms.connectivity.kcomponents.k_components.html

Approximation for node connectivity White and Newman fast approximation algorithm for finding node independent paths (White and Newman, 2001):

- http://networkx.readthedocs.io/en/stable/reference/generated/networkx.algorithms.approximation.connectivity.node_connectivity.html

Approximation for k -components The heuristics that I developed for a fast approximation to the k -component structure (Torrents and Ferraro, 2015; Torrents, 2015).

- http://networkx.readthedocs.io/en/stable/reference/generated/networkx.algorithms.approximation.kcomponents.k_components.html

My work on this front has taken quite more time and energy than initially planned, as now I'm also the maintainer of part of NetworkX and have to fix the problems that users find when using the software. So far I had to deal with several problems that arose from use cases that were far from my use in the thesis. Having people using the software for other purposes than analyzing collaboration networks provided an opportunity to improve the implementation of several parts of these algorithms making them more robust and generally applicable to many kinds of problems.

It is usually not considered academic work to develop software tools that implement the analysis on which empirical research is built. This is, I think, a bad practice, and something that is slowly changing. An essential element of scientific research is reproducibility, and the only way to incorporate reproducibility in the empirical analysis is not only to publish the data on which the analysis is based, but also to have tools that actually implement the analysis that can be audited, modified and shared freely (Ince et al., 2012).

D.2 Conference presentation and paper at the 14th Python in Science Conference (SciPy2015)

My work on the free software package NetworkX has allowed me to be selected as a sponsored student at the Python in Science Conference that is held every year at the University of Texas at Austin for several years: 2011, 2012, and 2015. These last year, July 2015, I presented a conference communication, and published a paper in the conference proceedings (Torrents, 2015). There is a video of the presentation, along with the full text pdf of the paper, in the official web site of the proceedings: http://conference.scipy.org/proceedings/scipy2015/jordi_torrents.html.

I also attach the accepted paper in the conference cited above as a companion of this report, the title of the paper is: “*Structural Cohesion: Visualization and Heuristics for Fast Computation with NetworkX and matplotlib*”. The peer review process of this paper has been quite challenging as it was reviewed by scientists not familiar with the social sciences. The Scipy proceedings have as intended audience scientists from any discipline that uses computation as a central part of their research. Thus the papers and the presentations in the scipy conference have to be accessible to scientists not familiar with the discipline of the author of the paper.

Most scientists that attend the scipy conference are from the Natural sciences disciplines, and the reviewers of my proceedings paper had also this background. This made adapting the paper to the intended audience quite hard and time consuming, as I had to rewrite many parts

of my original submission (which was already adapted from my work on the thesis) to meet the criteria of the reviewers.

I think that this work has been beneficial because it made my contribution more accessible to the audience of a scientific computing conference, which is highly interdisciplinary. The presentation was also a challenge for me as I had to deliver it in a very big room filled with hundred of scientists from other disciplines. I received positive feedback from the attendees to my presentation, and in the following months I received several emails from different people that attended the conference, or read the paper in the proceedings, asking for clarifications or related material to my work. Thus, I think that all the time and energy spent in making my research accessible for a wider interdisciplinary audience has been worth.

D.3 Paper at Journal for Social Structure (JoSS)

In December 2015 it was published a more sociological motivated version of the methodological work for my thesis at the Journal of Social Structure (JoSS), an electronic journal of the International Network for Social Network Analysis (INSNA) hosted by the library of Carnegie Mellon University. The current editor is James Moody (Professor of Sociology at Duke University). The title of the paper is “*Structural Cohesion: Visualization and Heuristics for Fast Computation*” (Torrents and Ferraro, 2015). This paper is also attached as a companion of this report.

Publishing this paper has also required more time and energy than initially planned. I submitted the first version of this paper to another journal, Social Networks, in late 2012. After two revisions the paper was finally rejected by the editor, despite the positive reviews of two of the three reviewers involved in the process. All this process took two years, and despite the rejection, the comments of the reviewers at Social Networks helped greatly to improve the paper.

Early 2015 I submitted the paper to the Journal of Social Structure, the paper was accepted after one round of review conditional on some minor modifications, which also improved the paper further, and took more time than expected. The paper was finally published on December 2015. The initial version of the paper, as submitted to Social Networks in late 2012 was significantly longer than the version finally published at JoSS.

I argue that these groups are a key element of the structural dimension of cooperation. That is, the kind of patterns of relations between the individual producers in a collaboration network, and their evolution through time, that foster the development of cooperation in knowledge intensive tasks, and allow projects such as Debian or Python to produce world class technological artifacts, such as an operating system or a programming language, by organizing voluntary work of hundreds of individuals that communicate mostly through the Internet.

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