

From communities to crowds: quantifying the subjective

Data, measurements, and models



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This dissertation is submitted for the degree of

Doctor of Philosophy

July 2020

– To Geetika, Medha , Chanda ... and now Arya.

DECLARATION

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text. The dissertation covers contributions for journals and conferences where I was the main contributor and primary investigator.

Sagar Joglekar
July 2020

ACKNOWLEDGEMENTS

Behind this dissertation, is a battalion, who either inspired, nudged, guided, mentored or supported me, to eventually pursue something which had been a dream in making for almost 20 years.

Firstly, I have to express my deepest gratitude to my advisor and mentor Dr. Nishanth Sastry. I still remember the long and detailed email he wrote, even before I joined his group, unwrapping every doubt I had about all things Ph.D. It was because of this email and the brutally honest but empathic advice within, is why I decided to take a leap of faith and pursue this journey under his wing. At every step, he has inspired me to explore the difficult and to be fearless doing so. With a deliberate balance of control and freedom, his style of mentoring is something I am truly thankful for and wish to internalize at some point.

The biggest curse of doctoral studies is the loneliness that it breeds. But I was immensely lucky to find friends on and off campus. I am truly grateful to find friends like Aravindh Raman, Changtao Zhong, Dmytro Karamshuk, Pushkal Agarwal, Emeka Obiedu and Miriam Redi, with whom I have had the pleasure of sharing countless coffees and endless inspiring chats. Some of these chats have even blossomed into full fledged research projects and generated grants and/or publications. I have been blessed with friends like Anand, Sanika, Marc and Roxy, who filled our life with fun, love and a warm feeling of being part of a family.

I have been fortunate in life to find mentors at different stages, who have shaped my career and life in some way. Here too, I was lucky to find mentors either through collaborations or shared interests, who have been quintessential in shaping my Ph.D. and my career. I would like to thank Luca Aiello, Miriam Redi, Gareth Tyson, Daniele Quercia, Pietro Panzarasa and Anna Simoni for their support and valuable mentoring.

Finally, it only makes sense to connect the dots in hindsight. To that end, I have to thank my friends and colleagues from Santa Barbara who gave me honest and balanced advice when I needed the most. I would like to thank Advait, Geetak, Bugra and Gina, who made sure my desire to do a Ph.D. became a drive and resulted in an action.

My decision to pursue a Ph.D., could not have been possible without the unconditional support of my family. Every curious thought in my mind can be traced back to how I was raised. My mother Medha and my sister Chanda, have been the biggest driving force behind all my actions. They have always inspired me to follow my heart, even if at times it meant me going away from them for a long haul. I would like to thank my other half of the family, Sanjeev, Sandhya and Rishikesh, who had faith in me when I needed it the most.

Last, but by long shot not the least, I have to thank my wife Geetika, who has been like a light house in a turbulent sea. Unwavering in her support and unparalleled in her guidance, she has gone above and beyond, to make this dissertation a reality. And hence I believe it is as much hers, as mine. And to conclude, I would like to thank Arya, our new born daughter. She made sure that I kept to the schedule of this Ph.D., by announcing hers’.

ABSTRACT

Research in the field of recommendation systems have shown that *subjective preferences tend to follow deterministic patterns, when looked at data in large sample sizes*. This principle underpins several of our present day online and off-line recommendation applications like e-commerce, restaurant recommendation, place recommendation or music recommendations. With the ever pervasive nature of the internet, we as a society have gone beyond treating the online spaces as a tool to access information, and have started treating them as a natural extension of the self. We spend more time than before as a part of a larger networked community, exchanging thoughts, debating ideas, expressing creativity and “socializing”. We also sometimes indulge in expression of human emotions like empathy, anger, sadness and sometimes seeking help. On the other hand, at times we behave like crowds; participating in entertainment and engagement channels and offering a piece of our attention budgets, without the explicit intent of being social. But in both cases, our decisions are often governed by our subjective perceptions of the online and offline worlds. At such a juncture, I examine the central thesis **Can we quantify properties of subjective nature, if the data is large enough, and originates from human communities or crowds?**. In this dissertation I develop data driven methods with the aim to quantify subjective qualities, through two case studies. I investigate the utility of said methods in designing interventions to improve the online and offline spaces. I do so by testing the validity of the central thesis in the context of two distinct scenarios, the first dealing with quantification of social support by looking at the network structure of online support networks and the second with quantification of subjective properties from crowd sourced opinions.

In the first study, I analyse on-line spaces involving networked communities where interactions between humans are purely with the intent of helping each other. In this study, I test the I develop frameworks to abstract out the graphical structure of these interactions. Using these abstractions, I examine these support communities from a macro scale to understand the signature behavioural patterns that makes these communities thrive. I then investigate presence of perceived support by finding discriminative local and global structures in these communities. I argue that these structures, which we call anchored motifs, are the

signatures of a supportive exchange process in online conversations. This informs my analysis about the nature of peer support in these communities and paves the way to do actionable interventions in the area of perceived support in online networks.

In the second study, I investigate utility of crowd's perception of aesthetics in physical spaces. As such the aim is to explore the potential of crowd perception in developing tools, to better design physical spaces. I do this by developing a pipeline that capitalizes on crowd sourced responses about perception of urban aesthetics. I develop a deep-learning driven framework, which is able to quantify the perception of intangible qualities like 'beauty of a space' through a crowd sourced rating of google street view images. I show that a general pattern of beauty in urban spaces can be learnt through crowd sourced opinion and deep learning models. I further develop a generative model to simulate beautification of urban spaces. Through a detailed literature review of the field of urban design, I develop a measurement framework which can provide insights into the predictors of urban beauty. I then develop the necessary tools to evaluate these metrics using computer vision techniques. I validate the value of these metrics through an expert survey and also validate the interventions using crowd sourced perception experiments.

Above all, in this dissertation, I contribute original frameworks and implementations for different approaches towards quantifying subjective signals from communities and crowds. These methods verify and validate several metrics developed for understanding subjective properties, like perceived support and perceived aesthetics, at scale. This provides a path forwards for A.I. driven design and curation of online and offline spaces.

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INTRODUCTION

There are things known and there are things unknown, and in between are the doors of perception - Aldous Huxley - Doors of perception

1.1 Introduction

We live in a world where information is being bombarded on our cognitive faculties from all sides, at all times. The internet is a continuous stream of information and each source is fighting with the other to get a piece of our attention budget. With the advent of machine learning and big-data, building systems that predict actions as a response to perceptual triggers has become the bread and butter of many companies. The use cases may range from understanding which adverts made a visitor do an unscheduled purchase, or which string of music tracks recommendations maximized a users time on a particular music platform. But in the end it all boils down to understanding what triggers result in human action or lack thereof [SDP12]. Nevertheless, the systems that surrounds a human interacting with the internet are all designed to figure out the best triggers which are perceived by the human as worthy of attention. Since the dawn of data driven design, the user's attention has become such a valuable commodity, such that the academic community has coined a term for it – “The Attention Economy” [DB01]. In the words of Matthew Crawford “*Attention is a resource, a person has only so much of it.*” [Cra15]. And this very resource has been the driving force behind the advertisement driven internet giants like Facebook and Google.

We live in the age of distraction, and more often than not our subjective perceptions are guiding our actions, instead of our conscious cognitive processes. Several studies have shown that engagement is almost always a game of stimulating our most basic urges, such as dopamine hits, presence of faces or simply arousal of emotions to increase the working memory [BSG14, JSR17, SFSJ06, Soa15].

On the positive side of this story, the capacity of subjective perceptions to influence actions, is also being used to design positive interventions. One such example is the emergence of more formal topical spaces on the internet, that facilitate providing peer-to-peer perceived social support [Cou05, BSBMDS16] or information exchange [FM08]. The ever pervasive nature of the internet allow these formal spaces to function almost like physical communities, with moderated and effective peer to peer exchange of thoughts, ideas and empathy [KGB⁺02, Squ15, HOG⁺10].

There has also been a series of studies [JK19, QOC14, QSAM15, Que15, QSA14] that looked into whether we can quantify the perception of the physical world based on the crowd-like behaviour of individuals online. Here crowd-like implies that there is no social interaction between two individuals generating the interaction data. These individuals take actions online(check-in on a platform, post a picture, tweet etc) influenced by their perceptions of the real physical space. In these situations, their perception of real spaces is influencing what they post or like online.

Both these examples show that in the age of the internet, our online and offline lives have been linked more deeply than ever. Our once assumed offline personal needs, like social support, are being addressed via online forums. At the same time, actions that we take offline are enriching and influencing our online presence. In both cases the subjective perception of our online and offline environment is impacting our life experience. This provokes the question:

| |
|---|
| Can quantifying properties of subjective nature help us design impactful interventions for our on-line and offline lives? |
|---|

This question has been the motivation behind all the works done in the past 4 years, eventually resulting into the formation of the central thesis of this dissertation. In the effort to pursue this question, we first need to understand what does it mean to “quantify the subjective”, in the context of web-scale data. But first, we need to clarify the framework that grounds this dissertation’s approach towards perception, affect and data. To do so we should try and understand each of these terms separately.

1.2 Perception and Affect

In this dissertation, I tried to build frameworks to capture the signatures of perception of the subjective. This was accomplished using large volumes of data and metrics designed around concepts from inter disciplinary fields. The utility of such an attempt, can only be justified if there is a real link between how humans take decisions at the most fundamental cognitive level and how they perceive the world around them. If there exists such a link, then the signatures found in the data can be explained and capitalized.

There has been an ongoing effort to unravel this link, through psychological, neuro-evolutional and philosophical arguments. I will try to gain inspiration from them, but a detailed critique is beyond the scope of my dissertation and expertise

Definition 1 *Affect*¹: *Any experience of feeling or emotion, ranging from suffering to elation, from the simplest to the most complex sensations of feeling, and from the most normal to the most pathological emotional reactions.*

Definition 2 *Perception*²: *The process or result of becoming aware of objects, relationships, and events by means of the senses, which includes such activities as recognizing, observing, and discriminating. These activities enable organisms to organize and interpret the stimuli received into meaningful knowledge and to act in a coordinated manner.*

¹American Psychological Association definition.

²American Psychological Association definition.

Emotions or ‘affects’ and perceptions have long been discussed in the psychology, neuroscience and philosophical literature. The two are tightly linked in our understanding of mind. Perception is a process, and affect is a result that this process sometimes evokes. Emanuel Kant in his prolific work, first discussed the utility and the philosophical reasoning behind presence of affects or emotions [Kan87]. In his opinion, emotions are pre-cognitive involuntary states, termed as "mere perceptions of unspecified bodily states" [Bor04]. But according to him, that does not mean they don’t influence our deepest level of well-being and decision making processes. The link between affect and perception has also been explored in several other cases. One way to look at it was through the framework of understanding the aesthetic. In some sense, the aesthetic is an affect inducing entity. The act of enjoying a gorgeous sunset or a beautiful flower defines a sentient perceptive mind, as much as language or art. An argument to link the aesthetic with perceptions was made by Perlovsky [Per14], where they propose that the phenomenon of affects arousing from perception of aesthetics, comes from a fundamental human need to enrich the knowledge about real world. An unexpected thing, stimuli or structure in physical space creates a dissonance between our expected model of the world and the perceived reality. And at some level we perceive it as aesthetically pleasing. Another recent study by Zadra et.al [ZC11] evaluated the relation between visual perception and emotions. They demonstrate that the conventional assumption of the disentangled functioning of perception and affects is not true. Humans are quite susceptible to perceiving different realities based on different aroused affects. So a happy person would perceive a 50\$ shoe to be a reasonably priced item, which a sad person may not.

The discussion on the formal definition and process of affects will continue, but there seems to be a consensus, at-least among the computer science and information science community that affects do influence our decisions and we perceive information through a filter of affects. Affective triggers can be generated when information is formatted or packaged in a certain way.

In such a setup, it is worth testing if certain affect driven interactions on the web leave a trail of patterns in the data of these interactions. Furthermore it is worth asking if these

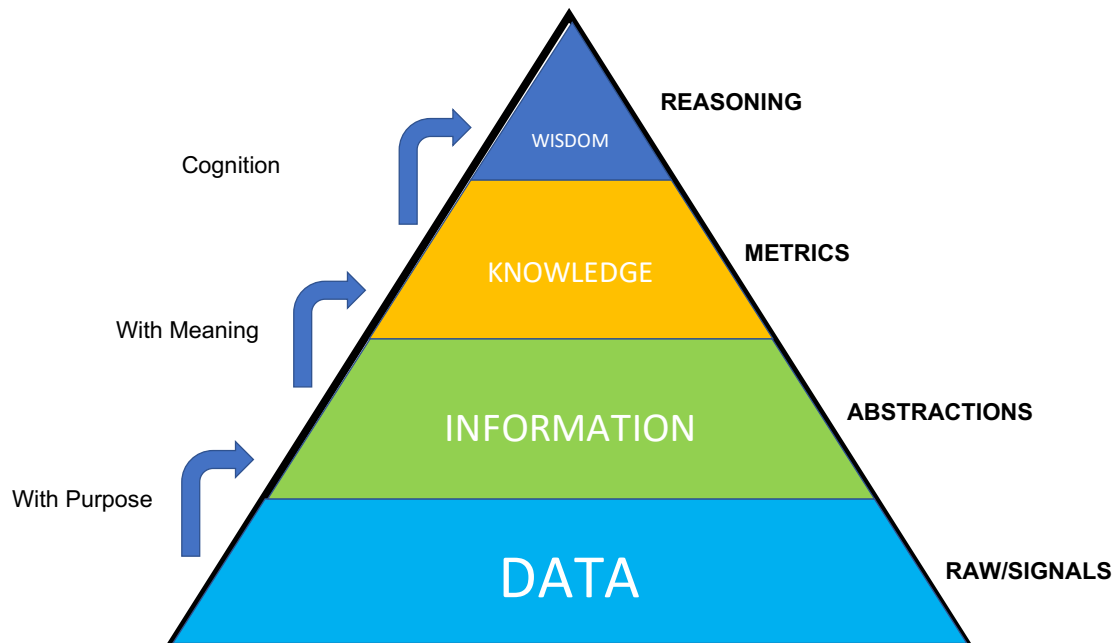


Fig. 1.1 The DIKW pyramid: The four layers of the pyramid represent the four distinct stages that the data goes through. The terms on the left hand side of the pyramid indicate the intent which results into the transformation of one layer into another. The terms on the right indicate the outcomes of each transformation.

patterns might in some way be used to improve, through interventions, our online and physical environments. But to arrive at these patterns, one needs to formalize the frameworks for approaching such a problem. The journey from data to the subjective signatures needs to be standardised.

1.3 The DIKW model

My work in this dissertation involves building pipelines that could extract signals about human processes from large scale data. But to make the process of building pipelines repetitive across use cases, we need to first settle on a framework that enumerates our intentions about the data. On the journey to develop the pipelines, one has to reflect on frameworks that codify operations on data. One such framework, which I found most relevant to my work, is the **Data , Information, Knowledge and Wisdom** model [Row07].

The original framework was theorized to elaborate the journey between raw data and actionable wisdom. To that end I link these pyramidal layers with the different outcomes of the pipelines I developed during this dissertation.

With the pyramidal structure of this framework, with each layer the data gains more structure and the relationships become more defined.

In this model, the most foundational layer consists of the pure form raw **Data or signals** that come from a source. If we are measuring subjective perceptions of humans, this source needs to be tied back to humans in some way. To that extent, the data must ideally be a product of human to human interaction online. Or it needs to capture the human perceived responses, through explicit exercises like crowd sourcing or public surveys. In this dissertation, I present solutions in the context of exactly these use cases, where the data sources are either from human to human interactions or a result of crowd based perception.

The **Information** layer compels any processing done on the data, to be with a sense of purpose or an end goal. For example, if the goal is to understand how humans exchange messages at times of distress, you would most certainly need to express the raw information about sender and recipient of messages into some form of a networked abstraction. This compulsion of goal generally forces us to choose an abstraction to structure the data into. The abstraction preserves the organization of data, but at the same time allows information to be operated on.

Knowledge. Defining knowledge has been an ongoing effort in the field of philosophy. But in the context of information science, knowledge involves collation of diverse sources of information and mix of contextual information, values and metrics to deliver a coherent understanding of the real world. For example, if you need to know the most popular user among a social network of users exchanging messages; you would look for the most central user in the network(abstraction) along with several other temporal and structural metrics to arrive at a few candidates. In this particular case, these metrics, along with the context of the social network's design, dawns the meaning of "popularity".

The final layer requires a literature driven approach that links the outcomes of the previous layer (the metrics), with a defined set of concepts and vocabulary in the field of intervention.

The very act of gaining insights using these metrics is what we can call **wisdom**. In order to maximize impact of this process, we need to make sure that we are able to reliably map the metrics that we design onto a set of literature backed vocabulary in the field of practitioners.

In our example, let's assume we need to get some insights about the dynamics of popular users. Particularly in the context of optimizing advertising delivery. For example we need to understand how a particular piece of advertising might percolate through the network if certain popular users advertise it [LS12]. However, to arrive at these insights we need to be grounded in the vocabulary of epidemiology, network physics and depending on the application, advertising or meme theory. Then using the abstractions of social networks and the metrics derived from them, one can design a pipeline that maps the metrics onto concepts like "virality", "influence" or "contagion".

This pyramidal approach inspires all the frameworks and data processing pipelines I developed in this dissertation. Figure 1.1 shows an illustration of the adopted version of Rowley's DIKW model, which I would refer back as a repeating motif throughout my dissertation.

1.3.1 Data

Data is one of the most fundamental contribution of this dissertation. To develop frameworks around quantification of human perceptions, so that we can do impactful interventions, we first need to make sure we formalize how we acquire, clean and condition our data. The foundational level of this pyramid is the data that the framework would work with, in order to ascend towards extracting wisdom. I worked with diverse forms of data such as textual data, video data and image data to understand how these might exhibit signatures of human perceptive processes. The relation between data and subjective attributes needs to be examined using some proxy such as interactions on a post, votes or engagement. For this reason, my research involved collecting data from sources where either human to human interactions happen, or the data is generated on account of a human expressing their opinion about a subjective quality, like in case of crowd based perceptions.

Interaction Data

The first case study of this dissertation focuses on online support communities, where human to human interactions which express support, are at the centre. It has been shown through several studies in medical informatics, that these communities play a very important role in providing support and respite in times of distress [AVKR16, MC12, PS15, BC11, IABS⁺17, HBCF16]. The communities are especially helpful when it comes to people suffering from long term illnesses or mental health issues. The key element that impacts the users is the perceived social support [Nam11], which delivers people in distress a sense of belonging to a group and a sense of empathy from the fellow supporters. To understand how users on these communities perceive social support, I work with data acquired from online health forums, where users share, give support and ask for support. I look at communities that deal with long term conditions like Lung illnesses, and communities where mental health patients seek support [JSC⁺18]. The data spans across a duration of 10 years, containing peer to peer support interactions of more than 30,000 users. I also crawled a popular forum based social network called Reddit³ to acquire a peer to peer support data regarding mental illness and suicidal thoughts. The data covers discussions around more than 30,000 calls for support, and includes the complete structure of the way people respond to these calls.

Image data

The other facet of my work looks at the problem of quantifying our perception of physical spaces. Whether a street is considered beautiful is a matter of subjective opinion. And yet research has shown that there are specific urban elements that are universally considered beautiful: from greenery, to small streets, to memorable spaces [Ale77, QOC14, SSH13]. These elements are those that contribute to the creation of what the urban sociologist Jane Jacobs called ‘urban vitality’ [Jac61]. Apart from vitality, these motifs in urban environments are also highly correlated with feeling of well-being, health and safety [KK89]. There have been studies where people have tried to use crowd sourcing to acquire subjective ratings of

³www.reddit.com

images [SPM15] which have shown some reasonable progress on this front. But the real gap in these studies is understanding the impact of urban elements on the perception of these subjective qualities. E.g. How much does presence of a green garden affect the subjective rating of beauty for that particular area? For this reason, I work with google street view data and crowd sourced subjective ratings of various places around the world [NPRH14], with the aim to understand how people perceive the sense of beauty in urban areas. Then using the semantics of urban design and architecture, developed by a detailed literature review, I aim to develop machine learning pipelines that can suggest interventions to change perceptions of physical spaces.

1.3.2 Abstractions

The act of aggregating information from data, almost always involves building structured abstractions. Throughout my dissertation, I either repurpose well known abstractions in computer science or develop my own using tools from fields like computer vision and Information theory. For the first study, I incorporate user meta data and the textual data of their activity, to build organized networked abstractions representing the conversation structures on the support forums. I use these abstractions to evaluate global and local structures in support communities, which would be discussed in detail in Chapter 3 and 4.

While working with image data, I use several pixel level abstractions to segment and group semantically similar pixels. I also use several state of the art object and scene detection algorithms, to extract semantic information from an image, with the aim at analysing correlations with the perception of subjective attributes of images with these metrics. I also use deep convolutional networks and generative models, to abstract out a representation of beauty. There will be a more detailed discussion of these abstractions in the later chapters (Chapter 5 , Chapter 6).

1.3.3 Knowledge

For extracting knowledge, we need to first associate meanings to certain computable metrics that we obtain from the abstractions. As discussed in the previous example, it could be as simple as associating the property of “popularity” to the metric of centrality. In this work, I developed several such metrics which related subjective properties with measurable structures in data. These structures could be in the form of topological motifs in the interaction graphs, or in the form of patterns in images. Some of these metrics are based on intuitions which I validate, and some based on extensive literature survey. To give an example, I develop the concept of anchored triads, which combines local structures in interaction graphs of users, with the positional parity of a user in the conversation. This helps me understand how a group of people behave around a person in distress in a supportive conversation, as against a general conversation.

1.3.4 Wisdom

Finally the wisdom underlies insights that come for experience. The experience could come simply from the scale of data or from cross disciplinary literature that puts forth theories of subjective experience. E.g. The theory of social support puts forth four categories of social support 1)Affective/Perceived 2)Instrumental 3)Informational 4)Networked [CS92]. Each type has its own specific traits. My dissertation looks at these theories from the lens of computational social science and networks science to develop metrics and methods to partly quantify signatures social support.

1.4 Research Thesis and Research Questions

To make any progress towards answering the guiding principle as articulated in 1.1, we first need to make progress towards quantifying the subjective. Hence the overarching central thesis of interest that I would explore through the two case studies is:

Can we quantify properties of subjective nature, if the data is large enough, and originates from human communities or crowds?

But this thesis question is quite open ended, and answering it in a generalized manner seems impractical in the scope of one Ph.D. For this reason, I need to first contextualize my work in the realm of practical applications, by deriving more focussed research questions, such that I can acquire data and test my hypothesis in an effective time bound manner. More so, to drive maximum impact, I would like to focus on applications which have the potential to have real world consequences, either through interventions or through inspired interest in the field.

1.4.1 PART 1 : Interactions on support communities

Humans are social animals in every aspect. The presence of social support systems in ones lives have shown to have huge quantifiable benefits. From speeding up recovery in cases of post-partum depression or in the cases of cancer survivors [CDSLS93, DS84, BCH⁺90] , to signs of positive turn around among patients suffering from alcoholism and depression [PFR⁺00, BAH⁺86], social support is a key predictor of positive prognosis for patients under distress. With the advent of internet, a lot of communities have sprung up, which provide a rich platform for patients to interact, exchange support as well as provide a perceived sense of community. These communities are moderated, only to an extent to curb toxic behaviour, but other than that are largely free form. Due to a very homogenous membership, where most members have either gone through or are going though similar distress, there is an emergent sense of support and affective empathy [DSSBSM16]. The key idea of this case study was **to quantify the signatures of social support in the behaviour and interaction patterns on these support communities**

Social support, or perception of help received from others, is a widely studied as a psychological resource used to cope with distress. The social support is generally

classified into one of the following categories viz. Informational, Tangible , Network or Emotional(affective) [CS92]. These categories measure the nature of social support along the idea of exchange of resources between the person in distress and the one providing support. For example, an informational support interaction could involve pure exchange of valuable information about dealing with an issue. Whereas as network support interaction could purely allow the recipient to acquire a wider network of people. In the part 1 of my thesis, I would like to quantify the nature of perceived social support from the structure of the dialogue and interactions between people. I conjecture that in doing so, we can tease out the signatures of network and informational support in online communities.

Despite the highly specific nature of support communities, they have been successful in maintaining their relevance. In such a context, it is highly valuable to examine the dynamics communities and understand the macro level behaviours of the users. Moreover, it is worth understanding how the interactions on these communities differ from generic interactions on the web. The discriminative differences are what I call signatures of support. Quantifying these signatures would facilitate these communities to be better poised to tackle any disturbances in the dynamics of social support. These signatures would also help us quantify the net utility these communities in terms of delivered informational or network support. With this in mind, I formulate the following research question for my first case study.

| |
|--|
| RQ1 <i>What dynamics of support communities help them thrive?</i> |
|--|

| |
|--|
| RQ2 <i>What differentiates users on support communities from generic ones?</i> |
|--|

| |
|---|
| RQ3 <i>What differentiates interactions on support communities from generic ones?</i> |
|---|

In order to make progress on these questions, I first had to collect data from two different communities designed for online social support. The first community is dedicated for patients suffering from chronic lung diseases, such as Asthma or Chronic Obstructive Pulmonary Disorder (COPD). This community was moderated by self appointed moderators, and everyone on this community was either a survivor or a patient of these diseases. This

community allowed patients to ask questions about symptoms and home remedies and sometimes just bond over social interactions. The second community I worked with dealt with people suffering from chronic depression and suicidal thoughts. This community was a safe haven for such people to vent out suicidal thoughts and get support from peers to manage these sudden flares of thoughts of self harm.

Through these two communities, I develop a pipeline to analyse the peer to peer interactions using abstractions derived from network science. The abstractions capture conversation level structure as well as the global interactions in a community. This allows me to probe the evolution of such a community both in terms of overall structure of the network as well as conversational interactions between users. I also develop metrics inspired from psychology and psychotherapy literature to quantify how these interactions can be qualified as supportive or non supportive. For example, the concept of communication accommodation theory (CAT) [CG88] prescribes the way in which three participants can participate in a group therapy session. The metrics that measure the branching of a conversation or the patterns in ties between 3 users (triads) align with these prescriptions.

Through a data driven analysis, I establish confidence on these metrics. Through this process, I also report my findings about the dynamics of users on these communities and key properties of user roles. I find that these conversations have a distinct nature when compared against regular baseline conversations over the web, and these distinct signatures could one day be used to curb toxicity as well as improve the support community interface.

1.4.2 PART 2 : Leveraging crowd's perceptions about aesthetics of real spaces

Urban aesthetics and presence of certain elements in the physical spaces that we use, have shown to have lasting effects on our mental health[SPM17] and physical well being[BBLO01, GCBK⁺05]. However, with the advent of access to large scale data and machine learning techniques, we have a unique opportunity to quantify what exactly comprises of urban aesthetics. In the next part of my dissertation, I aim at using the scale of the internet to try

and improve how our cities are perceived. In part 1, the interactions between networked users helped me understand the signatures of social support. In this part, we investigate if the opinions of a large number of disconnected users (crowds) can help us quantify something as subjective as the sense of beauty. In this study, I investigate the following research question:

RQ4 *Can opinions of disconnected crowds help us model the perception of aesthetics in real world?*

RQ5 *Can machine learning models based on crowd opinions help us improve real spaces?*

RQ6 *How much do the suggested improvements align with the expectations from the literature or the practitioners?*

Crowdsourcing is a method through which one could get inputs, subjective or otherwise, about a particular set of questions from a large number of real humans using the internet. In return the participants could be offered a tangible compensation, or in some cases, a gamified incentive. The **RQ4** motivates me to investigate if we can use crowdsourcing to quantify how people perceive urban spaces. Research has shown that if a large number of people could vote on a set of images, regarding their aesthetic quality, a trend emerges that favours some objective metrics of beauty[D⁺08, QOC14]. Can we link these metrics to urban elements? For this reason I work with google streetview images, where real people vote on aesthetic value of images through a large scale crowdsourced study. After evaluating for statistical trends in preference of aesthetic urban images amongst the voters, I attempt to answer **RQ5** by training a deep convolutional neural network model, which can discern between an aesthetically pleasing and unpleasant urban scene with a high degree of accuracy. Once we have a model that could “detect” beauty in urban scenes, we could then use machine learning and deep learning techniques to understand how different urban elements relate to the notion of beauty. I further develop a set of metrics which can explain the differences between a beautiful and ugly image in the vocabulary of urban design. These differences

are suggested as hints to practitioners, in order to improve an existing urban space. These hints are given in the form of suggested changes in different popular urban design metrics, which makes the whole process legible to practitioners in the field. I further test the validity of these metrics, by comparing them against expectations of the literature and those of real urban design practitioners (**RQ6**).

1.5 List of peer reviewed publications

I would like to list all the publications which resulted from the past 4 years of work, as well as collaborations I was able to strike with a diverse group of researchers. The author lead publications have influenced different chapters of this dissertation.

1.5.1 Original author contributions

List of papers (published, accepted and under peer review) which were either led by the author or where the author had a fundamental contribution

1. **Joglekar S**, Sastry N, Redi M. Like at first sight: understanding user engagement with the world of microvideos. In International Conference on Social Informatics 2017 Sep 13 (pp. 237-256). Springer, Cham.
2. **Joglekar S**, Sastry N, Coulson NS, Taylor SJ, Patel A, Duschinsky R, Anand A, Evans MJ, Griffiths CJ, Sheikh A, Panzarasa P. How online communities of people with long-term conditions function and evolve: Network analysis of the structure and dynamics of the asthma UK and British lung foundation online communities. *Journal of medical Internet research*. 2018;20(7):e238.
3. **Joglekar S**, Velupillai S, Dutta R , Sastry N "Online discussions about mental health in Reddit exhibit signatures of supportive conversations" Under Review

4. **Joglekar S**, Quercia D, Redi M, Aiello LM, Kauer T, Sastry N. FaceLift: a transparent deep learning framework to beautify urban scenes. *Royal Society Open Science*. 2020 Jan 16;7(1):190987.
5. Kauer T, **Joglekar S**, Redi M, Aiello LM, Quercia D. Mapping and Visualizing Deep-Learning Urban Beautification. *IEEE computer graphics and applications*. 2018 Sep 27;38(5):70-83..

1.5.2 Collaborative author contributions

List of papers where the contribution was significant, but were not led by the author. Contributions from these articles are not included in this dissertation

1. Agarwal P, **Joglekar S**, Papadopoulos P, Sastry N, Kourtellis N. Stop tracking me Bro! Differential Tracking of User Demographics on Hyper-Partisan Websites. In *Proceedings of the The Web Conference 2020*.
2. Bhatt S, **Joglekar S**, Bano S, Sastry N. Illuminating an ecosystem of partisan websites. In *Companion Proceedings of the The Web Conference 2018* 2018 Apr 23 (pp. 545-554). International World Wide Web Conferences Steering Committee.
3. Raman A, **Joglekar S**, Cristofaro ED, Sastry N, Tyson G. Challenges in the Decentralised Web: The Mastodon Case. In *Proceedings of the Internet Measurement Conference 2019* Oct 21 (pp. 217-229). ACM.
4. De Simoni A, **Joglekar S**, Taylor SJ, Patel A, Duschinsky R, Coulson N, Griffiths C, Panzarasa P, Sastry N, Anand A, Evans MJ. Structure and dynamics of online patients' communities: the case of Asthma UK and BLF online fora..
5. Young AP, **Joglekar S**, Garimella K, Sastry N. Approximations to Truth in Online Comment Networks.

6. Boschi G, Young AP, **Joglekar S**, Cammarota C, Sastry N. Having the Last Word: Understanding How to Sample Discussions Online. arXiv preprint arXiv:1906.04148. 2019 Jun 10.
7. Magdy W, Elkhatib Y, Tyson G, **Joglekar S**, Sastry N. Fake it till you make it: Fishing for Catfishes. In Proceedings of the 2017 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining 2017 2017 Jul 31 (pp. 497-504). ACM.

1.6 Thesis overview

In Chapter 2, I try to contextualize my work in the two regimes of human interactions (communities and crowds) by studying the background literature that deals within the similar areas. In Chapter 3 (based on article 2), I examine how supportive communities evolve and sustain over a long period of time. I show presence of an anti-rich club effect on these support groups, which implies that experienced users are more interested in helping new comers rather than forming a clique of their own. I define a quantitative metric for “expertise” and show that as one becomes adept, one becomes more willing to help. All these insights point towards answers for **RQ1** and **RQ2**. In Chapter 4 (based on article 3), I look at structural signatures in the interactions between users in a supportive conversations. I show that mapping the conversational exchanges onto a topological structure, exhibits keen preference for local supportive motifs, which I call “anchored motifs”. I discuss the utility of such a model of support conversation and draw parallels with the offline model of community support(Chapter 4) as per the mandate of **RQ3**.

In the second study, I investigate utility of perceptions of real world places through a crowd sourced rating of google street view images. As per **RQ4**, I develop models to extract the perception of the crowds using data driven inference methods(Chapter 5)(based on article 4). I then show that a general pattern of beauty in urban spaces can be learnt through a crowd sourced opinion and based on this finding, I develop a generative model to simulate beautification of urban spaces by using deep learning(Chapter 6)(based on article 4

and article 5). I validate the quantification of perception of real-world beauty using crowd validation. I contribute a way to use computer vision techniques to abstract out beautification process into explainable metrics used by architects and urban planners. The final contribution is a demo web application, that allows practitioners to examine and validate the utility of such a end to end system that captures citizen perceptions for urban design. These contributions are motivated by **RQ5** and **RQ6**. I close by enumerating the different research problems and future directions that I would like to pursue(Chapter 7)

BACKGROUND

Studying signals in user interaction data, where the interactions are driven by affective triggers, has been an active topic of research [Pic03, PPNH07, CGHH12, AJS⁺13]. As such it is worth discussing the different aspects in which the community of researchers have explored this area. The key aspects in which I would like to place my work is in terms of quantification of the subjective signals from data that originates from web scale applications. The two case studies in this dissertation attempt to quantify two distinct subjective properties, viz 1) Social support and 2) Aesthetic perception. Here we would try to first, explore the definitions of the concepts of social support and Aesthetic perception, and then examine the literature for methods, models and metrics.

2.1 Part 1: From communities

There has been a surge in the number of online communities, since the rapid adoption of social networks across the internet. The spectrum of types and applications of these communities is as abundant as the possible subjects discussed on the internet. These communities have become a dedicated space for online users to discuss about topical items. Often these communities take the shape of a forum, where topical threads are started by an original poster (OP) and a discussion commences on this post. The discussions could be in the form

of a debate¹, a banter² or a peer to peer topical discussion³. In this dissertation, we aim to understand the nature of social support and the signatures of social support which can be quantified from these online spaces. To that end we aim to look at forums which have been self certified to be dedicated for hosting supportive discussions.

2.1.1 Online social support

According to Shumaker et.al [SB84] social support is defined as "an exchange of resources between two individuals perceived by the provider or the recipient to be intended to enhance the well-being of the recipient." A lot of work has been done in understanding how social support functions and influences people in distress in the offline world. For example, a meta review [DiM04] showed that adherence to a medical treatment is 1.74 times higher, if the patient hails from a cohesive family structure. Social support has also shown to be a crucial factor in the positive prognosis of patients suffering from chronic and long term conditions [SY06, PFR⁺00, BAH⁺86, CDSLS93, DS84, BCH⁺90]. All this literature evaluates social support from a psychological stand point, in that, it looks at how a patient/subject is perceiving support from its real world network (family, friends, doctors etc.) More over most of this work uses the qualitative frameworks and tools as a way to measure off-line social support.

Social support, or the perception of help received from others, is a widely studied as a psychological resource used to cope with distress. Social support is generally classified into one of the following categories viz. Informational, Tangible , Network or Emotional [CS92]. These categories measure the nature of social support along the idea of exchange of resources between the person in distress and the one providing support. For example, an informational support could involve pure exchange of valuable information about dealing with an issue. Whereas as network support could purely allow the recipient to acquire a wider network of people through the support giver or a support platform (think societies like Alcoholic Anonymous).

¹www.kialo.com

²www.reddit.com

³<https://healthunlocked.com/blf>

The online world is very good at filling the gaps where offline support groups may fail. That is, the online groups, if designed in the right way, could provide essential informational, network, and at times emotional support at the click of a button. The internet makes both information and user networks, easily accessible. The utility of such spaces can be believed because of the evidence such as: online support groups being associated with quality of life [IKW09, Nam11, Cou05], improved control over additions [WW09], improved triaging with suicide ideation [CK17] and mental health issues [KGB⁺02].

Despite the interesting evidence, the common theme in most of these works is that they all take either a qualitative approach to understanding online support, or a language driven approach [DVZK⁺14, DSSBSM16, DSHF⁺17]. Most methodologies either utilize expert knowledge to dissect what is being said on these forums, or a natural language approach to understand the key language patterns on these forums. Either ways, the key missing bit in this picture is understanding how and where do the individual users fit in. How do they help in keeping the entire support community functioning. More over, we do not have any understanding about the structure of a supportive conversation online from the perspective of a user in distress. This is especially interesting, since there are obvious offline markers of a supportive conversation, whether it being a group, or a peer to peer setting. Not just that, but there are several therapy strategies like Communication accommodation [CG88] or group psychotherapy [Yal95]. So it is worth investigating these aspects of online support communities.

For this exact reason, **RQ1, RQ2 and RQ3** would make progress towards understanding the dynamics, local and global structures of online support communities.

2.1.2 Social networks, support, and metrics

Modelling and studying online social networks, through the lens of complex network theory and network physics has been an active area of research since the 1980s. The idea of looking at (offline) social structures as social networks was quite prominent in the fields of sociology [Sco88], but the most important leap in this field came with the advent of online social networks. This opened up new doors in measuring and understanding how humans

form networks, and do so at scale through the medium of online networks [MMG⁺07]. The first of these works [MMG⁺07] explored the idea of looking at large scale user graphs to measure and evaluate a lot of big picture attributes about online social networks. In that, they measure the long tailed nature of social links, the symmetric nature of social links and the overall sizes of connected components. A connected component in a social graph $G(V, E)$ – where V are the vertices or users and E are the edges between them – is a set of nodes $\{C\}$ where all nodes $\{c_i \in C\}$ have connected paths to all other nodes in $\{C\}$. The size of the largest connected component was often used as a proxy for the connectedness of a social graph [MSG14, TMP12, WRP⁺94]. Other global scale metrics explored for understanding social networks were degree distributions [MPP⁺13, NWS02, KW06], clustering coefficient [Ops13, TOS⁺06] and centrality [OAS10, BMBL09]. All these metrics aim to look at how nodes(users) in a social graph group together or how do they interact with each other as the size of the network increases. These insights help network physicists model how information or a contagion diffuses in a connected community. However, despite the large number of interesting works that look at network structure, there have been limited progress in using these tools to understand the nature of social support in online networks.

In the offline world, there have been some studies that look at the ego network of a person of interest, to infer the nature of social ties they have. In that, they look at the transitive nature of social networks around a person [GCL09, HL71, LCB01]. This means, how many friends of a person, are friends among themselves. A completion of this triad – which implies that friends of my friends are my friends – is called a triadic closure. In the online world, the theory of social capital and triadic closures were operationalized in terms of triadic census [Fau07, Fau08]. The census simply profiles any given network by counting individual instances of the individual sub-graphs made of two, three, or in some cases four nodes. These sub-graphs are called motifs. The importance of triadic motifs in social network research has been stressed so much so that in the words of Holland and Leinhardt [HL77]

“The essential issue of any notion of structure is how the components are combined, not the components themselves...this issue amounts to the proposition

that the lowest interesting level of structure...is the level of triples of nodes—the triadic level”

From the studies discussed here, the link between human to human interactions and their emergent network structure are quite evident. For this reason it is natural to extend this link to explore how perceived social support manifests in these interactions. In this dissertation, I aim to first quantify how network structures in support communities evolve, and second, discover the signature structural properties of these interactions over support communities.

2.2 Part 2: From crowds

The second part of the dissertation explores new methods to use crowd’s opinions, in order to build models of our subjective perception of urban spaces. The idea of using crowd based annotations or opinion mining has been popular and has been exploited in the recommendation systems literature for a while. Here I would introduce some background about the idea of crowd sourcing, how it applies to quantifying the subjective, and how it has been used to understand urban spaces and cities.

2.2.1 Crowd sourcing and the subjective

Crowdsourcing has been an important part of the computer science research for the past decade. The idea of crowdsourcing was first brought to attention by Jeff Howe [How06], where he introduced the idea of a logical equivalent of outsourcing – which is sending the jobs outside an area, where labour prices are competitive– but for more transactional and atomic tasks. This idea was quickly adopted by the academic community, right after the inception of services like Amazon Mechanical Turk or Crowdfunder [PCI10].

The natural extension of this new method was to use it for annotating large quantities of data. These annotations generally dealt with labels of objective nature, such as objects [VPR13], relationships between objects [KZG⁺17], or annotating textual data like named entities [FMK⁺10].

The key idea behind crowdsourcing is to get a cognitive input about unlabelled data by incorporating opinions of hundreds of “crowd-workers” exchange for money. This is

done in order to annotate the data with the most accurate objective labels, that come from a human annotator. This data then becomes the training set for a downstream machine learning algorithm . These algorithms would then learn the task of classifying unseen data into their respective correct labels.

But the very fact that a cognitive process is at the root of the annotations implies that this framework can even be applied to subjective properties, provided that the annotators can arrive at a consensus, and we have large enough samples. The most appropriate use case is that of annotating expressions or affects of humans in videos or images. Despite the subjective nature of perceived affect, most neuro-typical humans tend to agree on what constitutes the expression of anger, sadness, happiness , disgust etc. In that spirit, several studies [TMM16, KAH⁺16, KV16] tried to build machine learning models that could detect emotions from facial expressions, using data annotated by the crowd.

Apart from building a model of human affects from faces, crowdsourcing was also applied to the area of quantifying the actual affective stimuli in content. That is it tries to quantify the intangible property of a content that stimulates evocation of a particular emotion in the consumer of that content. For example, it is worth asking “Which emotion does an image of a sunset evoke in the human seeing it?”. This question goes one level deeper by trying to quantify that which evokes positive or negative sentiments. To that end Sentibank [B⁺13] explored this idea by training a deep learning model on Flickr images which were annotated for evoking positive or negative sentiments. The same team extended it to analyse how the evoked emotion changes as a function of culture and language [PRT⁺16]. Indeed they found that these evoked emotions are also dependent on the language, culture, and other social properties of the annotator. Although these works exposed some limitations in the approach of quantifying the subjective, they also showed that by and large, these techniques work if the data is large enough and there is considerable consensus among the annotators on the topic of the annotated subjective property of the data.

2.2.2 Crowds and the cities

So far, the most detailed studies for quantifying the perceptions of urban environments and their visual appearance have relied on personal interviews and the observation of city streets: for example, some researchers relied on annotations of video recordings by experts [SR04], while others have used participant ratings of simulated (rather than existing) street scenes [LH12]. But since the advent of services like the Google street view and Open Street Map, the Web has now been used to survey a large number of individuals. Place Pulse is a website that asks a series of binary perception questions (such as ‘Which place looks safer [between the two]?’) across a large number of geo-tagged images [SSH13]. In a similar way, Quercia *et al.* collected pairwise judgments about the extent to which urban scenes are considered quiet, beautiful and happy [QOC14] to then recommend pleasant paths in the city [QSA14]. Another study [SPM15] presented the annotators with a 10 point scale, which they would use to score a place(Street view) for its aesthetic beauty. All these studies relied on the crowds, in that the annotators were completely disconnected from each other, and their ratings were purely based on their exposure to the image or an urban scene. An important caveat here, as in case of multi lingual sentibank [PRT⁺16], is that the cultural and social background of the annotator would play a role in how they perceive an urban scene. But on average, these annotations proved very useful in understanding something as subjective as the perception of safety, beauty, or memorability in urban spaces.

This can be indicated by the fact that lately deep learning techniques have been used to accurately predict urban beauty [DNP⁺16, SPM17], urban change [NKR⁺17], and even crime [DNVZ⁺16a, AERA14]. Recent works have also showed the utility of deep learning techniques in predicting house prices from urban frontages [LSSGR18], and from a combination of satellite data and street view images [LPR19].

All the studies discussed above were successful in quantifying the subjective properties of an urban scene using predictive machine learning models. But there is a significant gap between predicting and explaining the prediction in order to guide interventions. This explainability problem is prevalent in almost all applied machine learning systems. In this

dissertation, I attempt to make some progress on the front of explaining the reasons behind perceiving an urban scene beautiful or ugly. These explanations also come in the form of urban design metrics, which can guide interventions from the practitioners of this field.

2.3 Discussion

The title of my dissertation enumerates the two regimes –communities and crowds– under which I explore the problem of capturing the signatures of perceived subjective properties, using customized metrics and models. The over arching thesis has always been understanding how human perceptions guide our actions on the web scale, and how these actions leave behind traces of the subjective triggers.

In the following chapters, I will discuss the different methods, metrics, and models that are developed in order to make progress in answering the central thesis of this dissertation.

CHAPTER 3

FROM COMMUNITIES: THE ACTORS OF ONLINE SUPPORT

”The original idea of the web was that it should be a collaborative space where you can communicate through sharing information... In an extreme view, the world can be seen as only connections, nothing else.“ - Tim Berners Lee[BLF01]

Attention budgets pretty much govern how we as consumers interact with online social networks. It has been shown that the dearth of this budget, promotes an engagement behaviour that prioritizes perceptive features and immediacy in the content [JSR17]. The scrollable user interfaces of platforms like Instagram and Facebook, allow mere seconds to decide whether a particular content is worth the user’s attention [Eik17].

However, there is a whole breed of online social networks, which aim at bringing the offline sense of networking, online. These networks are mostly designed around a specific purpose like technical discussions¹, subject specific questions² or simply around hobbies like knitting³ or art⁴. These communities embody the true essence [BLF01] of the internet, in that they strive at making geographical distance secondary, to the act of social networking and information sharing.

¹www.stackoverflow.com

²www.stackexchange.com

³www.ravelry.com

⁴www.artween.com/

3.1 Introduction to online social support

According to the seminal work by Shumaker and Browne [SB84], social support is defined as “an exchange of resources between two individuals perceived by the provider or the recipient to be intended to enhance the well-being of the recipient.” In the context of online spaces, the definition prescribes exchange of messages and information, in order to provide support to the recipient.

This exchange has been explored in detail in the field of computer mediated support [Cou05, WSUW95]. The main idea of understanding computer mediated communication is to zoom out from the message level interactions between users, and look at the actual “tie” between them. A tie connects a pair of actors by one or more relations. Pairs may maintain a tie based on one relation only, or they may maintain a multiplex tie, based on many relations, such as sharing information, giving financial or psychological support [GHW97]. Thus ties also vary in content, direction and strength. Ties are often referred to as weak or strong, although the definition of what is weak or strong may vary in particular contexts [MC84].

A lot of qualitative work has been done on understanding the dynamics [WBWB03, CK17] and utility [Nam11] of online social support. But most, if not all, studies looked at the content and thematic aspects of the supportive posts on these forums. But the key strength of online support communities is their networked collection of users, volunteering to provide online support. Some examples of such communities are r/SuicideWatch⁵, r/Depression⁶, Elefriends⁷. These communities are apt Petri dishes to study the structural signatures of the online social support networks. Once you could quantify the social support signatures in terms of computable metrics, platforms could then empower the participants of these communities and design interventions to curb negative behaviour like trolling.

In the context of this dissertation, I wanted to know how signatures of a perceived entity like social support, manifests on these formal social networks. This resulted in a framework

⁵www.reddit.com/r/suicidewatch

⁶www.reddit.com/r/depression

⁷<https://www.elefriends.org.uk/>

that uses a set of network metrics to measure the dynamics of support communities and the importance of individual actors for the health of this community.

This framework could bear significant potential impact on the problem of measuring health and utility of online forums.

3.2 Primer on online health communities

Recent work has proposed that online communities have the potential to influence health and health care sectors. Recent studies have suggested that the participation of people with long-term conditions (LTCs) in online communities (1) improves illness self-management [AVKR16], (2) produces positive health-related outcomes⁸ [MC12, PS15], (3) facilitates shared decision-making with health care professionals [BC11, IABS⁺17], and (4) may even reduce mortality [HBCF16].

There is also evidence that self-management support interventions can reduce health service utilization [PRS⁺14, TPE⁺14]. This is especially a crucial point as the world health services are facing the brunt of an ageing population.

Online communities have experienced an upsurge in popularity among people with chronic respiratory conditions such as cystic fibrosis [KM16], asthma [SLM⁺11], pulmonary hypertension [MMA⁺13] and chronic obstructive pulmonary disease (COPD) [WB13]. More than 15 million people in England suffer from a long-term condition or disability, and they account for at least 50 percent of all general practitioner appointments⁹. Thus, assessing how these online communities function, evolve and provide perceived support, can have important implications for health care sector. More so, understanding the dynamics of these online communities, have actual repercussions on how the platforms that host them, could become a better resource of self-management of LTCs.

On average, one in four people with an LTC who use the Internet tries to engage online with others with similar health-related concerns [Fox11]. In particular, it has been suggested that the value of participating in an online community lies in the possibility of gaining access to a range of people and resources quickly, easily [AH00], and anonymously [PS15], as well

⁸<https://bit.ly/2FLcs1F>

⁹<https://bit.ly/2EVFs9v>

as obtaining tailored information and emotional support [AFGG15, DSHF⁺17, SC16, Cou05, DSSBSM16]. However, most of this evidence comes from qualitative studies, whereas only recent years have witnessed an increasing interest in quantitative assessments of online communities as intervention mechanisms.

The potential future integration of online health support systems with formal health care provision should be underpinned by a better understanding of how they are used and by evidence of their effectiveness. Indeed, as suggested by the Medical Research Council [CDM⁺08], integrating online support systems with the more traditional health care provision would require the identification and comparative assessment of potential alternative intervention mechanisms.

With the clarity on the importance of online health forums for people suffering from LTCs, this chapter investigates the role of individual users and the inter-user exchanges in keeping an online health community functioning. We would like to know whether there are particular users who play crucial roles in the communities. What are some peculiar behaviours which differentiates users on support communities for others?

With this context, we aim to answer the **RQ1** and **RQ2**, which are:

RQ1 *What dynamics of support communities help them thrive?*

RQ2 *What differentiates **users** on support communities from generic ones?*

3.3 Dataset

This study was carried out in collaboration with HealthUnlocked¹⁰, the online forum platform that hosts the Asthma UK and British Lung Foundation communities. The data was aggregated, anonymised, and shared after proper Institutional Review Board and ethics approvals were taken to protect user privacy. The data was collected from registered users, who can choose to either write posts publicly or send private posts to one another. In the latter case, posts are shared between 2 users only, whereas when posts are written publicly,

¹⁰<http://www.webcitation.org/70Y10rppl>

a large number of users can become connected through threads of posts. In this study, I do not consider private posts. A thread is a series of posts made on one root post (RP), as a response to the root, or as a response to one of the responses to the root. This tree-like structure of posts can evolve indefinitely between posters and responders. For this study, user identifiers (IDs) were anonymized by the HealthUnlocked platform, and no demographic information was collected. The dataset included posts and their metadata (ie, the anonymized user ID numbers), user roles (eg, user, administrator, or moderator), date of posting, the hierarchical level of the post within the corresponding thread, and the dates on which the users joined and left the community. A sample of one such post can be seen in table 3.2. Both communities were moderated, and HealthUnlocked moderators (identified through metadata field "Role") were included in the analysis to assess their contribution and compare it with other users. Online communities on the HealthUnlocked platform benefit from additional functionalities compared to other online forums, such as built-in patient groups that moderate the content. In particular, the content accessed by users is tailored to their interests, and profiles highlight users' condition, chosen community, medications and treatments they use or find interesting. No data were collected on participants' characteristics, though only people declaring themselves to be older than 16 years were permitted to create an account and take part in the online communities. Table 3.1 summarizes the salient features of the dataset used for this work.

The datasets span, respectively, 10 years for the Asthma UK and 4 years for the BLF communities (see Table 3.1).

Despite the shorter time span, as a result of the larger number of users, the number of posts in the BLF community was higher than in Asthma UK, namely 875,151 compared to 32,780 respectively. Moreover, BLF users wrote a higher number of posts per user and were connected with a higher number of other users when compared with people in the Asthma UK forum (see Figure 2). In both communities, 60%-70% of registered users wrote no posts (ie, they were lurkers). Users who wrote more than one post contributed with a median of 8 (range 2-8947) and 5 (range 2-1068) posts in the BLF and Asthma UK communities, respectively.

| Dataset Properties | | |
|---|-----------------------|-------------------------|
| Property | AsthmaUK | British Lung Foundation |
| Time span of data | 02/03/2006-06/09/2016 | 13/04/2012-06/09/2016 |
| Total Time (weeks) | 548 | 230 |
| Total number of posts | 32,780 | 875,151 |
| Percentage of posts with at-least 1 reply | 87.3% | 93.1 % |
| Total number of users | 3345 | 19,837 |
| Users who contributed > 1 posts (%n) | 722 (21.6) | 6628 (33.4) |
| Users who contributed exactly 1 post(%n) | 331 (9.8) | 1186 (6.0) |
| Registered users who never posted (ie, lurkers), n (%) | 2292 (68.5) | 12,023 (60.6) |
| Number of posts per user, $\mu(\sigma)$ | 14.2 (55.0) | 66.9 (75.1) |
| Number of posts per users who posted >1, median (min - max) | 5.1 (2-1068) | 8.0 (2-8947) |
| Number of posts per users who posted >1, mean (SD) | 20.4 (65.6) | 88.1 (458.6) |
| Posts contributed by top 1% users by activity, n (%) | 10,457 (31.9) | 426,198 (48.7) |

Table 3.1 Salient statistics for the data acquired from AsthmaUK and BLF forums.

The number of official moderators among the highly active users was negligible; there were no moderators in the top 5% contributors to BLF and only 2 in the top 5% for Asthma UK. Thus, our network analysis predominantly reflects content originated from registered users. This also means that moderators on these forums have more of an observatory role and do not engage in active support.

When classified according to posting activity (ie, number of posts written to the forum), the top 5% users contributed to a substantial proportion of all posts: 58% and 79% in the Asthma UK and BLF communities, respectively. In the context of this thesis, *Superusers* were those who made high number of connections (exchange of messages) with other users across the lifetime of the community.

| Field | Sample Value |
|----------------------|---|
| Body | <i>"5 years ago i was diagnosed with emphsima asthma and copd after being rushed into intensive care. Since then ive had the inhalers and tablets but never really been able to talk to someone about my experiance so any help or advice would be very much apprieciated i have felt very lonely and frustrated at times with this complaint as getting used to not being able to do what i could is the worst part. I am 58 and always thought i knew about life but im lost with this. It seems my life is all about thinking of how i am going to be feeling when i get up in a morning."</i> |
| AuthorId | VVpb (anonymised) |
| Title | <i>"What is breathe easy?And any advice on copd please"</i> |
| SuperRecipientAction | "N/A" |
| Action | Level 0 post |
| ThreadId | q5XXV |
| Date | 2012-06-09 09:53:15 |
| PostId | q5XXV |
| Recipient | N/A |
| Role | N/A |

Table 3.2 An example of a record from Health unlocked British Lung Foundation forum. The fields describe meta data about the post, such as timestamp, PostId, AuthorId etc. The data also contains the main body of the post as well as meta information about the conversation structure. In this case, the post is a root level post. Hence the recipient field is "N/A" and the Action field contains "Level 0 post".

3.4 Graphs and their metrics

To understand the dynamics of these communities and their interaction structures, I convert the data from all the exchanges of messages between users into graphs. In these graphs the users are represented by nodes and messages are represented by edges between users. More formally imagine a directed graph $G(V, E)$ involving a set of users $V_i \forall i \in N$ where N is the total number of users interacting on a health community. For every message exchanged between a user i and a user j we create an edge E_{ij} . By this method the complete community would form a global graph based off total interactions between all pairs of users, which we call a global graph G_g . Similarly we may decide to only consider the users which exchanged messages on one particular thread. Such a graph is called a thread graph G_t .

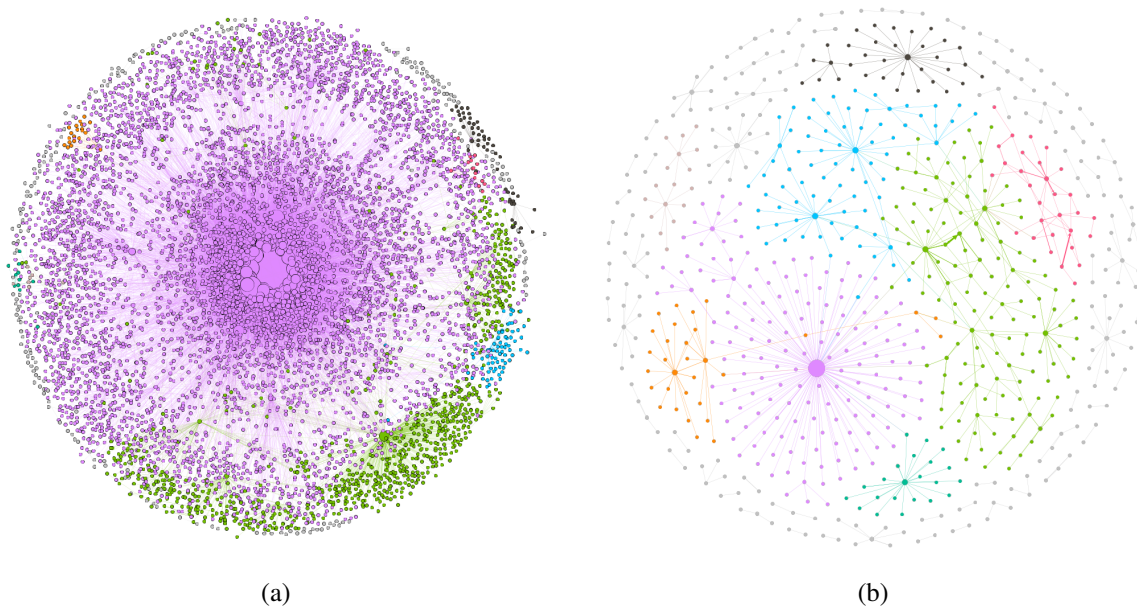


Fig. 3.1 Global graphs prepared from Asthama UK community3.1b and BLF community3.1a. The size of the node corresponds to the degree of the node and the color corresponds to the community membership

These graphs abstractions (G_g and G_t) represent the interaction structures which we intend to dissect. To understand the behaviour of these users, I evaluate several metrics on these graphs in order to understand the utility of these communities in terms of activity of sharing and support.

Degree distributions and connectivity

When you have a collection of nodes, connected to each other by edges, it is worth understanding how connected an average node is. More specifically, we would like to know the distribution of degrees, or the amount of edges a node has, across all the nodes in a graph. This metric is called the degree distribution of a graph, and it has been widely used in the complex networks literature as a measure to characterize types of graphs [MPP⁺13, AHK⁺07, LBKT08, RJC⁺19]. We are specifically interested the nodes(users) who belong to the highest 1% range of degrees. These users are the ones who are most

interactive and have established edges with a lot of other users by exchanging messages. These users are called “superusers”.

Largest connected component

A largest connected component of a graph $G(V, E)$ is the largest possible sub-graph $G_L(V_L, E_L)$ of G , such that each node in G_L has at least one valid connected path to every other node in G_L . By evaluating the largest connected component on G_g , we can find the subset of users in the community which form a cohesive community. Furthermore, by measuring the effect of removal of certain “superusers” from this sub-graph on the overall size and structure on G_L , one can deduce the importance of the said users to the cohesiveness of a community. We can also measure the characteristics of the largest component on a temporal basis. By examining the fraction of users in a given week that belong to the largest connected component, one can estimate the focused and cohesive nature of interactions.

Social capital and triadic closure

According to the literature, social capital is defined as those features of social structures, such as interpersonal trust and norms of reciprocity and mutual aid, which act as resources for individuals and facilitate collective action [CDSLS93, Col88] It is common to quantify social capital in the context of social networks, by looking at structural holes, or unmet potential social links in the network. This is where ties between otherwise unconnected neighbours are filled in, sometimes called as closures, thereby benefiting the broker and the two neighbours by adding an extra link for information to diffuse. Such mechanisms have been studied in the sociology literature for decades. Work by Granovetter [Gra77] explored these structural holes and proposed that they are detrimental for efficient diffusion of information and resources in social networks. He also at times called these the “forbidden triad”, referring to their propensity to close up in social networks. Such closures are, according to Ronald Burt [Bur04, Bur09], necessary for information brokerage, and at times directly equate to social capital of these broker nodes. In our case, as so much evidence has shown that the

brokers of social support are often the superusers, we would certainly want to investigate how these users affect the cohesion and structural holes in the graph.

3.5 How do support communities thrive ?

To answer the **RQ1**, it is first worth asking how the user interactions bind the community together. We would like to know if the messaging activity is highly concentrated around a few sets of users or is it covering a large fraction of the user base. More so, it is worth asking if there are any special users who bear the mantle of providing support. This can be observed from the measured metrics of the interaction graph. From table 3.1, it is evident that a minority of users are generating a bulk of data on these communities. E.g. the top 1% users by activity contributed 32% posts to AsthamaUK community. Such level of activity makes these users extremely important in understanding the dynamics of support on these communities. We term these users as “Superusers”. But before looking at the role of these superusers, it is first worth analysing the overall activity patterns on these communities. Do these communities drive enough engagement and activity to sustain them over long periods of time?

3.5.1 Temporal activity patterns

To calculate the activity patterns of users on these forum, we first work with the most basic of proxies, which is the weekly/daily activity. We arrive at it by calculating the amount of messages exchanged in a community across the whole life cycle of the data. This metric would expose how much activity is happening on a daily or weekly basis on a particular community. It is worth noting that this activity pattern would also shed light on how users are engaging with the community. A continuous engagement is good for the vitality of a community, however if a community revolves around purely functional interactions, you may see a bursty nature of user activity across time [PB15].

Figure 3.2 shows the activity patterns on both the health communities on a cumulative and weekly basis. It was quite evident that the BLF community was more active of the two,

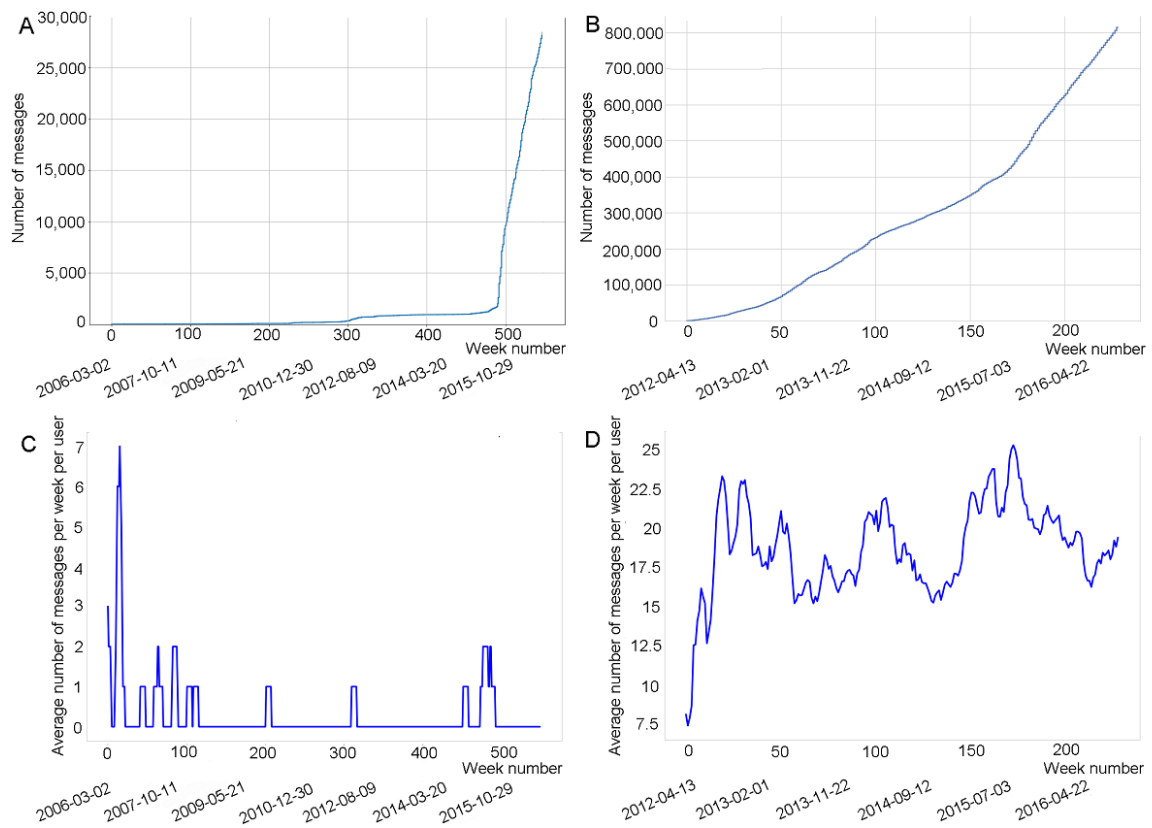


Fig. 3.2 Cumulative distributions of the number of posts as a function of time (weeks) within the Asthma UK (A) and the British Lung Foundation (B) communities. Calendar dates are reported below as week numbers (since the inception of the community). Panels C and D illustrate the average number of posts per user per week within Asthma UK and British Lung Foundation, respectively

in that, the community exhibits a consistent engagement by the users across the lifetime of the data as well as on a weekly basis. The Asthma forum however shows a bursty nature, despite being more than twice as old as the BLF community. One possible explanation can arise from the nature of these two illnesses. Asthma tends to be an episodic disease, with flare-ups in patients happening from time to time. These flare-ups are also often seasonal in nature, happening in sync with the pollen cycles in the air [DTLB12]. On the contrary, the British Lung Foundation forum deals with, alongside Asthma, diseases that are chronic in nature such as Chronic Obstructive Pulmonary Disorder (COPD) and Emphysema. This

means these patients are constantly activated and tend to engage with the community on a more frequent basis.

3.5.2 Cohesive conversations

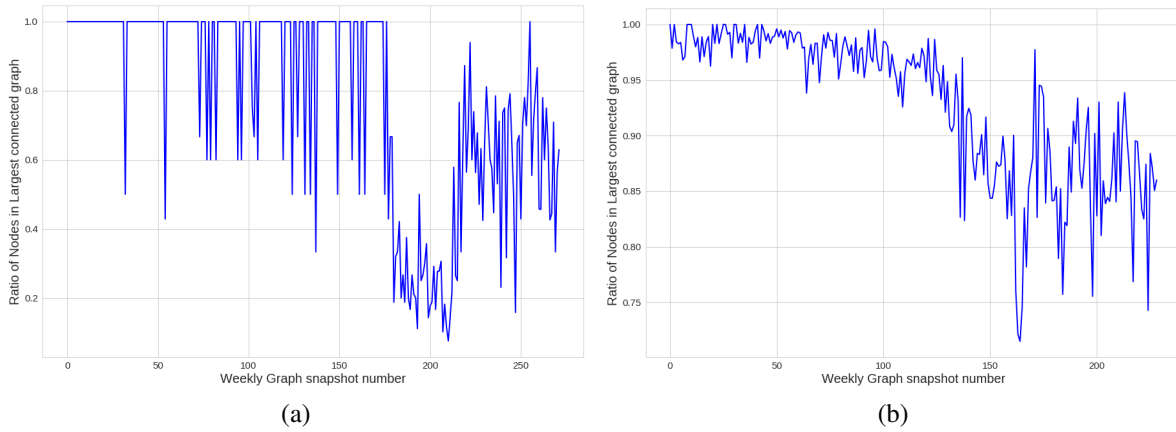


Fig. 3.3 Fraction of users that are part of the largest component as a function of time (weeks) for Asthma UK 3.3a and the British Lung Foundation 3.3b.

To understand the first aspect of the community's resilience, I examine how is the coverage of communications between the users, on a weekly basis, given that messages are exchanged between the most active users within that week. To do so, imagine a sorted list of message interactions over a particular time period T_k , sorted in chronological order defined as $L_k = [E_{ij} \forall i, j \in N]$, where E_{ij} is a message between user i and user j , with N total users being active in a given time period T_k . Now imagine this time period T_k is of 7 days. I calculate such K lists for the K weeks the community has been active. For each such list, I induce a graph $G_k(V, E)$ such that the nodes in V are the active users in that particular list, and the edges in E are corresponding to the messages exchanged in the list L_k between any two users. Now for each such graph G_k I calculate the largest connected subgraph $G_{\theta_k}(N_k, E_k)$ such that all nodes in N_k have at least one path between them. Calculating the fraction $\frac{N_k}{N}$ would give us the total fraction of users who are part of the same conversation network for a given week. After calculating and plotting these fractions across a total of 250 weeks for each community, we see that whenever there is an activity on these networks, almost always,

the active nodes belong to the largest connected sub graph. This implies that activity on support forums is cohesive and even if bursty at times, is all encompassing with the users.

It is worth noting that as the activity on the communities increases, you see an increase in fragmentation of the graph structure with the ratio of nodes in the Largest component dropping considerably (See figure 3.3a and 3.3b). Which means there are concurrent discussions happening with disjoint set of users.

3.5.3 Fragile global structure

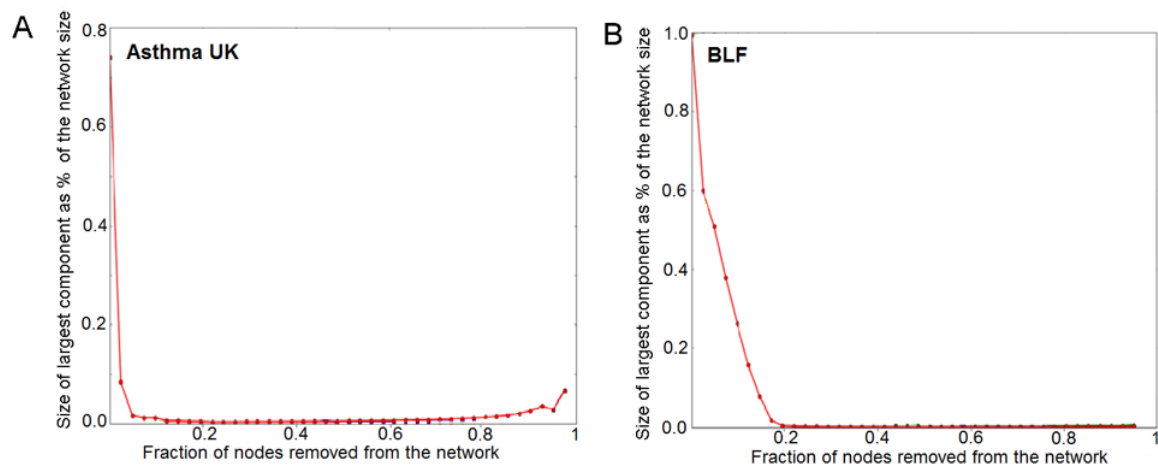


Fig. 3.4 Results of progressive removal of superusers. Both communities collapse drastically, in terms of connectivity, with BLF showing a marginally more resilience

Despite the exchange on a weekly basis is quite cohesive, it is pertinent to understand the resilience in terms of user responsibility in helping, in order to examine the health of such a community. Moreover, I want to know if the conversation network is held together by a more or less uniform contribution of nodes, or if there is a skew in the responsibility of nodes. This can be tested by using the sensitivity analysis methods, popular in the network science [BDSZ16, AJB00], which measures the network's capacity to diffuse information as you remove nodes based on certain property. In our case, we want to understand the importance of the *Superusers*, or the users who are disproportionately more active. Hence we begin by first sorting all the nodes in the macroscopic graph $G(V, E)$ in order of their degrees. The degree of a node in the global graph is proportional to the diverse set of users

that node has communicated with, over the period of the community's lifetime. We then start removing nodes from the top, by progressively removing nodes in increments of 1%. I then compute the size of the largest connected component G_k and compute the ratio of number of nodes in G_k as compared to the original global undisturbed network. Figure 3.4 shows the performance of global graphs of both the communities to this attack. It is worth noting, that what we observe is that a top 10% nodes by activity are responsible for most of the cohesive connectivity of the community. This also means that the top 10% of these nodes have the most diverse connections in terms of number of users contacted. This gives hope to health care industry, since these nodes can act like efficient information diffusers, if used in a targeted fashion.

3.5.4 Anti-rich conversations

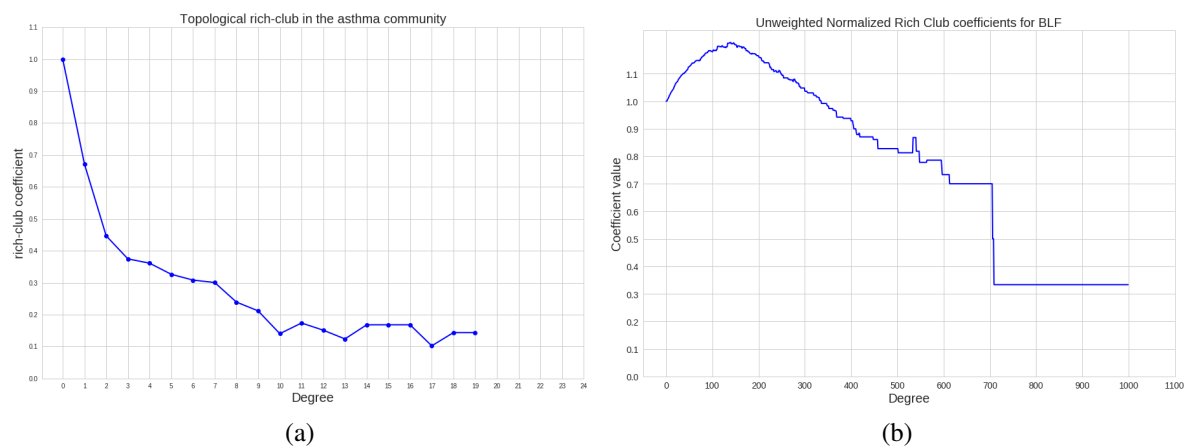


Fig. 3.5 Plots of rich-club coefficients for each viable degree in the respective communities. Both communities exhibit values less than 1, indicating an anti-rich behaviour by the well connected nodes.

The “rich-club” coefficient is a metric designed to measure the extent to which well-connected users tend to connect with one another, to a higher degree than expected by chance [CFSV06]. To this end, for each value k of a node's degree (ie, the number of other users a given user is connected with), we computed the ratio between the number of actual connections between nodes with degree k or larger and the total possible number of such connections [OCPR08].

We then divided this ratio by the one obtained on a corresponding random network with the same number of nodes and degree distribution (ie, the probability distribution of the degrees over the whole network) as the real network, but in which links were randomly reshuffled between nodes.

Formally let $G(V, E)$ be a global graph representation of the community. Let $V_{>k}$ be the set of vertices in the graph having degree higher than k . Let there be $N_{>k}$ such vertices having $E_{>k}$ edges between them. In such case, the rich club coefficient for degree k in the graph G is given by

$$\phi(k) = \frac{2E_{>k}}{N_{>k}(N_{>k} - 1)} \quad (3.1)$$

In this equation $\frac{N_{>k}(N_{>k}-1)}{2}$ represents the maximum number of edges possible between $N_{>k}$ nodes. These coefficients are highly dependent on the size of the network, which makes them hard to compare. So I normalize the network by comparing against a random null model of rich-club coefficients $\phi_{rand}(k)$. This is obtained by generating an ensemble of random networks, each having the same degree distribution as that of G , but with links randomly placed. The ratio $\frac{\phi(k)}{\phi_{rand}(k)}$, gives us an un-correlated trend about the rich-club effect in G .

Thus, the rich-club coefficients may take values lower or higher than 1, depending on whether the real network has a higher or lower tendency to coalesce into rich clubs than randomly expected. In particular, networks that display a high rich-club coefficient (ie, greater than 1, are also said to show a “rich-club effect,” namely the tendency to organise into a hierarchical structure in which highly connected nodes preferentially create tightly knit groups with one another [MdfCC07]. .

In most previous studies the rich-club coefficient in the technical and real world networks exhibits values larger than 1 as the degree of a node goes up. This shows a propensity to create rich-clubs, with highly connected nodes preferentially connecting with other highly connected nodes. Thus these networks exhibit exclusive clubs of (topologically) rich nodes, as illustrated in previous work [ZM04, CFSV06]. What we observe however in the cases of support communities is that in general we end up with a less than 1 rich-club co-efficient as the value of degrees k goes up. This means, rich nodes are exhibiting an anti-rich behaviour,

where nodes which have a higher degree prefer in engaging with new nodes with lower degree. This implies an active information exchange from a well connected node to a sparsely connected node, which we would expect in a supportive interaction according to the definition of social support.

3.6 What differentiates users on support communities from generic ones?

Once we establish that these support communities are thriving and are providing what seems to be an active supportive environment for the users(anti-rich superusers), it is worth delving into the analytical methods for quantifying these supportive interactions. More so we would like to have concrete metrics that characterize a given community as a supportive one. To do so we need to understand how are the users on these communities driven to help each other, and whether there is a correlation between the “richness” of a user, as defined in previous section, and its propensity to help. More so we would like to know how consistent are these so called “rich” users in providing support.

3.6.1 Propensity to help

We would like to understand how users on support communities, as a group behave as they become more seasoned. Fortunately, there is an approximate way for us to capture a user’s role as a support seeker and as a support giver. As described in Section 3.3, the forum activity consists of a root poster, asking a question to the forum board, and the members responding to that question in a cascaded fashion. These responses, along with the original question constitute what is called as a *thread*. To that end, we define the following two roles on these communities¹¹

¹¹There are other ways to qualify someone as support giver/seeker, mainly using language structure, but here we consider only the bare minimum requirement to be considered as one, using the position in conversation structure

In the context for support forums, a support seeker is a user who begins a thread by posting on the forum, a question, or a query, to which others may respond to. Similarly a support giver is a user who responds to any post by a support seeker.

With this in mind, I aim to model the behaviour of users on these support communities in terms of being a support giver or a support seeker.

We first begin by calculating the average number of questions per user and answers per user across the dataset, by finding the mean number of questions and answers posted by any user on the forum. We consider an expected probability of answering a question by a user as P_a as $2/3$ and the probability of posting a question as P_q as $1/3$. With this information we modify the definition of “Z-score” to quantify the expertise, used by Adamic. et. al [ZAA07] to arrive at the expression of expertise in the context of our support community.

A user has two possible actions at any given time, while interacting with the community. They can either post a question on the forum, or answer to existing questions. The probability of doing either actions are P_a and P_q respectively. To that end, we try to model this interaction process as a Bernoulli process with two outcomes, having asymmetric probabilities.

Proof 1 Consider a Bernoulli process for a user to choose to answer or post a question on the forum, with asymmetric probabilities for answering (P_a) and posting a question (P_q). For any user i the total number of posts n_i are the sum of total number of questions posted q_i and answers posted a_i and $n_i = a_i + q_i$. For a Bernoulli process the variance for the whole forum is given as:

$$\sigma_{forum} = \sqrt{nP_a(1 - P_a)}$$

$$\sigma_{forum} = \frac{\sqrt{2n}}{3}$$

Similarly the mean for this process can be written as :

$$\mu_{forum} = nP_a = \frac{2n}{3}$$

Z_{score} of a random variable X is defined as

$$Z_{score} = \frac{X - \mu}{\sigma}$$

Substituting the values for σ_{forum} and μ_{forum} inside the expression for Z_{score} we arrive at the modified Z-score as

$$Z_{score} = \frac{a - 2q}{\sqrt{2(a + q)}} \quad (3.2)$$

Equation 3.2 depicts the modified notion of Z-score for the question answering process of our support community. I calculate this particular metric for each user in both the communities based on their posting history.

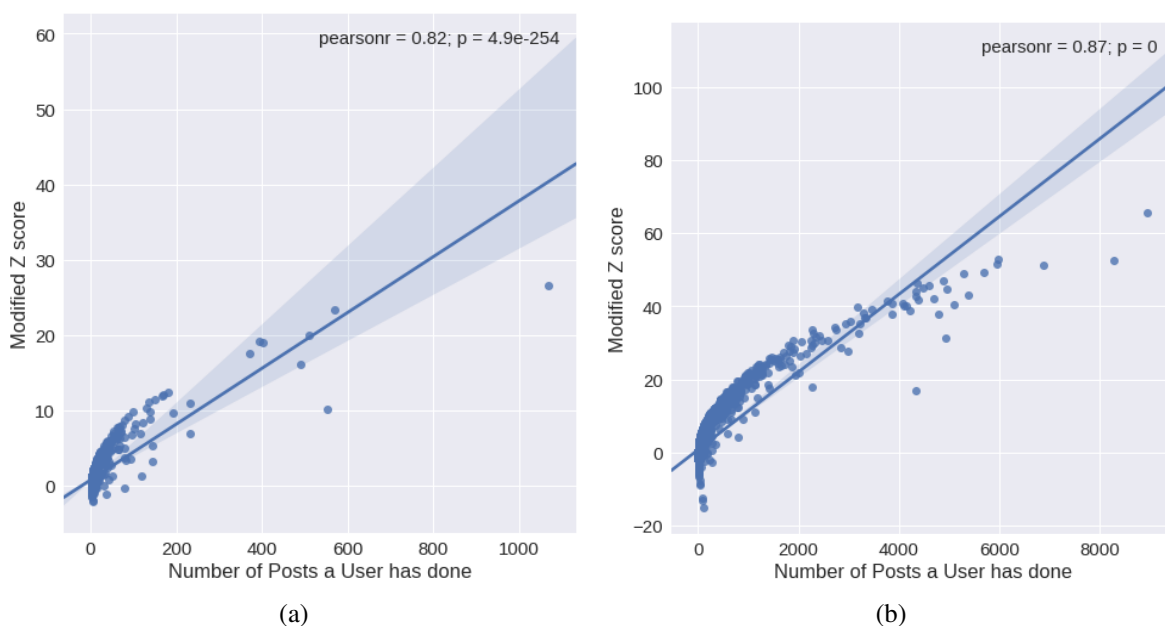


Fig. 3.6 Scatter plots for the Z_{score} values for (a) Asthma UK community and (b) British Lung Foundation community. Both communities show a strong positive correlation between a user's activity and their propensity to answer questions.

I then find the correlation between a users Z-score and the total number of posts a user has done in their lifetime on the forum. Figure 3.6a and Figure 3.6b shows the results of this analysis for both the communities. It is quite evident, that as the users become more seasoned and post more actively, they are more likely to answer on questions rather than

post new ones. This also implies that based on the rich club results from Section 3.5.4, these communities are thriving not only for the “rich” users, but also for the sparse users. Users on these communities are more open to new members and provide active support to them. Developing metrics like this makes quantifying whether a particular community works for the subscribers a tractable problem.

3.6.2 Superusers and structural holes

One of the key aspects of utility of any social network is driven from the social capital offered as a result of the subscription.

Till now we looked at the global macro structural properties of this support graph using the global graphs G_g , where we look at the user’s interactions with other users across the lifetime of the community. But often the supportive interactions happen in a lifetime of a single thread, revolving around a topic or query. So to examine the effect of the superusers on the social cohesion, we correlate the total number of posts done by super users on any given thread, to the amount of closed triangles found in the corresponding thread graph G_t .

The resultant scatter plot can be seen in Figure 3.8, where we can see a net positive correlation of 0.44, with a very low p-value. This means there is a general trend of higher triadic closures in a conversation, with the amount of rich user participation.

3.7 Discussion

In this chapter, we found that support communities show peculiar temporal and interaction dynamics. **RQ1** asked about the dynamics of support communities. We find that support communities exhibit a high level of engagement and participation. The communities are held together by the superusers. The removal of these superusers, collapses the network structure of these communities. **RQ2** asked about differentiating properties of users on support communities. We find that the users exhibit an anti-rich behaviour. This means that the superusers are engaging with less active users and are practising inclusion. We also find that users on support communities progress onto being support givers from support seekers

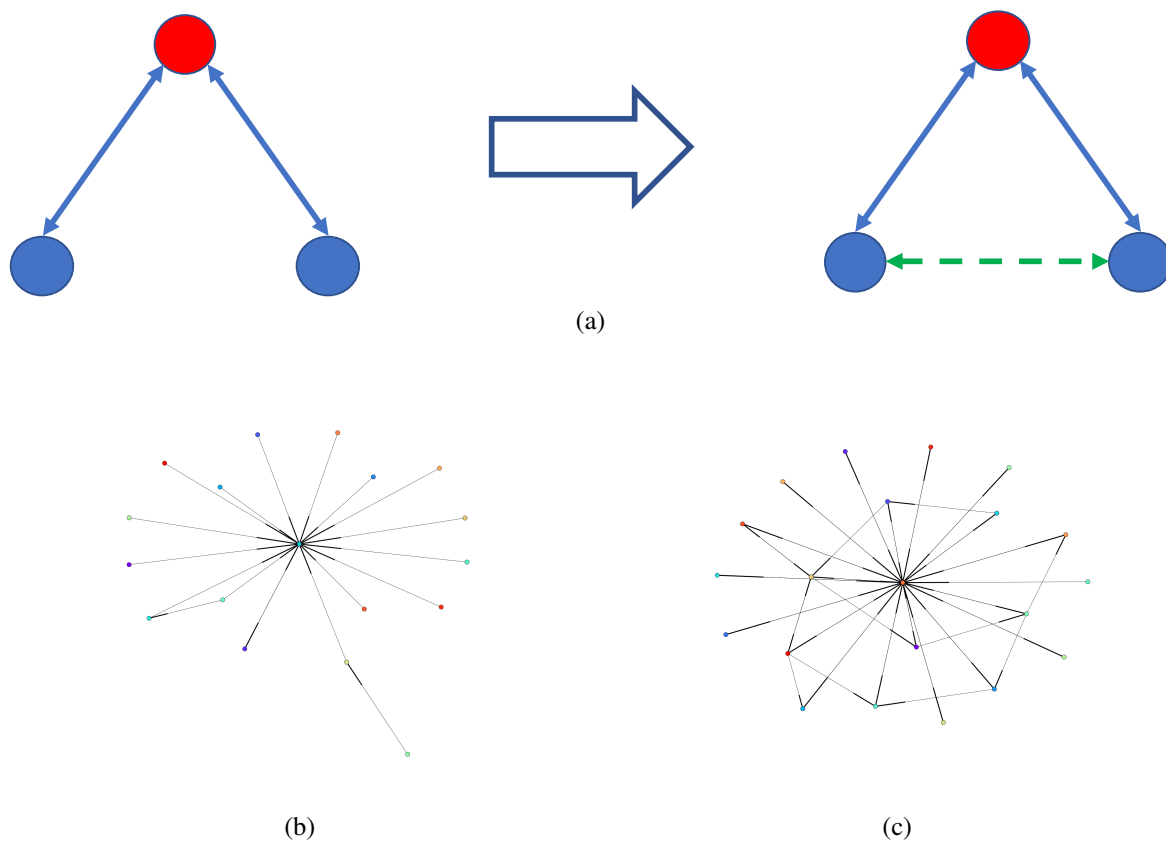


Fig. 3.7 Figure 3.7a shows an example of closure among three nodes, where a structural hole between a cluster of three nodes is closed by addition of the green link. Figure 3.7b shows a thread level interaction graph showing lots of structural holes between participating nodes. On the other hand Figure 3.7c shows an example of a thread level interaction graph where a superusers have contributed multiple times. The graph with multiple superuser contributions tend to have larger amount of triadic closures.

with time. The idea of perceived support stems from the fact that the user in distress is not only getting the crucial information about the disease, but also benefits from the social capital of the allied users. We observe that superusers tend to have a positive effect on the social capital of a conversation, promoting more social cohesion.

There is immense value in understanding how social support thrives on the internet, especially because of its potential to relieve the load off the ever so burdened health services. The work till now focussed on the global interactions of support givers and seekers on a community. It investigated the dynamics of support communities and looked at individual user's role in the larger scheme of things.

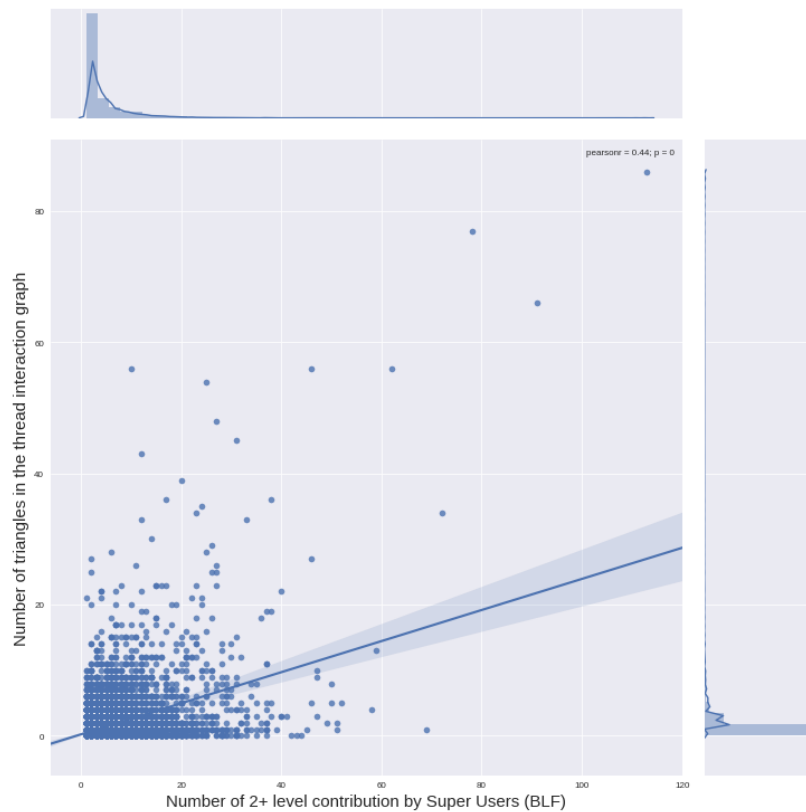


Fig. 3.8 Scatter plot between the number of closed triangles in a conversation thread, with the total number of posts done by a superuser in that thread. A positive correlation of 0.44, with a p-value of 0 is observed. This indicates that the presence of a super user in a thread improves the over all cohesion of that thread and closes structural holes

In the next chapter we would explore the role of the conversation structure from the scale of an entire conversation(macro) and from the scale of the immediate local interactions in the ego network of a user(meso). This goes beyond looking at the individual actors of support, and quantifies the peculiar structure of a supportive conversation on the web.

CHAPTER 4

FROM COMMUNITIES: SIGNATURES OF SOCIAL SUPPORT

The global structure of social support communities allude to the fact that these communities are exhibiting some mechanisms different from generic communities, which facilitate exchange of social support. They also seem to have an effect on the cohesiveness of the communities. In the previous chapter, we saw the behavioural signatures of support groups. The utility of ‘rich’ users who are the most active and promiscuous when it comes to responding. We also quantified the dynamic of evolution of users from support seekers to support givers. We measured the way brokerage of superusers works in providing closures in the conversation threads, adding more closed triangles between participants of a conversation as superusers contribute.

These results make it relevant for us to investigate the signatures of social support when it comes to individual conversations on the web. Quantifying how support manifests in terms of the structure of conversation might give us more insights in how online support can be moderated and nurtured properly as an augmented channel for the health care sector. This may also help us with feature engineering, if we need to automate the process of detecting and tackling online toxic behaviour.

Inspired from the DIKW pyramid, we have now experienced the transformation of raw social network interaction data into abstractions that bring out peer to peer interaction patterns as well as the structure of dialogue between users. We have also extracted the knowledge about emergent behaviours of users using topological metrics. In this chapter we will zoom in

from the global perspective and look into the conversation level (macro) and neighbourhood level (meso) structures of support.

A valid criticism of the results from Chapter 3 is that they were derived by analysing a support community that is highly moderated. This sort of moderation is often absent on most popular open online platforms. One such popular and open platform is Reddit¹. Reddit offers its users, anonymity, and very limited moderation. The limited amount of moderation comes from volunteers appointed by a particular community, which is called a sub-reddit. A sub-reddit is a sub-section of Reddit, which is a topical community, where only topical conversation threads can be posted. Any user can subscribe and post to such a topical sub-reddit, provided they abide by the simple rules of the sub-reddit. For example, if a sub-reddit deals with politics, like *r/politics*, one must make sure that the threads posted on this subreddit deal with political subject matters. There are several sub-reddits on this platform that deal with peer to peer support. A few examples include *r/SuicideWatch*², *r/Depression*³, *r/Bipolar*⁴. Utility of these communities in providing support, and a place to vent have been explored before [DD14, DCKD⁺16]. However, in the context of my dissertation, I want to understand how such peer to peer support mechanisms are manifested in the dialogue structure. To do so, I need to look at these conversation threads from an over-all structural perspective(macro) as well as from a user-centric perspective(meso).

4.1 An argument for studying mental health forums

The new platforms like facebook and reddit have become so ubiquitous, that some research suggests that they might be affecting our broader psychological state [CLPS12]. But on the positive side, studies have also proposed different ways in which this medium could be used for measuring and intervening in the matters of mental health [DCKD⁺16, DD14]. These platform define the way humans interact in the present age, and developing an understanding of their effects and utility is of high importance. Reddit is one of the largest

¹<http://reddit.com/>

²<https://www.reddit.com/r/SuicideWatch/>

³<https://www.reddit.com/r/Depression/>

⁴<https://www.reddit.com/r/Bipolar/>

online communities which contains a number of topical sub-communities. On this platform, several subreddits are specifically tailored to mental health-related topics, such as *depression*, *anxiety* or *alcoholism*. These fora offer a unique opportunity to study the way people describe or discuss their problems in their own voice. This has motivated several researchers to probe the different aspects of support online, like language [CK17], anonymity in social support [DD14] or risk factors [Gko17]. Recent studies have shown promising results in modelling and measuring signals and patterns in reddit communities related to mental health. For instance, statistical relations of mental health and depression communities with suicidal ideation have been studied [DD14, DCKD⁺16]. The authors explored linguistic and social characteristics that evaluate user's propensity to suicidal ideation. Approaches to classify reddit posts as related to certain mental health conditions have also been successfully developed, showing that there are certain characteristics specific to mental health-related topics in posts that can be automatically captured[Gko17]. Furthermore, in a study focused on reddit posts related to anxiety, depression and post-traumatic stress disorder, the authors show that these online communities exhibit themes of supportive nature, e.g. gratitude for receiving emotional support[PCC18]. Positive effects in participation in such fora have also been shown by improvements in members' written communication[PC18]. The supportive nature of comments in the SuicideWatch forum has also been studied by automatic identification and classification of helpful comments with promising results[KRMH⁺16].

One of the most challenging, and devastating, global mental health concerns is suicide. Suicidal behaviour includes any thoughts, plans or acts someone makes towards ending their life. In health care services, preventing death by suicide is a priority, but accurately predicting whether or not someone is at risk of committing suicide is difficult. Moreover, a large proportion of deaths by suicide occur in populations that have never been seen by health service providers. Several online platforms are used for expressing suicidal thoughts and reaching out for support. On Reddit, the subreddit *SuicideWatch* currently⁵ has almost 94k subscribers, and is a lightly moderated forum that is intended to offer peer support for people at risk of, or are worried about others', suicidal behaviour. The moderators take the intent of

⁵As of 27th June 2018

peer support seriously, and are governed by guidelines that prohibits false promises, abuse, tough love and other clinically frowned upon methods of conversations⁶ This setup gives us an ideal petri-dish to measure what constitutes a supportive conversation. More specifically, owing to the results from Chapter3, we would like to develop methods that would allow us to understand the macroscopic and mesoscopic signatures of support. Formulating this problem needs to follow the methodological framework discussed in Chapter 1, whereby we collect the necessary data and device appropriate abstraction/s, to quantify how the macroscopic and mesoscopic signatures of support in these conversations manifests. These signatures could be captured using different metrics that signify a particular behaviour of interaction.

4.1.1 Research questions

Most previous studies have aimed at dissecting the *content* of posts and their characteristics in relation to other posts. One important aspect of online communities is its supportive *function* – users turn to these platforms not only to express their thoughts and concerns, but also to receive support (instrumental or perceived) from the community. In the previous chapter, we looked at how the supportive functions of these communities is facilitated through the super users and how these actors influence the structure of this community. But this structure was explored from a global perspective, where all the users on the community were networked based on their interactions between each other. However, on a conversational level, these interactions may manifest different structural signatures as compared to the global level.

This motivates our investigation of the networks at the conversational level by looking at the entire conversation (macro) and at the immediate interactions between neighbours (meso). In this chapter we would like to ask the following research question, as discussed in Chapter 1

RQ3 *What differentiates interactions on support communities from generic ones?*

⁶<https://bbc.in/24rJYQH>

| Terminology | stands for |
|-------------|--|
| <i>RP</i> | Root post which begins a new thread on a subreddit |
| <i>OP</i> | Original poster who posts the Root post for a thread |
| <i>SW</i> | The suicide watch Subreddit |
| <i>FP</i> | Front page of Reddit. |

Table 4.1 Notations and Terms.

To model the interactions in an online community, we represent each conversation happening over these forums using graph-based abstractions (user graphs and reply graphs) as described in Section 4.3. To measure global structure of these conversations, we use network topological metrics such as centrality: which measures importance of nodes in a network in terms of relaying information, branching factor: which measures how a conversation fans out over time, return distance: which measures how soon do users return back to the conversation and symmetric edges: which measures reciprocity of users in a conversation. To measure interactions amongst immediate neighbours of the users (mesoscopic view), we measure inter response times: which measure urgency of response to a message, semantic alignment between messages and local interaction motifs known as Triadic motifs. These novel motifs give an idea about how distinctive are interactions between subgroups of users, when compared against graphs obtained from baseline conversations.

4.2 Data

Reddit is a platform where a user can create a post on a subreddit, and other reddit users can interact by posting at different levels of the thread or by up or down voting posts. We analyzed root posts in the SuicideWatch subreddit (SW)⁷, building on the work of Gkotsis et al. [Gko17]. We crawled SW to get hierarchical threaded conversations, by iteratively pursuing each conversation at progressively deeper levels until the whole thread had been obtained.⁸ This resulted in a dataset of 50,754 SW threads totalling in 419,555 individual posts. To provide a baseline against which to compare nature of conversations on

⁷<https://www.reddit.com/r/SuicideWatch/>

⁸The code to crawl reddit for threads can be found at <https://github.com/sagarjoglekar/redditTools>

| Field | Sample Value |
|----------------------|--|
| Body | "Distress phone lines can be a really great resource for both you and your friend and his mom. Also I'm not sure if they have this service in your area but where I live, they have what is called the "mobile response unit" which is basically a mobile crisis response unit of nurses, social workers and mental health counsellor who will come to a person's house and do a mental health assessment on them and determine who the best course of action is from there.." |
| AuthorId | Perrythepervypus |
| Destination AuthorId | ETKMMMFA |
| Thread depth | Level 0 |
| ThreadId | 2elozq |
| Timestamp | 1409066895.0 |
| Up votes | 2 |
| Down votes | 0 |

Table 4.2 An example post from the SuicideWatch community. The post text is accompanied by a timestamp, author id, number of up votes, downvotes. The post is also accompanied by the depth at which the post occurs, which helps us to capture the conversation structure of the thread

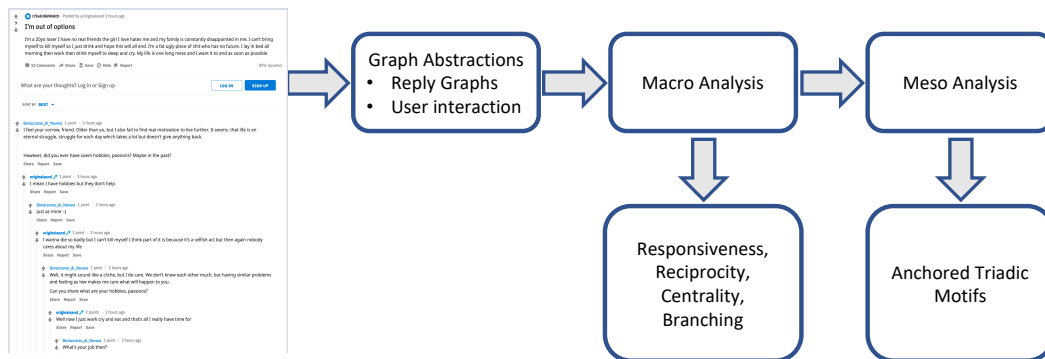


Fig. 4.1 A reddit thread is converted into abstractions (Reply graphs and User interaction graphs). Macroscopic and mesoscopic analysis is performed on these graphs, and statistical over- or under- representation of these metrics is evaluated.

the SW sub-reddit, we need an equally large sample of conversations from posts done on the thousands of other non-support sub-reddits. To that end, we acquired a similar number (49,773) of baseline threads from any other subreddit popular enough to land on the frontpage (FP). These posts have gathered enough engagement to bubble to the frontpage, and belong to a vastly diverse set of sub-reddits.

Comparing the suicide watch threads with the baseline, gives us confidence over our network metrics, and any claims made there forth. The two conversation datasets from *r/SuicideWatch* and *Frontpage* are very similar in terms of macro statistics. For example the median amount of responses for a *Suicide watch* thread were 6 and for baseline *Frontpage* posts were 8. The median conversation depth (the depth of the hierarchy of the responses) is 2 for both the datasets. The median amount of unique authors participating in a post are 2. Owing to the long tailed nature of the datasets, we perform our analysis on threads which have been conversed on at least 5 times. Which means we consider graphs which have more than 5 posts on the root post. This results in our datasets to shrink to 25k threads for *SuicideWatch* and 30k threads for *Frontpage*. We further clean the dataset, by removing threads where the root author has deleted their user account, which is a common practice to preserve anonymity in more controversial posts. The resulting dataset has 20k threads in *Suicidewatch* and 23k threads in the *Baseline*.

4.3 Abstractions

To understand the dynamics of supportive conversations, we first need to formalize the abstraction of networked conversations as well as the content posted in these conversations. In case of forum based platforms where users interact in a nested dialogue fashion, and original poster or *OP* posts a start of a thread. This thread is then open for comments by all the community users. In case of *Reddit*, such a community is called a *Subreddit*, which is a moderated collection of users who subscribe to it. These users may post new threads onto the *subreddit* as far as the post follows the *subreddit* rules. Enforcement of these rules is the responsibility of the moderators. The user who starts a thread is called the *Original Poster* or **OP** and the headlining post which the *OP* begins with is called the *Root Post* or *RP*.

Reply Graphs

The first abstraction mimics directly the structure of conversation threads on *Reddit*. These abstractions are called *Reply Graphs*. We formulate a reply graph $R\{P, E, W\}$ as a thread of

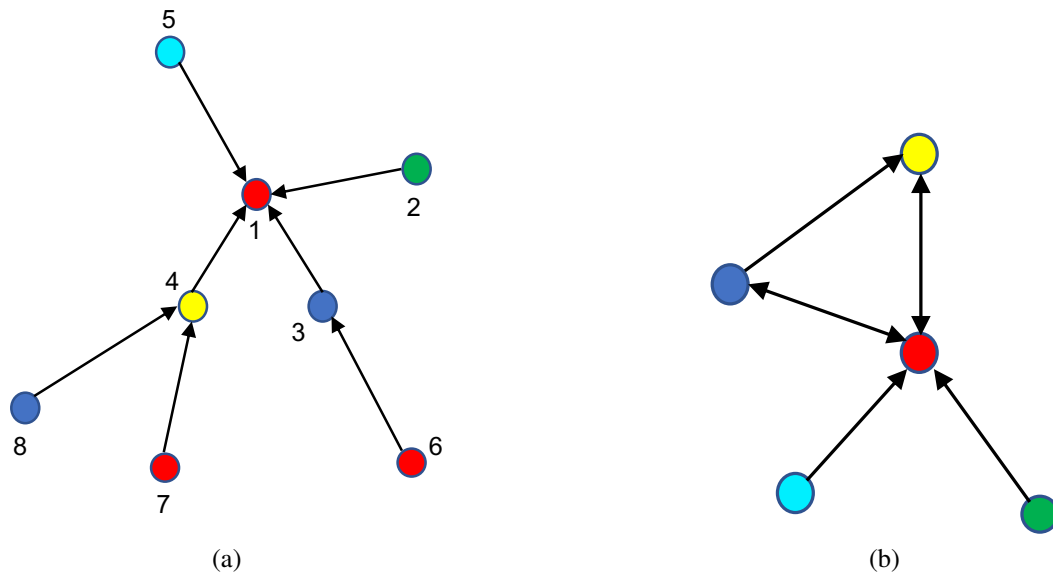


Fig. 4.2 Figure 4.2a shows a sample reply graph constructed from a real thread in SW that contains 8 posts by 5 unique users. Each node represents a post and a directed edge is drawn from one node to another node when the first node is a reply to the second node. Thus, for example, Node 1 is the original post, with four replies (posts 2, 3, 4 and 5). Each node is given a colour based on the author of the post that the node represents, and each distinct colour represents a distinct author. Thus, from the reply graph, we can deduce that the original poster (Red node) obtained replies from the blue, green, yellow and purple users. In turn, the red node replied back to purple and yellow nodes, but not to the blue and green nodes. The entire list of directed interactions is captured in a user interaction graph in Figure 4.2b, where each coloured node represents the corresponding user who wrote a post on the thread, and the directed edges represent the replies.

multi-layered posts in a thread in response to the root post RP in the sub-reddit. Each graph R consists of posts $P_i, P_j, i, j \in N$, where $N+1$ is the total number of responses in the thread and edges E_{ij} such that an edge E_{ij} exists *iff* post P_i was in response to post P_j in the hierarchy of responses. The weight of the edge E_{ij} is found by calculating the cosine similarity between semantic vector V_i for post P_i and the semantic vector V_j of post P_j . This abstraction works well in modeling the conversational nature of these forums. For convenience of the reader, we present a couple of example pairs from SW and Frontpage baseline datasets in Figure 4.2

User interaction Graphs

In this method, we represent each thread as a directed graph $G\{V, E, W\}$ where V is the set of all users participating in a particular thread and E are the directed edges which correspond to interactions between two users $V_i, V_j \in V$. The weight of each directed edge E_{ij} corresponds to the average of all the edge weights between $V_i, V_j \in V$ in the corresponding reply graph $R\{P, E, W\}$ as described above. This means that each reply graph is then mapped to a User graphs where the nodes are users rather than posts. Another salient distinction between the two abstractions is that reply graphs resemble an n-ary tree and user graphs are directed cyclic graphs.

4.3.1 Network characteristics

Figure 4.3a shows the distribution of maximum depths across all Reply graphs for SW and Baseline subreddits. The SW threads depths have a median depth of 2 and mean of 4 compared to median depth of 2 for BL and a mean of 2.5. This shows that statistically the depths of Suicide watch and baseline graphs are quite similar. This implies that on an average, conversations from both communities extend to similar number of to and fro exchanges, which translate into the depth of the tree structure.

4.4 Metrics

Once you are able to develop abstractions from the data, it becomes possible to develop metrics on these abstractions so as to derive insights about the mechanics of support. These metrics are then used to validate structural differences between supportive conversations and generic casual conversations from our baseline set, and come up with a theory for links between supportive conversations and the structure of the conversation, if we find any.

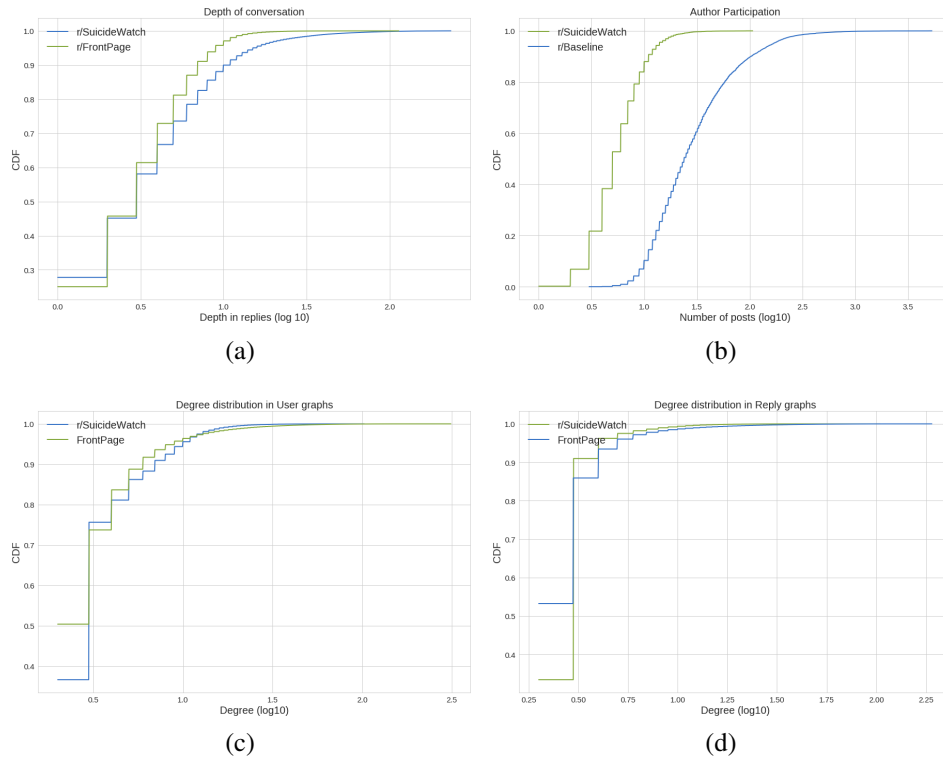


Fig. 4.3 Fig 4.3a shows the distribution of maximum depths of Reply Graphs for Subreddit *r/SuicideWatch* and the baseline *Frontpage* conversations. Fig 4.3b shows the distribution of unique authors per thread in the two datasets. Fig 4.3d shows Distribution of degrees for Reply Graphs, *r/SuicideWatch* and *FrontPage*. Fig 4.3c shows the degree distributions for the reply graphs

Semantic Alignment

We then extract the word embedding vectors for each post using Doc2Vec[LM14], which extends the word2vec [MSC⁺13] word embeddings to represent a whole document or paragraph. We extract these embedding vectors for each post in R^N space – where N is the dimensionality of the embedding – for all the posts across the complete hierarchy of threads. We then quantify the edge weights of each interaction amongst the reply tree as the cosine distance between the response post and the hierarchically higher post, to which the responder has posted to. This captures the semantic alignment between the hierarchically adjacent responses. This method is quite popular and used in community based question

answering[MN16], Medical semantic similarity [DVZK⁺14] and other medical informatics applications[ZYW17].

More formally, if user V_i has responded with post P_i to a post P_j written by user V_j , we extract the word embedding in R^N for both posts P_i and P_j . If these embeddings are represented by N dimensional vectors ψ_i^N and ψ_j^N then the edge weight for the edge E_{ij} in the corresponding reply graph would be

$$W_{ij} = \frac{\psi_i^N \cdot \psi_j^N}{\|\psi_i^N\|_2 \|\psi_j^N\|_2} \quad (4.1)$$

This metric standardizes all edge weights between 0.0 and 1.0, 1.0 implying that the posts P_i and P_j are most aligned, and 0.0 implying the post have least semantic similarity. This metric also abstracts out the content of the post in terms of semantics which can then be used as edge weights in the graph abstractions.

Centrality

For this metric we use the User Graphs. Node centrality is a metric that measures how central a node is in a network. It directly reflects the importance of the node when it comes to membership of the shortest connecting paths between all the nodes in the graph. More formally, we use betweenness centrality of a node which is defined as

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (4.2)$$

where $\sigma_{st}(v)$ is the total number of shortest paths from node s to node t and σ_{st} is the number of those paths that pass through v . To understand whether the thread starters (*OP*) have a special place in the network, we evaluate both centrality of the node corresponding to the *OP*, as well as median centrality across all the nodes in a user graph.

Symmetrical users

We define a symmetric user and a symmetric edges for user graphs. For a user V_i in the user graph $G\{V, E, W\}$ as described in Section , a symmetric user is a user who interacts with any user V_o or the *OP* and receives a response back from that user or the *OP*. We find the fraction

$$U_{sym} = \frac{\text{total number of symmetric users}}{\text{Total users in a thread}} \quad (4.3)$$

Urgency

To understand the urgency in how Suicide watch subreddit users responds to the *OP* and each other, compared to the baseline threads on the Frontpage, we calculate differences between the posting times between consecutive response messages in a reply graph. We then compute the median response times per thread, for posts in response to any *OP* authored posts and in general across all other post responses.

Branching Factor

Branching factor is a quantity that reflects the fan out of a conversation as it evolves. To measure this phenomena, we use the reply graphs, which resemble a n-ary tree, to evaluate the branching factor. The branching factor is formally described as

$$\tau = \frac{1}{|D|} \sum_{d \in D} \frac{1}{|N_d|} \sum_{n \in N_d} InDeg(n) \quad (4.4)$$

4.5 Macroscopic analysis: at conversational level

Through our analysis we find several discriminatory factors among Suicide watch conversations and generic front page conversation. We show that some of these factors are archetypal of suicide watch conversations such that they are over-expressed in suicide watch conversations to a very high degree. We also show that certain properties of these conversations can be backed by sociological theories of real life support conversations.

4.5.1 Peculiarity of threads of Support

We begin by characterizing the two networked abstractions, namely Reply Graphs and Interaction graphs as described in Section 4.3. We do so by first comparing these two abstractions with a baseline control conversation threads using certain macroscopic network properties.

Responses to *OP* are very urgent in supportive setting

Understanding the inter message times can act as a good proxy for the urgency in a conversation. To understand how Suicide watch subreddit users responds to a *OP* and other users as compared to other sub-reddit threads on the frontpage, we calculate differences between the posting times between consecutive messages in a reply graph. Figure 4.4a shows comparison using CDFs of inter-message response times for SW and FP threads. It can be seen that SW *OP* are responded with the highest urgency amongst the 4, especially compared to either the *OP* or any other users or sub-reddits.

Interactions on suicide watch forums are statistically more symmetric

Despite signs of urgency and engagement, we ask the question: what percentage of conversations happening on these subreddits are symmetric in nature ? For this The median value for U_{sym} for SW is 20% where as for FP is 0%. This shows that SW subreddit engages is a lot more symmetric conversation that the baseline threads. If we define a set of users who engage in symmetric activity with the *OP* , it would be worth while to investigate how much of the total message activity on the thread is carried out by these set of symmetric users . To calculate this we find the fraction of messages on each thread written as part of this symmetric conversation. Figure 4.4b shows the trend. It can be see that SW threads contain a higher prevalence of symmetric message exchanges compared to the baseline Frontpage threads. This shows a higher engagement from the *OPs* side when participating in a supportive conversations

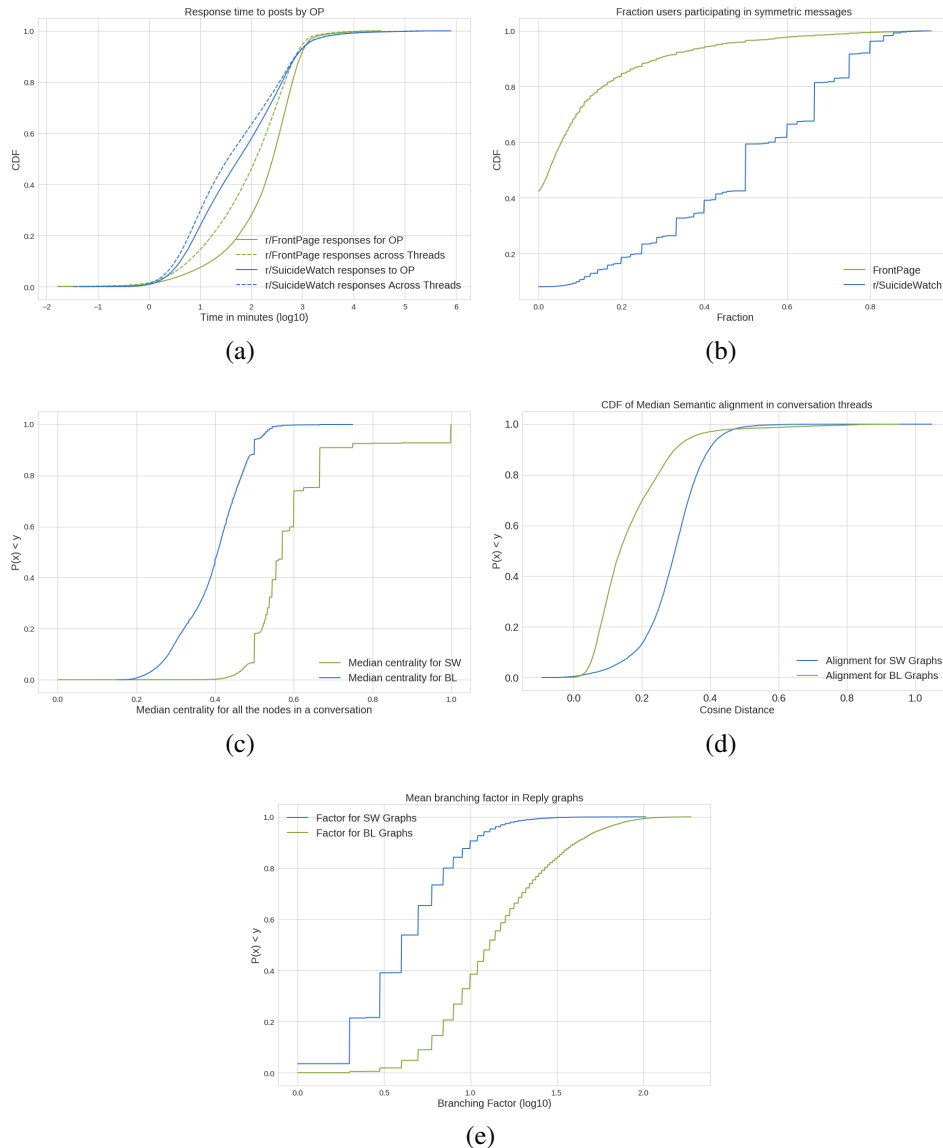


Fig. 4.4 This panel shows the cumulative distribution (CDFs) of Macroscopic features for SuicideWatch sub-reddit data . These are compared with the control dataset of generic conversations on reddit from the FrontPage. 4.4a depicts results for Urgency; 4.4b for Reciprocity; 4.4c for OP's centrality in an interaction graph; 4.4d for Semantic alignment and 4.4e for Branching. SW conversations score higher on reciprocity, urgency and semantic alignment than FP. The SW conversations tend to branch less and tend to have higher centrality when compared to FP.

***OP* is the most central user in supportive conversations**

To understand how embedded is the *OP* in a conversation thread, we compare the betweenness centralities of *OP*s in the *SW* dataset with the baseline *FP* dataset. Betweenness centrality

is a good proxy of understanding how closely linked is a node with the rest of the network. When we calculate this metric for the user graphs, we see that Suicide watch *OPs* tend to have highest centralities compared to generic *FP* threads both in terms of *OP* centrality as well as median centrality across all the users. The high centrality of *OPs* in *SW* conversations implies a high level of embedded-ness as well as a *OP* centric approach by other participants in the conversation. The Figure 4.4c shows the Empirical CDFs of centralities.

Supportive responses are semantically aligned, more so when they are in response to the *OP*

We measure semantic alignment based on word embeddings (see equation 4.1) of the source post and the reply post, at every edge of the reply graph. The detailed method of extracting semantic alignment along a post and its response is described in Section 4.4. Extracting such similarity metrics, we compare the trend in semantic alignment of response text with the parent text in the reply graphs. We find that the semantic alignment is considerably higher in the SuicideWatch conversations as compared to the Frontpage baseline posts. The alignment is further increased when we look at responses posted to the posts done by the *OP* in SuicideWatch. This implies that the conversations of suicide watch community tend to be not just *OP* centric in structure, but also tend to be more aligned to the topical content of *OP*'s posts. We would expect this person centric approach in an interaction where social support is exchanged between a helper and a person in distress, which in our case is the *OP*.

Supportive conversations branch out considerably less compared to baseline

Branching in a conversation thread could be either a sign of digression or a sign interestingness resulting in more people joining in. To measure this phenomena, we use the reply graphs, that mimic the conversation structure of the threads. By using the method described in Section 4.4, we found that Suicide watch threads, tend to branch less as compared to our baseline conversations. This implies that suicide watch threads tend to remain on topic and more often than not, a one-on-one conversation. Albeit many such dialogues may emerge with many participants, and hence that explains the high centrality of the *OP* in all user interaction

graphs. If the participants on a thread seldom interact amongst themselves, the corresponding interaction graph will have the *OP* as the most central node.

4.6 Mesoscopic analysis: Anchored triadic motifs.

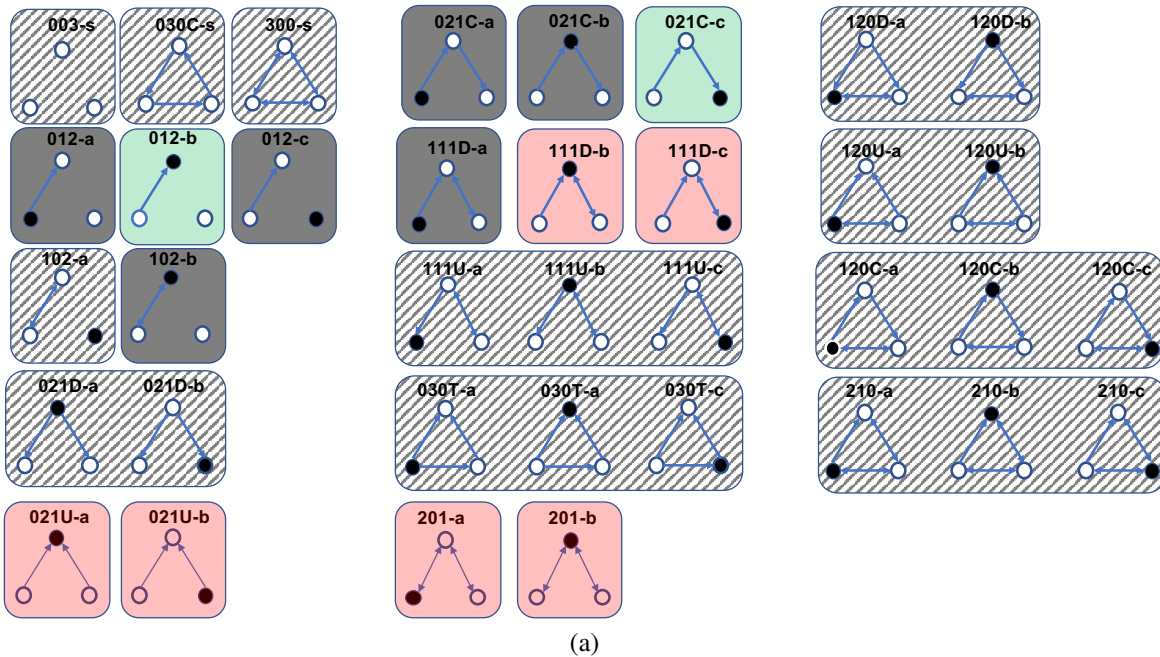


Fig. 4.5 Figure 4.5a shows the 36 different types of Anchored Triadic motifs that are looked for in the user graph data. The motifs with **green boxes** are **over expressed in the baseline dataset** by significant amount. The motifs with **red boxes** are **over-expressed in the Suicide watch dataset** by significant amount. The motifs with **grey boxes** are present in significant numbers in both datasets, but neither over nor under expressed in any datasets based on their Z scores. The motifs in **grey hatched boxes** are very rare in both the baseline and suicide watch datasets, with less than 5 mean occurrences per graph per bin.

Network motifs are local sub-networks between 2 or 3 nodes. Such local patterns are highly useful in quantifying local interactions and the resulting macro structure of the network[MSOI⁺02]. They have been used in a variety of applications and networks, from economics [ZSSH14] to cellular protein-protein interaction networks [YLSK⁺04]. These local interaction patterns have been studied before, and have been fundamental in the study of social structural processes[Fau07]. They help social scientists quantify the type of hierarchies in the social network[*Dav67, DL67*].

But in the setup of a typical support community network like SuicideWatch, the conversation shows clear distinction between the users who respond to a call for help and the user/s who are asking for help. In the case of Reddit we define the former as the *OP* who starts the conversation thread. In this context, it would be worth understanding how *OP*s immediate neighbours interact with *OP* in case of a supportive community like SuicideWatch, when compared against the baseline.

For this reason, we changed the definition of the triadic motifs to accommodate the role of a node around which the motif is developed in the conversation graph structure. In conventional literature, the local interactions are measured in terms of census of 16 triadic motifs[Fau07], which cover all possible patterns of non-isomorphic graphs, or graphs which cannot be mapped or morphed into each other. In this method, there is no special treatment to any node, and positional parity of all nodes is treated equally. This means, role of a node in the conversation cannot be incorporated in this analysis. For this reason we extend this methodology by introducing anchors, or nodes with special importance, since we would like to know how a graph evolves around the person in distress, which is the *OP* in our case. A symmetric link with the *OP* implies that the *OP* is part of a to and fro communication, however a triad with a symmetric link between two non-*OP* nodes implies that the conversation does not involve the *OP*.

By fixing a role for a node in a motif, each of the 16 triadic motifs as seen and developed in the field[Fau07, HL77], can be unravelled into 36 sub-variants of these motifs by varying the anchored node, as seen in Fig 4.5. Each sub-variant is non-isomorphic to others in its category from the perspective of the anchored node. The resulting motif types grow from 16 to 36, since some of the anchored motifs are iso-morphic, which means they look identical to some other motif from the perspective of the anchor. These motifs are then counted using custom tweaked census methods based on *Bataglej et.al's* work[BM01]. Since the anchor is important while conducting the census, we modify *Bataglej et.al's* triadic census method to return the positional information of each node in a motif, along with the count. This then allows us to segregate each counted triplet of nodes belonging to a given triadic variant, into their

corresponding anchored triadic sub-variants. The code for performing the anchored triadic census is open sourced and can be found at <https://github.com/sagarjoglekar/redditTools>

Each motif as seen in Figure 4.5a is named using a particular recipe. The first three letters, follow a M-A-N pattern which signifies the number of "Mutual" , "Asymmetric" or "Null" edges present in that particular triad. E.g. the motif 030 has 0-Mutual(bi-directional), 3-Asymmetric(unidirectional) and 0-Null(disconnected) edges. There are some motifs with an added modifier letter (C-U-D-T) attached to further differentiate between different triad types with the same M-A-N pattern. To this, we additionally attach a variant label (a, b or c) to distinguish the different anchored network motifs that result from the different positions of the *OP*. The naming is done in accordance with Holland et. al's work[HL71].

To methodically understand the over or under expression of these anchored triadic motifs in the suicide watch community, we use the user interaction graphs for the Front page baseline posts as a control group. We analyse 10,000 user interaction graphs each for the baseline and the suicide watch datasets. We progressively select graphs with variable sizes i.e. number of users present in the interaction graphs. We do so by binning each dataset in ranges of graph sizes in increments of 5 nodes per bin. The resulting graphs would fall in the following 7 bins, with increasing number of nodes present : 1 - 5 , 6 - 10 , 11 - 15 , 16 - 20 , 21 - 25, 26 - 30, 31 - 35 and 36 - 40. We stop sampling above 40 nodes per graph, as the population of conversations that contain more than 40 unique users participating is extremely scarce for both the datasets. We then do the census for the 36 unrolled motifs for each of these bins, for both the datasets. Once the census is done, we calculate Z_{scores} for the Suicide watch conversations, using Baseline conversations as the null model, to understand over or under expressions of certain motifs. For any given bin B_I , let there be k baseline graphs that fall in that particular bin noted by G_{BL} , and let there be n suicide watch graphs falling in the same bin signified by G_{SW} . For such a setup, let M_{BL} signify a vector of k elements, where each element is the total number of occurrences of particular motif m in each graph from the set G_{BL} . With this sample of graphs as the null model, the mean would be $\mu_{null} = \frac{1}{k} \sum_{m_i \in M_{BL}} m_i$, where m_i is the count of motif m in the i^{th} graph in G_{BL} . The standard deviation σ_{null} is $std(M_{BL})$ Once we have the null model parameters for the baseline graphs for a particular

bin, we calculate Z_{scores} for all the graphs from suicide watch samples G_{SW} from the same corresponding bin as random variable Z where the i^{th} element is the Z_{score} for graph i in G_{SW} .

The score is calculated by the following formula

$$Z_i = \frac{m_i^{sw} - \mu_{null}}{\sigma_{null}} \quad (4.5)$$

where m_i^{sw} is the total number of occurrences for motif m in the i^{th} graph for the suicide watch samples. We then plot the mean of random variable Z and the standard error in Z to understand the over/under expression trends.

4.6.1 Patterns in local interactions

It is often useful to express large interaction graphs, as the sum of local interactions between two or three nodes at a time. This method is quite prevalent in the Social sciences, for studying social structures by looking at local interaction between agents[Fau07]. Such analysis is quite useful in expressing local structures in the graphs and has been used in several network analysis works[WLH14, SM15]. For this reason we conduct a census of the 36 Anchored triadic motifs (described in Section 4.6) across all the selected graphs. From the amount of over or under expression of the network motifs, researchers have made inferences about the nature of local interaction. They do so by comparing the amount of density of each triad in a real network as against the expected quantity in a null model based on the number of edges[Fau07]. We perform binning of user graphs as described before in Section 4.6, and perform over or under expression analysis in comparison with the baseline null model, using Z-scores of the motif occurrences.

We find that anchored motif variants **021U-a**, **021U-b**, **111D-b**, **111D-c**, **201-a** and **201-b** are significantly over expressed in suicide watch conversations across all sizes of graphs as seen from figures 4.6a,4.6b,4.6c,4.6d, 4.6e,4.6f. Similarly anchored motif variants **012-b** and **021C-c** are significantly over expressed in the null model(baseline) graphs across all sizes.

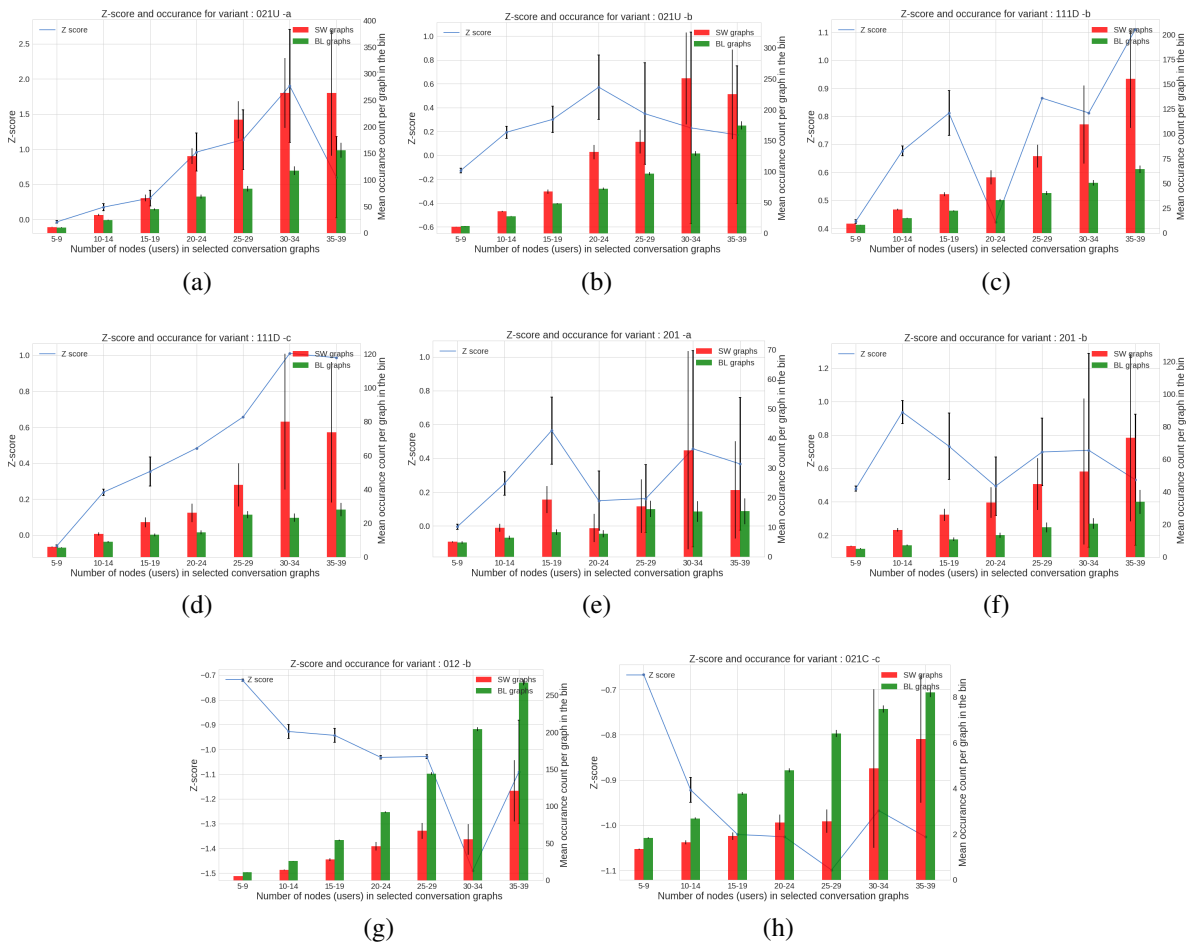


Fig. 4.6 This panel shows the Z-scores of the abundant and over expressed Anchored motifs found in both datasets. There are variants which are over expressed in Suicide watch (Like figures 4.6a,4.6b,4.6c,4.6d, 4.6e,4.6f), which form the top six plots. The bottom 2 plots show motifs which are over expressed in the Baseline over Suicide watch, as their Z-scores are negative. Figure 4.6g and Figure 4.6h.

From previous studies on triadic structure, it was inferred that transitive triads are naturally more common than expected in social structures of human social networks. Interestingly, our analysis shows that transitive triads are rarer in Suicide watch, as against the baseline conversations. But in the defence of previous studies, the networks we study are of human conversations and not of human social ties. Also these conversations are happening with an intent of providing support, which makes one user (the one in distress) the centre of conversation. These conversational preferences make the macro and meso level structural signatures peculiar.

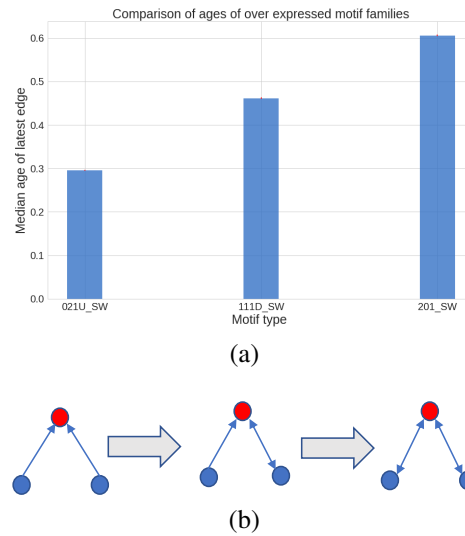


Fig. 4.7 Figure 4.7a represents the median completion times of the three motifs over expressed in SW, where the *OP* is at the apex (most central) position. This plot shows that as the time goes by, the symmetric nature of interaction between the *OP* and those who engage with them increases. The Figure 4.7b shows a toy example of what sort of dialogue exchange could lead to the motif lifetime distributions seen in Figure 4.7a

4.7 Conclusions and Outlook

In this chapter, we investigated **RQ3**, which enquired about structural differences between interactions on support communities vs those on generic communities. We analysed this RQ within the context of Reddit, which provides us with an optimal mix of supportive and generic conversations. In line with the DIKW pyramid, we first developed abstractions which could capture the structure of individual conversations. We then developed metrics that could quantify various structural patterns in these interactions. These patterns were then analysed using statistical tools like the Z-score. These patterns in interactions indicate that conversations on SuicideWatch tend to be more *OP* centric, with non-transitive dialogues between users who respond to a call for help. More so, the *OP* tends to be highly central in the conversation as well as part of several mutual interactions. These behaviours are highly particular to SuicideWatch when compared with the baseline conversations. Further investigation of local structures in conversation graphs show that the supportive conversation graphs evolve quite differently as compared to the generic ones. The *OP* centric attitude of

supportive conversations give rise to a distinct set of triadic motifs, which get over expressed by a considerable margin in supportive conversations.

Several studies have looked at the social-tie structures and shown certain triadic motifs to be important in maintaining social hierarchy [SM15, SM12, HL76, HL71]. But these expected structures are not the ones prevalent in supportive conversations. Transitive triads like *030T* and *210C* are shown to be overexpressed in ties that show social hierarchies. This points to a very different approach towards interactions with distressed users, and may have great implications on detection of toxic behaviour and enabling of helpful online conversations. Further work needs to be done in modelling these conversations. With the advances in machine learning, both the language and the network structure could be used in compliment to develop unique embeddings for support. A true inter disciplinary aim is to enable use of such frameworks, to understand at risk individuals online and offline.

There are other relevant triads are not even active in supportive conversations as seen from Figure A.0 (Discussed in Appendix 1). The most interesting ones are the motifs that exhibit triadic closures, which have been shown to be fundamental for social capital in networks [BDIF14, Gra77, JK19]. The absence of these motifs in either Suicide watch or baseline graph structures indicates that the conversational graphs online evolve differently to social graphs. This phenomenon needs to be explored further.

In conclusion, quantifying perceived social support is an ongoing effort. But my work proposes new and computable metrics for conversation graphs which could help us quantify the amount of social support exchanged in an online forum.

4.7.1 Implications

Online spaces are used by a diverse set of users. One of the main challenges in front of open online spaces like Twitter and Facebook is to make them safe and toxicity free. This however is in direct contradiction with the free and open philosophy that underpins the creation of the internet. At such a juncture, it is worth investigating a setup where these platforms offer a differential policy towards toxic or non mainstream behaviour online. The main challenge in allowing differential behaviour policing, is to understand where to draw the line. My work

sheds some light towards finding specific interactions online which are the best candidates for policing for toxic behaviour. By quantifying the structures of peer support in online spaces, we can enable public platforms to be allow serendipitous supportive interactions to happen, without clamping down on their open nature.

CHAPTER 5

FROM CROWDS: REAL WORLD PERCEPTION OF BEAUTY

Beauty is nothing other than the promise of happiness – Stendhal, On Love

In part one, I delved deeper into the problem of quantification of perceived social support through online communities. This work showed that there are quantifiable signatures of social support in the structure of online communities, and these can be exploited to build models of supportive and safe interactions online, which could directly benefit persons in distress. Capturing the signatures of a subjective quantity, like the perception of social support, through the analysis of online conversations has implications on how we design better online spaces in the future. This feat is achieved through investigating networked, interacting users in communities. But the question to ask is, can unconnected agents, in large enough quantities(crowds) be used to extract signatures of subjective perceptions.

In this spirit , in the second part of my thesis, I extend the motif of perception driven design of spaces, to the offline world. The core idea is about asking a similar question, that is: **"Can we quantify the signatures of subjective perception of the real world through crowd opinions?"**.

It has been shown through multiple studies, that the physical spaces that we use have measurable effects on our health [MVG⁺06, LM11], our outlook towards exercise [TGL⁺14], health of seniors [TNW02] and general all round well being [GTMM⁺15, NPK13]. More importantly, all these studies point to the value of aesthetically pleasing spaces for an overall liveable city. This intuition motivates the choice of quantifying the aesthetic perception of

real spaces. More so it motivates the question: Can crowd's opinion help capture a subjective quantity like the aesthetic? However, the question about whether an urban space is considered beautiful or not is highly subjective. To that end, we need to refine the hypothesis that we are aiming to prove. The perception of aesthetic in urban spaces are affected by location, culture, background of the crowd member and several other subjective attributes. This is why, I aim at quantifying what aspects of an urban scene "on an average" are found aesthetically pleasing to the crowds.

Research has shown that there are specific categories of urban elements that are universally considered beautiful e.g. greenery, small streets, memorable spaces, open skies [Ale77, QOC14, SSH13]. These elements are those that contribute to the creation of what the urban sociologist Jane Jacobs called 'urban vitality' [Jac61]. The idea of this work is to test the quantifiable and predictive nature of these elements. In this section of my dissertation, I show that this is feasible using cutting edge deep learning and computer vision techniques and some metric design which associates meaning to the patterns in data. I use google streetview images as the source of data for photographs of urban scenes. I use crowd opinion to capture the predictive motifs of urban beauty. And I use literature drive metrics to explain and quantify the urban perception of beauty. This follows that in this chapter, I would like to answer the RQ5 of my dissertation.

RQ5 *Can opinions of disconnected crowds help us model the perception of aesthetics in real world?*

5.1 Related Work

The problem of designing better cities, has been a on going obsession for various fields. A lot of work was done in the past in just understanding the concept of good , liveable cities. One of the most prominent figure in the campaign to re-vitalize our cities was Jane Jacobs in the late 50s. Jacobs's seminal work on urban vitality [Jac61] discusses the idea

of how a design of a city might be the driving reason behind how urban vitality thrives. Christopher Alexander was another such prominent voice who in his book undertook a cataloguing exercise of typical “patterns” of good urban design [Ale77]. This effort showed that certain patterns of placements of roads, trees, walkways, parks and areas of social interactions are highly crucial in promoting a thriving social environment. In the fields of psychology, environmental design and behavioral sciences, research has studied the relationship between urban aesthetics [RAS00] and a variety of objective measures (e.g., scene complexity [KKW72], presence of nature [KK89]) and subjective ones (e.g., people’s affective responses [Ulr83]). As mentioned before, the relation between greenery and the design of spaces around us has been linked with measurable effects on our health [MVG⁺06, LM11], our outlook towards exercise [TGL⁺14], health of seniors [TNW02] and general all round well being [GTMM⁺15, NPK13].

With this premise, it is worth exploring the literature to understand how different fields are working towards using this relation between the humans and the spaces they occupy.

Ground truth of urban perceptions. So far, the most detailed studies of perceptions of urban environments and their visual appearance have relied on personal interviews and the observation of city streets: for example, some researchers relied on annotations of video recordings by experts [SR04], while others have used participant ratings of simulated (rather than existing) street scenes [LH12]. The Web has recently been used to survey a large number of individuals. Place Pulse is a website that asks a series of binary perception questions (such as ‘Which place looks safer [between the two]?’) across a large number of geo-tagged images [SSH13]. In a similar way, Quercia *et al.* collected pairwise judgments about the extent to which urban scenes are considered quiet, beautiful and happy [QOC14] to then recommend pleasant paths in the city [QSA14]. They were then able to analyze the scenes together with their ratings using image-processing tools, and found that the amount of greenery in any given scene was associated with all three attributes and that cars and fortress-like buildings were associated with sadness. Taken all together, their results pointed in the same direction: urban elements that hinder social interactions were undesirable, while elements that increase interactions were the ones that should be integrated by urban planners

to retrofit cities for happiness. Urban perceptions translate in concrete outcomes. Based on 3.3k self-reported survey responses, Ball et al. [BBLO01] found that urban scenes with positive aesthetics properties not only are visually pleasurable but also promote walkability. Similar findings were obtained by Giles et al. [GCBK⁺05].

Deep learning and the city. Computer vision techniques have increasingly become more sophisticated. Deep learning techniques, in particular, have been recently used to accurately predict urban beauty [DNP⁺16, SPM17], urban change [NKR⁺17], and even crime [DNVZ⁺16a, AERA14]. Recent works have also showed the utility of deep learning techniques in predicting house prices from urban frontages [LSSGR18], and from a combination of satellite data and street view images [LPR18].

To sum up, a lot of work has gone into collecting ground truth data about how people tend to perceive urban spaces, and into building accurate predictions models of urban qualities. This trove of human annotated ground truths about urban spaces is vital in understanding human perception at scale. In this chapter we would look at a way to transfer the collective perception of humans in to a machine learning model. Doing so we would validate whether machine learning models can actually capture the subjective perceptions of people.

5.2 The Data

To begin with, we need highly curated training data with labels that reflect the crowds consensus on beauty. Unfortunately, it is difficult to get data where there is a consensus on the crowds on an absolute value of beauty. However there are datasets available where crowds have voted on pairwise comparisons of urban images for their relative beauty. The two most prominent examples are from MIT media lab [DNP⁺16] called the place pulse and from Bell labs [QPAC13].

We start with the Place Pulse dataset that contains 110k Google Street Views across 56 cities across 28 countries around the world [DNP⁺16]. The voting on these scenes is taken in the form of a gamified interface, where two random images from this set are shown, and the participant is asked to choose the more beautiful of the two. The interface looks similar

Which of these two images look more beautiful



Fig. 5.1 Example of a pairwise comparison, where a user is asked to choose the more beautiful among the two.

to Figure 5.1, where by one would preferentially end up choosing the image on the right, due to its objectively superior aesthetics as compared to the one on the left. Over the course of time, they gather votes on more than 1.2 million pairwise comparisons, distributed across 110k images, given by more than 81k volunteers from 162 countries, with a good mix of people residing in both developed and developing countries. The pictures were labelled by volunteers through an ad-hoc crowdsourcing website¹. Volunteers were shown random pairs of images and asked to select which scene looked more beautiful, safe, lively, boring, wealthy, and depressing. To our knowledge, no independent systematic analysis of the biases of Place Pulse has been conducted yet. However, it is reasonable to expect that representation biases are minimized by the substantial size of the dataset, the wide variety of places represented, and the diversity of gender, racial, and cultural backgrounds of the raters. This process, still does not solve the problem of obtaining an annotated dataset of beautiful and ugly looking urban neighbourhoods. For that to happen, we first need to translate these comparisons in to some form of an ordinal ranking of images.

¹<http://pulse.media.mit.edu>

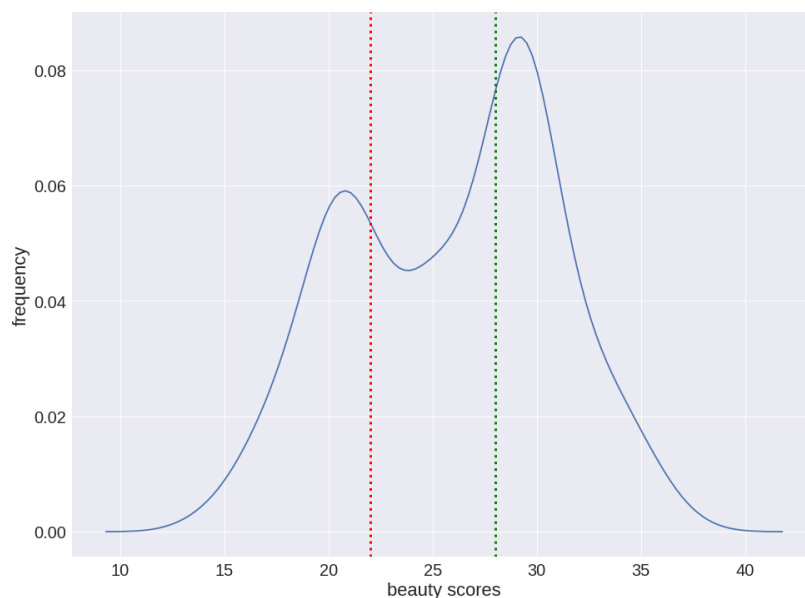


Fig. 5.2 Frequency distribution of beauty scores. The red and green lines represent the thresholds below and above which images are considered ugly and beautiful. Conservatively, images in between are discarded.

5.2.1 Partitioning the data

To solve the problem of annotating images in terms of beauty we need to have at the very least, a sense of relative ranking in terms of most popularly voted to be beautiful to the least. This approach would not quantify beauty in the absolute sense but in terms of relative consensus, provided we have enough pair wise votes.

To solve the problem of transforming the pairwise voting of the crowd into relative ordinal ranking, we use a popular Bayesian algorithm, used in several multiplayer gaming systems to order leader boards called TrueSkill [HMG07]. This algorithm works by first initializing all the players (which in our case are urban street view images) with equal “skill” (which in our case implies a relative sense of beauty). The algorithm then assumes competitions among the players in a 1-on-1 fashion. In the case of our work, these competitions are the pairwise votes. Each victory results in addition of some “skill”(beauty) in the victor player’s profile (street-view image) and reduction in “skill” in the loser’s profile. The more skillful the opponent, the higher the rewards in update of one’s skill. With enough average number of competitions played by each player, a steady state order of skilled players emerges. For our



Fig. 5.3 Sample pairs of street view images ordered by lowest final skill rating on the left to highest on the right.

dataset, we initialize all images with a “skill” level of 25 and a variance of 3, which signifies the uncertainty in the skill level. This uncertainty would drop, as more competitions are won or lost by any given image. For the sake of accuracy and stability, we filter only the images which have more than 8 votes on them. This reduces our usable dataset from 100k images to just over 20k. But having more than 8 votes, results in a steady state bi-modal distribution of skills as shown in Figure 5.2. This allows us to order the streetview images in an ordinal rank based on relative beauty as seen in Fig 5.3.

Despite having a consensus on the ordering of most of the images, we still end up with some images near the initialized skill level of 25. This means the skills of these images have not been decisively updated through the voting data. To work around these borderline cases, we partition the distribution of images along two margins in the trueskill space. The thresholds for partition are values less than $\mu - \sigma$ for the ugly set of images and values more than $\mu + \sigma$ for the beautiful set of images. This results in the threshold Trueskill values of 22 and 28. We select all images with a Trueskill value less than 22 and assign them to the ugly set of images. We then select all the images with the Trueskill value above 28, and assign them to the beauty bin.

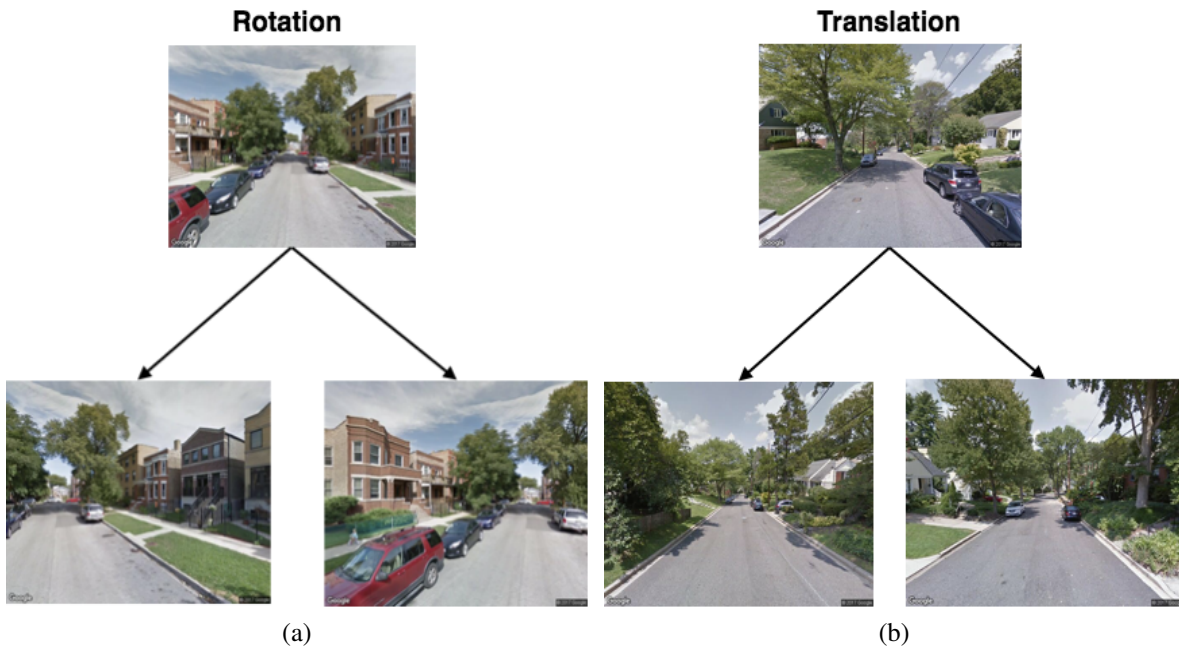


Fig. 5.4 Two types of augmentation: (a) rotation of the Street Views camera (based on rotation); and (b) exploration of scenes at increasing distances (based on translation).

5.2.2 Augmenting the data

Partitioning of the data after evaluating the Trueskill scores on images is a lossy process. By the time we filter images along minimum number of votes, and based on their trueskill scores, we are left with 15,000 street-view images. It has been a well known problem in the area of deep learning, that the algorithm's performance is often limited by the amount of clean curated data available to train on. Another real danger of training on limited data is the phenomenon of overfitting. Overfitting happens when the model under consideration is reasonably complicated with millions of parameters, but the data used to train it is not sufficient to generalize the model's inference. In such cases, the model over fits to the training dataset whereby the model memorises the training data, to reduce the training error. But this model is doomed to perform poorly on a generalized set of data. To avoid this particular set of problems, I needed a way to enrich the current high confidence set of streetview images. The enrichment needs to be such that we do not add noise to the dataset, but at the same time

increase the diversity of the kind of samples the model is supposed to learn. This means we need more images which are similar but not identical to the two partitions.

The solution I develop involves two approaches. First, we feed each scene’s location into the Google Streetview API to obtain the snapshots of the same location at different camera angles² (i.e., at $\theta \in -30^\circ, -15^\circ, 15^\circ, 30^\circ$). We assume that any image taken as a variant of a beautiful image at different angles of rotations can safely inherit the label of “beauty” since the field of view only changes by $\pm 30^\circ$. With this simple (yet conservative) assumption we are able to immediately inflate our dataset by up to a factor of 5. However, the resulting dataset is still too small for robust training. Therefore, again, we feed each scene’s location into the Google Streetview API, but we now do so to obtain other scenes at distance $d \in \{10, 20, 40, 60\}$ meters. This will greatly expand our set of scenes, but it might do so at the price of introducing scenes whose beauty scores have little to do with the original scene’s. This addition of noise may have an adverse effect on the deep learning algorithm’s performance for detecting beauty. This addition of translational data, could be done using some heuristics. Imagine a scene I translated in space by 10 meters. The newly acquired scene I_{10} , may be useful in our augmented dataset *iff* the translated scene I_{10} is visually “similar” to the original scene I . The same heuristic metric can be used to either accept or reject any image I_m translated by m meters, into the augmented dataset. For this heuristic test to work, we first need to devise a way to compute the “similarity” measure between two images I and I_m . One well known way to evaluate image “similarity” is by represent them in a high dimensional features space, obtained from a pre-trained neural network [ZIE⁺18]. This is done by using the activations of a the last but two (or last but one) fully connected layer of a trained convolutional neural network during a forward pass [BL15, LYHC15, VS16] as features of the image. These activations are then treated as vectors in R^N euclidean space, such that they follow the distance and angle metrics. This allows comparison of images along a similarity metric simply by comparing the cosine distances or Euclidean distance between their feature vectors. For the sake of similarity of application, we use the best performance version of a pre-trained PlacesNet deep learning model [ZLX⁺14]. PlacesNet was trained

²Google streetview API allows the users to set the bearing and heading of the mast camera, used to acquire the image

on streetview images, and is trained with the end goal of classifying streetview images into scene types, such as a beach, highway, garden etc.

For all scenes I_m at increasing distance $m \in \{10, 20, 40, 60\}$ meters, we take only those whose similarity scores with the original scene is above a threshold. In a conservative fashion, we choose that threshold to be the median similarity between rotated and original scenes (those of the first augmentation step). This assures that the translated images are at the very least as similar to the original, as the rotated images.

Which scenes are more suitable for translation?

To make sure this additional augmentation has not introduced any unwanted noise, we consider two sets of scenes: one containing those that have been taken during this last step, i.e., the one with high similarity to the original scenes:(*taken-set*), and the other containing those that have been filtered away because their similarity metric went above the threshold:(*filtered-set*). Each scene is then scored with PlacesNet [ZLX⁺14] and is represented with the five most confident scene labels, as per the original output of the model . We then aggregate labels at set level by computing each label’s frequency on the *taken-set* and on the *filtered-set*. Finally, we characterize each label’s propensity to be correctly augmented as:

$$\text{prone}(\text{label}) = fr(\text{label}, \text{taken-set}) - fr(\text{label}, \text{filtered-set}) \quad (5.1)$$

This reflects the extent to which a scene with a given scene label is prone to be augmented or not, according to our decided threshold method. From Figure 5.5, we find that, as one would expect, scenes that contain high amount of visual continuity over long stretches such as highways, fields and bridges can be augmented at increasing distances while still showing resemblances to the original scene. By contrast, scenes that contain peculiar features with smaller continuity such as gardens, residential neighbourhoods, plazas, and skyscrapers cannot be easily augmented. These scene types also tend to be found in high density parts of the city in which visual diversity within short distances might well be experienced.

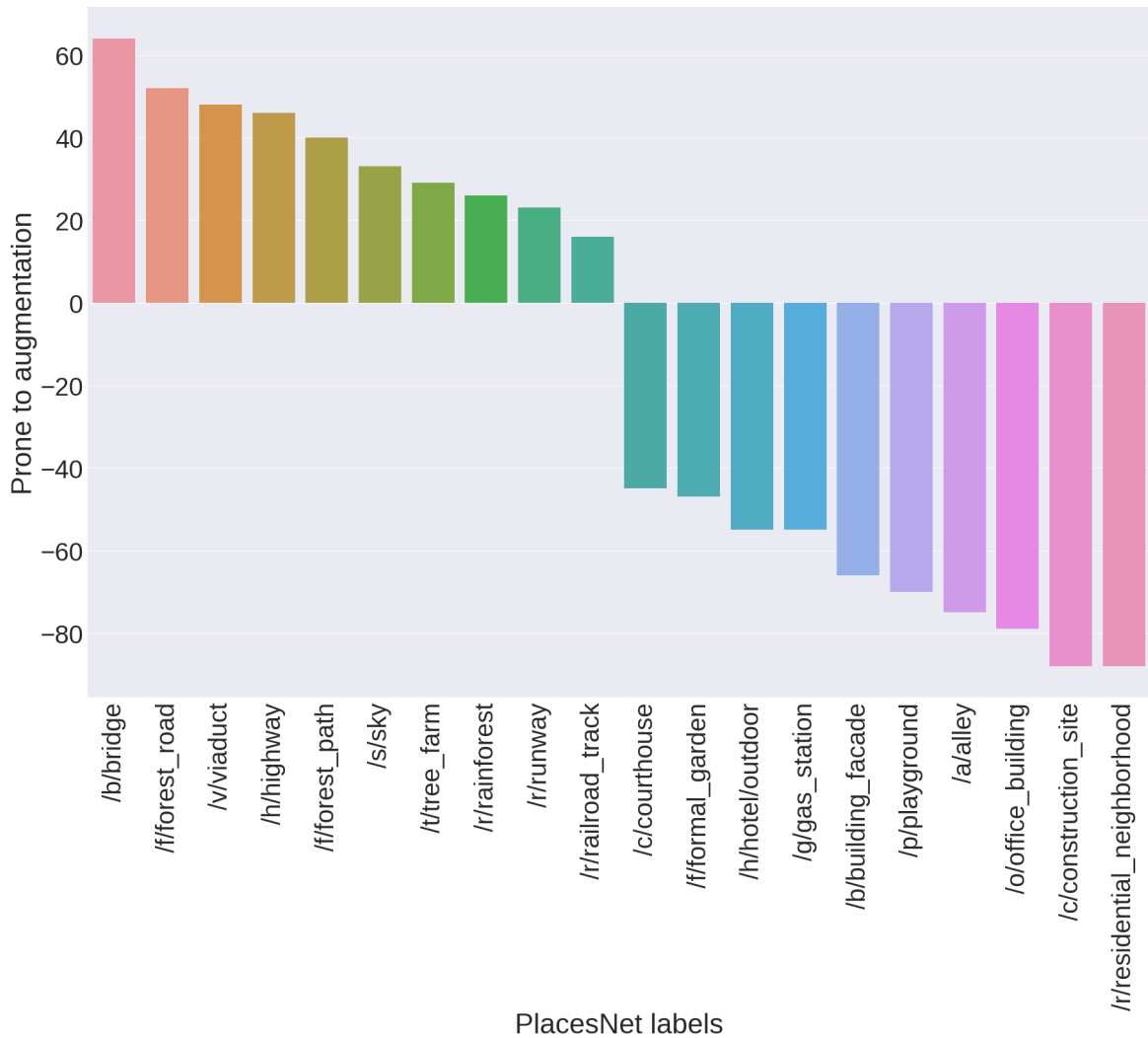


Fig. 5.5 The types of scene that have greater propensity to be correctly augmented with similar scenes at increasing distances.

5.3 Building a beauty Classifier

| Augmentation | Accuracy (Percentage) |
|-------------------------------------|-----------------------|
| None | 63 |
| Rotation | 68 |
| Rotation + Translation | 64 |
| Rotation + Conservative Translation | 73.5 |

Table 5.1 Percentage accuracy for our beauty classifier trained on differently augmented sets of urban scenes.

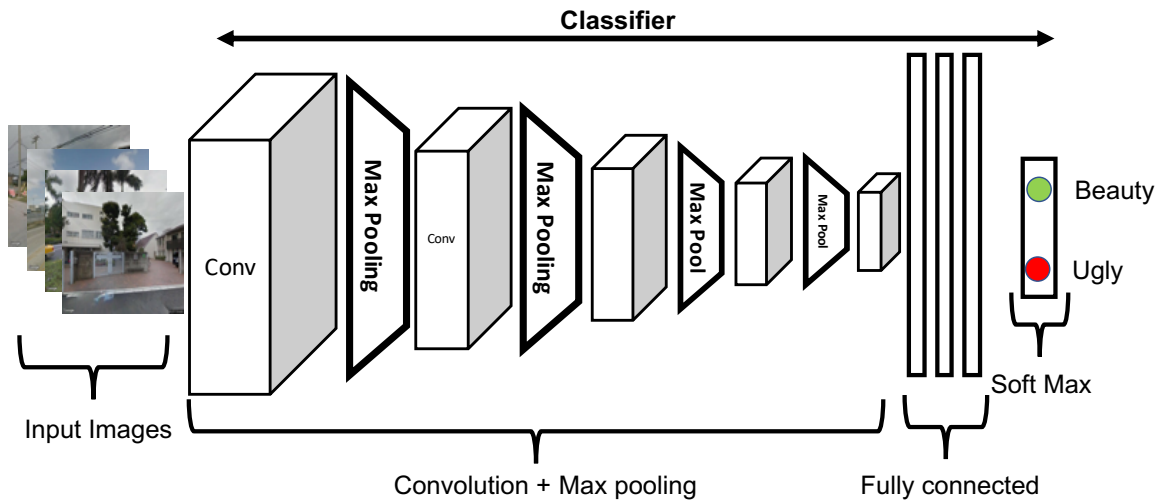


Fig. 5.6 The complete architecture of the beauty classifier. The model contains 5 convolutional layers, interleaved by max-pooling layers. Final layers contain fully connected layers and the outcome Softmax layer.

Having this highly curated set of labeled urban scenes, we are now ready to train classifier C with labels reflecting our beauty assessments. The challenge here is to understand if a deep learning model is able to capture the essence of something as subjective as **perceived urban beauty**.

As for classifier C , we use the CaffeNet architecture, a modified version of AlexNet [K⁺12, SLJ⁺15] as seen in Figure 5.6. This has a conventional architecture with 5 convolutional layers; interleaved with max pooling and normalization layers; and terminated by: (i) three 4096 dimensional fully connected layers interleaved with dropout layers [SHK⁺14] (the dropout ratio is set to 0.5 to prevent over-fitting), and (ii) by a Softmax layer that classifies the input image into one of two classes of beautiful(1) and ugly(0). The network is trained for 30,000 epochs with ADAM optimizer³

Having C at hand, we now turn to training it. The training is done on a 70% split of the data, and the testing on the remaining 30%. All this is done on increasingly augmented sets of data. We start from our 15k images and progressively augment them with the snapshots

³The best performance model can be found here: <https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/ATXYTP>

obtained with the 5-angle camera rotations, and then with the exploration of scenes at increasing distance $d \in \{10, 20, 40, 60\}$ meters. The idea behind this data augmentation is that the model's accuracy should increase with increasing levels of augmentation. Indeed it does (Table 5.1): it goes from 63% on the set of original scenes to a value as high as 73.5% on the set of fully augmented scenes, which is a notable increase in accuracy for this type of classification tasks. Furthermore, our results match previous ones: for example, Dubey et.al's [DNP⁺16] model showed an accuracy of 70%, which is comparable to ours. The comparable, and at times better, performance of this classifier with respect to the baseline shows that 1) the notion of subjective beauty can be learn't from a crowd's participation and 2) the novel method of augmenting data, can make deep learning better accessible when the data is sparse and of urban nature.

5.4 Implication of a beauty classifier

In this chapter **RQ4** aimed at investigating the possibility of modelling subjective perceptions of aesthetics in real world, using the opinions of a vast disconnected crowd.

We found that using a crowd based pooling of opinions about urban beauty, we can make measurable progress towards quantifying the aesthetic in the context of urban scenes. This too can be done at scale, with a proposed novel way of augmenting sparse datasets. However, just capturing the perception is not enough to make any meaningful contribution towards the urban science. A lot of work has been put in understanding the impact of the urban aesthetic of citizen's health, well being, economical vitality etc. The unanimous consensus points to the fact that cities and their compositions deeply affect our health and well being. At this juncture it is more valuable to first understand if the notion of beauty captured by our deep learning model is analogues to that perceived by real humans. If that is indeed the case, it is worth understanding what aspects of an urban scene are predictive of the perceived beauty. This shall be of immense value to the practitioners of urban design, architecture and urban activism.

In the next chapter, we would explore exactly that. The guiding question is, can the learnt representation of urban beauty be utilized to understand the predictive motifs of urban design for beauty? Can these insights be used in a constructive way to improve existing urban scenes ? And finally, can such a framework be useful to the cause of urban design ?

CHAPTER 6

FROM CROWDS: RECREATING THE URBAN PERCEPTIONS

“What I cannot create, I do not understand” – Richard Feynman

Feynman said this insightful quote in context of understanding deeper concepts in physics. If one cannot teach a concept, one does not understand it deeply. This notion, albeit disconnected with the premise of my thesis, is as relevant as when it comes to building models of any phenomenon. If a model cannot simulate reality, the model has not really captured the essence of what it is trying to learn.

In the last chapter, we saw that a large scale crowd poll about perception of urban spaces, can be used to train a machine learning model that can differentiate between an aesthetically pleasing and unpleasant urban image. We also showed that despite the challenges, we can enrich urban data, using certain spatial heuristics. This however did not address an important question, that is, what is the validity of the learnt representation of beauty? Can we use the model’s understanding of beauty to our benefit? Is the model actually learning what humans perceive to be the signatures of beauty? All these questions entail from the final research questions of my dissertation work:

RQ5 *Can machine learning models based on crowd opinions help us improve real spaces?*

RQ6 *How much do the suggested improvements align with the expectations from the literature or the practitioners?*

We would try to explore the answers to these questions in this chapter, by systematically dissecting the model of beauty learned in the previous chapter. This, as per the definition framed by Feynman, can be done by first using the model to generate what it “thinks” is the notion of urban beauty. These generations can be used as recommendations of possible improvements of any given un-aesthetic place. Next, I quantify these recommendations using metrics designed around urban design literature. Finally, I validated these metrics and recommendations through a user study.

This method of investigation essentially calls back to the DIKW pyramid, where, to derive insights from data, you first create abstractions that come naturally to the structure of data. In this case, the natural abstraction is the structure of the image itself. You are then supposed to represent the knowledge in the abstractions in the form of metrics that could motivate human wisdom. In this case, we believe that the beauty classifier we trained in Chapter 5 has some pertinent knowledge learnt by training on the crowd sourced opinions on beauty. In this chapter, we would develop metrics that operate on this knowledge, to automatically generate wisdom inducing insights about how the essence of urban aesthetics.

6.1 Related work

Deep learning has been a hot topic and a tool to explore modelling of large datasets in the recent days. The applications of this has seen a steady expansion in the fields other than computer vision and pattern recognition. To list a few, deep learning has made steady headway in natural science allied fields like drug discovery [GHS16], urban science [PZ17, COR⁺16, LLCG17], health informatics [RWD⁺16]. The most common forms of deep

learning models have been the convolutional neural nets, which we have seen in action in the previous chapter. These convolutional neural networks are essentially layered hierarchical structures of neurons, which can be trained to extract higher dimensional relationships between features in data. This approach has allowed researchers to not only train models to perform simple tasks like detecting objects [K⁺12] or detecting faces [RPC17], but it has also enabled researchers to quantify much more subjective and intangible properties from images, such as emotions [KLP13], sentiments [B⁺13] or ambiance of a place [R⁺15].

Since the introduction of Generative Adversarial Networks (GANs) [GPAM⁺14], deep learning has been used not only to analyse existing images but also to generate new ones altogether. This family of deep networks has evolved into various forms, from super resolution image generators [LTH⁺17] to fine-grained in-painting technologies [PKD⁺16]. Recent approaches have been used to generate images conditioned on specific visual attributes [YYSL15], and these images range from faces [TPW16] to people [MSG⁺18]. In a similar vein, Nguyen *et al.* [NDY⁺16] used generative networks to create a natural-looking image that maximizes the activation of a specific neuron in the discriminator. This method was used to bring out the latent representation of an image, that maximizes its probability of a particular class. In theory, the resulting image is the one that “best activates” the neuron under consideration. In practice, it is still a synthetic template that needs further processing to look realistic. Finally, with the recent advancement in Augmented Reality, the application of GANs to generate urban objects in simulated urban scenes have also been successfully shown [AMM⁺18].

These approaches motivated my work to use GANs, to further investigate the question “What makes an urban scene beautiful?”. To that extent, I design a framework that utilizes GANs in tandem with the beauty classifier, to reconstruct what the classifier presumes to be beautiful. This is done in a way, that provides an incremental change in a target scene to enhance its beauty. Finally, in accordance with the DIWW framework, I develop metrics to better articulate the knowledge learnt by the model. These metrics are novel and are designed around well known metrics in the literature pertaining to urban design and architecture. Finally, I show that this pipeline indeed adds value in the day to day tasks of practitioners of

urbanism and the output suggestions around aesthetics of spaces, indeed is perceived to be more aesthetic compared to the input images.

6.2 GAN primer

A new breed of deep learning algorithms have allowed researchers to generate synthetic data samples, based on knowledge and structure learnt from real data samples (x). These family of algorithms are called Generative Adversarial Networks or GANs. GANs work by simultaneously training a Generator $G(z; \theta)$ and a Discriminator $D(x)$ model, who try to outwit each other through training on real samples. The Generator tries to learn to generate the most “real” looking synthetic samples by learning the distribution of x , and the discriminator $D(x)$ tries to learn to maximize the accuracy on guessing which sample comes from a generator and which comes from the real data. At the peak performance, the generator becomes so good, that the discriminator’s accuracy cannot go beyond 50% mark, implying a totally random guess.

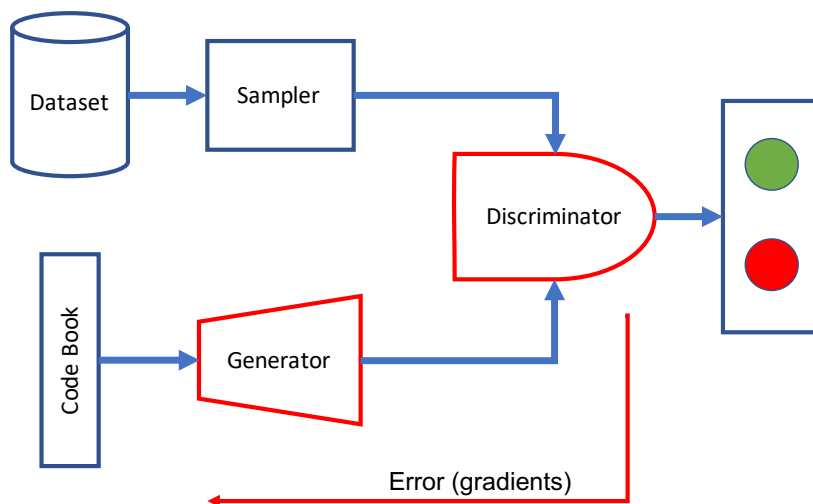


Fig. 6.1 A simplified illustration of the architecture of a Generative Adversarial Network. The red components are trained in tandem, one at a time. The discriminator D tries to maximize accuracy to differentiate between I and the generated version \hat{I} . And the Generator G tries to minimize accuracy of D to 50% thereby making $\hat{I} \approx I$

The training of these arrangements of neural networks happens in a lock step mode. A simplified version of this arrangement can be found in Figure 6.1. The input to the generator $G(z; \theta)$ is initialized using a prior like a gaussian, which essentially creates a codebook of gaussian noise. More formally the discriminator $D(x)$ tries to maximize assigning a correct probability to each sample x_i to be either from the generator G or the real dataset x . At the same time, the generator G is trying to minimize the loss $\log(1 - D(G(x)))$. Essentially G and D are locked in a two player min-max game with the value function $V(D, G)$ formalized as :

$$\min_G \max_D V(D, G) = \mathbb{E}_{x \sim p_{\text{data}}(x)} [\log D(x)] + \mathbb{E}_{z \sim p_z(z)} [\log(1 - D(G(z)))] \quad (6.1)$$

For the premise of my dissertation, I train a generator based on the structure seen at Dosovitsy et.al [DB16a], on the entire dataset of streetview images obtained in accordance to the strategies discussed in Chapter 5. The results of the capacity of this generator to approximate streetview scenes can be seen from Table 6.1.

6.3 Framework Design

Having the trained classifier before, the next step is to generate synthetic images, that maximize the probability of that image being classified as beautiful. The key aim behind this approach is to leverage the latent abstraction of beauty that the classifier has learned.

To achieve this, first we need to train a GAN model that can reliably generate synthetic streetview scenes. A GAN consists of a N dimensional input layer that accepts a N dimensional code. This code activates a series of fully connected and up-convolutional layers. An up-convolutional layer performs an inverse operation of that of a convolutional layer. It upsamples the input and then performs a de-convolution [DTSB15] on the result. The architecture of this network is based on the work by Dosovitskiy *et.al* [DB16a] and the code for reproducing the generator can be found on the author's page¹. I then train this

¹https://lmb.informatik.uni-freiburg.de/resources/binaries/arxiv2016_alexnet_inversion_with_gans/release_deepsim_v0.5.zip

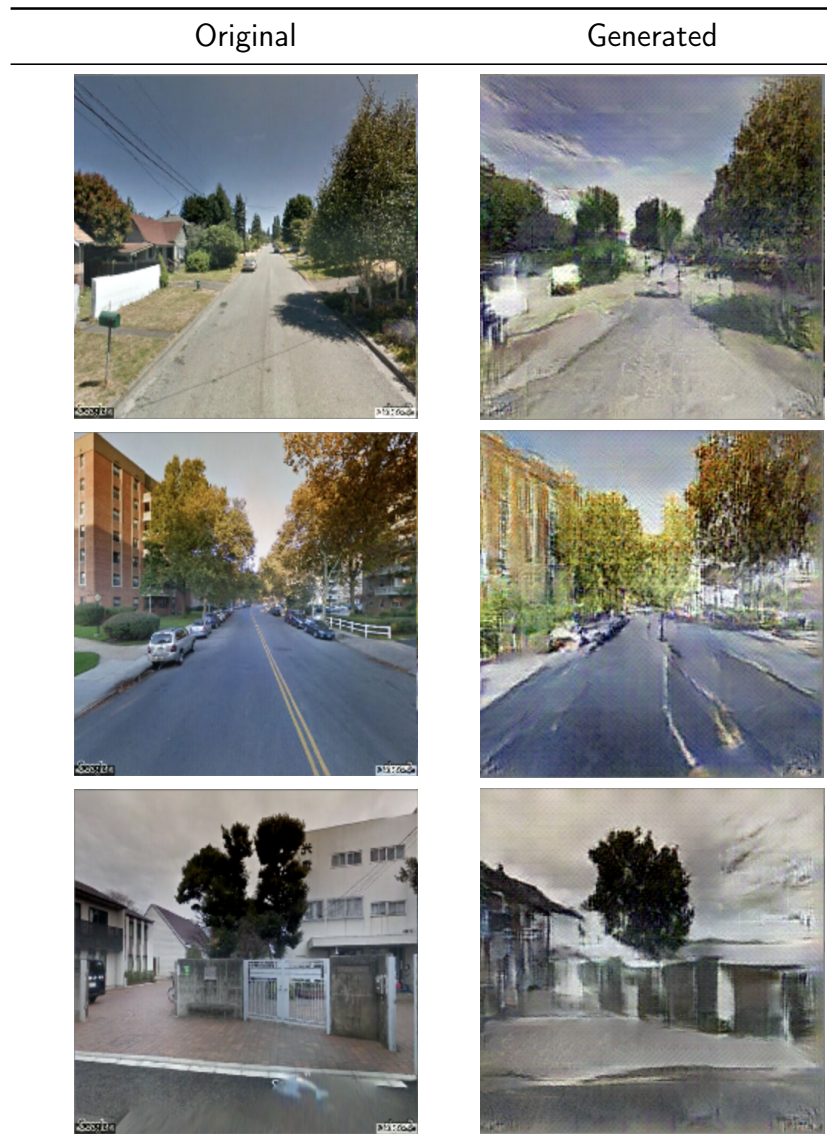


Table 6.1 Examples of our generator's outputs. The original scenes and the generated ones are shown side by side.

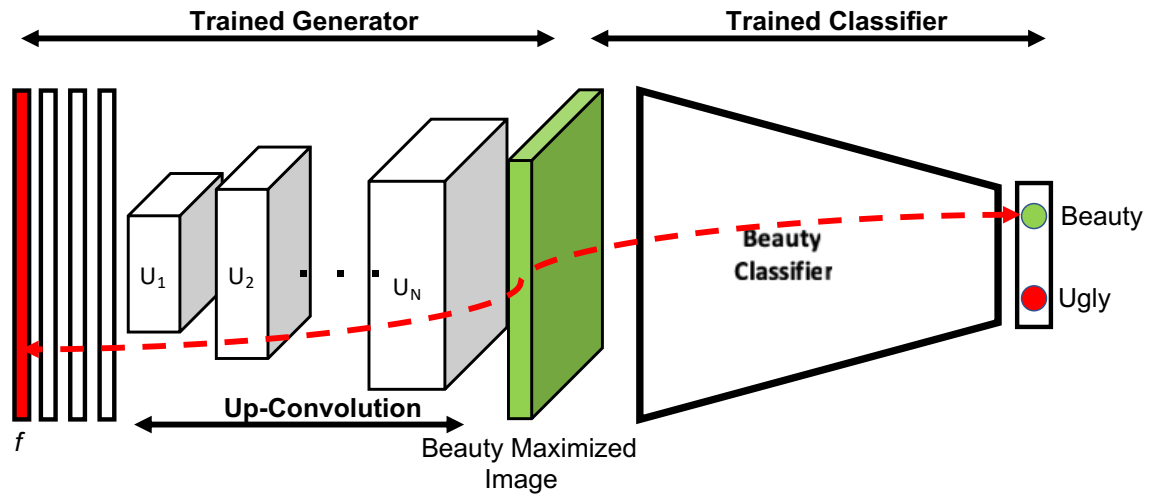


Fig. 6.2 Architecture of the synthetic beauty generator. This consists of a generator of synthetic scenes concatenated with a beauty classifier. The green block is the beauty maximized template \hat{I}_j , which is subject to forward and backward passes (red arrow) when optimizing for beauty.

| Symbol | Meaning |
|-------------|--|
| I_i | Original urban scene |
| Y | Set of annotation classes for urban scenes (e.g., beautiful, ugly) |
| y_i | Annotation class in Y (e.g., beautiful) |
| \hat{I}_j | Template scene (synthetic image) |
| I' | Target Image |
| C | Beauty Classifier |

Table 6.2 List of notations

generator on the set Streetview images curated in Chapter 5. In the interest of reproducibility, the trained models for the classifier and the generator, along with the serialized streetview data can be found at <https://dataverse.harvard.edu/dataverse/Facelift>. The resulting generator is able to generate synthetic streetview images, examples of which can be found in Figure 6.1.

After separately training this generator, which we denote as G , is then arranged in tandem with the beauty classifier C , such that the output of G is fed directly into the classifier C . The simulated arrangement of this framework can be see in figure 6.2 As a result, given the two classes: ugly y_i and beautiful y_j , the end-to-end model transforms any original scene I_i

of class y_i (e.g., ugly scene) into template scene \hat{I}_j that maximizes class y_j (e.g., beautified template scene).

More specifically, given an input image I_i known to be of class y_i (e.g., ugly), our framework outputs \hat{I}_j , which is a more beautiful version of the input I_i (e.g., I_i is morphed towards the average representation of a beautiful scene) while preserving I_i 's details. The technique for mutating the input image in order to maximize the classifier's output neuron is based on "Deep Generator Network for Activation Maximization" (*DGN-AM*) [NDY⁺16]. Given an input image I_i , *DGN-AM* iteratively re-calculates the color of I_i 's pixels in a way the output image \hat{I}_j both maximizes the activation of neuron y_j (e.g., the "beauty neuron") and looks "photo realistic", which is done by conditioning the maximization to an "image prior". This is equivalent to finding the feature vector f that maximizes the following expression:

$$\hat{I}_j = G(f) : \arg \max_f (C_j(G(f)) - \lambda \|f\|) \quad (6.2)$$

where:

- $G(f)$ is the image synthetically generated from the candidate feature vector f ;
- $C_j(G(f))$ is the activation value of neuron y_j in the scene classifier C (the value to be maximized);
- λ is a L_2 regularization term.

Here the initialization of f is key. If f were to be initialized with random noise, the resulting $G(f)$ would be the average representation of category y_j (of, e.g., beauty). Instead, since f is initialized with the feature vector corresponding to I_i , then the resulting maximized $G(f)$ is I_i 's version "morphed to become more beautiful".

The input image is also key. It makes little sense to beautify an already beautiful image, not least because such beautification process would result in a saturated template \hat{I}_j in our framework. For this reason, to generate an image that maximizes the beauty neuron in the classifier C , we restrict the corresponding input image to be in class y_i (i.e., ugly scenes as per the divisions in Figure 5.2). We do the opposite when maximizing the ugly neuron.

We now have template scene \hat{I}_j (which is a synthetic beautified version of original scene I_i) and need to retrieve a realistic looking version of it. We do so by: *i*) representing each of our original scenes in Step 1 (including \hat{I}_j) as a 4096 dimensional feature vector derived from the FC7 layer of the PlacesNet [ZLX⁺14]; *ii*) computing the distance (as L_2 Norm) between \hat{I}_j 's feature vector and each of the original scene's feature vector; and *iii*) selecting the original scene most similar (smaller distance) to \hat{I}_j . This results into the selection of the beautified scene I_j .

6.4 Motifs of urban beauty

Since original scene I_i and beautified scene I_j are real scenes with the same structural characteristics (e.g., point of view, layout), we can easily compare them in terms of presence or absence of urban elements extracted by computer vision tools such as Segnet [BKC15] and PlacesNet [ZLX⁺14]. That is, we can determine how the original scene and its beautified version differ in terms of urban design elements.

6.5 Evaluation

The goal of this framework is to transform existing urban scenes into versions that: *i*) people perceive more beautiful; *ii*) contain urban elements typical of great urban spaces; *iii*) are easy to interpret; and *iv*) architects and urban planners find useful. To ascertain whether the transformation meets the aesthetics criteria of people (**RQ5**) and whether the recommendations from the transformation are useful **RQ6**, we answer the following granular questions next:

Q1 Do individuals perceive the transformed scenes to be beautiful?

Q2 Does our framework produce scenes that possess urban elements typical of great spaces?

Q3 Which urban elements are mostly associated with beautiful scenes?

Q4 Do architects and urban planners find the insights about the transformation useful?















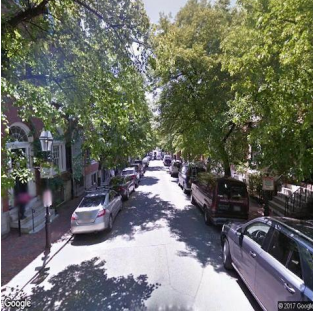
| Original (I_i) | Latent Beauty representation (\hat{I}_j) | Beautified (I_j) |
|---|---|---|
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |

Table 6.3 Examples of the transformation process, which tends to add greenery, narrow roads, and pavements. The three columns represent the original input image (I_i), generated template (\hat{I}_j), and the final beautified version (I_j)

6.5.1 Q1 People's perceptions of beautified scenes

To ascertain whether the transformed scenes are perceived by individuals as they are supposed to, we run a crowd-sourcing experiment on Amazon Mechanical Turk. We randomly select 200 scenes, 100 beautiful and 100 ugly (taken at the bottom 10 and top 10 percentiles of the Trueskill's score distribution of Figure 5.2). Our framework then transforms each ugly scene into its beautified version, and each beautiful scene into its corresponding 'uglified'. These scenes are arranged into pairs, each of which contains the original scene and its beautified or uglified version. On Mechanical Turk, we only select verified masters as our crowd-sourcing workers (those with an approval rate above 90% during the past 30 days), pay them \$0.1 per task, and ask each of them to choose the most beautiful scene for each given pair. We make sure to have at least 3 votes for each scene pair. Overall, our workers end up selecting the scenes that are actually beautiful 77.5% of the times, suggesting that the transformed scenes are indeed perceived to be more beautiful by people.

6.5.2 Q2 Are beautified scenes great urban spaces?

To answer that question, we need to understand what makes a space great. After reviewing the literature in urban planning, we identify four factors associated with great places [EC13, Ale77, Jac61] (Table 6.4): great places mainly tend to be walkable, offer greenery, feel cozy, and be visually rich. Walkable streets are perceived to be safer and have been shown to influence the vitality of a city street [Jac61]. Greenery too is linked to mental well being, beauty, and closeness to nature [Ale77]. Openness, or the feeling of cosiness, is linked to feeling of safety and exploration. Too much openness is linked to our evolutionary need to become alert about dangers. Too little openness makes us weary about line of sights. This means openness is linked to the feeling of safety in an inverted 'U' relationship. Finally, visual complexity, or the measure of the diversity of physical objects visible in your perspective, is also linked in an inverted 'U' fashion with our sense of beauty.

To automatically extract visual cues related to these four factors, we select 500 ugly scenes and 500 beautiful ones at random, transform them into their opposite aesthetic qualities

| Metric | Description |
|-------------------|--|
| Walkability | Walkable streets support people’s natural tendency to explore spaces [EC13, QASD15, Spe12]. |
| Green Spaces | The presence of greenery has repeatedly been found to impact people’s well-being [Ale77]. Under certain conditions, it could also promote social interactions [QOC14]. Not all types of greenery have to be considered the same though: dense forests or unkempt greens might well have a negative impact [Jac61]. |
| Landmarks | Feeling lost is not a pleasant experience, and the presence of landmarks have been shown to contribute to the legibility and navigability of spaces [Lyn60, QOC14, EC13, QPAC13]. |
| Privacy-Openness | The sense of privacy conveyed by a place’s structure (as opposed to a sense of openness) impacts its perception [EC13]. |
| Visual Complexity | Visual complexity is a measure of how diverse an urban scene is in terms of design materials, textures, and objects [EC13]. The relationship between complexity and preferences generally follows an ‘inverted-U’ shape: we prefer places of medium complexity rather than places of low or high complexity [Ulr83]. |

Table 6.4 Urban Design Metrics

(i.e., ugly ones are beautified, and beautiful ones are ‘uglified’), and compare which urban elements related to the four factors distinguish uglified scenes from beautified ones.

We extract labels from each of our 1,000 scenes using two image classifiers. First, using PlacesNet [ZLX⁺14]. PlacesNet is a deep learning framework which is trained to detect the type of place visible in an input image. The framework classifies the input image into one of the 205 place type labels that it is trained on. We label each of our scenes according to a classification containing 205 labels (reflecting, for example, landmarks, natural elements), and retain the five labels with highest confidence scores for a particular scene. We then manually classify each of these 205 labels into the 4 built environment types namely *Walkable*, *Architectural*, *Natural*, and *Landmark*. The definitions of these 4 categories can be found in the Appendix 2 (Chapter B). For example the label of ‘Plaza’ is considered a Walkable label, whereas the label of ‘Cathedral’ is considered to be a Landmark. These categories are

inspired by the guidelines for measuring urban design [EC13]. At the end of this manual exercise, we are left with 117 PlacesNet labels belonging to the 4 built environment categories (See Table B.1). All the remaining labels are discarded, since they do not fall into any of these 4 categories. Second, using Segnet [BKC15], we label each of our scenes according to a classification containing 12 labels. Segnet is trained on dash-cam images, and classifies each scene pixel with one of these twelve labels: road, sky, trees, buildings, poles, signage, pedestrians, vehicles, bicycles, pavement, fences, and road markings.

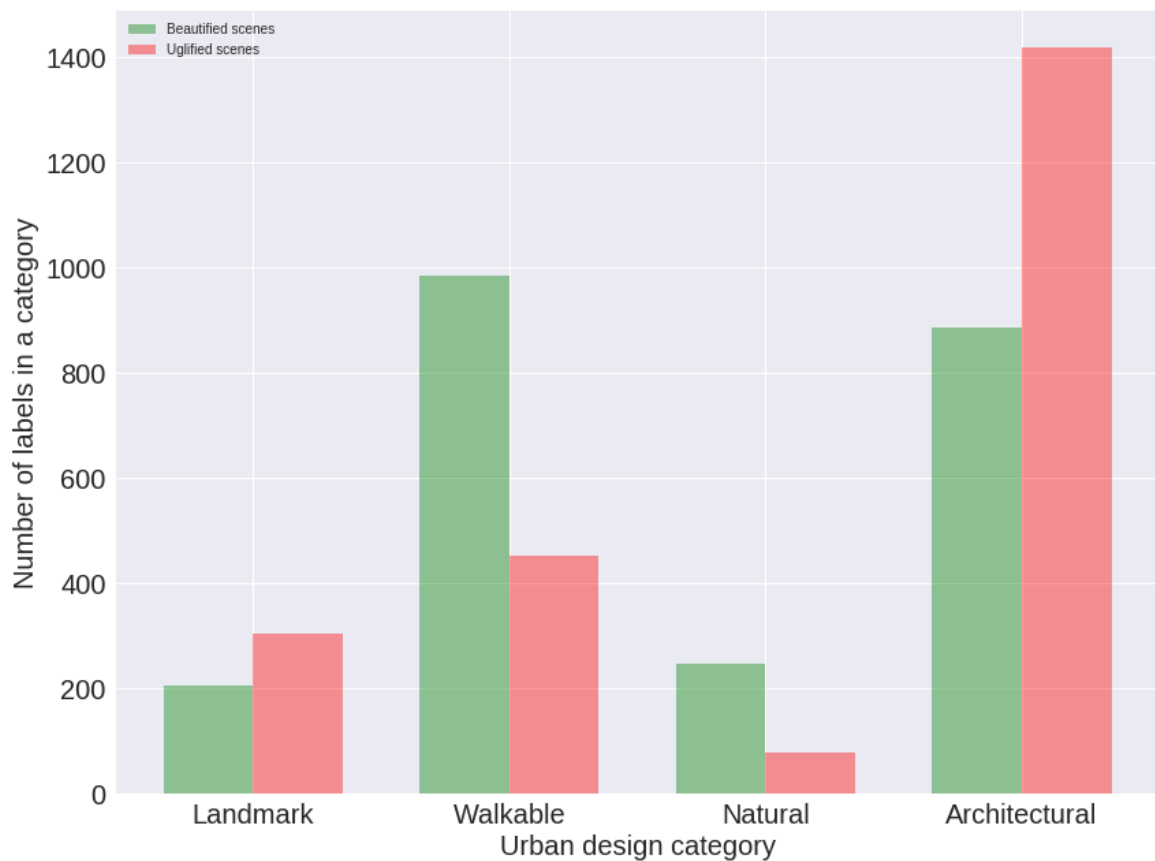


Fig. 6.3 Number of labels in specific urban design categories (on the x -axis) found in beautified scenes as opposed to those found in uglified scenes.

Having these two ways of labelling scenes, we can now test whether the expectations set by the literature describing metrics of great urban spaces (Table 6.4) are met in the Face-lifted scenes.

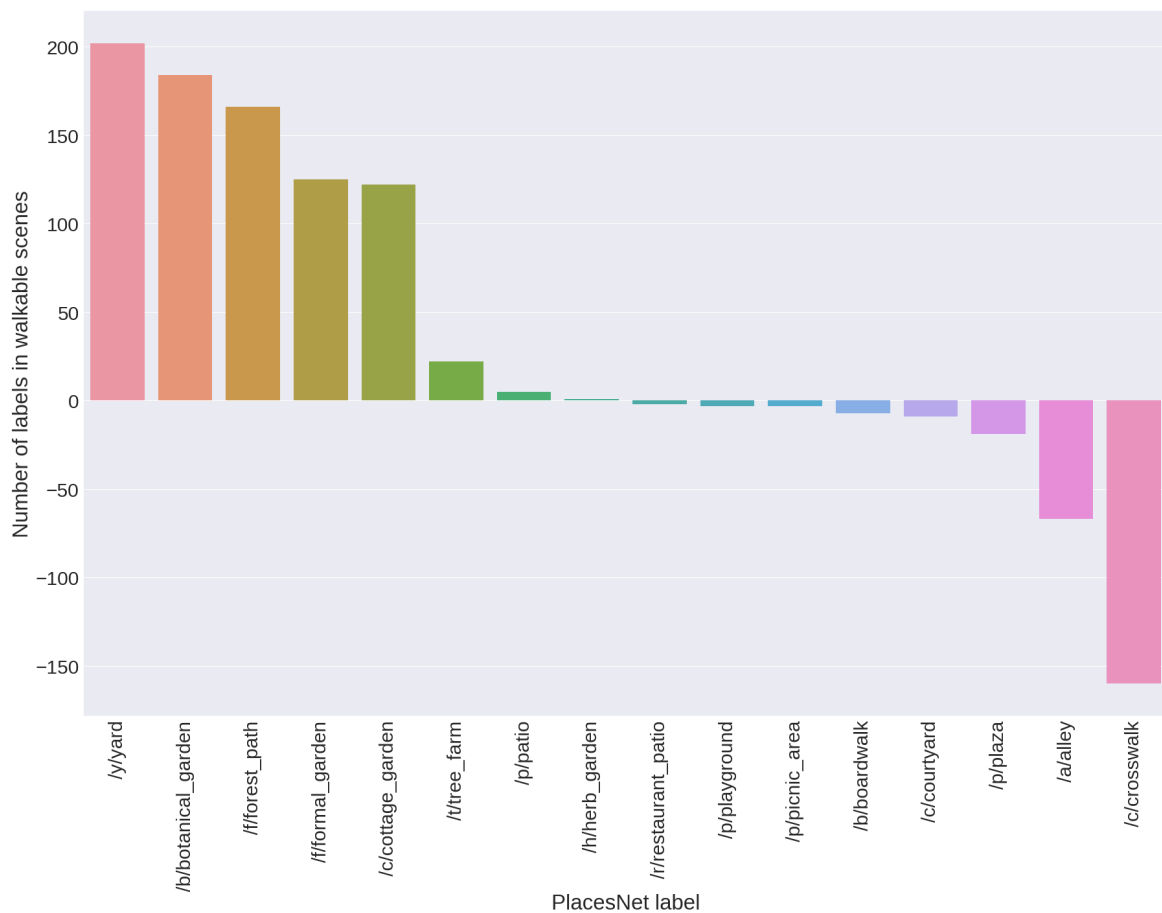


Fig. 6.4 Count of specific walkability-related labels (on the x -axis) found in beautified scenes minus the count of the same labels found in uglified scenes.

H1 Beautified scenes tend to be walkable. We manually select only the PlacesNet labels that are related to walkability. These labels include, for example, *abbey*, *plaza*, *courtyard*, *garden*, *picnic area*, and *park*. To test hypothesis *H1*, we count the number of walkability-related labels found in beautified scenes as opposed to those found in uglified scenes (Figure 6.3): the former contain twice as many walkability labels than the latter. We then determine which types of scenes are associated with beauty (Figure 6.4). Unsurprisingly, beautified scenes tend to show gardens, yards, and small paths. By contrast, uglified ones tend to show built environment features such as shop fronts and broad roads. Hence walkable scenes are indeed associated with beauty.

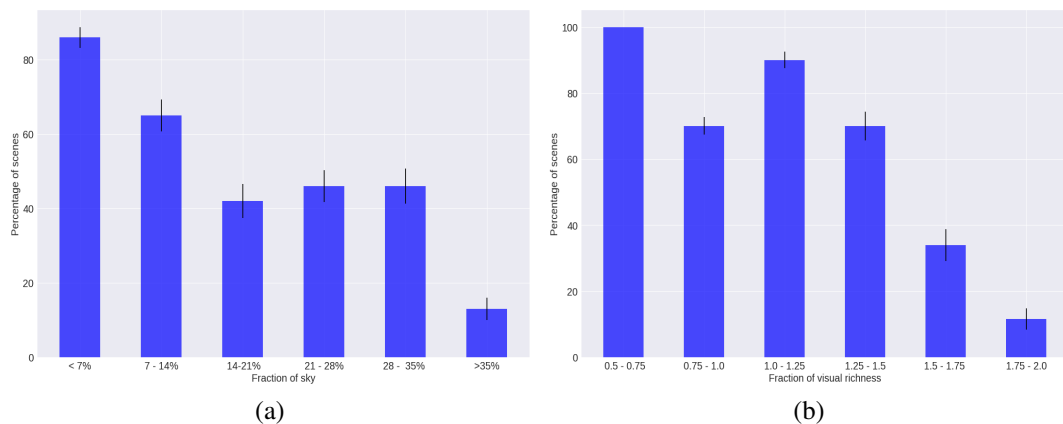


Fig. 6.5 The percentage of beautified scenes (y-axis): (a) having an increasing presence of sky (on the x-axis); and (b) having an increasing level of visual richness (on the x-axis). The error bars represent standard errors obtained by random re-sampling of the data for 500 iterations.

H2 Beautified scenes tend to offer green spaces. We manually select only the PlacesNet labels that are related to greenery. These labels include, for example, *fields*, *pasture*, *forest*, *ocean*, and *beach*. Then, in our 1,000 scenes, to test hypothesis *H2*, we count the number of nature-related labels found in beautified scenes as opposed to those found in uglified scenes (Figure 6.3): the former contain more than twice as many nature-related labels than the latter. To test this hypothesis further, we compute the fraction of ‘tree’ pixels (using Segnet’s label ‘tree’) in beautified and uglified scenes, and find that beautification adds 32% of tree pixels, while uglification removes 17% of them. This points to the fact that presence of greenery in a scene is indeed associated with the sense of beauty.

H3 Beautified scenes tend to feel private and ‘cozy’. To test hypothesis *H3*, we count the fraction of pixels that Segnet labeled as ‘sky’ and show the results in a bin plot in Figure 6.5a: the x-axis has six bins (each of which represents a given range of sky fraction), and the y-axis shows the percentage of beautified vs. uglified scenes that fall into each bin. Beautified scenes tend to be cozier (lower sky presence) than the corresponding original scenes.

H4 Beautified scenes tend to be visually rich. To quantify to which extent scenes are visually

| Pair of urban elements | β_1 | β_2 | β_3 | Error Rate (Percentage) |
|------------------------|-----------|-----------|-----------|-------------------------|
| Buildings - Trees | -0.032 | 0.084 | 0.005 | 12.7 |
| Sky - Buildings | -0.08 | -0.11 | 0.064 | 14.4 |
| Roads - Vehicles | -0.015 | -0.05 | 0.023 | 40.6 |
| Sky - Trees | 0.03 | 0.11 | -0.012 | 12.8 |
| Roads - Trees | 0.04 | 0.10 | -0.031 | 13.5 |
| Roads - Buildings | -0.05 | -0.097 | 0.04 | 20.2 |

Table 6.5 Coefficients of logistic regressions run on one pair of predictors at the time.

rich, we measure their visual complexity [EC13] as the amount of disorder in terms of distribution of (Segnet) urban elements in the scene:

$$H(X) = -\sum p(i) \log p(i) \quad (6.3)$$

where i is the i^{th} Segnet's label. The total number of labels is twelve. The higher $H(X)$, the higher the scene's entropy, that is, the higher the scene's complexity. It has been suggested that the relationship between complexity and pleasantness follows an 'inverted U' shape [Ulr83]: we prefer places of medium complexity rather than places of low or high complexity. To test that, we show the percentage of beautified scenes that fall into each complexity bin (Figure 6.5b): we do not find a strong evidence of the 'inverted U' shape hypothesis, in that, beautified scenes are of low to medium complexity, while uglified ones are of high complexity.

6.5.3 Q3 Urban elements of beautified scenes

Logistic regression is often used to compute relationships between predictor variables and an outcome variable which maps to $\{0, 1\}$. The relationships between outcome variable and the set of predictors can be interpreted through the values of the β coefficients.

To determine which urban elements are the best predictors of urban beauty and the extent to which they are so, we run a logistic regression, and, to ease interpretation, we do so on

one pair of predictors at the time:

$$Pr(\text{beautiful}) = \text{logit}^{-1}(\alpha + \beta_1 * V_1 + \beta_2 * V_2 + \beta_3 * V_1.V_2) \quad (6.4)$$

where V_1 is the fraction of the scene's pixels marked with one Segnet's label, say, "buildings" (over the total number of pixels), and V_2 is the fraction of the scene's pixels marked with another label, say, "trees". The result consists of three beta coefficients: β_1 reflects V_1 's contribution in predicting beauty, β_2 reflects V_2 's contribution, and β_3 is the interaction effect, that is, it reflects the contribution of the dependency between V_1 and V_2 in predicting beauty. We run logistic regressions on the five factors that have been found to be most predictive of urban beauty [QOC14, EC13, Ale77], and show the results in Table 6.5.

Since we are using logistic regressions, the quantitative interpretation of the β coefficients is eased by the "divide by 4 rule" [GH06]. This interpretation is based on Gelman's explanation about of relationship between logistic coefficients and the logit outcome variable. This is an approximate way to interpret the relationship between predictors and outcome variable in a logistic regression. We can take the β coefficients and "divide them by 4 to get an upper bound of the predictive difference corresponding to a unit difference" in the probability of the image being in the beauty class [GH06]. For example, take the results in the first row of Table 6.5. In the model $Pr(\text{beautiful}) = \text{logit}^{-1}(\alpha - 0.032 \cdot \text{buildings} + 0.084 \cdot \text{trees} + 0.005 \cdot \text{buildings} \cdot \text{trees})$, we can divide - 0.032/4 to get -0.008: a difference of 1 in the fraction of pixels being buildings corresponds to no more than a 0.8% *negative* difference in the probability of the scene being beautiful. In a similar way, a difference of 1 in the fraction of pixels being trees corresponds to no more than a 0.021% *positive* difference in the probability of the scene being beautiful. By considering the remaining results in Table 6.5, we find that, across all pairwise comparisons, trees is the most positive element associated with beauty, while roads and buildings are the most negative ones. These results match previous literature in urban design of what makes spaces great, adding further external validity to our framework's beautification.

| Use case | Definitely Not | Probably Not | Probably | Very Probably | Definitely |
|------------------------------|----------------|--------------|----------|---------------|------------|
| Decision Making | 4.8% | 9.5% | 38% | 28.6% | 19% |
| Participatory Urban Planning | 0% | 4.8% | 52.4% | 23.8% | 19% |
| Promote Green Cities | 4.8% | 0% | 47.6% | 19% | 28.6% |

Table 6.6 Urban experts polled about the extent to which the interactive map visualization promotes: (a) decision making; (b) citizen participation in urban planning; and (c) promotion of green cities

6.5.4 Q4 Do architects and urban planners find it useful?

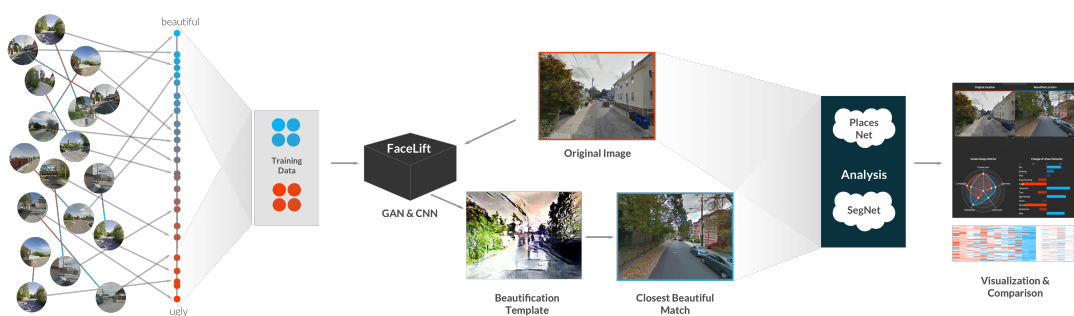


Fig. 6.6 An end to end illustration of the framework.

To ascertain whether practitioners find the framework potentially useful, we build an interactive map of the city of Boston in which, for selected points, we show pairs of urban scenes before/after beautification (Figure 6.7)². We then send that map along with a survey to 20 experts in architecture, urban planning, and data visualization around the world. Questions were asked with a non-neutral response Likert scale (Table 6.6). That is because previous work [BFT12, Moo08] has shown that such a scale: (i) pushes respondents to “take a stance”, given the absence of a neutral response; and (ii) works best if respondents are experts in the subject matter of the survey as responses of the “I don’t know” type tend to be rare (as it has been the case for our survey). The experts had to complete tasks in which they rated the framework based on how well it supports decision making, participatory urbanism, and the promotion of green spaces. According to our experts (Table 6.6), the tool can very probably supports decision making, probably support participatory urbanism, and definitely promote green spaces. These results are also qualitatively supported by our experts’ comments, which

²It is worth noting that the visualization is not claimed to be my original contribution. The design of the interactive map was done by the first author of article 5. This visualization was christened as “Facelift”



Fig. 6.7 Interactive visualization showing the transformed scenes in Boston. A more complete map can be explored at www.goodcitylife.org/facelift

include: “The maps reveal patterns that might not otherwise be apparent”, “The tool helps focusing on parameters to identify beauty in the city while exploring it”, and “The metrics are nice. It made me think more about beautiful places needing a combination of criteria, rather than a high score on one or two dimensions. It made me realize that these criteria are probably spatially correlated”.

6.6 Conclusion

In this chapter, I designed and evaluated a framework that automatically beautifies urban scenes by combining recent approaches of Generative Adversarial Networks and Deep Convolutional Networks [DTSB15, DB16a, DB16b]. The key intention behind this arrangement of diverse models was to leverage the notion of urban beauty learnt by the models in chapter 5. This framework allowed us to mutate any given image so as to maximize its perceptual beauty. This was indeed proven by the overwhelming agreement amongst Amazon mechanical Turkers about the model's outputs. This points to the fact that the opinions of a large crowd can indeed give us insights about the key improvements to be done in a real urban space, so as to make it more beautiful. This insight alludes to the fact the answer to **RQ5** is indeed "Yes".

But just generating prettier versions of images is not enough, since that does not give usable insights to practitioners; who in the end are responsible to execute the job of urban design and planning. To allow this to happen, we need to translate the transformations done in the image space, into metrics that can drive decision making. To achieve this, the framework is able to explain which urban elements have been added/removed during the beautification process. These additions/subtractions from the source image are then articulated in terms of 5 important urban design metrics. After conducting a user study with practitioners in the field, we found that the majority of participants positively reacted to the framework and almost all of them saw a future where Artificial Intelligence could help them to incorporate crowd's perception into the design process, which answers the **RQ6**.

6.6.1 Limitations and biases

The framework is as good as its training data, and more work has to go into collecting reliable ground truth data on human perceptions. This data should ideally be stratified according to the people's characteristics that impact their perceptions, such as gender, cultural background, location, and language. The other main limitation is that generative models are hard to

control, and more work has to go into offering principled ways of fine-tuning the generative process.

Like any supervised deep learning based framework, this work is only able to learn what is present in the data. Hence the method of acquiring annotations for urban images can introduce huge biases in the model. The current model is trained on images acquired from a previous study of public perception of the city [NPRH14]. However, their study allowed anyone from the general public all around the world to annotate the images. This creates difficulties in separating out the cultural influences on the annotator's subjective opinion. Moreover because the pair wise choice is simply done by clicking one of the two images, the data might have noise introduced by non-serious participants clicking at whim. Such biases are bound to be picked up by the deep learning model. One can argue that the preference of our model for greenery, is a form of bias in the data. Another bias introduced because of the data is the model's lack of preference to pedestrians. This bias stems from the fact that Google tries to remove most of the people from their street view images for privacy reasons. Hence people, which makes up a major aspect of urban vitality, are more or less missing from most dataset images.

Despite the drawbacks, I believe this approach towards augmented urban design may very well be commonplace in the near future. After all, "we delight in complexity to which genius have lent an appearance of simplicity." [DB08] In the context of future work, that genius is represented by future technologies that will help us deal with the complexity of our cities.

6.6.2 Implications

In the works through my Ph.D., the idea of quantifying the subjective has always been the central theme. The subjective is where most of our human experience takes place. As Emanuel Kant instructs, "Look closely, the beautiful may be small". And indeed, the insights that drive the quantification of beauty in this part of my work, seem to be almost intuitive. Concepts like greenery, walkable spaces, complexity, and open spaces seem drive our perception of the aesthetic, which may be grounded in our evolutionary need to be safe

and close to nature. Despite of the seemingly intuitive root causes, the implications of these simple properties of urban spaces on mental and physical health seem to be far more crucial in today's world. At such a juncture, it is worth while to develop these frameworks to capture human subjective experiences. Thankfully because of the convergence in our online and offline lives, we are generating far more data about our offline experiences in the online realm. Data generated from our interactions with different on-line services, may very well improve our off-line lives.

CLOSING NOTES

“The unity of all science consists alone in its method, not in its material ... It is not the facts themselves which form science, but the method in which they are dealt with.” - Karl Pearson

The guiding principle for this dissertation has been understanding how human subjective opinions can be leveraged for social good. The aim was to advance the understanding of how something as subjective as expression of support or perception of beauty, can be quantified. I explored two realms of this problem, one dealing with groups of humans forming communities around a supportive cause, and other looking at a vast set of un-related people expressing their subjective opinions about urban aesthetics. In both cases, the key was the set of methods used to tease out the signatures of these subjective qualities from data. To that end, Karl Pearson’s quote is very apt and encapsulates the key contributions of my work.

Working with a framework, of first acquiring and curating **Data**, then building key abstractions on top to capture the **Information**, then building metrics to extract the **Knowledge** allowed me to build a pipeline to work with data from a diverse set of applications. The hope is that this pipeline can be used to generate **Wisdom** that drives interventions

The work done in my dissertation is going to inspire the vision for my research in the near future, and I would like to close this journey by walking through a few aspects of what I imagine would be the path forward. I would also like to reflect on what has been done and what remains to be done in the context of this dissertation.

7.1 Reflection

The central thesis of my dissertation, as stated in Chapter 1 was as below:

Can we quantify properties of subjective nature, if the data is large enough, and originates from human communities or crowds?

Being a vastly open ended problem, I decided to direct my efforts in two key directions
1) The regime of web scale data, where the subjective is quantified from the signals of online interactions between connected users (communities) and 2) The regime where the web scale data is a direct result of some subjective perception of vastly disconnected users(crowds).

In the first regime, I investigated the utility of online forums in providing social support for people in distress. With **RQ1** and **RQ2** I explored the temporal dynamics of support communities from the perspective of individual users. We find that a few high contributing users, which are termed as superusers, are tantamount to the support dynamics and the health of the community. They are important towards the cohesiveness of the community and provide brokerage of social capital. There is also an overall propensity to help each other, which increases with time and experience. With **RQ3**, I developed methods to quantify the signatures of supportive interactions in the conversation structure on these communities, using a novel way to perform triadic census of the network structure. Investigation in the first regime allowed me to show that the exchange of support over a large connected community can be quantified by analysing the different structural aspects of that community.

In the second regime, I investigated how online opinions of large disconnected crowds about subjective properties could be used to quantify the subjective in the real world. With **RQ4**, I showed that by using opinions of the crowds about urban beauty, we can train a deep learning model that could differentiate between beautiful and ugly urban spaces to a high degree of accuracy. **RQ5** investigated the utility of this model, in not just recognizing beauty but also recreate it and explain it through a set of literature driven metrics. These metrics

are inspired from the field of urban planning and architecture, which are then validated for accuracy and relevance by investigating for **RQ6**. Investigations in the second regime allowed me to show that subjective properties, like the perception of beauty, can be indeed quantified from opinions of disconnected crowds, and can be leveraged for interventions.

7.2 Open problems

Throughout this dissertation, I came across interesting problems which I would have loved to investigate, but couldn't in the interest of focus and time. I would like to enumerate a few as an exercise in reflection. At the very least, I would like to discuss the problems and illuminate them for further investigation by the community.

7.2.1 Triadic closures in conversation graphs

Triadic closure has been shown to be an important mechanism in the literature of social networks [Gra77, MVF11] through which social ties get established. The mechanism has also been widely explored as a measure to for recommendation systems [ST14, LTH⁺13].

Despite this wide prevalence in social networks, dialogue structures on reddit in the context of social support seem to exhibit a different behaviour, as seen in Chapter 4. As seen from the results in Appendix A, motifs that resemble a triadic closure are very rare in either cases. However the precursors to a triadic closure, such as 201 variants, 111 variants and 021 variants are all expressed with statistical significance in the baseline as well as supportive conversations. Triadic closures have shown to be vital for information diffusion in networks [BGV⁺16]. Hence investigating closures in dialogue structures on reddit could lead to some interesting counter intuitive mechanisms.

7.2.2 Colouring ties in conversation graphs

In my dissertation I explored the utility of language in capturing the strength of ties in a dialogue graph (as seen in Chapter 4). However, it is important to note that just

measuring alignment between two exchanges might be resulting a loss of crucial information. Linguistically, it would be worthwhile to capture the essence of dialogues along a multi-dimensional scale, since that is how actual exchanges take place. To that end, it would be of value to colour the links using affective components of an exchange between two people, such as empathy, affection, trust, anxiety, animosity, friendship etc. These colours could further help us develop methods to detect toxic behaviours online and capture the overall tone of a discussion.

7.2.3 Exploring cultural biases in subjective perception

An important limitation in using the crowd's opinion to quantify the subjective is the trade-off between data volume and data bias. To train any reliable deep learning model, you need a reasonable volume of data to train. This limits the amount of stratification one can do in the crowd opinions along cultural, geographical and social lines. Stratifying data further could lead to over-fitted models. But using the bulk of data as one monolithic chunk endangers the model to learn the least common denominator in the subjective preferences. That means the cultural nuances about the concept of beauty that enrich our world are all averaged out. Indeed as seen in Chapter 6 the FaceLift model tends to associate foliage with beauty to a high degree. There are methods in the literature to solve these problems, by teasing out biases in the models by partitioning the data in a clever manner.

7.3 Future Outlook

In this Ph.D I aimed at exploring and exploiting the potential of machine learning, to understand how the subjective can be sensed from web scale data. To that end, it is worth discussing about how the methods I developed align with the research I intend to pursue.

In the future I would like to extend this work along two key dimensions which are based on a shared theme "*Capitalizing on the subjective perceptions to deliver impactful interventions*".

7.3.1 Empathic healthcare

Improving healthcare to provide an empathic experience to patients in an economical and scalable way is the most crucial challenge of 21st century. The world saw an explosive growth in population during the baby boomer generation. This same cohort has now become the largest ageing cohort in the history of the world. On account of this and the rise of chronic diseases, the health care sector has seen unprecedented growth in the past decade¹. With growth, comes the challenges of scale. Despite ever increasing investment², the UK's NHS still is riling under the pressure of rising patient numbers, dwindling staff and longer wait times [May18]. Longer wait times also imply that doctors are on an average spending less time with the patients. This has taken a serious toll on the doctor patient empathic communication. It has been shown that the doctor patient relationship plays a vital role in accuracy of diagnosis of the disease ,prognosis of the patient and overall satisfaction of the patient [JBS⁺11, Ben91].

At such a juncture, there is a rising need to solve frictions along these points of contacts for the NHS. At the same time, it is extremely important to provide psycho-social infrastructure for this ageing population, especially at times when the ailments are chronic in nature, and the social support structures are fragile. The vision for an empathic healthcare, puts forth a framework where the psycho-social aspects of health are put at the centre of the system, along with the biological well being. This can be done by re-engineering several pipelines, through which a patient engages with the healthcare systems. This means that a treatment plan is not just a relationship between the doctor and the patient, but involves a support structure of both AI-driven agents, peers, online-volunteers and healthcare workers. My work done with the Chronic Obstructive Pulmonary Disease community shows that patients of chronic diseases tend to thrive as a part of an online social support community, and at times can take up the mantle to provide crucial information [JSC⁺18]. My work with the suicide watch support community also shows that there are quantifiable structures of support

¹<https://www2.deloitte.com/global/en/pages/life-sciences-and-healthcare/articles/global-health-care-sector-outlook.html>

²<https://www.bbc.co.uk/news/health-46524257>

which exhibit a patient centric structure of engagement. I foresee that with the help of A.I. models trained on these empathic interactions, we could one day see virtual support groups which are supported by the healthcare provider and allow self and group management of chronic conditions. This would allow the healthcare providers to save costs in terms of lost appointment times for patients of chronic conditions. But at the same time, it would provide a true bio-psycho-social framework for chronic symptom management. Overall, I see that empathic signatures in communications, can be learnt at scale, provided that we can pinpoint where exactly such interactions are happening. And I think my work paves a path forward for that to happen.

7.3.2 Perceptive urbanism

Urbanism is a term used commonly to describe works that deal with problems and mechanisms that shape an urban environment. There has been a sharp rise in research in the field of urbanism due to the age of open data. Many of these works look at open urban data about socio-economic indicators in conjunction with social outcome variables like health [SBL⁺12, VQC⁺15], well being [CSH⁺17], quality of air [MD03] etc. Some more inter-disciplinary works have also shown that built environment in cities resonate with our personality and perception of qualities like safety, richness and beauty [DNPVZ⁺16b, DNP⁺16]. Some other studies have also shown that something as simple as presence of green canopy can be correlated with reduced depression related prescriptions [HKR⁺18].

In the same vein, my work done on crowd based urban design, allowed me to leverage perception of the crowds to improve urban spaces. I believe the most natural extension in this case is utilizing these methods to explore further linkages between our urban environment and our quantified self. Questions like "how does the city influence our mental health?" or "how does built environment influence the air we breath?" are now within the reach of data science. The possibility of linking perception driven metrics in urban spaces, with socio-economic or health indicators is what I define as perceptive urbanism. This aspect of urbanism could actually be immensely helpful in developing interventions with minimum costs but maximum impact.

7.4 Conclusion

In the hindsight, this work has been a result of a series of fortunate accidents which allowed me to explore and exploit interesting topics in the fields of information retrieval, network science and at times social sciences. Being a computer scientist in today's age, I believe, is as much an exercise in a broad understanding of today's social problems, as it is about technical details and methods to solve them. My Ph.D. has given me an unfettered opportunity to spend my time and resources in broadening my horizons. I hope I keep the pursuit alive in the due course of my career.

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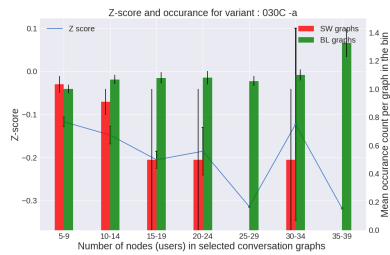
APPENDIX A

APPENDIX 1: RARE ANCHORED MOTIFS IN SOCIAL SUPPORT

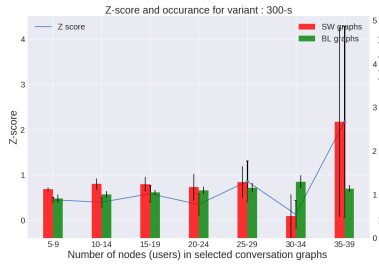
I evaluate the prevalence of all the Anchored Triadic motifs as defined in Chapter 4. As explored by previous studies [SM15, SM12, HL76, HL71], the social-tie structures and certain triadic motifs are predictors of social hierarchy in communities. Albeit these studies looked at community structures of Apes and tribal populations, they act as a very peculiar proxies for understanding how communities in the wild evolve. The important point to note here is that graphs that emerge from conversations, may not be synonymous to the graphs that form due to actual social ties. But in the context of a conversation, the interactions between peers can be assumed to be a purely transactional tie.

The internet has opened up new mechanisms of formation of these ties. And at that, the mechanisms seem to generate new patterns of conversations, based on the kind of interaction the participants of a community perform. To that end both the supportive and baseline communities exhibits a dearth of transitive triads like *030T* and *210C*, which are more prevalent in real life communities with hierarchies

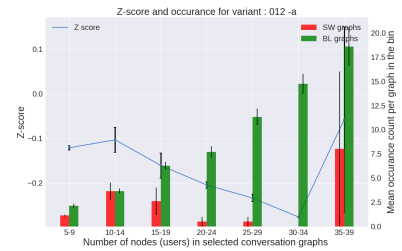
One of the most interesting outcome of this exercises, which I failed to pursue further is the complete lack of triadic closures. Triadic closure has been a very important aspect of studies around online social capital. The key premise here is that a weak tie can act as a bridge between two disjoint nodes in a community. However, in the context of conversation structures, this phenomenon seems to be completely absent from the picture.



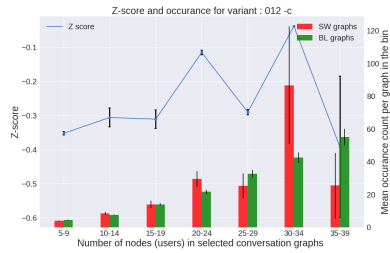
(1.a)



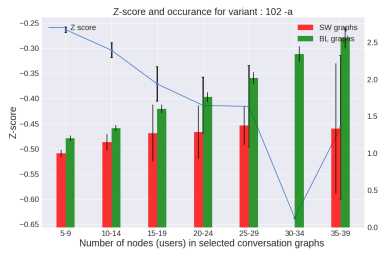
(1.b)



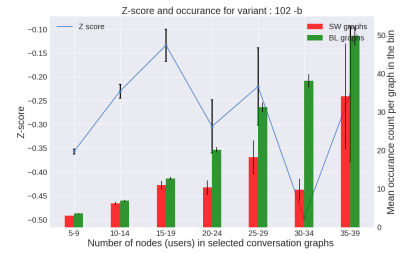
(1.c)



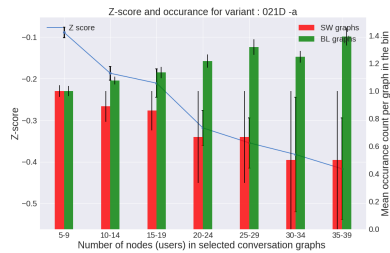
(2.a)



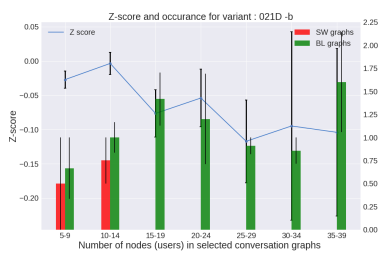
(2.b)



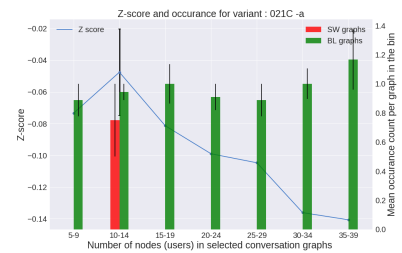
(2.c)



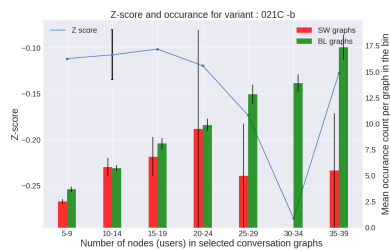
(3.a)



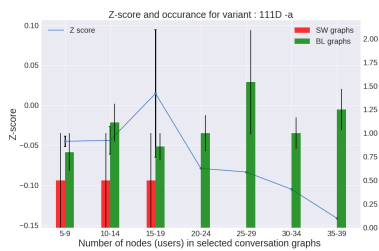
(3.b)



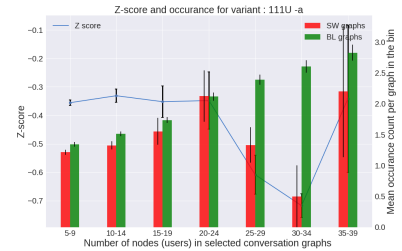
(3.c)



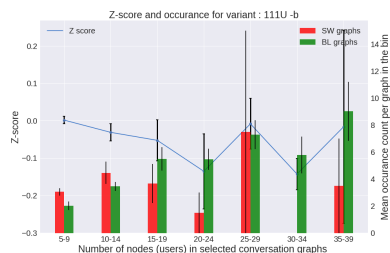
(4.a)



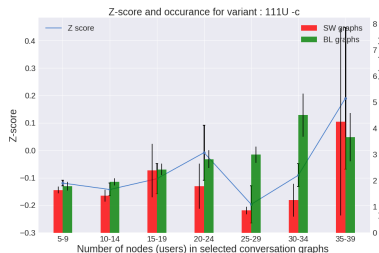
(4.b)



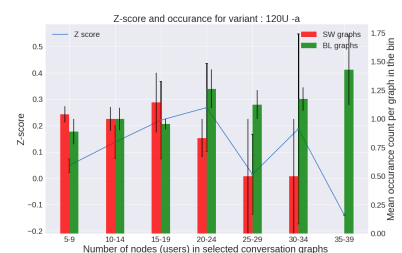
(4.c)



(5.a)



(5.b)



(5.c)

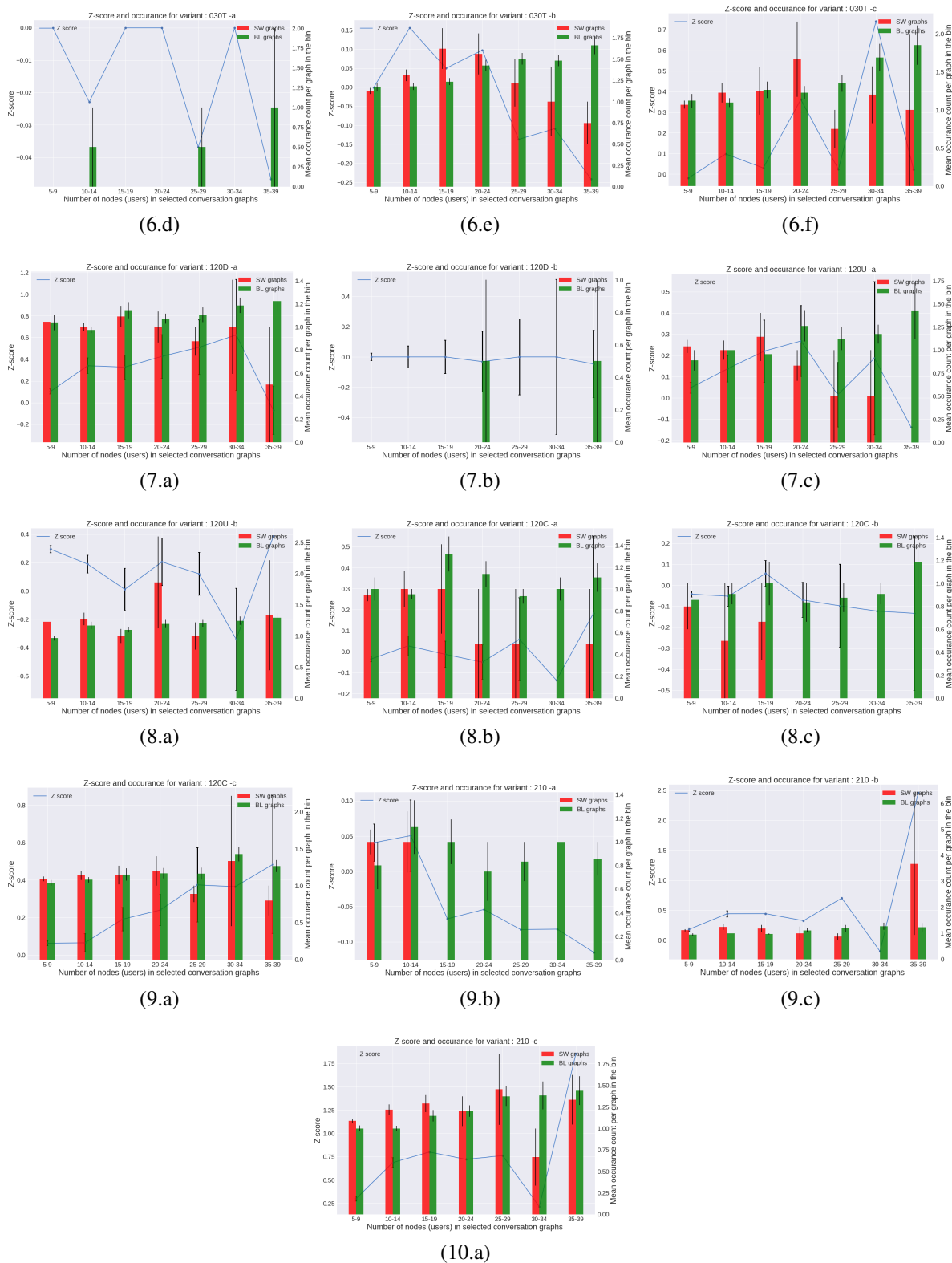


Fig. A.0 This figure lists out all the insignificant Anchored motifs, either by the virtue of rare occurrence (<5 mean motifs per bin) or by account of low Z-score.

APPENDIX B

APPENDIX 2: CATEGORIZATION OF PLACESNET LABELS

As discussed in Chapter 6 I classified the labels from Placesnet, a deep learning framework to recognize the types of outdoor places [ZLX⁺14], into 4 distinct categories namely Architectural, Natural, Landmarks and Walkable. These categories were picked up to understand the effect of 4 broad classes of built and natural entities on urban beauty. The definitions for the category descriptions were defined based on the guidelines from [EC13].

Definition 3 *Walkable* *A scene from PlacesNet was defined to be walkable, if the scene is perceived to facilitate people to walk.*

Definition 4 *Landmarks* *A scene from PlacesNet was defined to be a Landmark, if the scene can be used to articulate, remember or communicate location relative to an object.*

Definition 5 *Architectural* *A scene from PlacesNet was defined to be Architectural, if the scene can be described to be a part of the city's built environment.*

Definition 6 *Natural* *A scene from PlacesNet was defined to be Natural, if the scene evokes the feeling about being in proximity with nature.*

Once the labels were classified, I developed metrics around the built environment of a place, based on the frequencies of labels belonging to the four categories. A detailed categorization of the scene labels into the four categories can be found in Table B.1.

| Architectural | Walkable | Landmark | Natural |
|---------------------------|------------------|------------------|---------------------|
| Apartment building | Abbey | Airport | Badlands |
| Building Facade | Alley | Amphitheatre | Bamboo Forest |
| Construction Site | Boardwalk | Amusement Park | Canyon |
| Courthouse | Botanical Garden | Arch | Coast |
| Drive way | Corridor | Amphitheatre | Corn field |
| Door way | Cottage garden | Baseball Field | Creek |
| Forest road | Courtyard | Basilica | Desert (Sand) |
| Garbage dump | Crosswalk | Bridge | Field (cultivated) |
| Golf course | Fairway | Castle | Field (wild) |
| Highway | Food court | Cemetery | Mountain |
| Hotel | Forest path | Cathedral | Snowy Mountain |
| Inn | Formal Garden | Church | Ocean |
| Ice skating rink | Herb Garden | Dam | Orchard |
| Motel | Outdoor Market | Dock | Pond |
| Office building | Nursery | Cemetery | Rainforest |
| Parking Lot | Patio | Fire station | Rice paddy |
| Railroad track | Pavilion | Fountain | River |
| Residential neighbourhood | Picnic area | Gas Station | Rock arch |
| Restaurant | Playground | Harbour | Sand bar |
| Runway | Plaza | Hospital | Sea Cliff |
| School House | Patio | Lighthouse | Ski slope |
| Skyscraper | Shopfront | Mansion | Sky |
| Slum | Topiary garden | Mausoleum | Snow field |
| Supermarket | Tree farm | Pagoda | Swamp |
| Outdoor swimming pool | Veranda | Palace | Valley |
| Tower | Vegetable garden | Racecourse | Wheat field |
| Water tower | Yard | Ruin | Desert (vegetation) |
| Wind farm | | Rope Bridge | |
| | | Ski Resort | |
| | | Baseball stadium | |
| | | Football stadium | |
| | | Subway Station | |
| | | Train Station | |
| | | Temple | |
| | | Wind mill | |

Table B.1 Classification of Places-net labels into the four categories.