

From communities to crowds: quantifying the subjective

Data, measurements and models



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– To the pillars of my life ... 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.

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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 recommendation applications like online e-commerce or restaurant recommendations, or music recommendation. 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. We also at times behave like crowds, participating in entertainment and engagement channels, offering a piece of our attention budgets. At such a juncture, I examine the thesis **Can we quantify entities 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.

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. I develop frameworks to abstract out the graphical structure of these interactions. I then investigate presence of perceived support by finding discriminative local and global structures in these communities. Using established inter-disciplinary theories, I argue that these structures, which we call motifs, are the signatures of a supportive processes 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 this utility indicates potential in designing better offline spaces using crowd perception. I do so, 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 expert survey and also validate the interventions using crowd sourced perception experiments.

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



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CHAPTER 1

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 sources, building systems that predict actions as a response to perceptual triggers is the bread and butter of many companies. The use cases may range from understanding which advertise made a visitor do an unscheduled purchases on amazon, 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 [135]. Nonetheless the systems that surrounds a human interacting with the internet, are all figuring out the best triggers which are perceived by the human as worthy of attention. The term “Attention Economy” [35] was actually coined for this very reason. In the words of Matthew Crawford “*Attention is a resource, a person has only so much of it.*” [33]. We live in the age of distraction, and more often than not, our subjective perceptions are guiding our actions, than 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. [11, 70] [127] [134].

An interesting side effect of dwindling attention budgets is the emergence of more formal topical spaces on the internet. 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 [65, 78, 137]. In such an environment, as computer scientists, it is worth asking the questions:

How do subjective human perceptions manifest in data?

Can quantifying these help us design better interventions ?

These two questions are going to be the guiding principles of my dissertation. But first of all, we need to clarify the relation between perception, affects and data. To do so we should try and understand each of these terms separately in the context of the field of application.

1.2 Perception and Affect

Across my work , I would try to build frameworks to capture subjective human perceptions in the realm of human to human interactions and subjective intangible qualities like the sense of beauty or the sense of perceived support. The utility of such an attempt, can only be justified if there is a real link between how humans function at the most fundamental cognitive level and how they perceive the intangible, including the aesthetic. 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

1 Affect¹: *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.*

2 Perception²: *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.*

Emotions or ‘affects’ and perceptions have long been discussed in the psychology, neuroscience and philosophical literature. Emanuel Kant in his prolific work, first discussed the utility and the philosophical reasoning behind presence of affects or emotions[71]. In his opinion, emotions are pre-cognitive involuntary states, termed as "mere perceptions of unspecified bodily states"[18]. But that does not mean they don’t influence our deepest level of well-being and influence our decision making processes. The link between affect and perception has also been explored in several other cases. An argument to link perception of affect producing aesthetics was made by Perlovsky[114], where they propose that the phenomenon of affects arousing from 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 at some level and we perceive it as aesthetically pleasing. Another recent study by Zadra et.al[153] evaluated the relation between visual perception and emotions. They demonstrate that the conventional assumption of the disentangled functioning of perception and affects is not necessarily true. Humans are quite susceptible to perceiving different realities based on different aroused affects.

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

¹American Psychological Association definition.

²American Psychological Association definition.

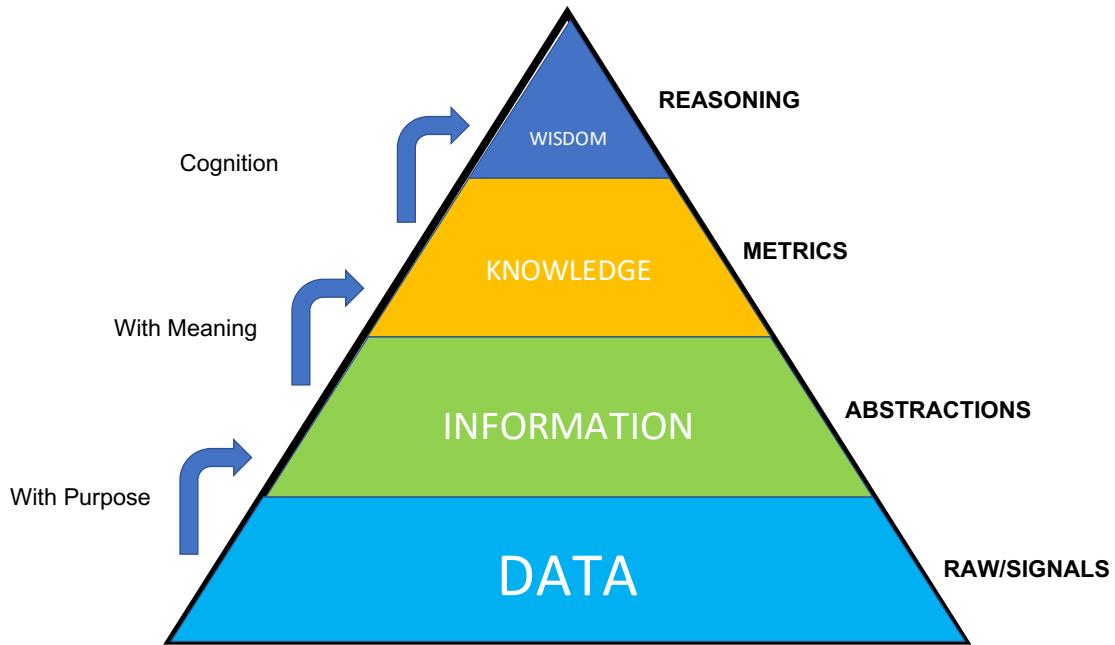


Fig. 1.1 The DIKW pyramid

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 patterns might in some way be used to improve our online and physical environments. But to arrive at these patterns, one needs to understand the frameworks of approaching such a problem. The journey from Data to subjective signatures, has to go through a series of operations.

1.3 The DIKW model

On the journey to develop metrics and pipelines, one has to reflect on frameworks about operations on data. One such popular framework is the **Data , Information, Knowledge and Wisdom** model[123].In this dissertation I posit and demonstrate through case studies, that for any reasoning about subjective perceptions , you need to develop frameworks that extract knowledge from data in a format that is aligned with the ontological framework of the application. In the context of this dissertation, ontology implies a set of concepts, definitions

and relations between entities defined around a common set of axioms. I show that if a set of relations and definitions of concepts in the area of intervention are present, ‘a’ solution can be reached. This is provided that the frameworks are designed to interpret metrics extracted from the data in relation to the ontology of the area of application. But to reach this step, the data needs to pass through the 4 layers of the DIKW pyramid model.

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 various data sources and methods of collecting and curating data, which pertain to human-human interactions or human responses.

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. The abstraction preserves the organization of data, but at the same time allows information to be operated on. As a result, almost always the output of this process is some form of a data abstraction.

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 needs a cognitive process and an ontological framework, to extract actionable insights, which we can call **wisdom**. By classical definition of ontology, it

defines properties of and relations between objects or concepts. For this very reason, these ontological frameworks need to be originating from the fields of intervention. In our example, lets 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 [85]. However , to arrive at these insights we need to be grounded in the ontological frameworks of epidemiology, network physics and depending on the application, advertising or meme theory. Then using the abstractions of social networks, the metrics derived from them, and the ontological basis of all the aforementioned fields, one can design a pipeline that could deliver us these insights with reasonable accuracy.

Figure 1.1 shows an illustration of the adopted version of Rowley's DIKW model, which I would refer back as a repeating motif for my dissertation.

1.3.1 Data

Data is one of the most fundamental contribution of this work. To develop frameworks around quantification of human perceptions, such that we can do impactful interventions from this approach, we first need to make sure we formalize how we acquire, clean and condition our data. The most base level of this pyramid is the data that the frameworks would work with in order to progress on these lines. I work 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. 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 beauty of a place, or how much someone “likes” an image or a video.

Interaction Data

In the first case study of this dissertation focusses on is online support communities, where human to human interaction is at the centre of the utility of these communities. 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 [5] [98, 113] [14, 66] [61]. 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 [102], which delivers people in distress a sense of belonging to a group and 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 [69]. 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 forum data regarding mental illness and suicidal thoughts. The data covers discussions about more than 30,000 calls to support, and incorporates the complete structure of the way people respond to these calls.

Media data

The other facet of my work looks for quantification of how we perceive physical spaces. Whether a street is considered beautiful is a matter of subjective opinion, yet research has shown that there are specific urban elements that are universally considered beautiful: from greenery, to small streets, to memorable spaces [2, 116, 124]. These elements are those that contribute to the creation of what the urban sociologist Jane Jacobs called ‘urban vitality’ [67]. Apart from vitality, these motifs in urban environments are also highly correlated with feeling of well-being, health and safety [72]. There have been studies where people have tried to use crowd sourcing to acquire subjective ratings of images [128] 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 of that particular area. For this reason, I work with google street view data and subjective ratings of various places

³www.reddit.com

around the world [101], with the aim to understand, how people perceive the sense of beauty in urban areas. Then using the ontological basis 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 organized 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 2 and 3.

While working with media 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 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. A more detailed discussion of these abstractions would be done in the later chapters (Chapter 4).

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 my case, I develop several of these metrics to related subjective properties with measurable structures in data. 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 role of a user in a supportive conversation, to understand how these conversations evolve.

1.3.4 Wisdom

Finally the wisdom , in definition underlies insights that come from 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)Appraisal. Each type has its own specific traits. My dissertation looks at these theories from the lens of computational social science, and develops processes to quantify signatures of affective support.

1.4 Research Thesis and Research Questions

The overarching thesis question of interest that I would explore through the two case studies is:

How do we quantify perceived qualities from data, if the data source is human and the scale is large?

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 : Supportive interactions on the web

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 [13, 28, 48] , to signs of positive turn around among patients suffering from alcoholism and depression [21, 112], 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 [44]. The idea of this case study was to quantify how supportive processes evolve over these communities, using abstraction methods from the fields of network science. The hope in doing so, is that the communities would be better poised to tackle any disturbances in the dynamics of these supportive communities as well as quantify the net utility these communities offer to the users.

The investigation of these would lead me to form the following research questions

RQ1 How do support communities thrive?

RQ2 How do we quantify support on these communities?

RQ3 Are there any macroscopic signatures of supportive conversations?

RQ4 Are there any mesoscopic signatures of supportive conversations?

To achieve this 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 try to mimic the conversation structure which allows me to probe the evolution of such conversations both in terms of macroscopic properties as well as local interactions between users. I also develop metrics inspired from psychology and sociology literature to quantify how these interactions can be qualified as supportive or non supportive. 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 aesthetic perceptions 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[129] and physical well being[12, 55]. However, with the advent of large scale data access, 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 this study, I investigate the following research question:

RQ5 *Can crowdsourcing and machine learning help us quantify how humans perceive beauty in urban settings?*

RQ6 *Can we leverage the quantification of the crowd’s subjective perception, to improve real spaces?*

RQ7 *Do humans and experts find the improvement realistic?*

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 **RQ5** 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[34, 116]. Can we link these metrics to urban elements? For this reason we 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, we 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 (**RQ6**). I further try to build a tool, which could use the quantified notion of beauty in urban spaces, to hint practitioners about possible actions to beautify any given 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. In the pursuit of answering the **RQ6** and **RQ7**, I propose deep neural network and generative adversarial network models to make an end-to-end pipeline which can be then used to visualize how different urban elements affect the perception of beauty in the real world.

1.5 Thesis overview and original contributions

In Chapter 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 original insights point towards answers for **RQ1** and **RQ2**. In Chapter 3, I look at global(macro-) and local(meso-) structures of supportive conversations. I show that mapping the conversation 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** and **RQ4**.

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 **RQ5**, I develop models to extract the perception of the crowds using data driven inference methods(Chapter 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 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 **RQ6** and **RQ7**. I close by enumerating the different research problems and future directions that my work would pursue as a early career scientist(Chapter 6)

1.6 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.

1.6.1 Original author contributions

List of papers, published and in review, which were led by the author or where the author had fundamental contribution

1. **Joglekar, Sagar**, Nishanth Sastry, and Miriam Redi. "Like at First Sight: Understanding User Engagement with the World of Microvideos." International Conference on Social Informatics. Springer, Cham, 2017.
2. **Joglekar, Sagar**, et al. "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 20.7 (2018).
3. **Joglekar, Sagar**, et al. "Online discussions about mental health in Reddit exhibit signatures of supportive conversations" Under Review
4. **Joglekar, Sagar**, et al. "FaceLift: A transparent deep learning framework beautifying urban scenes" Under Review
5. Kauer, T., **Joglekar, S.**, Redi, M., Aiello, L. M., & Quercia, D. (2018). Mapping and Visualizing Deep-Learning Urban Beautification. IEEE computer graphics and applications, 38(5), 70-83.

1.6.2 Collaborative author contributions

List of papers, published and in review, where the contribution was significant, but were not led by the author

1. Bhatt, S., **Joglekar, S.**, Bano, S., & Sastry, N. (2018, April). Illuminating an ecosystem of partisan websites. In Companion of the The Web Conference 2018 on The Web Conference 2018 (pp. 545-554). International World Wide Web Conferences Steering Committee.
2. De Simoni, A., **Joglekar, S.**, Taylor, S. J., Patel, A., Duschinsky, R., Coulson, N., ... & Evans, M. J. (2017). Structure and dynamics of online patients' communities: the case of Asthma UK and BLF online fora.
3. YOUNG, A. P., **Joglekar, S.**, GARIMELLA, K., & SASTRY, N. (2018). Approximations to Truth in Online Comment Networks.
4. Agarwal, P , **Joglekar, S.**, Papadopoulos, P., , SASTRY, N. & Kourtellis, N. (2018) Hyper-partisan websites: Personalization of user experience on polarized websites.
5. Raman, A , **Joglekar, S.**, De Christofaro,E., SASTRY, N. & Tyson, G. (2019) Challenges in the Decentralised Web: The Mastodon Case, To appear IMC 2019

CHAPTER 2

FROM COMMUNITIES: THE ACTORS OF SOCIAL 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[17]

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 perceptual features and immediacy in the content [70]. The scrolling user interface of platforms like Instagram and Facebook, allow mere seconds to decide whether a particular content is worth the user's attention [49].

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 [17] of the internet, in that they strive at making geographical distance secondary, to the act of social networking and information sharing.

3 According to the seminal work by Shumaker and Brownell [133], 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."

¹www.stackoverflow.com

²www.stackexchange.com

³www.ravelry.com

⁴www.artween.com/

Under this construct , these communities are apt Petri dishes to study the signatures of the online social support. 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. More specifically I develop methods and frameworks, to extract the signatures of perceived *social support* on communities designed around users who have underwent or are undergoing physical or mental distress. These methods and frameworks could bear significant potential impact on the health and utility of these forums. The first step us to understand the structure and utility of these communities. More over, having a primer on these communities would help the reader get an idea about the methods developed over the course of this dissertation.

2.1 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 [5], (2) produces positive health-related outcomes⁵ [98, 113] , (3) facilitates shared decision-making with health care professionals [14, 66], and (4) may even reduce mortality [61].

There is also evidence that self-management support interventions can reduce health service utilization [106, 144]. 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 [76], asthma [139], pulmonary hypertension [91] and chronic obstructive pulmonary disease (COPD) [150]. 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 appointments⁶. Thus, assessing how these online

⁵<https://bit.ly/2FLcs1F>

⁶<https://bit.ly/2EVFs9v>

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 [52]. 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 [7], and anonymously [113], as well as obtaining tailored information and emotional support [4, 30, 43, 44, 132]. 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 [32], integrating online support systems with the more traditional health care provision would require the identification and comparative assessment of potential alternative intervention mechanisms.

In this chapter, I aim to uncover and understand how these communities function, evolve, and operate in the role of a supportive entity, from a macroscopic perspective. Further it is worth knowing if there exists any particular mechanism, by which individual users evolve into the role of support givers.

Ultimately, once we understand the mechanisms of peer support, we can proceed in looking for discriminative signatures of these supportive exchanges. In this chapter, we would illuminate the answers for **RQ1** and **RQ2** using a large scale dataset of a pulmonary illness support group. The questions are:

RQ1 *How do support communities thrive?*

RQ2 *How do we quantify support on these communities?*

2.2 Dataset and properties

The data was collected from HealthUnlocked⁷, the online platform provider of the Asthma UK and British Lung Foundation communities. Registered users 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, a large number of users can become connected through threads of posts. A thread is a series of posts made on one root post, 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. Only posts that were shared publicly were collected and analyzed. For this study, user identifiers (IDs) were anonymized by the HealthUnlocked platform, and no demographic information was collected. The data set 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 in which the users joined and left the community. Both communities were moderated, and HealthUnlocked moderators (identified through metadata linked to posts) 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 2.1 summarizes the salient features of the dataset used for this work.

⁷<http://www.webcitation.org/70Y10rppl>

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)	1053 (31.5)	7814 (39.4)
Users who contributed exactly 1 post(%n)	331 (31.4) 722	1186 (15.2)
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 2.1 The summary of salient attributes of the data used for this work

The data sets span, respectively, 10 years for the Asthma UK and 4 years for the BLF communities (see Table 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.

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 with other users across the lifetime of the community.

2.3 Interaction Graphs

To understand the reason behind how these communities thrive and in order to quantify the conversation structures, I convert all the message exchanges into graphs, where 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} . 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 and messages exchanged across one particular thread discussing a particular issue. Such a graph is called a thread graph G_t .

These graphs are the abstractions of how users interacted on the community either around a particular query (Thread graphs) or over all as a part of the bigger community (Gobal graph). To understand the behaviour of these users, I evaluate several metrics on these graphs to understand the utility of these communities in terms of activity of sharing and support. This abstraction also makes it feasible for us to investigate how a particular community grows with time and how particular users evolve with time.

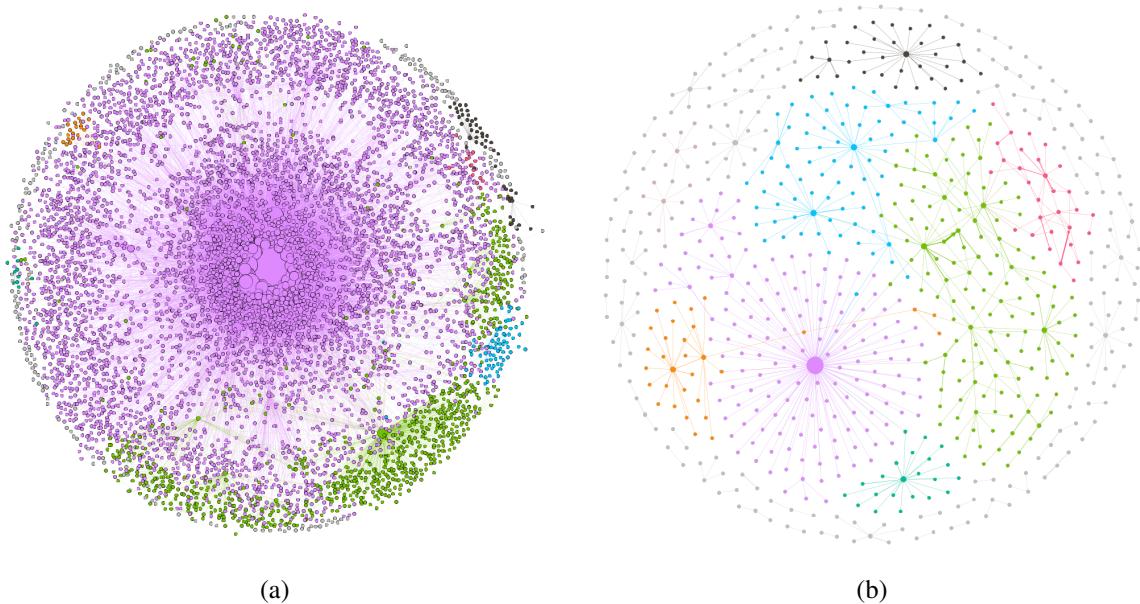


Fig. 2.1 Global graphs prepared from Asthma UK community2.1b and BLF community2.1a. The size of the node corresponds to the degree of the node and the color corresponds to the community membership

2.4 How do support communities thrive ?

This question sets the primer about the peculiarity of support communities. Do these communities have enough interest and activity, to sustain over long periods of time? Are all users equally involved in the vitality of the community or is this a group of users? How important are these users?

2.4.1 Activity Metrics

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

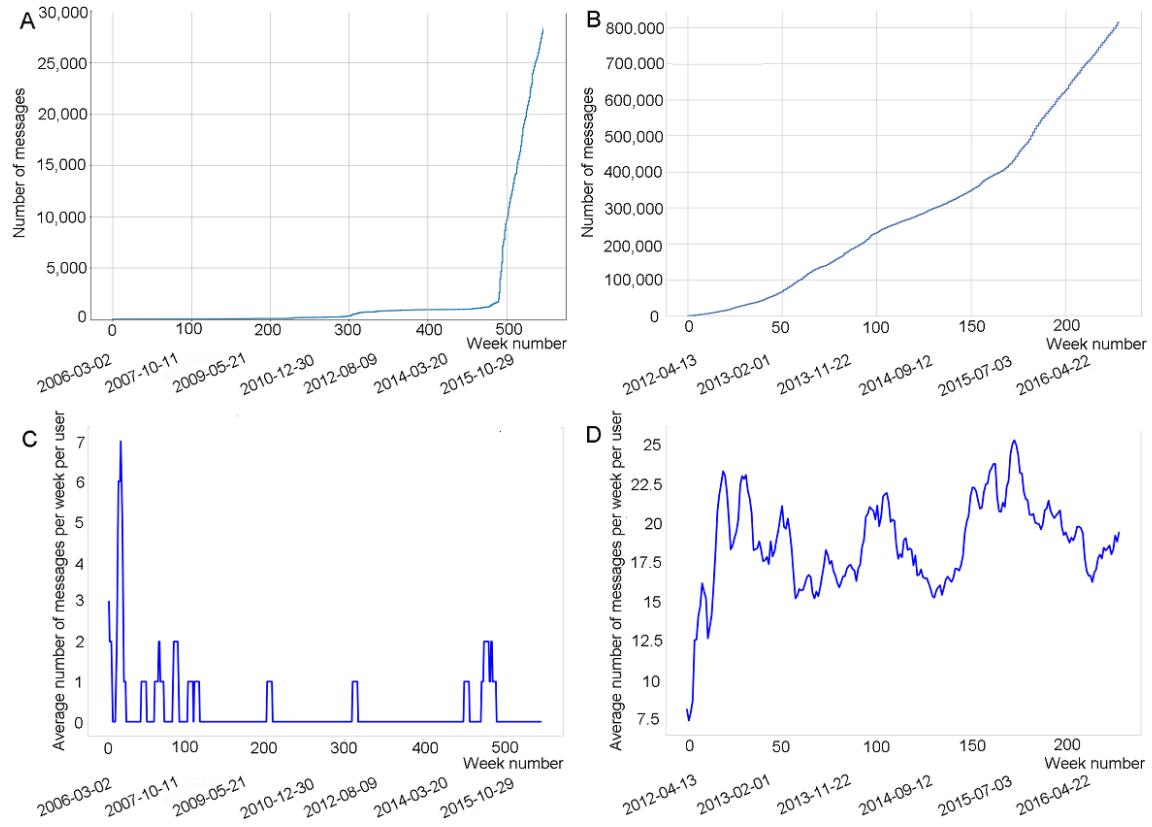


Fig. 2.2 Cumulative distributions of the number of posts as a function of time (weeks) within the Asthma UK (A) and the British Lung Foundation (B) communities. Calendars dates are reported below as week numbers (since the inception of the community). Panels C and D illustrate the average number of posts per user per week within Asthma UK and British Lung Foundation, respectively

community, however if a community revolves around purely functional interactions, then you may see a bursty nature of communication [108]. From these basic analysis, it was quite evident that the BLF community was more active of the two, in that, the community exhibits a consistent engagement of the users across the lifetime of the data. Asthma forum however shows a bursty activity, despite being more than twice as old as the BLF community. The trends can be seen in Figure 2.2.

Remark 1 *It is worth noting that as the activity on the community increases, you do see an increase in fragmented reply networks, which means concurrent discussions are happening with disjoint set of users interacting.*

2.4.2 Community resilience

The activity patterns does not tell the real story about the cohesiveness of any particular community. To answer the **RQ1**, it is first worth asking how the user interactions bind the community together. We would like to know if the user activity is highly concentrated 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 topological properties of the interaction graph. From table2.1, 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 AsthmaUK community. Such level of activity makes these users extremely important in understanding the dynamics of support on these communities.

Cohesive conversations

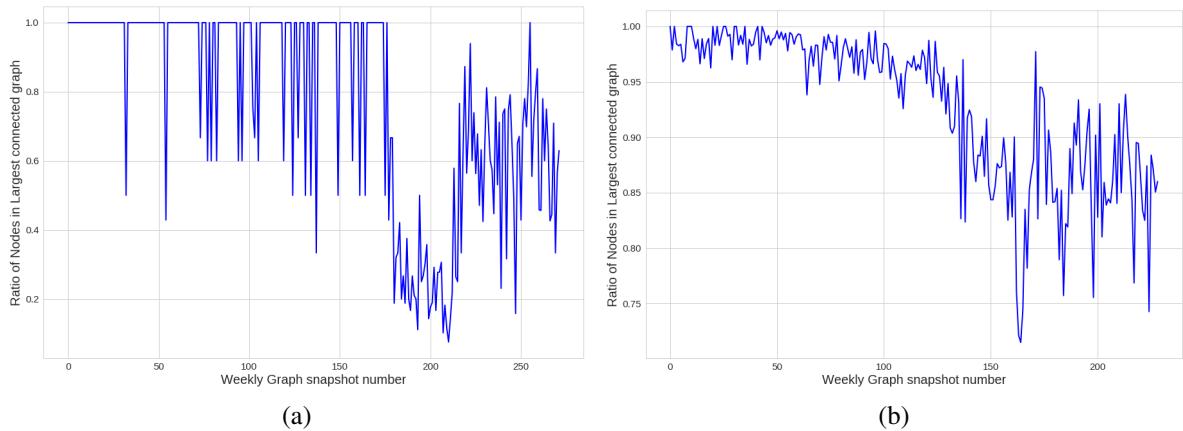


Fig. 2.3 Fraction of users that are part of the largest component as a function of time (weeks) for Asthma UK 2.3a and the British Lung Foundation 2.3b.

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.

4 Largest Connected component : A largest connected component of a Graph $G(V, E)$ is the largest possible subgraph $G_L(V_L, E_L)$ of G , such that each node in G_L has at least one valid connected path to every other node in G_L

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.

Fragile communication structure

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 [1, 20], 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

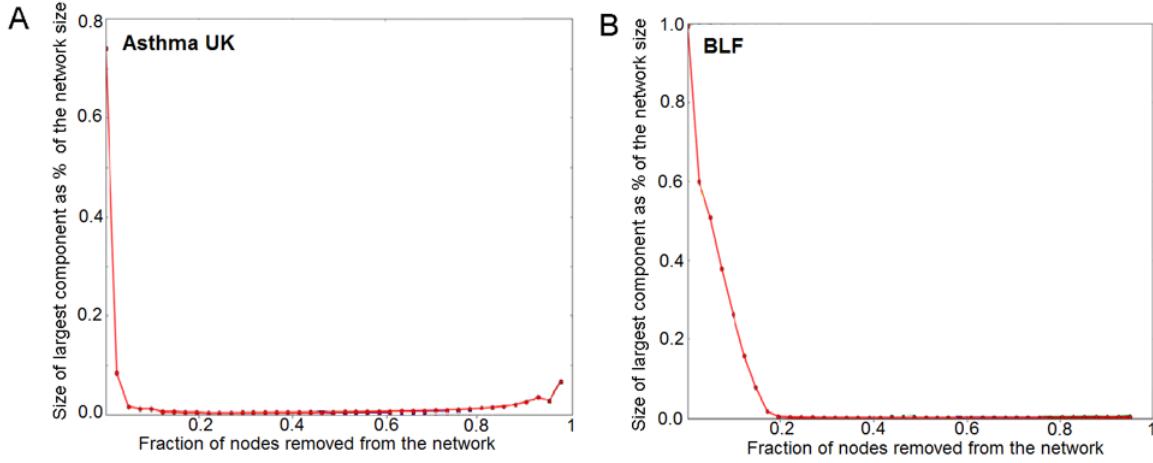


Fig. 2.4 Results of progressive removal of nodes based on connectivity. Both communities collapse drastically, in terms of connectivity, with BLF showing a little more resilience

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 2.4 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.

Anti-rich conversations

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 [27]. 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 [105]. We

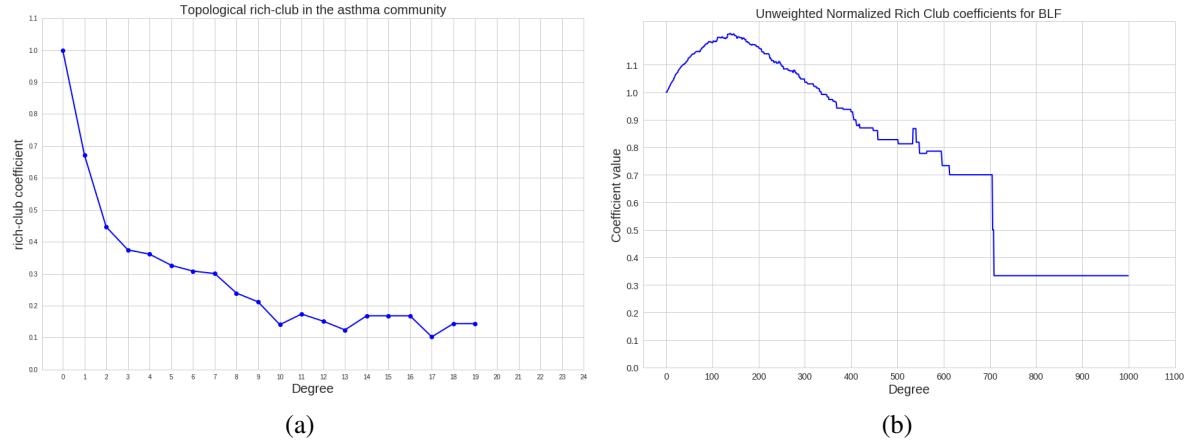


Fig. 2.5 Plots of rich-club coefficients for each viable degree in the respective communities.

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

$$\phi(k) = \frac{2E_{>k}}{N_{>k}(N_{>k} - 1)} \quad (2.1)$$

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 [93]. .

Remark 2 *It is worth noting that most previous studies in base lining rich-club effect in technical and real world networks have shown a propensity to create rich-clubs. Thus these networks exhibit exclusive clubs of (topologically) rich nodes, as illustrated in previous work [27, 157]*

What we observe from this analysis is that communities in general have a less than 1 rich-club co-efficient value for a spectrum of degrees k . This means, rich nodes are exhibiting an anti-rich behaviour, where nodes which have a higher degree, prefer engaging with new nodes with lower degree. This implies an active information exchange from a well connected node to a sparsely connected node, which follows according to the definition of social support(definition 3).

2.5 How do we quantify support on these communities?

Once I establish that these support communities are thriving and are providing what seems to be an active supportive environment for the patrons, 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.

2.5.1 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 2.2, 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 communities⁸

5 Support seeker: *a user who begins a thread by posting on the forum, a question, or a query, to which others may respond to.*

6 Support giver: *a user who responds to any post by a support seeker.*

Using these definitions I aim at modelling the statistical propensity of someone being a support giver or a seeker, as a function of their “richness”. We first begin by calculating across the dataset, the average number of questions per user and answers per user, by finding the mean number of questions or 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 [154] to arrive at the expression of expertise in the context out our support community.

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:

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

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

⁸There are other ways to qualify someone as support giver/seeker, mainly using language sturcture, but here we consider only the bare minimum requirement to be considered as one, using the position in conversation structure

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

$$Z_{score} = \frac{a - 2q}{\sqrt{2(a + q)}} \quad (2.2)$$

Equation 2.2 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.

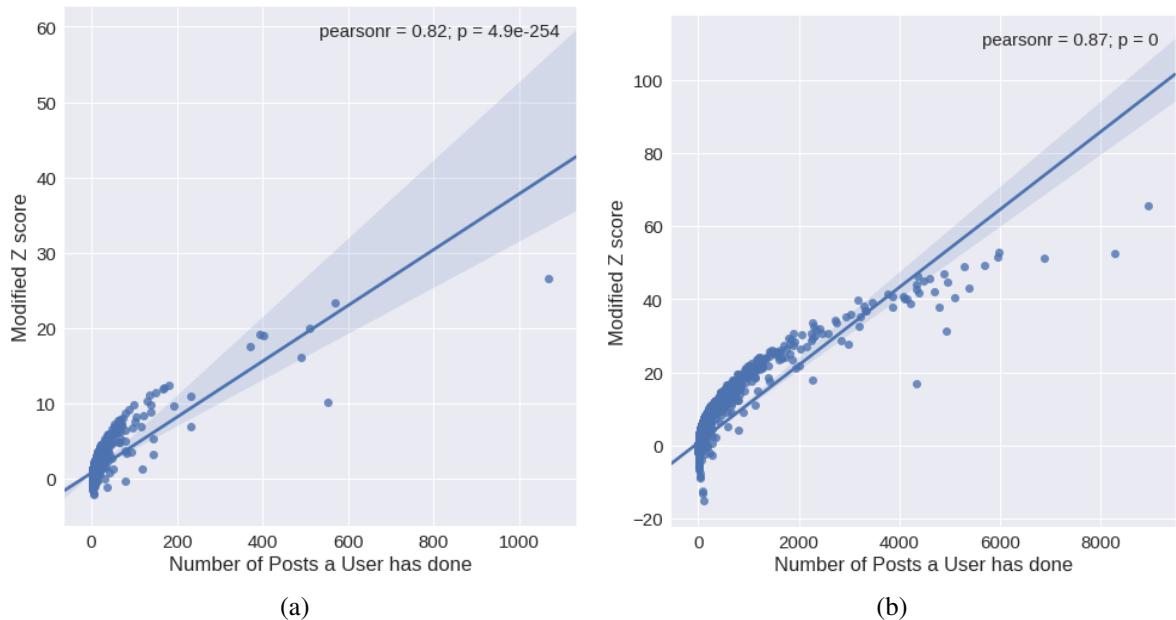


Fig. 2.6

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 2.6a and Figure 2.6b 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 2.4.2, 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.

2.6 Rich users 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.

7 Social capital (Sociology): *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 [26, 28]*

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 [58] 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. Such closures are, according to Ronald Burt [22, 23], 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 “rich” nodes or the super-users, we would certainly want to investigate how these agents affect the local cohesion and structural holes.

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 rich users 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 .

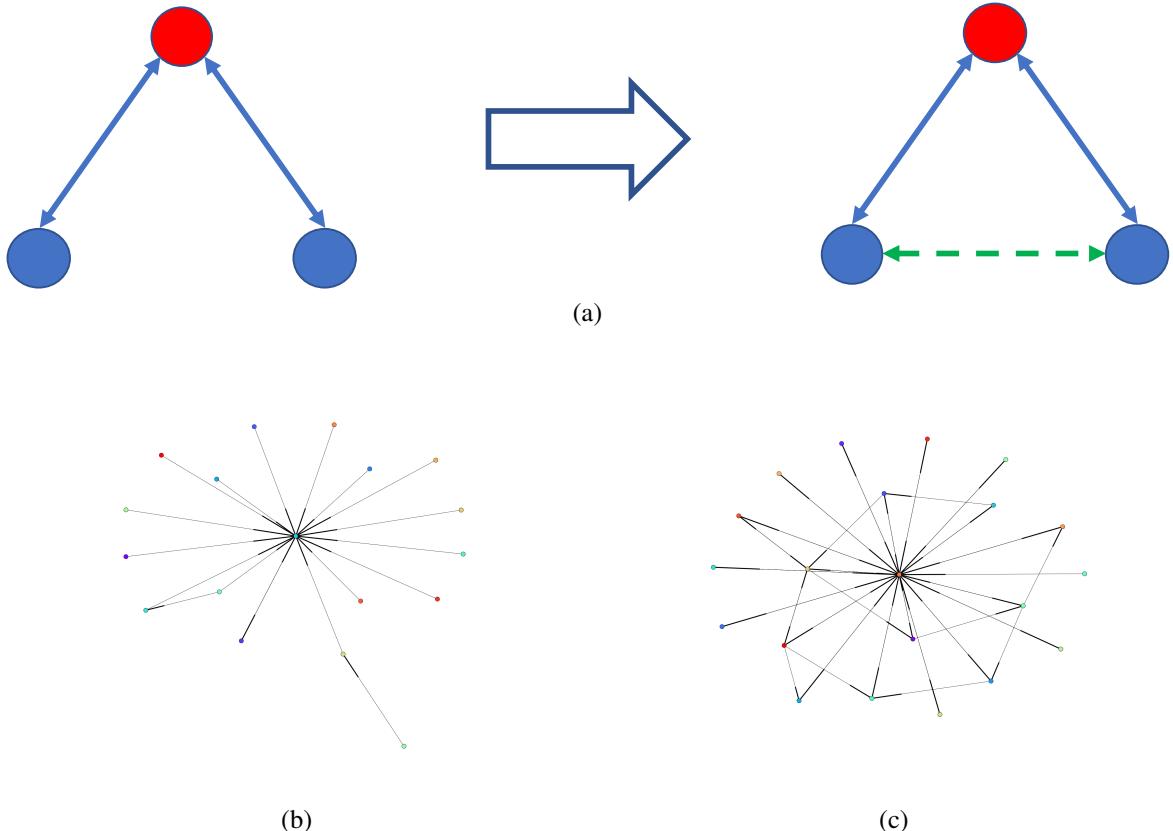


Fig. 2.7 Figure 2.7a shows an example of closure among three nodes, where a structural hole between a cluster of three nodes is closed by addition of the green link. Figure 2.7b shows a thread level interaction graph showing lots of structural holes between participating nodes. On the other hand Figure 2.7c shows an example of a thread level interaction graph where a ‘rich’ user has contributed multiple times. This graph also shows more closures

The resultant scatter plot can be seen in Figure 2.8, 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.

The research questions asked at the beginning of this chapter, required us to look at these communities from the perspective of its users. It was evident, that these communities do provide a supportive space. When looking at macroscopic structure of a support network,

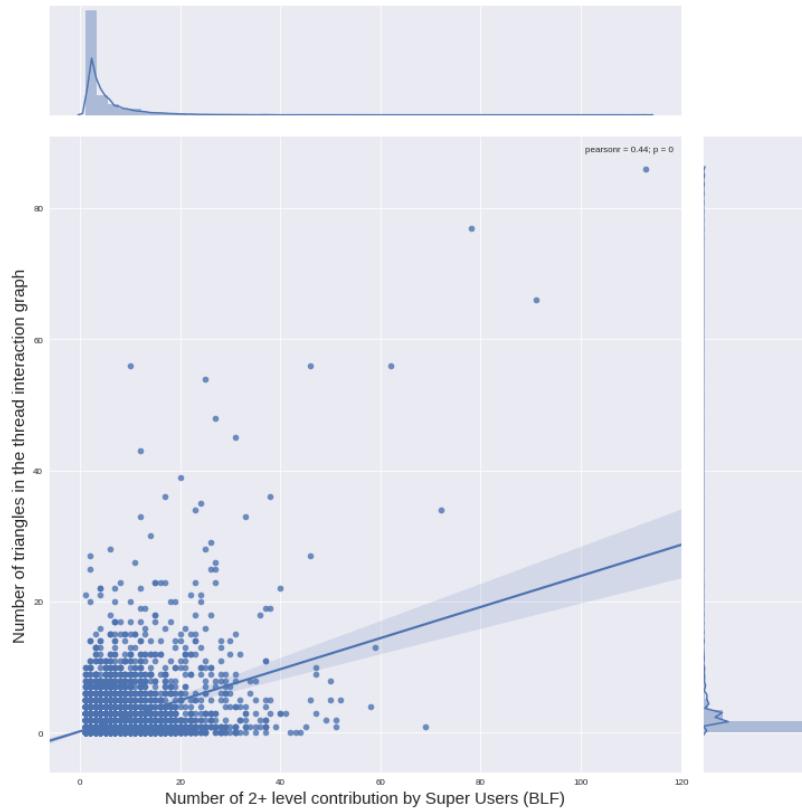


Fig. 2.8 Scatter plot between the number of closed triangles in a conversation thread, with the total number of posts done by rich users in that thread. A positive correlation of 0.44, with a p-value of 0 is observed

we find that certain groups of users are highly crucial for the vitality and survival of the whole exchange process. But we also observe that these groups are in flux, and users tend to become more supportive with experience. The idea of perceived support stems from the fact that the user in distress is not only getting the instrumental information, but also benefits from the social capital of the allied users. We observe that supportive users tend to have a positive effect on the social capital of a conversation, promoting more social cohesion.

Social support is a multi-dimensional perceived entity, and I am attempting to capture the mechanics of support through online conversations. It has been an active area of study from a sociological and psychological perspective. There is immense value in understanding how social support thrives on the internet, especially because of its potential of relieving some burden from the ever so burdened health services. The work till now did focus on the global interactions of support givers and seekers on a community. However, the actual action of

peer support happens over a single thread of conversation. Aggregating these conversations over a period of time, allows us to look at how users behave by and large across different conversations. What is interesting and important to understand is how can we measure the act of peer support in an individual supportive conversation. How does a supportive conversation evolve, and are there any peculiar signatures we could observe in comparison with generic conversations? For this reason, it is important to look at a finer granularity of interaction, what we term as *mesoscopic* view of the conversation. In the following chapter, we would do exactly that, and unravel the discriminative patterns in meso and macro representations of conversation threads.

CHAPTER 3

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 than generic communities. They also seem to have an effect on how people perceive support when in distress. In the past 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. The dynamic of evolution of users from support seekers to support givers. We also saw the way brokerage works in providing closures in the conversation threads, adding more closed triangles between people as ‘rich’ or expert users 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 structure in conversation, might gives us more insights in how online support can be utilised properly for health care. This may also point to the features to look at, if we need to automate the process of quashing 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 patters 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 look into the the macro and the micro signatures of a supportive dialogue on these communities.

A valid criticism of the results from Chapter 2 is that the results were driven by a support community which is highly moderated. This sort of moderation is often absent on more

popular open 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, or in the case of Reddit, 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 deals with political subject matters. There are several subreddits on this platform that deal with peer to peer support. A few examples include r/SuicideWatch² , r/Depression³,r/Bipolar⁴. Utility of these communities in providing a support, and a place to vent have been explored before [39, 40]. 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 a over-all structural perspective(macro) as well as from a user-centric local perspective(meso).

3.1 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 [24]. 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 [39, 40]. 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 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

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/>

of support online, like language [25], anonymity in social support [39] or risk factors [56]. 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 [39, 40]. 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[56]. 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[110]. Positive effects in participation in such fora have also been shown by improvements in members' written communication[109]. The supportive nature of comments in the SuicideWatch forum has also been studied by automatic identification and classification of helpful comments with promising results[74].

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 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 Chapter2, we would like to develop methods that would allow us to understand the macroscopic and mesoscopic signatures of support. Formulating this problem

⁵As of 27th June 2018

⁶<https://bbc.in/24rJYQH>

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.

3.1.1 Research questions

Most previous studies have aimed at studying 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 this received support, manifests in the network structure in the short term and long term users. What remains to be explored is how these supportive conversations themselves look on a macro as well as local (meso) scale. More specifically, in this chapter we would like to arrive at answers to the following two research question, discussed in Chapter 1

RQ3 Are there any macroscopic signatures of supportive conversations?
--

RQ4 Are there any mesoscopic signatures of supportive conversations?

To model the network topology in an online community, we represent each conversation happening over these forums using graph-based abstractions (users and replies) as described in Section 3.3. To measure global structure of these conversations, we user 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 measure local interactions, we measure inter response times: which measure urgency of response to a message, semantic alignment between messages and local interaction motifs

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 3.1 Notations and Terms.

known as Triadic motifs : which gives an idea about how distinctive are interactions between subgroups of users.

3.2 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. [56]. 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 over 50k SW threads totaling around 500k individual posts.

To provide a baseline against which to compare the hypothesized supportive nature of the SW sub-reddit, we acquired 50k baseline posts from any other subreddit popular enough to land on the frontpage.

We crawl the Frontpage posts for 2 weeks accumulating over 50 thousand reddit threads in the process. 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 pure macro statistics. E.g. 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 all 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

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

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

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 suicide watch and 30k threads for Baseline. 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 Suicide watch and 23k threads in the baseline.

3.3 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, an 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 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 3.1

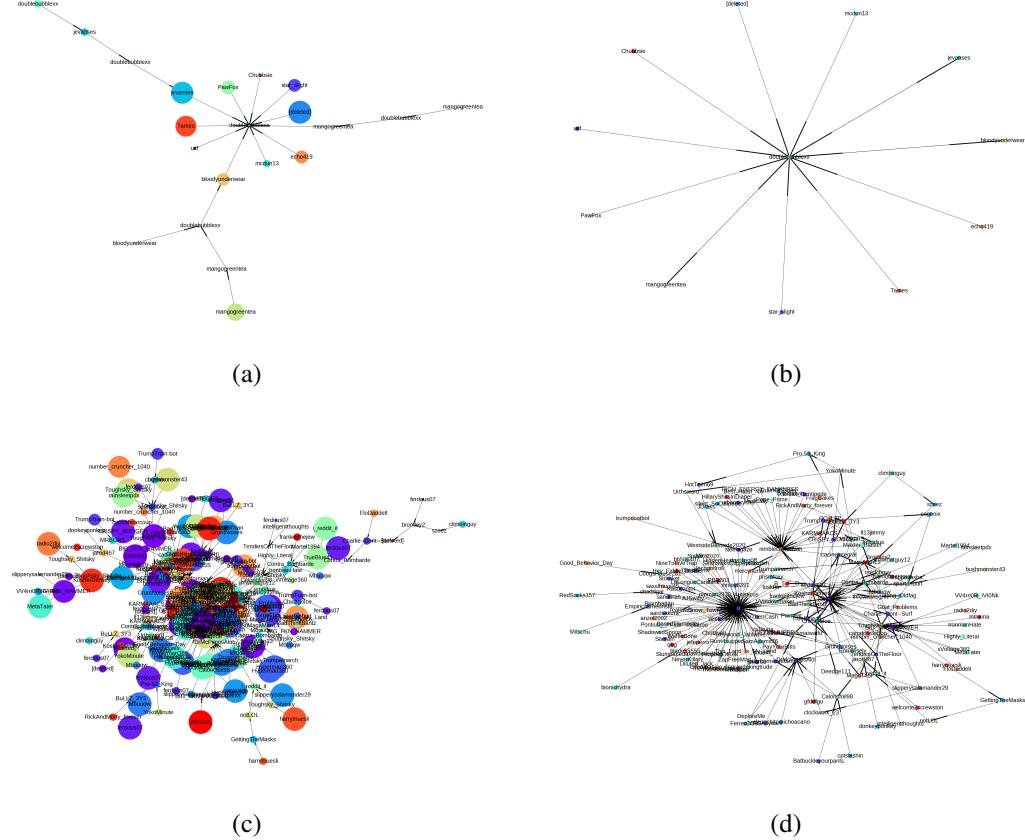


Fig. 3.1 Example User graphs and their corresponding Reply graphs, Figure 3.1a shows a random thread from the Suicide Watch sub-reddit along with the preserved structure of posts in the thread and 3.1b shows the corresponding user graph that arises by capturing the user to user interaction in the thread from the reply graph. In comparison we have user graph Fig 3.1d and its corresponding reply graph Fig 3.1c from one of the Front page threads

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.

3.3.1 Network characteristics

Figure 3.2a 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.

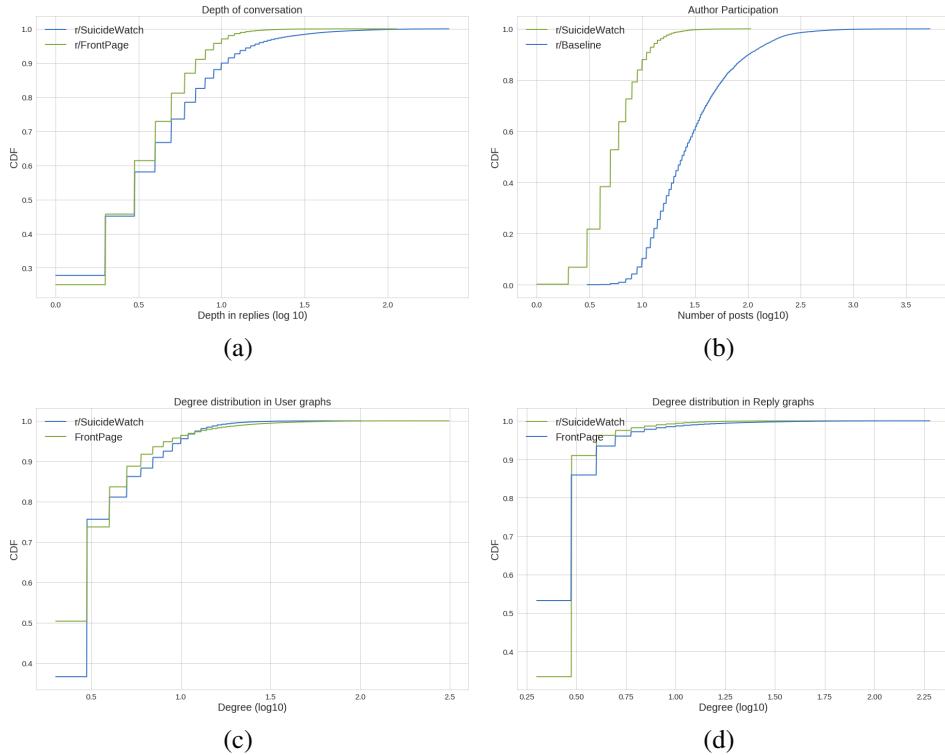


Fig. 3.2 Fig 3.2a shows the distribution of maximum depths of Reply Graphs for Subreddit r/SuicideWatch and the baseline Frontpage conversations. Fig 3.2b shows the distribution of unique authors per thread in the two datasets. Fig 3.2d shows Distribution of degrees for Reply Graphs, r/SuicideWatch and FrontPage. Fig 3.2c shows the degree distributions for the reply graphs

3.4 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.

Semantic Alignment

We use a popular word embedding method called *Word2Vec* [95] which learns representations of a set of words from a corpus of text, which in our case is the text from Suicide Watch and baseline fora. These representations can be used to extract text embedding vectors for each post which belong to a N dimensional space R^N . These vectors are tested for their alignment using cosine distance in R^N , which from literature is shown to correspond to the semantic similarity in the textual space. This method is quite popular and used in community based question answering[94], Medical semantic similarity [45] and other medical informatics applications[158]. We first train two independent word2vec models on the Suicide watch and Front page post corpora. We then extract the word embedding vectors for each post using Doc2Vec[81], which extends the word embeddings to represent a whole document or paragraph. We extract these embedding vectors for each post in R^N 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. More formally, if user V_i has responded with post P_i to a post P_j by user V_j , the edge weight of of edge E_{ij} in the corresponding reply graph would be

$$W_{ij} = \frac{V_i \cdot V_j}{\|V_i\|_2 \|V_j\|_2}$$

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 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

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

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

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

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

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

Median semantic alignments

This metric quantifies the overall semantic alignment between response posts across a particular conversation thread. For any reply graph $R\{P, E, W\}$, we compute The median of all the edge weights calculated using the definition of semantic alignment This metric quantifies the overall semantic alignment in a conversation. We also do the same calculation between responses to any post authored by the *OP* to test whether responses to *OP* demonstrate any special pattern of all alignment in supportive vs generic threads.

3.5 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.

3.5.1 Peculiarity of threads of Support

We begin by characterizing the two networked abstractions, namely Reply Graphs and Interaction graphs as described in Section 3.3. 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 3.3a 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 AS is 0%. This shows that SW subreddit engages in a lot more symmetric conversation than 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 3.3b 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

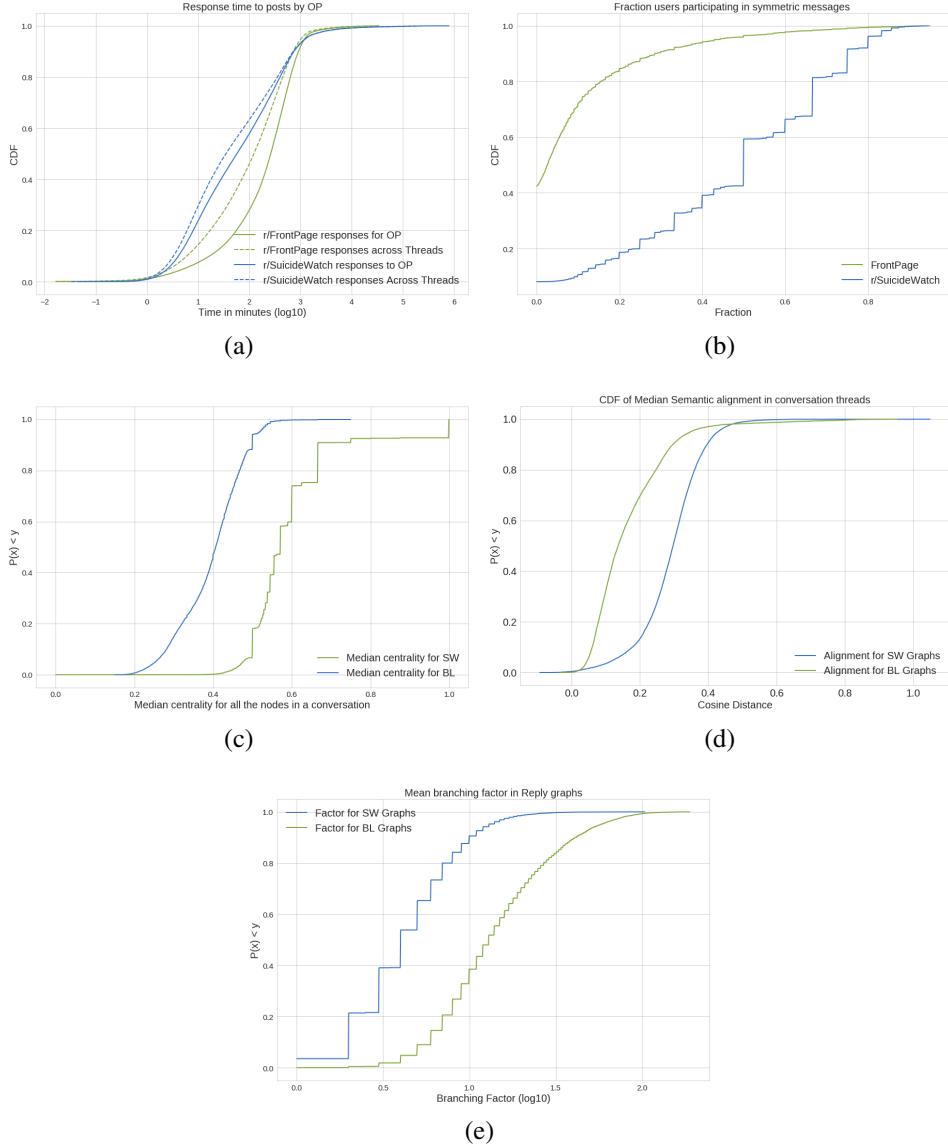


Fig. 3.3 Panel shows CDFs of different network metrics. Fig.3.3a shows the response time distributions, Fig.3.3b shows symmetrically engaged users, Fig.3.3d shows topical similarities across posts and 3.3e shows the branching factors of reply graphs.

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 *OPs* 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 embeddedness as well as a *OP* centric approach by other participants in the conversation. The Figure 3.3c 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 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 3.4. Extracting such similarity metrics, we compare the trend in response text being in semantic alignment with the parent text in the reply graphs.

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 3.4, 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.

3.6 Mesoscopic analysis: Anchored triadic motifs.

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[96]. They have been used in a variety of applications and networks, from economics [155] to

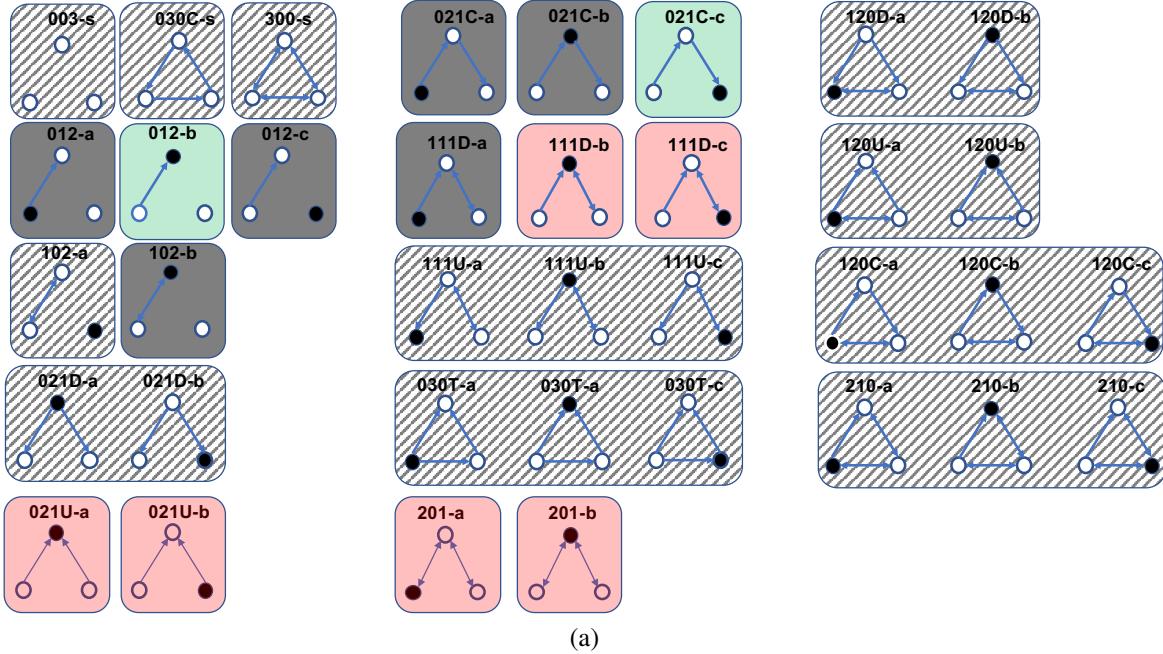


Fig. 3.4 Figure 3.4a shows the 36 different types of Anchored Triadic motifs that are looked for in the user graph data. The motifs with **green boxes** are **over expressed in the baseline dataset** by significant amount. The motifs with **red boxes** are **over-expressed in the Suicide watch dataset** 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.

cellular protein-protein interaction networks [152]. These local interaction patterns have been studied before, and have been fundamental in the study of social structural processes[51]. They help social scientists quantify the type of hierarchies in the social network[36, 37]. But in the setup of a typical support community network like r/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. 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 due course of the conversation. In conventional literature, the local interactions are measured in terms of census of 16 triadic motifs[51], 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 build on top of this methodology but by introducing anchors, or nodes with special importance. This is because, we would like to know how a graph evolves around the person in distress or 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[51, 64], can be unravelled into 36 sub-variants of these motifs by varying the anchored node, as seen in Fig 3.4. Each sub-variant is different from the other from the perspective of the anchored node. The resulting motifs to measure grow from 16 to 36, since some 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[15]. Each motif as seen in Figure 3.4a 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 letter modifier attached, to signify the flow of information in the triad. The naming is done in accordance with Holland et. al's work[62].

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

$$Z_i = \frac{m_i^{sw} - \mu_{null}}{\sigma_{null}}$$

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.

3.6.1 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[51]. Such analysis is quite useful in expressing local structures in the graphs and has been used in several network analysis works[131, 149]. For this reason we conduct a census of the 36 Anchored triadic motifs (described in Section 3.6) 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[51]. We perform binning of user graphs as described before in Section 3.6, and perform over or

under expression analysis in comparison with the baseline null model, using Z-scores of the motif occurrences.

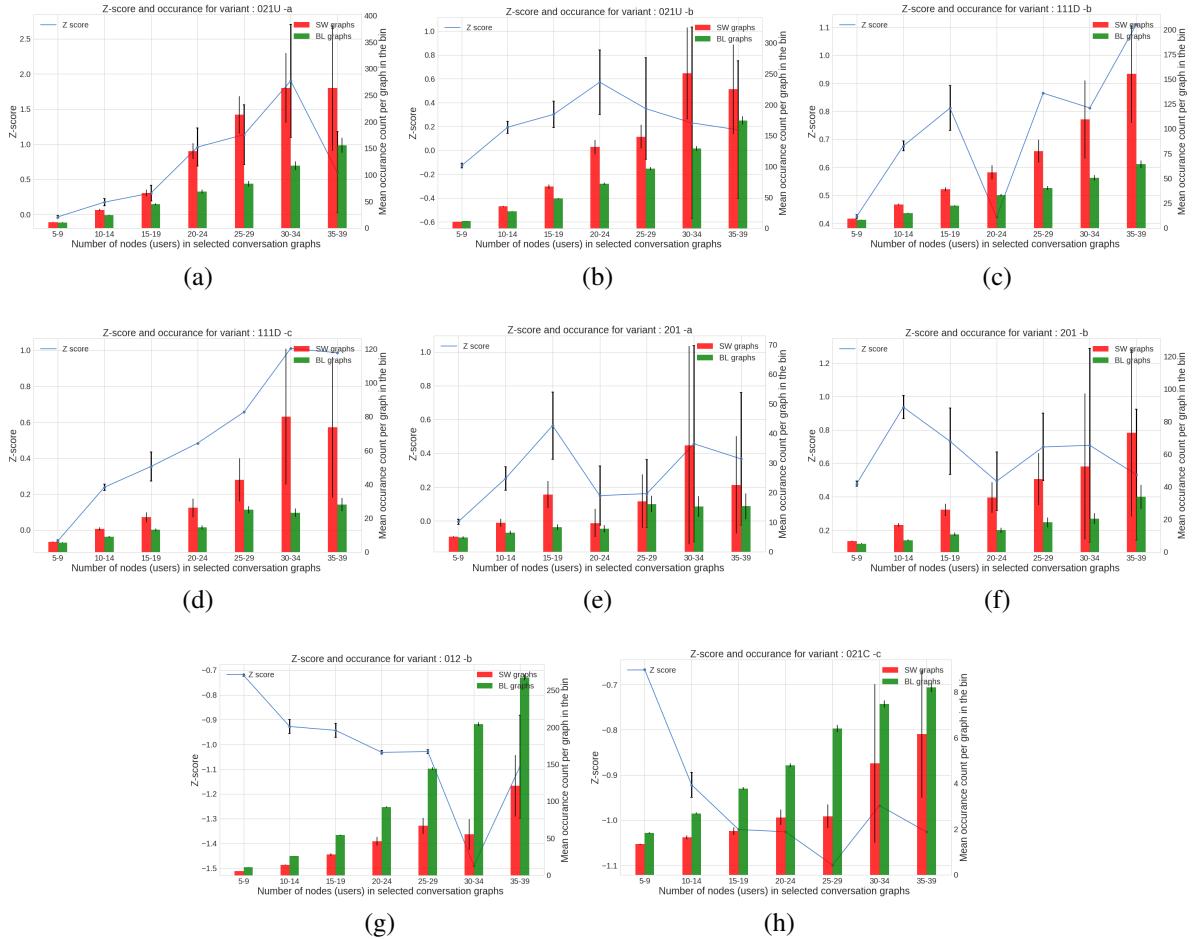


Fig. 3.5 This panel shows the Z-scores of the abundant and over expressed Anchored motifs found in both datasets. There are variants which are over expressed in Suicide watch (Like figures 3.5a,3.5b,3.5c,3.5d, 3.5e,3.5f), which form the top six plots. The bottom 2 plots show motifs which are over expressed in the Baseline over Suicide watch, as their Z-scores are negative. Figure 3.5g and Figure 3.5h.

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 3.5a,3.5b,3.5c,3.5d, 3.5e,3.5f. Similarly anchored motif variants **012-b and 021C-c** are significantly over expressed in the null model(baseline) graphs across all sizes.

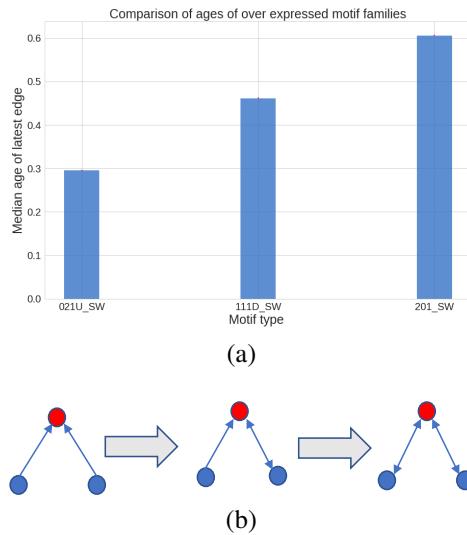


Fig. 3.6 *Figure 3.6a shows the plot for mean motif life times as a fraction of the entire thread life. The lifetime is measured as the time at which the latest edge of motif is formed. The Figure 3.6b shows a toy example of what sort of dialogue exchange could lead to the motif lifetime distributions seen in Figure 3.6a*

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.

3.7 Conclusions and Outlook

These patterns in local interactions indicate that conversations in suicide watch 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 r/Suicidewatch when compared with the baseline conversations. Further investigation of local structures in graphs

show that there is a radically different way the conversation graphs evolve. The difference is not only between supportive conversation graphs and generic conversations, but also overall in supportive conversations and any social graphs. Several studies have looked at the social-tie structures and shown certain triadic motifs to be important in maintaining social hierarchy [62, 63, 130, 131], 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. These and many of other relevant triads are not even active in supportive conversations as seen from Figure 3.6. This points of a very different approach at interaction 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 interdisciplinary aim is to enable use of such frameworks, to understand at risk individuals online and offline.

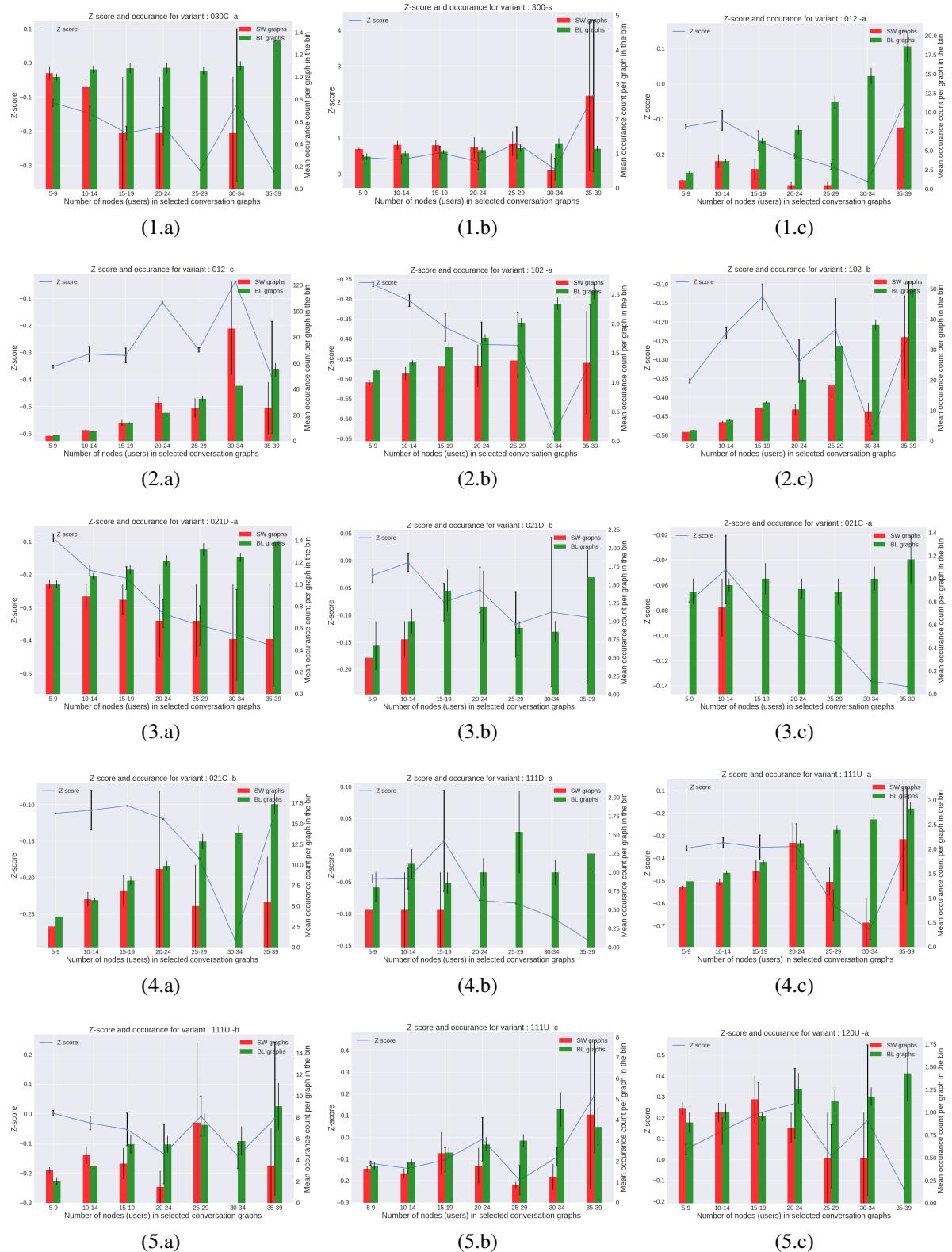
In conclusion, quantifying perceived social support is an ongoing effort. But my work has shown that there are computable methods, which could capture the mechanics of support in online conversations.

3.7.1 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 for users. 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 the open nature.

3.7 Conclusions and Outlook

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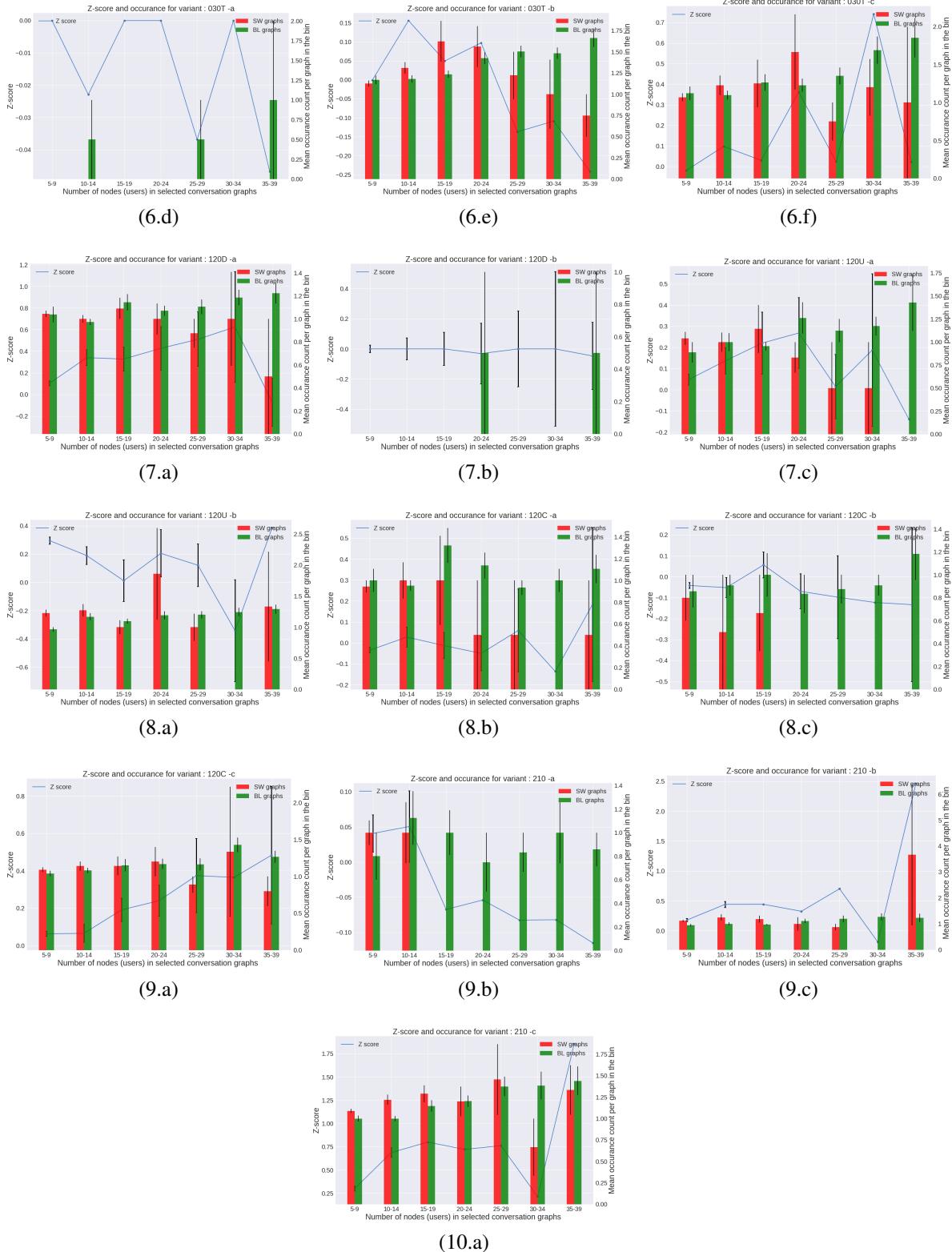


Fig. 3.6 This figure lists out all the insignificant Anchored motifs, either by the virtue of rare occurrence (<5 mean motifs per bin) or by account of low Z-score.

CHAPTER 4

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 and content 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 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 [83, 90], our outlook towards exercise [143], health of seniors [142] and general all round well being [53, 104]. 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 [2, 116, 124]. These elements are those that contribute to the creation of what the urban sociologist Jane Jacobs called 'urban vitality' [67]. 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 crowdsourcing and machine learning help us quantify how humans perceive beauty in urban settings?*

4.1 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 [67] 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 [2]. 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 [121] and a variety of objective measures (e.g., scene complexity [73], presence of nature [72]) and subjective ones (e.g., people’s affective responses [145]). As mentioned before, the relation between greenery and the design of spaces around us has been linked with measurable effects on our health [83, 90], our outlook towards exercise [143], health of seniors [142] and general all round well being [53, 104].

With the premise of all this, 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 [125], while others have used participant ratings of simulated (rather than existing) street scenes [87]. 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 [124]. In a similar way, Quercia *et al.* collected pairwise judgments about the extent to which urban scenes are considered quiet, beautiful and happy [116] to then recommend pleasant paths in the city [118]. 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.* [12] 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. [55].

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 [47, 129], urban change [100], and even crime [6, 41]. Recent works have also showed the utility of deep learning techniques in predicting house prices from urban frontages [80], and from a combination of satellite data and street view images [79].

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.

4.2 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 of 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 [47] called the place pulse and from Bell labs [117].

We start with the Place Pulse dataset that contains 100k Google Street Views across 56 cities around the world [47]. 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 to Figure 4.1, where 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 pairwise comparisons, distributed across 100k images, given my more than

Which of these two images look more beautiful



Fig. 4.1 Example of a pairwise comparison, where a user is asked to choose the more beautiful among the two.

81k participants. 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.

4.2.1 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 [60]. 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

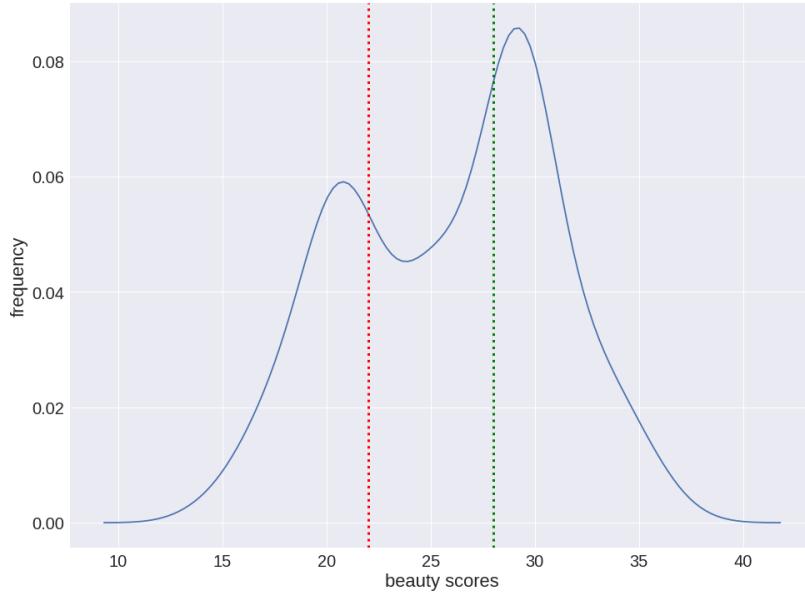


Fig. 4.2 Frequency distribution of beauty scores. The red and green lines represent the thresholds below and above which images are considered ugly and beautiful. Conservatively, images in between are discarded.

competitions played by each player, a steady state order of skilled players emerges. For our 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 4.2. This allows us to order the streetview images in an ordinal rank based on relative beauty as seen in Fig 4.3.

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. We conservatively 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



Fig. 4.3 Sample pairs of street view images ordered by lowest final skill rating on the left to highest on the right.

them to the beauty bin. We arrive at these values of partitioning, by conservatively evaluating how many images we are left with, without polluting the data with borderline cases.

4.2.2 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 over fitting. 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

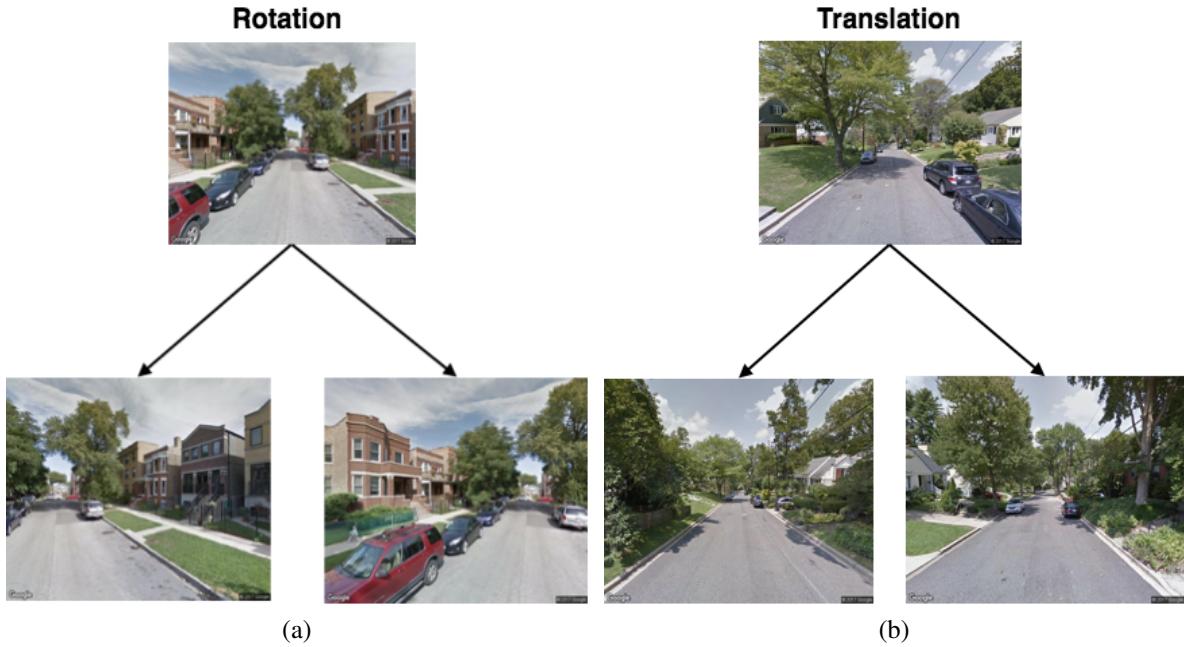


Fig. 4.4 Two types of augmentation: (a) rotation of the Street Views camera (based on rotation); and (b) exploration of scenes at increasing distances (based on translation).

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 angles¹ (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 $+ - 30^\circ$. 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

¹Google streetview API allows the users to set the bearing and heading of the mast camera, used to acquire the image

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 device 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. This is done by using the activations of a the fully connected layer of a trained convolutional neural network during a forward pass [8, 86, 146]. 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 distances 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 [156]. PlacesNet was trained on streetview images, and is trained with the end goal of classifying streetview images into scene types, such as a beach, highway, garden etc. We represent the two scenes I and I_m with visual features derived from the $FC7$ layer of PlacesNet and compute the similarity between the two corresponding feature vectors using L1 norm. 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

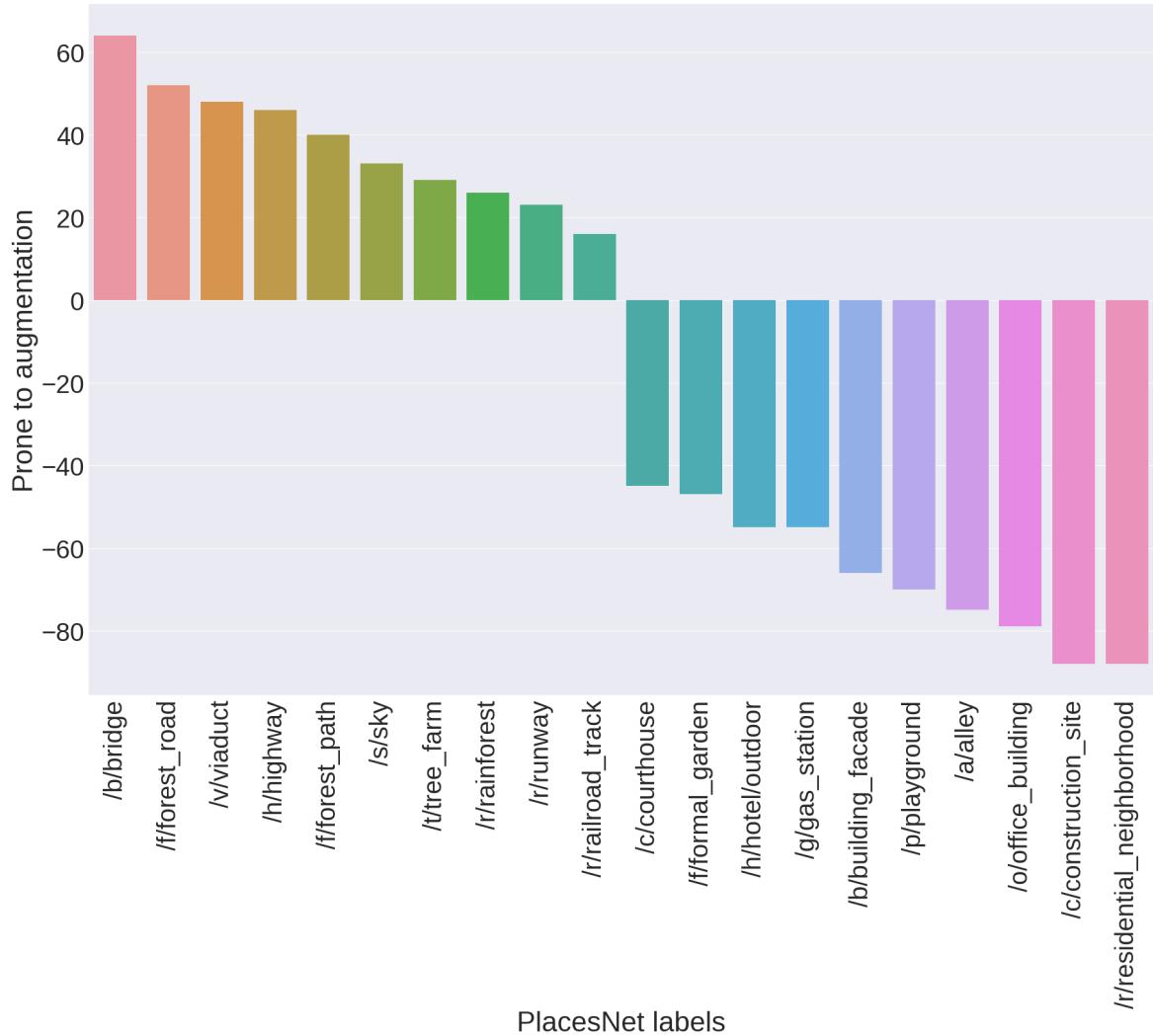


Fig. 4.5 The types of scene that have greater propensity to be correctly augmented with similar scenes at increasing distances.

threshold: (*filtered-set*). Each scene is then scored with PlacesNet [156] 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: $\text{prone}(\text{label}) = \text{fr}(\text{label}, \text{taken-set}) - \text{fr}(\text{label}, \text{filtered-set})$. 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 4.5, we find that, as one would expect, scenes that contain high amount of visual continuity over long stretches such as highways, fields and

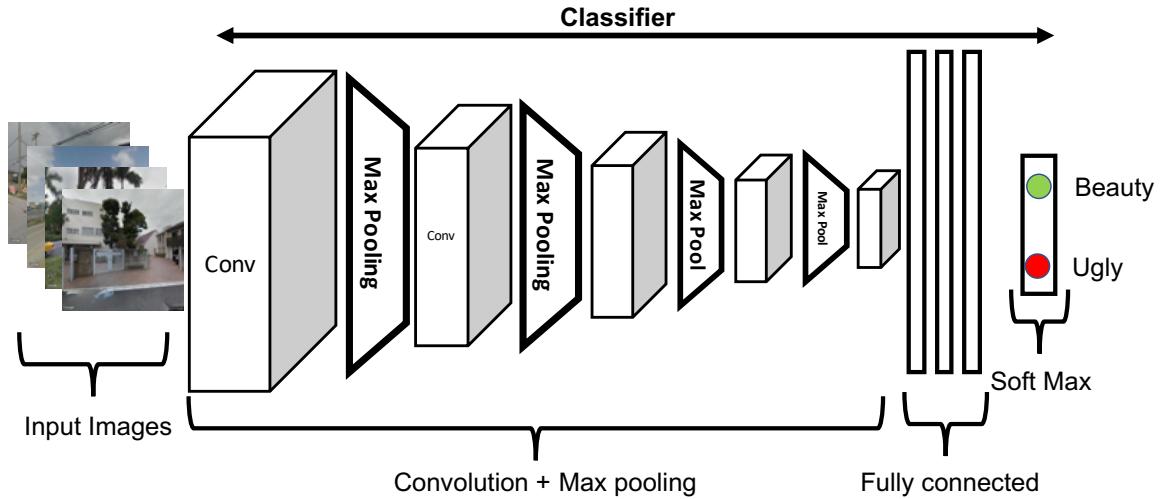


Fig. 4.6

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.

4.3 Building a beauty Classifier

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

Table 4.1 Percentage accuracy for our beauty classifier trained on differently augmented sets of urban scenes.

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 [77, 140] as seen in Figure 4.6. 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 [138] (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).

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 20k images and progressively augment them with the snapshots 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 4.1): 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 [47] 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.

4.4 Implication of a beauty classifier

In this chapter, we found that using a crowd based pooling of opinions of 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 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 analogous 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 5

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:

RQ6 *Can we leverage the quantification of the crowd’s subjective perception, to improve real spaces?*

RQ7 *Do humans and experts find the improvement realistic?*

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 aesthetic. These generations can be used as recommendations of possible improvements of any given un-aesthetic place. Next we quantify these recommendations using metrics designed around urban design literature. Finally we validated these metrics and recommendations through a user study.

This approach essentially calls back to the DIKW pyramid approach, where by, 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 saw in Chapter 4 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 arrive at wisdom inducing insights.

5.1 Related

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 [54], urban science [29, 84, 107], health informatics [120]. 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 [77] or detecting faces [119], but it has also enabled researchers to quantify much more subjective and intangible properties from images, such as emotions [75], sentiments [19] or ambiance of a place [122].

Since the introduction of Generative Adversarial Networks (GANs) [57], 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 [82] to fine-grained in-painting technologies [111]. Recent approaches have been used to generate images conditioned on specific visual attributes [151], and these images range from faces [141] to people [89]. In a similar vein, Nguyen *et al.* [103] 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 [3].

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.

5.2 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. This means the Generator

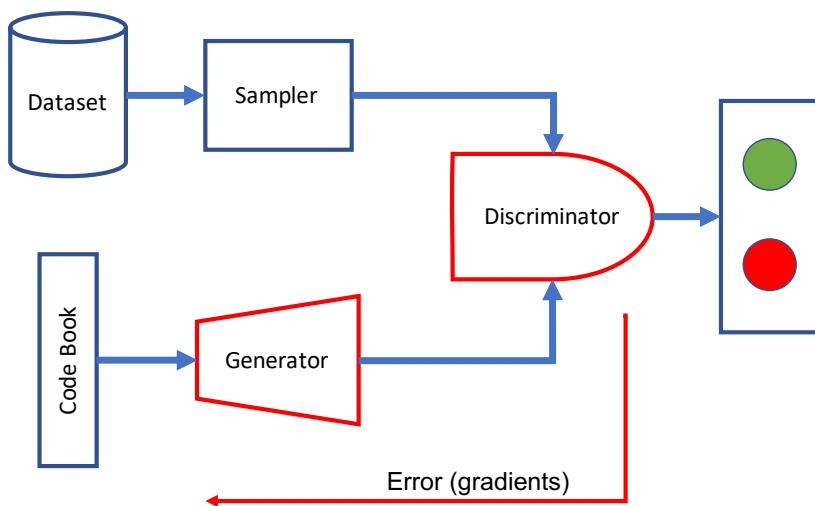


Fig. 5.1 A simplified illustration of the architecture of a Generative Adversarial Network. The red components are trained in tandem, one at a time. The discriminator D tries to maximize accuracy to differentiate between I and the generated version \hat{I} . And the Generator G tries to minimize accuracy of D to 50% thereby making $\hat{I} \approx I$

The training of this arrangements of neural networks happen in a lock step mode. A simplified version of this arrangement can be found in Figure 5.1. 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 $\text{log}(1 - D(G(x)))$. Essentially G and D are locked in a two player min-max game with the value function $V(D, G)$ formalized as :

$$\min_G \max_D V(D, G) = \mathbb{E}_{x \sim p_{\text{data}}(x)} [\log D(x)] + \mathbb{E}_{z \sim p_z(z)} [\log(1 - D(G(z)))] \quad (5.1)$$

For the premise of my dissertation, I train a generator from the works by Dosovitsy et.al [46] on the entire dataset of streetview images obtained in accordance to the strategies discussed in Chapter 4. The results of the capacity of this generator to approximate streetview scenes can be see from Table 5.1.

5.3 Framework Design

Having the trained classifier at hand and the trained generator of synthetic beautified scenes, the next step is to reconstruct synthetic images using the generator, that maximize the probability of that image being classified as beautiful. The simulated arrangement of this framework can be see in figure 5.2 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 technique outputs \hat{I}_j , which is a more beautiful version of it (e.g., I_i is morphed towards the average representation of a beautiful scene) while preserving I_i 's details. The technique does so using the “Deep Generator Network for Activation Maximization” (*DGN-AM*) [103]. 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

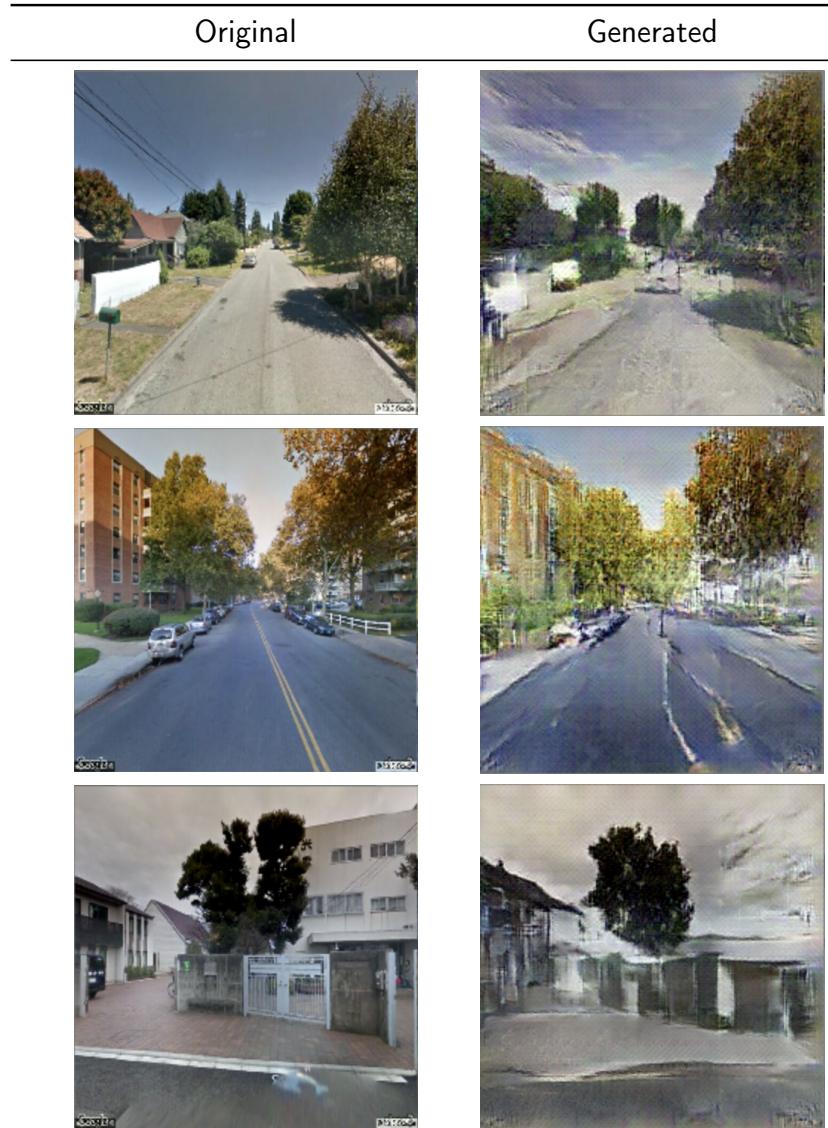


Table 5.1 Examples of our generator's outputs. The original scenes and the generated ones are shown side by side.

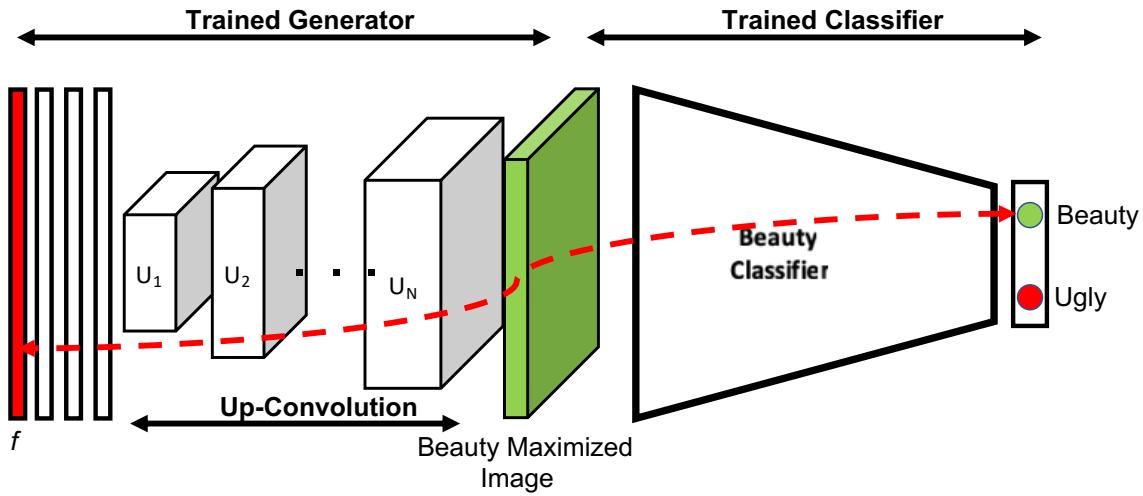


Fig. 5.2 Architecture of the synthetic beauty generator. This consists of a generator of synthetic scenes concatenated with a beauty classifier. The green block is the beauty maximized template \hat{I}_j , which is subject to forward and backward passes (red arrow) when optimizing for beauty.

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 5.2 Notations

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:

$$\hat{I}_j = G(f) : \arg \max_f (C_j(G(f)) - \lambda ||f||) \quad (5.2)$$

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 4.2). 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 [156]; *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 .

5.4 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 [9] and PlacesNet [156]. That is, we can determine how the original scene and its beautified version differ in terms of urban design elements.

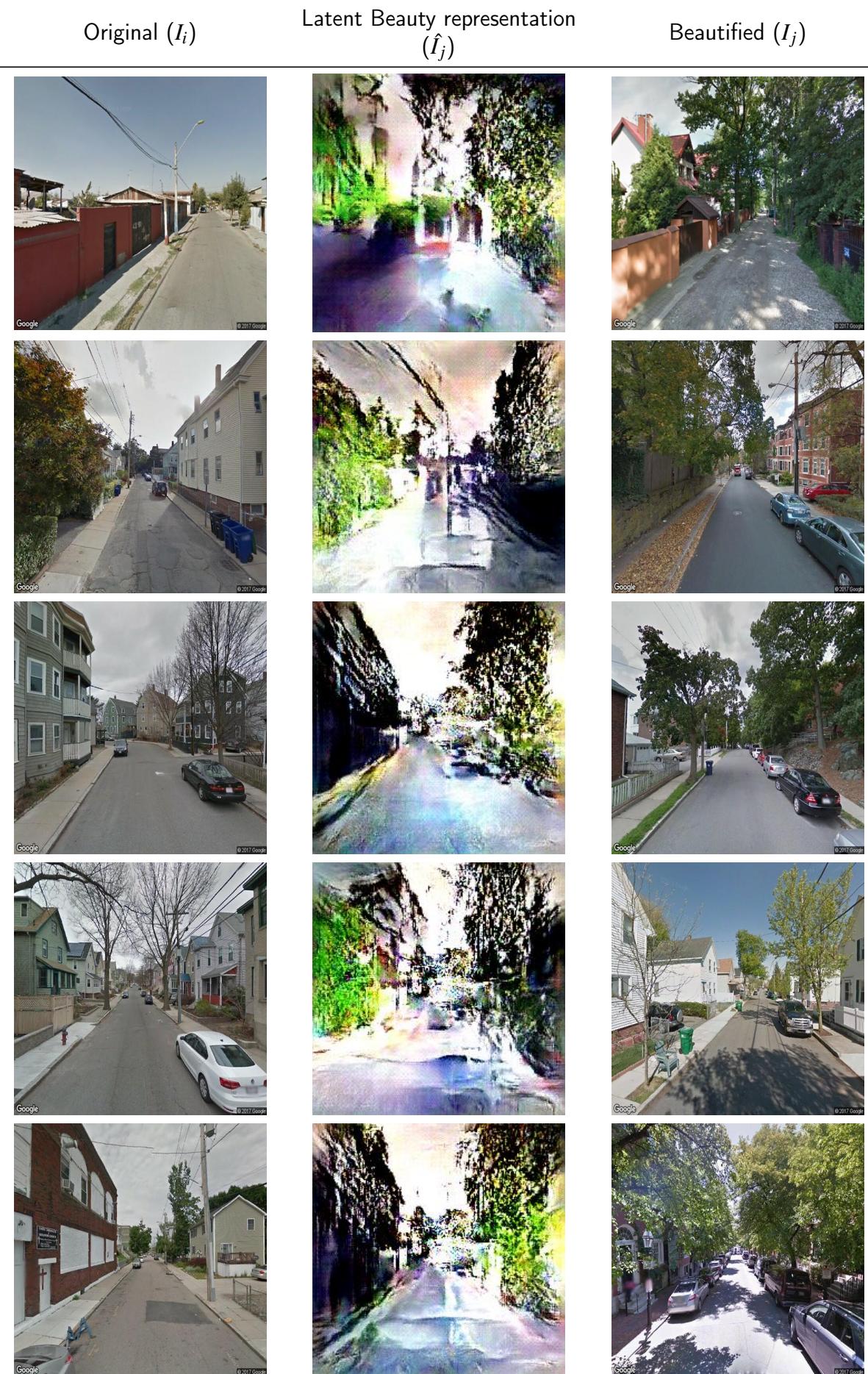


Table 5.3 Examples of the “FaceLifting” process, which tends to add greenery, narrow roads, and pavements.

5.5 Evaluation

The goal of FaceLift 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 FaceLift meets that composite goal, we answer the following questions next:

Q1 Do individuals perceive “FaceLifted” 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 FaceLift’s insights useful?

5.5.1 Q1 People’s perceptions of beautified scenes

To ascertain whether “FaceLifted” 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 4.2). 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 “FaceLifted” scenes are indeed perceived to be more beautiful by people.

5.5.2 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 [2, 50] (Table 5.4): they mainly tend to be walkable, offer greenery, feel cozy, and be visually rich.

Metric	Description
Walkability	Walkable streets support people's natural tendency to explore spaces [50, 115, 136].
Green Spaces	The presence of greenery has repeatedly been found to impact people's well-being [2]. Under certain conditions, it could also promote social interactions [116]. Not all types of greenery have to be considered the same though: dense forests or unkempt greens might well have a negative impact [67].
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 [50, 88, 116, 117].
Privacy-Openness	The sense of privacy conveyed by a place's structure (as opposed to a sense of openness) impacts its perception [50].
Visual Complexity	Visual complexity is a measure of how diverse an urban scene is in terms of design materials, textures, and objects [50]. 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 [145].

Table 5.4 Urban Design Metrics

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 (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 [156], 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 the scene. Second, using Segnet [9], 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.

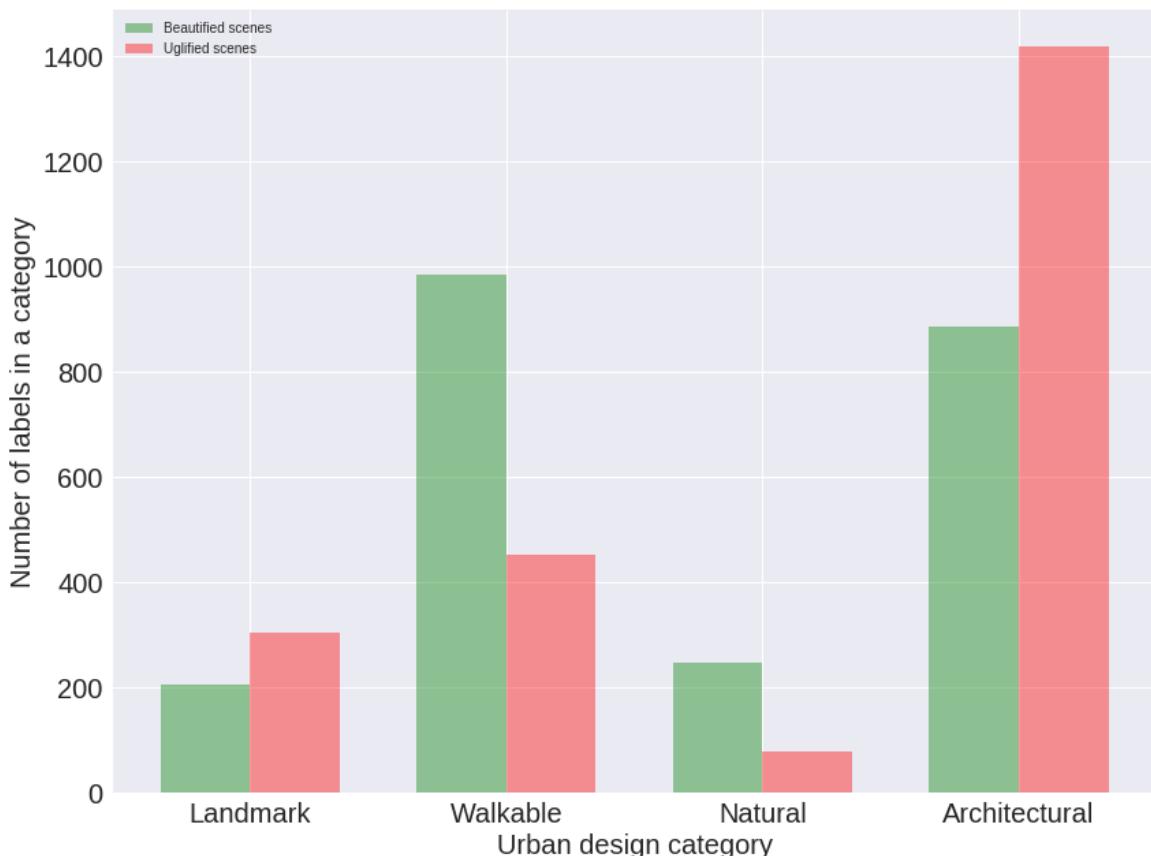


Fig. 5.3 Number of labels in specific urban design categories (on the *x*-axis) found in beautified scenes as opposed to those found in uglified scenes.

Having these two ways of labeling scenes, we can now test whether the expectations set by the literature describing metrics of great urban spaces (Table 5.4) are met in the FaceLifted 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 5.3):

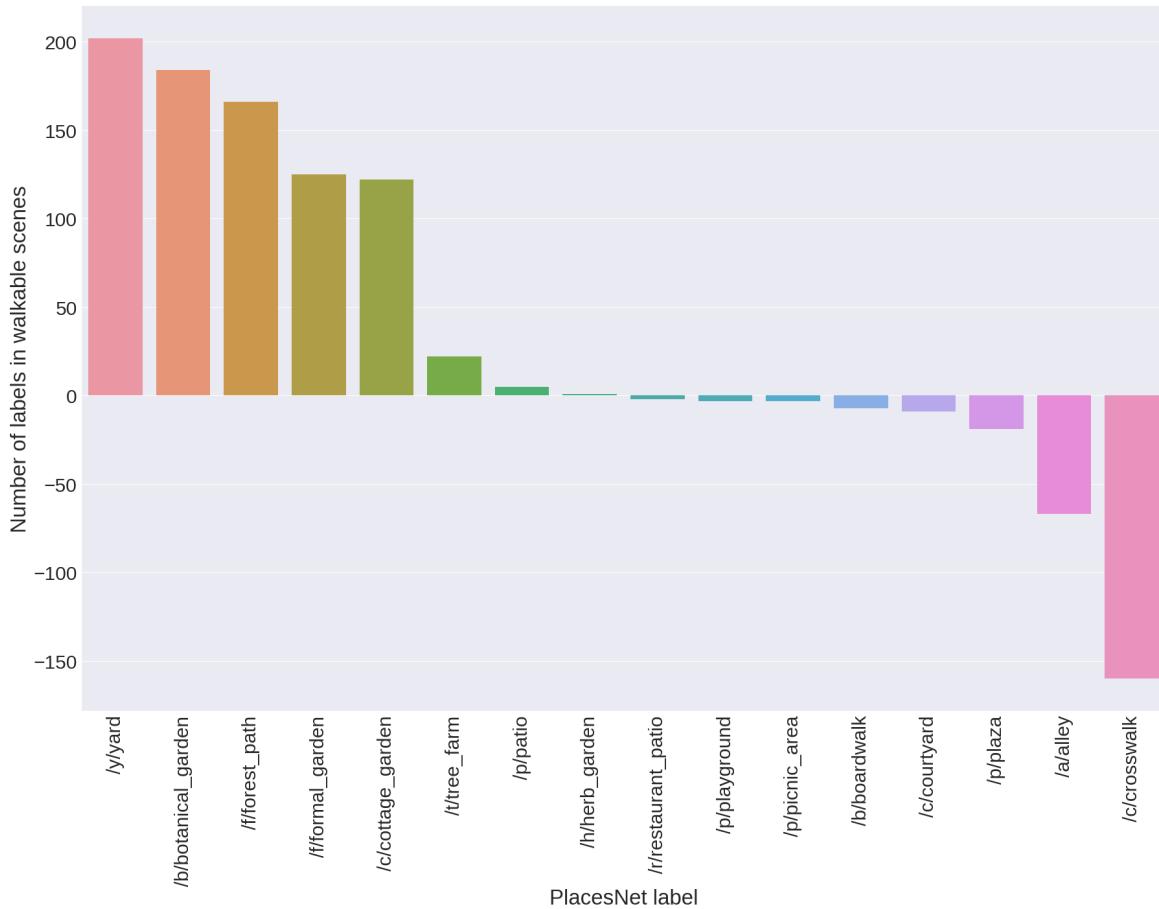


Fig. 5.4 Count of specific walkability-related labels (on the *x*-axis) found in beautified scenes minus the count of the same labels found in uglified scenes.

the former contain twice as many walkability labels than the latter. We then determine which types of scenes are associated with beauty (Figure 5.4). 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.

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 5.3): 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

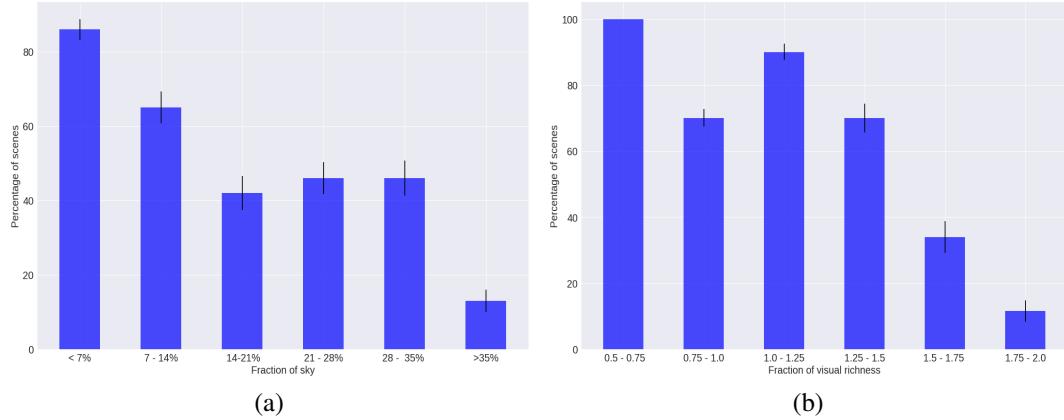


Fig. 5.5 The percentage of beautified scenes (y-axis): (a) having an increasing presence of sky (on the x-axis); and (b) having an increasing level of visual richness (on the x-axis). The error bars represent standard errors obtained by random re-sampling of the data for 500 iterations.

‘tree’) in beautified and uglified scenes, and find that beautification adds 32% of tree pixels, while uglification removes 17% of them.

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 5.5a: 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 rich, we measure their visual complexity [50] as the amount of disorder in terms of distribution of (Segnet) urban elements in the scene:

$$H(X) = - \sum p(i) \log p(i) \quad (5.3)$$

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 [145]: we prefer places of medium complexity rather than places of low or high

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 5.5 Coefficients of logistic regressions run on one pair of predictors at the time. complexity. To test that, we show the percentage of beautified scenes that fall into each complexity bin (Figure 5.5b): 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.

5.5.3 Q3 Urban elements of beautified scenes

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:

$$Pr(\text{beautiful}) = \text{logit}^{-1}(\alpha + \beta_1 * V_1 + \beta_2 * V_2 + \beta_3 * V_1.V_2) \quad (5.4)$$

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 [2, 50, 116], and show the results in Table 5.5.

Since we are using logistic regressions, the quantitative interpretation of the beta coefficients is eased by the “divide by 4 rule” [147]: 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 beauty [147]. For example, take the results in the first row of Table 5.5. In the model

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 5.6 Urban experts polled about the extent to which an interactive map of “FaceLifted” scenes promotes: (a) decision making; (b) citizen participation in urban planning; and (c) promotion of green cities

$Pr(\text{beautiful}) = \text{logit}^{-1}(\alpha - 0.032 \cdot \text{buildings} + 0.084 \cdot \text{trees} + 0.005 \cdot \text{buildings} \cdot \text{trees})$, 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 5.5, 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.

5.5.4 Q4 Do architects and urban planners find it useful?

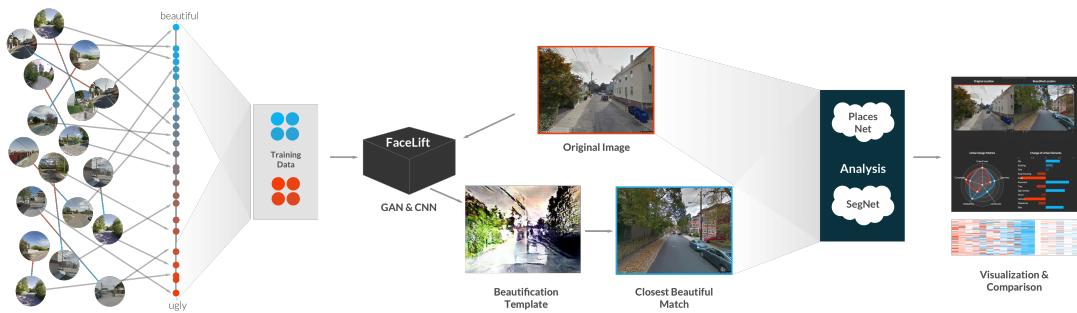


Fig. 5.6 An end to end illustration of the FaceLift framework.

To ascertain whether practitioners find FaceLift 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 5.7). 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 5.6). That is because previous work [10, 99] has shown that such a scale: (i) pushes respondents to “take a stance”, given

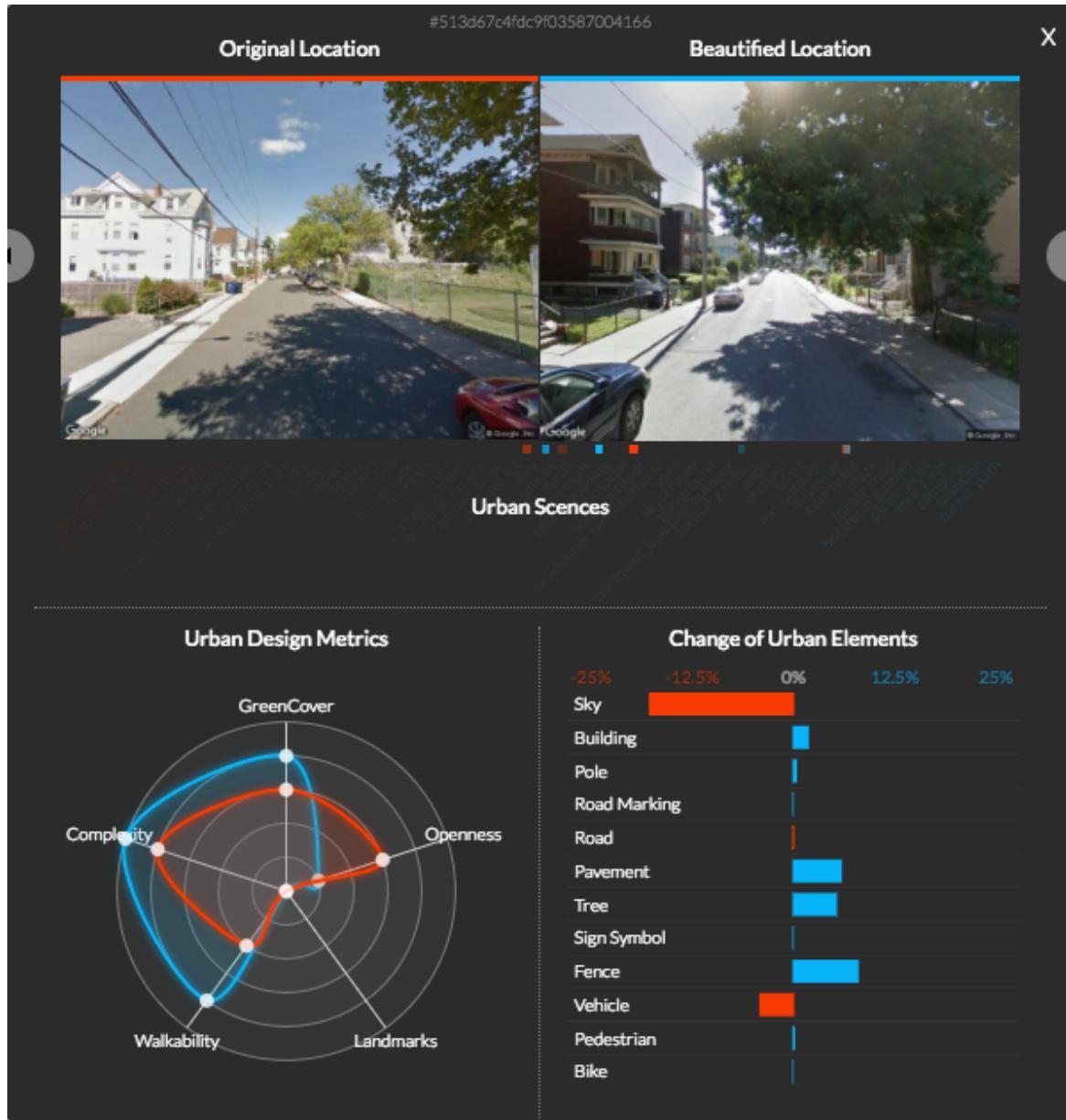


Fig. 5.7 Interactive map of FaceLifted scenes in Boston.

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 is has been the case for our survey). The experts had to complete tasks in which they rated FaceLift based on how well it supports decision making, participatory urbanism, and the promotion of green spaces. According to our experts (Table 5.6), 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 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*”.

5.6 Conclusion

FaceLift is a framework that automatically beautifies urban scenes by combining recent approaches of Generative Adversarial Networks and Deep Convolutional Networks. To make it usable by practitioners, the framework is also able to explain which urban elements have been added/removed during the beautification process.

There are still important limitations though. One is data bias. 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. 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.

Despite these limitations, FaceLift has the potential to support urban interventions in scalable and replicable ways: it can be applied to an entire city (scalable), across a variety of cities (replicable). To turn existing spaces into something more beautiful, that will still be the duty of architecture. Yet, with technologies similar to FaceLift more readily available, the complex job of recreating restorative spaces in an increasingly urbanized world will be greatly simplified.

After all, “we delight in complexity to which genius have lent an appearance of simplicity.” [38] In the context of future work, that genius is represented by future technologies that will help us deal with the complexity of our cities.

5.6.1 Limitations and biases

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 the study on streetscore [101]. However their annotation is open to general public and there is not way we can remove biases that come with culture and location, in a highly subjective effect like beauty. 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. 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 data is the model's lack of preference to pedestrians. This bias was established well in advance because Google tries to remove most of the people from their street view images for privacy reasons. Hence people, which make up a major aspect of urban vitality, are completely missing from most dataset images and hence from the facelift transformations. Another Limitation of our work is in the metric formation. The computational metrics developed to capture the real urban design metrics are designed using heuristics. There needs to be more crowd and expert validation to establish the validity of their formulation.

5.6.2 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 existence 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. Greenery, walking spaces and open spaces seem drive our perception of the aesthetic, which may be grounded in our natural roots and evolutionary need to be safe and close to nature. Despite of the root causes seeming intuitive, 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, online. Data acquired from how we interact with different on-line services, may very well improve our off-line lives.

CHAPTER 6

CLOSING NOTES AND OUTLOOK FOR THE FUTURE

“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 for the next few years, and I would like to close this journey by walking through a few aspects of what I feel is the path forward.

6.1 Empathic Healthcare

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 [92]. 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 [16, 68].

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 [69]. My work with the suicide watch support community also shows that there are quantifiable structures of support 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

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>

are supported by the healthcare provider and allow self and group management of chronic conditions. 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.

6.2 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 [126, 148], well being [31], quality of air [97] etc. Some more inter-disciplinary works have also been shown that built environment in cities resonate with our personality and perception of qualities like safety, richness and beauty [42, 47]. Some studies have also shown that something as simple as presence of green canopy can be correlated with reduced depression related prescriptions [59].

In the same vein, my work done on crowd based urban design, allowed me to leverage perception of the crowd 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 call perceptive urbanism. This aspect of urbanism could actually be immensely helpful in developing interventions with minimum costs but maximum impact. All these questions, when looked at through the lens of crowd perceptions, could result in much more explainable and actionable insights. I hope to work towards this vision.

6.3 Conclusion

In the hindsight, this work has been a result of 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 science. 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 is it 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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