Introduction
Structure Matters

Why do we see the behaviors that we do in the world? This is a question that has challenged many notable figures, including Darwin, Saussure, Wittgenstein, Lévi-Strauss, Durkheim, and many other past and recent thinkers. The conclusions that they arrived at, time and again, identified how things in the world – from species, to thoughts, to culture – relied on the interconnectivity of the systems in which they arose. Behaviors are a consequence of the environments in which they emerge and the historical trajectories that have brought them about.

The biologist Theodosius Dobzhansky claimed as much when he said "Nothing in biology makes sense except in the light of evolution" (Dobzhansky, 1973: p. 125). The linguist John Firth reiterated it when he said that "You shall know a word by the company it keeps" (Firth, 1957: p. 11). These are structural claims about the origins of life and meaning. Organisms originate from a marriage of ancestry and environment. The meanings of words depend on their relationships with other words. And so on it goes. People aggregate into mobs of like-minded fanatics and beliefs nestle among one another like a huddle of penguins.

One of the tools that has brought this structural vision of life and meaning into focus is network science. By describing the relationships that bind systems together, network science provides a quantitative precision to these earlier ideas. As a ruler measures length, allowing us to compare human height with the Burj Khalifa, network science measures structure, giving us the ability to compare networks of human relationships with the organization of the environments in which they occur, the patterns of activation in our brains and – more enchantingly – with the architecture of our thoughts. When we stop seeing isolated things and start focusing on the relationships between them, we are inviting a structural view of behavior that can be compared across disciplines.

This cross-disciplinary insight is one of the catalysts behind the science of complex systems. Complex systems approaches attempt to identify general principles of systems that apply across domains. By general principles, I mean principles that are abstracted away from the particulars of the environment in which they are found. When someone describes a scurrying procession of driver ants, searching for prey on the forest floor in the Gold Coast of Ghana, alongside the rejoicing voices of a group of improvisational singers in a nearby church, we have something that approximates literature. Understanding how the ants and the singers solve a similar coordination problem is a view from complex systems.

Both the ants and the singers are navigating structured spaces – whether among the forest's fractal underbrush or the melodic and rhythmic conventions of song. And, for both, the quality of their navigation depends on the structure of their communication: who communicates with whom, when, and by what means. The structural features of communication the ants and singers share apply to 1970s jazz fusion as well as they do to a murmur of starlings, the challenges of international politics, or the way people use what they know to learn what they don't. This shared structure across domains invites us to think about behavior using network science and, when we do, we have behavioral network science.

Viewing behavior in this way, phenomena become symptoms of the structural processes that govern them. The goal of the behavioral network scientist is to articulate the structure and processes of this government.

0.1 Structure in the World

We should care about structure because it helps us to understand how and why systems work like they do. That, in turn, helps us to anticipate what they are likely to do next – and what, if anything, we should do about it. That is, for all the grand unified generality of complex systems, behavioral network science shines most brightly when it tells us about specific things. Let me give you three examples.

Structure can tell us what kinds of systems we are dealing with. When Krebs (2002) mapped the network structure of the 9/11 terrorist cells – identifying each individual and the relationships among them – what he observed was peculiar for a social network. The 19 hijackers had sparsely interacted. This is rare among social networks. Our friends' friends tend to become our friends. Close-knit groups form from like-minded individuals. And coordinated groups need coordinated communication. On the face of it, the structure of the terrorist cells lacked these features. But this was by design. Sparsely connected social networks are perfectly sensible for criminal networks. Many criminal networks invoke similar behavioral immune systems, insulating themselves from compromise by limiting what the individuals know about one another and how often they interact. This makes it harder for authorities to identify and compromise them.

Structure also tells us about the kinds of individuals we need to maintain social health. Such social health is critical for winter-over crews at the Amundsen-Scott South Pole Station in the Antarctic. These crews are, for all practical purposes, people trapped together in a cage for nine months. Johnson et al. (2003) pioneered research on the network structure of these teams and found that the social health of the group went hand in hand with its social structure. This structure also depended critically on specific group roles. Certain kinds of people were the linchpins of community health. One of these people was the leader. Not just any leader, however. Successful leaders were recognized for their expressive leadership – a form of leadership focused on social cohesion. This requires knowing what needs to be done but also getting people to care enough about one another to do it with good cheer. Expressive leaders build self-motivated communities. Another kind of person was the 'positive deviant' – that is, the clown. Through their ability to defy social conventions, the clown acts as what network scientists call a broker between various teams (such as nonscientists and scientists), eventually bringing individuals together who would otherwise remain apart.

Structure also helps predict where certain kinds of events will happen. Consider Juárez, a city that lies on the border between the USA and Mexico. During the early 2000s it was the murder capital of the world. What makes a place like Juárez so dangerous? In our effort to explain such things, we often reach for exhausted stereotypes or true but inexact explanations like "drug cartels." The latter is half right, but there are drug cartels in many peaceful places far beyond Juárez. What differs about Juárez is almost entirely structural – it is what it is because of its relationship with other places. According to Wainwright (2016), Juárez is one of the critical gateways for drug trafficking between South and North America. Those who control Juárez control access to a large slice of the North American market. Juárez is therefore a place with what network scientists call high betweenness: to go from one place to another, one must pass through it. During the 1990s, control over Juárez was thrown into question, and the disputes that arose reflected the value of its betweenness.

These three examples demonstrate several things. Foremost, they demonstrate how an understanding of the basic principles of network science can help guide our behavioral intuition. When we see a certain behavior in the world, we can better hypothesize about what gave rise to it if we understand how structure works. In the same way that a knowledge of Latin can help us infer the meaning of a novel word, a knowledge of structure helps us make sense of complex relationships.

What these examples also demonstrate is how behavior can bring network science to life. When we see an abstract principle from network science embodied in issues that we care about and for which we already have some understanding, the principle becomes approachable. And it starts to become something we can recognize at a party.

0.2 Structure and Process

Like a map, structure is a simplification. But when our understanding of structure functions at its best, it helps us think about how structure and behavioral processes interact.

For sparsely connected terrorist cells, we can see how a disconnected structure prevents a certain kind of disruptive process such as getting one individual to rat out the others. But if the process were different – for example, if the police took down criminals like lions single out a stray from the herd – then the structure would be different. Criminals would crowd together like gazelles on the African savanna. Similarly, our mental health benefits from our social relationships, as if it were contagious. Knowing this, it becomes evident why people who act as social connective tissue keep communities healthy. And, finally, Juárez's structural position matters because of where drugs originate and how they move. Legalizing drugs or otherwise changing the conditions by which they are trafficked would change the processes driving the drug market and change Juárez as a result. Structure lives and dies by its processes.

There are countless examples. US Route 66 is a structural bygone that fell into decline not because we changed the physical structure of space, but because we changed the way we moved through it. Similarly, our social networks have changed because online environments make it easier to find people who share our obsessions. And the processes we use to search memory mean the aging mind can both know more and be harder to search at the same time. Behavior is awash with examples like these. Creativity, child learning, opinion dynamics, the beliefs of conspiracy theorists, and much more are a consequence of structure and process. The beauty of structure is that it helps us understand the processes better, and vice versa.

0.3 Behavioral Network Science

Behavioral Network Science is written for those who are interested in gaining a better grasp of the relationship between structure and behavior. It does this by combining behavioral science with network science in a way that allows them to inform one another.

Behavioral science is a developing interdisciplinary field focused on understanding what makes people tick. It encompasses fields such as behavioral ecology, business, behavioral economics, psychological science, informatics, experimental philosophy, and the cognitive sciences more generally. Above all, behavioral scientists are comfortable with theoretical and experimental tests of hypotheses that utilize quantitative approaches (i.e., advanced counting). Network science is a quantitative discipline aimed at describing structure and the processes that influence it.

By combining these, this book aims to provide a serious investigation of theory and practice in behavioral science in a way that highlights why structure matters and how we can use network science to understand it better. In all cases, I have aimed to communicate ideas as if the reader knew little about the behavioral theory or the network methodology. An interested reader should have no problem seeing how it all comes together. That said, the behavioral science chapters focus on open questions in the behavioral sciences and, in most cases, present novel analyses which attempt to integrate and extend what we already know. I could not bring myself to write a book that merely relayed what I already knew; there is excitement in knowing the snow is fresh.

There are of course many excellent books that provide an introduction to network science. I could not have written this book without them. These range from Wasserman and Faust's (1994) classic text *Social network analysis: Methods and applications* (which I read like it was on fire many years ago), to more recent contributions like Newman (2018) *Networks*, Barabási and Posfai's (2016) *Network science*, Menczer, Fortunato, and Davis's (2020) *A first course in network science*, and Borgatti, Everett, and Johnson's (2018) *Analyzing social networks*. All of these books should be read twice. They go more deeply into the technical aspects of network theory than this book and they should be on any card-carrying network scientist's reading list. There are also books dedicated to the history of social networks (Freeman, 2004), the networks of crowds and markets (Easely & Kleinberg, 2012), and networks in neuroscience (Fornito et al., 2016; Sporns, 2016). These books are all excellent and inspiring for anyone interested in network thinking.

However, there are few books that focus on the psychology and cognitive theory of behavioral science as it is informed by network science. And that's a shame, because the two topics go well together. Moreover, if part of the aim of network science is to understand how it matters for people, then it makes sense to take a close look at what we already know about what makes people do what they do. That is something about which behavioral scientists have much to say.

The meat of this book presents a series of chapters that each tackle a new problem in the behavioral sciences, laying out its theoretical and experimental foundations, and then offering an approach to better understanding it using network science. In essence, each of these chapters poses a scientific riddle about behavior and then uses network science to unravel it.

0.4 The Structure of the Book

This book was written to meet readers at their level of interest. It is laid out in four parts. Readers who are interested in enriching their understanding of network science can start at the beginning with **A Brief Guide to Network Science**. This will give readers a short course on how networks are constructed, what we can measure with them, and how we can grow our own. It is designed to be quick and dirty, with an emphasis on practical understanding, and I try to provide brief but memorable real-world examples for many of the concepts. If read while working through the online code, the reader will be making and measuring networks in short order.

Following the brief guide, the book gets down to the business of behavior. Readers with a specific behavioral interest can choose the chapter that most piques their interest in one of the three parts that make up the behavioral section of the book. Part II focuses on issues of **Language**, showing how we can apply network science to understand language, language acquisition, language emergence, and language evolution. Part III, **Mind**, presents a series of chapters investigating mental processes, such as false memories, memory search, cognitive aging, and creativity. Part IV, **Society**, visits a series of topics associated with social dynamics, focusing on social illusions, the wisdom of crowds, opinion dynamics, group conflict, and an alternative pathway for scientific funding inspired by a merit-based universal basic income.

The behavioral science chapters also follow a methodological arc. Earlier chapters focus more on applying and developing metrics for measuring nodes, edges, and networks. Later chapters develop behavioral models that try to explain behavior by generating it, in the same way we might try to write down a recipe for vegan cheesecake. It is not easy, but it can be done. And as better recipes produce better cakes, better models produce better explanations of behavior. The later chapters focus more on getting beliefs into individuals and use agent-based models to let them act out their parts in the social fabric.

0.4.1 The Online Code

Most everything in this book comes with the code and data to reproduce it. The book is written exclusively in R (R Core Team, 2023) using RMarkdown (Allaire et al., 2020). The annotated code necessary to reproduce the analyses and figures is provided on the book's website for each chapter. The primary graphing package is igraph (https://r.igraph.org/reference/index.html). All the additional packages necessary to run the code are designated in the code. Statistically, I've generally gone for the interocular trauma test: the results should hit you between the eyes. In the few cases where this isn't true, more statistical details can be found in the online code. I've dominantly left the statistical minutiae out of the text, as it would have otherwise been too cumbersome. Generally speaking, the statistical tests one might use for networks are not different from other data types. Other books describe the underlying details of these tests better than I can (e.g., Field et al., 2012). Just the same, networks do have their peculiarities and I address these where they arise.

0.4.2 Using This Book in the Classroom

Early drafts of this book have been used as a text for undergraduate and postgraduate coursework. These have been taught to social scientists interested in learning more about network science and mathematical scientists interested in learning more about behavioral science.

Short courses can focus on the first three chapters, to provide a foundation in network science that will rapidly bring readers up to speed. They are especially effective when combined with specific examples cherry-picked from later chapters that demonstrate principles in action.

Longer courses can start from the beginning and explore a few chapters per week alongside the online code.

To give a bird's-eye view of the terrain, Table 0.4 provides each chapter's behavioral theme alongside its methodological focus.

Table 0.4 Each chapter's behavioral theme and methodological focus

Chapter	Theme	Methods
1	Network representation	Kinds of networks and how to build them from data
2	Network metrics	How to measure properties about nodes, communities, and networks as a whole
3	Generative network models	How to grow your own networks
4	Language structure	Degree and degree distributions
5	Child vocabulary learning	Fitting models of network growth to real data
6	How distinctiveness aids learning	Various ways to build edges based on shared features in multilayer networks
7	Comparing early and late talkers	Three approaches to measuring small-world networks
8	Where new words are born into language	Using biological theory to understand node origins
9	Language emergence	Agent-based modeling of community information emergence
10	False memories	Spreading activation on a network
11	Memory search	Comparing animal foraging models with network search algorithms
12	Explaining age-related cognitive decline as enrichment	Using prediction-error models to simulate aging

Table 0.4 (Continued)

Chapter	Theme	Methods
13	Creativity	Producing structural differences from process differences
14	Structural illusions	Degree-attribute and aggregation illusions in network data
15	Group problem solving	Agent-based models of collective search and network annealing
16	Opinion dynamics and perceived normality	Agent-based models of segregation with Bayesian beliefs
17	Conspiracy beliefs and incoherence	Comparing network coherence and pointwise mutual information
18	Game theory and brinkmanship	Agent-based models of cooperation and escalation
19	Merit-based universal basic income	Agent-based models of wealth redistribution and eigenvector centrality

0.5 Acknowledgments

In a book about structure, one cannot help but to consider the network of all influencers. This must start with things like the Great Programmer, ancestors, grandparents, parents, and all the other scientific mentors along the way. This book owes much to them. The subgraph of more recent influencers is, however, easier to list.

This book was made possible by fellowships from the Royal Society and the Alan Turing Institute. By supporting research that bridges the mathematical and social sciences, they helped me to realize the appeal and importance of crossing the yawning divide that sometimes separates these disciplines. The University of Warwick was also instrumental in creating an interdisciplinary atmosphere where the behavioral sciences flourish. It has continued to promote behavioral science initiatives within and across disciplines. This has created a lively community of researchers willing to walk around campus to visit one another for nothing more than a biscuit and some lively discussion.

The pleasure of writing this book was enhanced by the many people who helped along the way. Cynthia Siew, especially, got the ball rolling during a too-short visit to Warwick. Cynthia played a substantial role in the early stages to help shape the vision of this book. Stephen Acerra at Cambridge University Press was also ever optimistic, and his enthusiasm helped the book to reach the finish line. Many others have acted as expert readers and advisers, providing feedback and offering invaluable criticism. Thanks to Adrian Bangerter, Adriano Lamieri, Alessandro Miani, Charlie Pilgrim, Chris Strelluf, Clay Beckner, Daniel Read, Daniel Sgroi, Danyang Hu, Dasol Jeong, Dirk Wulff, Emmanuelle Volle, Ethan Freestone, Eugene Malthouse, Eugenio Proto, Eva Jimenez, Friederike Schlaghecken, Gordon Brown, Halleyson Li, Iain Murdoch, Jens Vogelgesang, Joshua Cox, Kita Sotaro, Li Ying, Lucas Castillo, Mahathi Parvatham, Marcela Ovando-Tellez, Massimo Stella, Michael Hattersley, Michael Vitevitch, Mikhail Spektor, Paolo Turrini, Pascal Wagner, Richard Moore, Rowan Munson, Simon De

Deyne, Yoed Kenett, Yuqi Ye, Yuval Hart, Zoran Kovacevic, and many others. They have all helped to straighten my crooked thinking. Many have also been generous with data and code. Thanks also to the many students at the University of Hohenheim, the University of Lugano, and the University of Warwick, who suffered through early drafts of this work and pointed out the errors that others too kindly assumed I would recognize on my own. The remaining errors are left in for others to enjoy.

Finally, thanks to my closest friend, Sara, who has kept the craft of life properly ruddered, and whose eye for detail has played a critical part in helping shape the final form of this book. And thanks to Fionniain, Kaleia, and Sonora, whose unfailing curiosity and good humor hold the hand of thought open to William James's "wild facts" – where the new discoveries lie.