

The Structural Dimension of Cooperation

Cooperation Networks as Cohesive Small Worlds
PhD Thesis Defense

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Large Scale Cooperation

The last half of twentieth century has witnessed a key shift in knowledge intensive production processes.

The rising importance of collective research and cooperation (Wuchty et al., 2007)

- During most of the last century important papers or inventions were mostly developed by a single author
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Socialization concept drawn from the Marxian tradition (Adler, 2007)

- In Political Science: transfer of ownership from the private to the public sphere.
- In Psychology: process whereby people new to a culture internalize its knowledge, norms and values.
- Marx's use was broader than either and encompasses both:

The [...] 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; [...]). (Marx, 1990, 1024)

The Structural Dimension of Cooperation

└ Large Scale Cooperation

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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 are mostly created by teams in 2000s.

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Macro level approach

Cooperation as a macro level phenomenon in which the center of analysis is the collective or group (Marx, 1990; Adler and Heckscher, 2006; Adler, 2015).

- Focus on large organizations and groups: Collaborative Communities
 - Shared values and goals
 - Generalized trust
 - Authority forms

Theoretical Approaches to Cooperation

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Cooperation as a micro level phenomenon in which the center of analysis is the dyad (Axelrod and Hamilton, 1981; Watts, 1999; Eguíluz et al., 2005).

- Reductionist approach: Cooperation as an atomic process.
 - Strategic dyadic interactions.
 - Agent-based models.
 - Payoffs of different strategies.

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A Meso level approach to Cooperation

Focus on Cooperation networks: patterns of relations that direct producers establish in the production process.

- Structural approach, that is, a network approach.
 - Sub-groups that are more connected internally than with the rest of the network.
 - Longitudinal analysis of the formation and dissolution of these groups.
 - Key mechanisms to explain and understand large scale cooperation.

Main Topic and Research Question

The central topic of this thesis is to understand and explain under which conditions and through which social mechanisms large scale cooperation operates.

Free and Open Source Software as a case study

Free Software is computer software that allows users to run, copy, distribute, study, change and improve it.

- Availability of detailed data about the production process.
- Impressive increment of scale in the last two decades.
- Allows to analyze the development methods of FOSS from the perspective of a knowledge based production process.
- focusing on the patterns of relations between direct producers we can analyze key mechanisms that enable and foster large scale cooperation.

Research question

How does large scale cooperation work in knowledge intensive and technically complex production processes developed in new organizational environments, such as Free and Open Source Software projects, where loosely coupled individuals that rarely meet face to face have to coordinate through internet in order to produce world class software products, without relying on hierarchy or market as coordinating mechanisms.

Group Cohesion in the sociological literature

Central concept that has a long and illustrious history in sociology. Its use in most sociological research has been ambiguous at best (Moody and White, 2003):

- 1 sloppy definitions of cohesion with lack of generality.
- 2 grounded mostly in intuition and common sense.

Group cohesion (Doreian and Fararo, 1998) can be divided analytically into:

Ideational component based on the members' identification with a collectivity.

Relational component based on the patterns of connections among members.

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Relational component based on the patterns of connections among members.

The relational component of group cohesion has been the focus of Social Network Analysis.

Network theory measures used to define group cohesion

Classical measures cliques, clans, clubs, k -cores, lambda sets, ...

Community algorithms detect groups of nodes more densely connected among them than with the rest of the network.

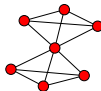
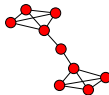
Neither the classical approaches nor new developments in community analysis work well in empirical analysis of group cohesion.

Key properties that a cohesion measures should have

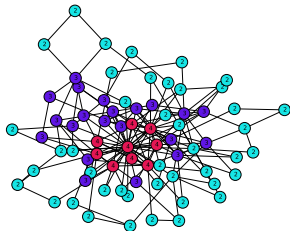
Robustness its qualification as a group should not be dependent on the actions of a single individual.



Overlap a cohesion measure should allow some actors to be part of more than one cohesive subgroup.



Hierarchical highly cohesive subgroups are nested inside less cohesive ones.



The structural cohesion model

The structural cohesion model (White and Harary, 2001; Moody and White, 2003) is based on two mathematically equivalent definitions of cohesion.

Precise definition of group cohesion based on **node connectivity**

- a group's structural cohesion is equal to the minimum number of actors who, if removed from the group, would disconnect the group.
- a group's structural cohesion is equal to the minimum number of node independent paths linking each pair of actors in the group.

This equivalence relation has a deep sociological meaning because it allows to define structural cohesion in terms of:

- the difficulty to pull a group apart by removing actors.
- multiple relations between actors that keep a group together.

Measures of structural cohesion

Node connectivity $\kappa(G)$

Local given two nodes u and v , $\kappa_G(u, v)$ is the minimum number of nodes that must be removed to destroy all paths that join u and v .

Global the minimum number of nodes that must be removed in order to disconnect a graph G .

$$\kappa = \min\{\kappa_G(u, v) : u, v \in V(G)\}$$

Average node connectivity $\bar{\kappa}(G)$

the sum of local node connectivity between all pairs of different nodes of G divided by the number of distinct pairs of nodes. (Beineke, Oellermann, and Pippert, 2002).

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

k -components

A k -component is a maximal subgraph that has, at least, node connectivity k : we need to remove at least k nodes to break it into more components.



Structural cohesion is a powerful and robust explanatory factor for a wide variety of interesting empirical social phenomena:

- likelihood of building alliances and partnerships among biotech firms (Powell et al., 2005)
- school attachment and academic performance of young people and the tendency of firms to enroll in similar political activity behaviors (Moody and White, 2003)
- emerging trust relations among neighborhood residents and the hiring relations among top level US graduate programs (Grannis, 2009)

Some problems with the structural cohesion model

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 hundreds nodes and edges due to its computational complexity.
- it is not implemented in most popular network analysis software packages.

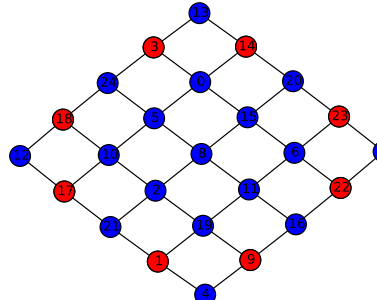
Exact Algorithm

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.

- 1 Identify the node connectivity, k , of the input graph.
- 2 Identify all k -cutsets at the current level of connectivity.
- 3 Generate new graph components based on the removal of these cutsets.
- 4 If the graph is neither complete nor trivial, return to 1; otherwise end.

```
import networkx as nx
from networkx import convert_node_labels_to_ints

G = nx.Graph()
G = nx.grid_2d_graph(5,5)
list(nx.all_node_cuts(G))
[[{1, 9}, {22, 23}, {17, 18}, {3, 14}]
# To compute k-components
kcomponents = nx.k_components(G)
```



The heuristics we developed are based on:

Approximation to local node connectivity

White and Newman (2001) fast approximation algorithm for finding good lower bounds of the number of node independent paths between two nodes.

```
import networkx as nx
from networkx.algorithms import import approximation as apxa
# Exact computation of node connectivity
exact = nx.node_connectivity(G)
# Lower bound approximation
aprox = apxa.node_connectivity(G)
```

Whitney's theorem

inclusion relation among node connectivity $\kappa(G)$, edge connectivity $\lambda(G)$ and minimum degree $\delta(G)$ for any graph G :

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

“ k -cores can be regarded as seedbeds, within which we can expect highly cohesive subsets to be found” Seidman (1983, 281)

Main logic of the heuristics

- 1 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.
- 2 Build an auxiliary graph H in which two nodes are linked if they have at least k node independent paths connecting them.
- 3 Complete subgraphs in H 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. That is, k -components.

Trade Accuracy for Speed

Network	Bipartite				Unipartite			
	# nodes	# edges	Av. degree	Time(s)	# nodes	# edges	Av. degree	Time(s)
Debian Lenny	13,121	20,220	3.08	1,105.2	1,383	5,216	7.54	204.7
High Energy (theory)	26,590	37,566	2.81	3,105.7	9,767	19,331	3.97	7,136.0
Nuclear Theory	10,371	15,969	3.08	1,205.2	4,827	14,488	6.00	3,934.1

A Network Model for Collaborative Communities

A new form of community, qualitatively different from the traditional *Gemeinschaft* and the modern *Gesellschaft* (Tönnies, 1974)

Collaborative Communities (Adler and Heckscher, 2006)

Novel organizational form —both inside and outside large capitalist corporations— strongly grounded on large scale cooperation which defy the traditional dichotomy between **hierarchy** and **market** as coordinating mechanisms.

- Generalized trust
- Conscius cooperation and High individual interdependence
- Shared values and Value-rational basis for legitimate authority

Network (structural) model for Collaborative Communities

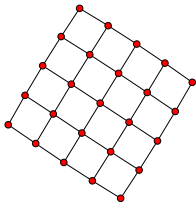
Cohesive Small World Based on the well known Small World and Structural Cohesion Models. Which structural conditions enable trust and value congruence?

- Small Worlds: Local clusters connected by shortest paths.
- Structural Cohesion: Increasingly cohesive groups nested inside each other.

Pure Structural Cohesion

- Robust to node removal
- Not necessary short average distance
- Not necessary local clustering

Pure Structural Cohesion

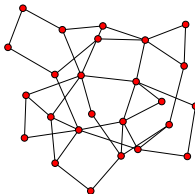


$n=25$, $m=40$, $CC=0.00$, $APL=3.33$, $SWI=0.00$, nodes in GBC=100%

Cohesive Small World

- Intersection of the two models
- Short average distance
- High local cluster coefficient
- Robust to node removal

Cohesive Small World

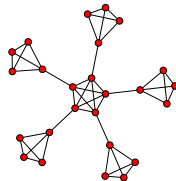


$n=25$, $m=40$, $CC=0.19$, $APL=2.67$, $SWI=1.57$, nodes in GBC=100%

Pure Small World

- Short average distance
- High local cluster coefficient
- Not necessary robust to node removal

Pure Small World



$n=25$, $m=45$, $CC=0.82$, $APL=3.38$, $SWI=4.23$, nodes in GBC=20%

The structural cohesion model

The structural cohesion model (White and Harary, 2001; Moody and White, 2003) is based on two mathematically equivalent definitions of cohesion (Menger's theorem).

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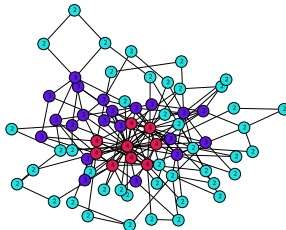
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Free and Open Source Projects: Debian and Python

Free Software, broadly defined, is computer software that allows users to run, copy, distribute, study, change and improve it.

The Debian Project: 1999-2012

- A free Operating System
- 392 developers in 1999, 1435 in 2012
- 2876 programs in 1999, 10469 in 2012
- Widely used in servers (google), desktops (Ubuntu) and embedded devices (raspberry pi)

The Python project: 1999-2014

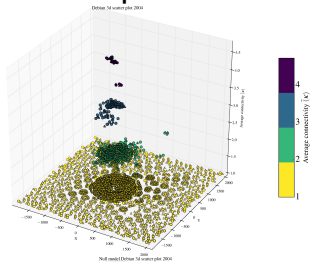
- A free Programming Language
- 9 developers in 1999, 62 in 2014
- 1137 files in 1999, 2134 in 2014
- Widely used in web development (reddit, youtube) and scientific computing

Building and Analyzing Cooperation Networks

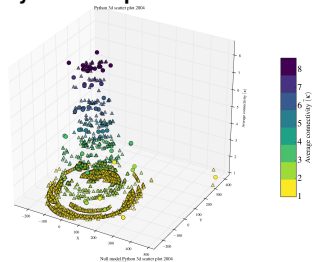
- Cooperation networks are bipartite or two mode (both developers and programs)
- A developer is linked to the package or source code file that she works on
- Structural Cohesion Analysis: κ -components as sub-groups
- Small World Analysis: Average Path Length and Clustering Coefficient

Structural Cohesion Analysis

Debian Cooperation Network 2004



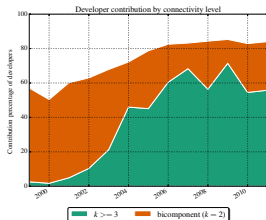
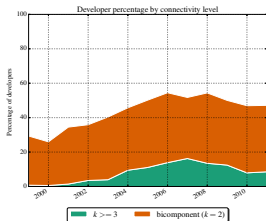
Python Cooperation Network 2004



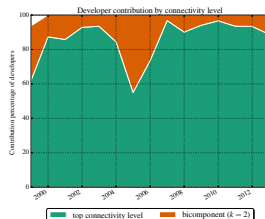
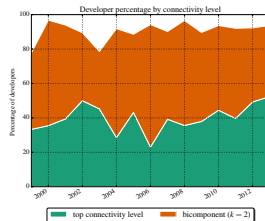
Iron law of the Oligarchy or an Open Elite?

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.

Debian Contributions

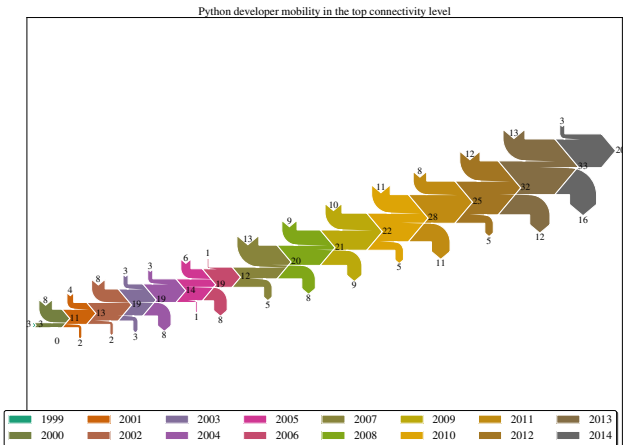


Python Contributions



Cooperation Networks' Connectivity Hierarchies as Open Elites

Sankey diagram of Python developer mobility in the top connectivity level.



Modeling robustness as median active live of individuals in the project

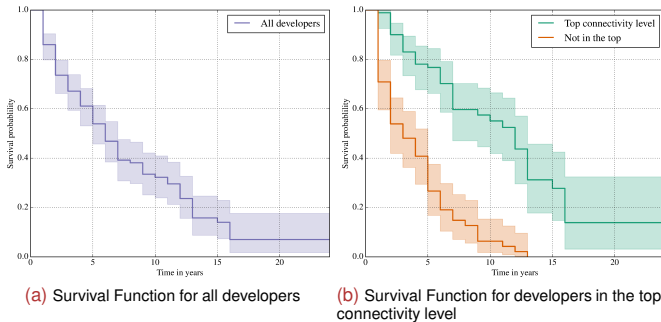


Figure: Estimation of the survival function using the Kaplan-Meier estimate. The median survival time of a developer in the community, defined as the point in time where on average half of the population has abandoned the community, is 6 years if I consider all developers (left). But if I consider separately 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.

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