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Steps Toward more Adaptive Internets: charting Open-Source, P2P and Local-First Networks

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The fabrics of web, social and digital, tie us together, occasionally in tangles.

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2 ABSTRACT

This study explores the development and implementation of Peer-for-Peer (P4P) networks, a family of open-source, peer-to-peer, and local-first communication protocols. Rooted in the principles of complexity theory and an ontological basis in complex realism, the research examines how small, modular, and community-driven infrastructures can serve as adaptive solutions in response to ecological, social, and technological crises.

Through a mixed-methods approach, including interviews with nine case studies and an in-person workshop, the study identifies design principles that enable resilience and sustainability in P4P ecosystems. Findings highlight the critical role of modularity—both technical and social—in fostering self-organization, adaptability, and mutual aid within decentralized networks. The study also introduces the concept of "nested isomorphism," revealing how the structural patterns of technical systems influence the organizational structures that develop them.

P4P protocols, such as Willow, Mapeo, and Scuttlebutt, demonstrate the viability of localized and distributed communication infrastructures that prioritize user agency and digital sovereignty. These systems challenge the colonial structures of global internet infrastructure by empowering communities to build and maintain their own resilient networks.

This research contributes to complexity theory by expanding the understanding of self-organizing systems and isomorphic tendencies of technical and organizational structures. The research presents a framework for designing future communication infrastructures that align with principles of sustainability and inclusivity. The implications of these findings extend to the fields of open-source development,

decentralized networks, and adaptive infrastructure design, offering pathways toward a more equitable and resilient digital future.

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4 GLOSSARY

WORD	MEANING	SOURCE
Append−Only Logs	Similar to Distributed ledgers, immutable databases	(Tarr et al., 2019)
Centralized	Control or storage is maintained by single point	(Korpal & Scott, 2022)
CRDTs	Distributed Consistency Mechanisms	(van Hardenberg & Kleppmann, 2020)
Data Sovereignty	The right to govern data collection, ownership and application of its own data.	(Glasze et al., 2023; Marley, 2019)
Decentralized	Control of infrastructure is distributed among contributors	(Korpal & Scott, 2022)
Distributed	Each node in the network (computer or user) is connected directly to other nodes, forming a mesh or grid structure	(Baran, 1964)
Distributed Ledgers	Databases maintained at different nodes instead of at a central location. They are identical, and each contains all the transactions.	(Weking et al., 2020)
DOSNs	Distributed Online Social Networks	(Chowdhury et al., 2015; Masinde & Graffi, 2020)
DWeb	Term referring to the Decentralized Webs, includes cryptocurrency initiatives as well as DOSNs	(Bodo & Trauthig, 2022)
FLOSS	Free- Libre- Open-Source Software	(Crowston et al., 2012)
Git	Distributed Version Control Systems (DVCSs)	(Chacon, 2014)
Glocalization	A prodct or service that is developed and distributed	(Roudometof, 2023) for digital glocalization,

	flobally but also adjusted to accomodate consumers in a local market	website for definition[1]
Grassroots System	“Informally, a distributed system is grassroots if it can have autonomous, independently-deployed instancesgeographically and over time—that can interoperate once interconnected.” p. 2	(Shapiro, 2023)
Nested Systems	Sub-systems, and how systems relate to each other.	(Byrne & Callaghan, 2022)
P2P	“P2P networks, peers interact directly, build an overlay network, share resources, and can make autonomous local decisions” p. 1	(Daniel & Tschorsch, 2022)
Torrent	A torrent file identifies corresponding pieces of a large file, enabling distributed storage of large files broken up into small pieces	(Buford et al., 2009)
Web 2.0	Internet design relying on Internet Service Providers (ISPs) and a client/server data structures	(M. Anderson, 2019)
Web 3.0	P2P driven internet architecture, often involving append-only logs or distributed ledgers	(Korpal & Scott, 2022)

1 https://www.investopedia.com/terms/g/glocalization.asp

5 INTRODUCTION

PROBLEM AREA

The World Wide Web has been the dominant infrastructure for global digital communication for over four decades. This worldwide reach is mirrored by its physical infrastructure, with vast networks of undersea cables connecting continents (Tranos, 2013). However, this era of globalization may be nearing its end, driven by the unprecedented environmental collapse humanity now faces. The cascading effects of this collapse remain uncertain (IPCC Report Calvin et al., 2023). As a new era rapidly approaches, there is an urgent need for adaptive strategies and resilient infrastructures (Brozović, 2023).

One notable area of recent development is communication infrastructure. A growing number of open-source communication protocols have emerged, characterized by local-first qualities. Unlike traditional client-server models, local-first applications continue to function even when disconnected from the wider web. These protocols often leverage peer-to-peer (P2P) architectures for local connectivity and append-only logs for data immutability (Korpal & Scott, 2022). Within this realm, a family of distributed communication protocols emerged (Daniel & Tschorsch, 2022; Ermoshina & Musiani, 2022; Roscam Abbing et al., 2023), here referred to as Peer-4-Peer, and includes (but not limited to) protocols such as, Briar, Qaul, Secure Scuttlebutt (SSB), the dat ecosystem, P2Panda, Willow, Iroh, Cable, IPFS, Holochain and more.

These protocols are defined by their qualities of Local-First (Kleppmann et al., 2019), P2P architectures and are Open-Source. The term P4P is considered a reflection of the mutual-aid ethos of the networks (Kropotkin, 1902). However, as open-source projects, these protocols face common challenges, including reliance on voluntary contributions, unstable funding, and fluctuating participant engagement. This paper proposes strategies to alleviate these pressures within the P4P context.

Similarly to how *Glocalization* becomes a marketing buzzword in corporate PowerPoint presentations, this paper explores the journey of global open-source projects—often born from forum discussions and blog posts—into the hands of local communities striving for their own data-sovereign infrastructures.

The framework for researching the development of such infrastructures is grounded in complex realism. Complex realism posits that each component, such as a branding office, is intricately interconnected with the broader world through deterministic relationships. The branding office will impact the world around them, through chain reactions. How, exactly, the branding office (and all its employees with their Powerpoint presentations) eventually affect the life of a little boy by the name Bart in Springfield, is difficult to predict. This is relational determinism, the ontology of Complex Realism (Byrne & Callaghan, 2022).

From this theoretical foundation, the research questions were developed:

- **How can the maturity of open-source P2P local-first communication (P4P) networks be enabled?**
    - How are implementation and development processes shaped by qualities of self-organizing systems?
    - How does protocol architecture relate to organizational design in self-organized development environments?

These questions stem from the theoretical basis of this study, which assumes that terms like “local” and “global” are intrinsic properties of complex systems rather than isolated variables. A deeper discussion of the theoretical framework follows.

THEORETICAL BASIS

The theoretical foundation of this paper is rooted in complexity theory and its associated ontology of complex realism (Byrne & Callaghan, 2022). Complexity theory examines the behavior of systems composed of numerous interacting components, emphasizing that the collective dynamics cannot be fully understood by analyzing individual parts in isolation (Jean Boulton et al., 2015). This framework is particularly effective for studying non-linear systems, where outcomes are inherently unpredictable and deviate from the simple cause-and-effect relationships characteristic of linear systems.

The influence of complexity theory extends beyond the natural sciences, notably into the fields of organizations and management. In this context, complexity theory promotes decentralized decision-making and views organizations as complex adaptive systems. Local interactions within these systems can give rise to emergent behaviors that benefit the broader organization (Drazin & Sandelands, 1992; Stacey, 1996)

A central concept in complexity theory is self-organizing systems, which can spontaneously organize and develop structured patterns without any central authority or external control. This phenomenon, first conceptualized by cyberneticist W. Ross Ashby in the 1940s, highlights the capacity of decentralized and adaptable systems to achieve order through the interactions of their components (Anzola et al., 2017; Estrada-Jimenez et al., 2021; Fuchs, 2006; Gershenson & Heylighen, 2004; Heylighen, 2010; Jean Boulton et al., 2015; Miller & Page, 2007) Self-organization has since been observed across diverse domains, from the spontaneous ordering of molecules in physics and chemistry to emergent behaviors in ecological and social systems (Gershenson & Heylighen, 2004).

Self-organizing systems exhibit resilience by adapting to disturbances while maintaining functionality. This resilience enables these systems to self-regulate and reconfigure in response to changing conditions, stabilizing through the formation of new patterns and relationships. In certain cases, such adaptability transcends resilience, achieving "antifragility." Antifragile systems not only endure disruptions but also improve and strengthen as a result, becoming more robust and capable over time (Taleb, 2016)

METHODOLOGY

Complexity Theory serves as an ontological approach for both qualitative and quantitative research (Byrne & Callaghan, 2022). Given the inherently unpredictable nature of complex systems, changes within these systems are often qualitative rather than quantitative. Research grounded in complexity theory seeks to identify the underlying principles guiding such systems and the patterns that emerge.

This paper examines the implementation of local-first and data-sovereign infrastructures from the perspectives of nine communities and their associated communication protocols. A multiple-case study approach was employed, focusing on Peer-4-Peer (P4P) protocols. The analysis synthesizes findings across cases to identify commonalities and differences (Hunziker & Blankenagel, 2024). Data collection included 16 interviews, the creation of rich picture drawings, document gathering, and a workshop involving 14 P2P developers. The interviews were analyzed using an inductive coding approach, and the literature review utilized diverse search strategies to ensure comprehensive coverage.

The data analysis process employed inductive coding to identify recurring themes without relying on predetermined codes. This process was inspired by the "5W-1H" approach (Williams & Moser, 2019) and evolved into a more refined analytical coding framework over three iterative rounds. Insights from the workshop were integrated into the analysis to provide additional perspectives, although it is important to note that workshop participants primarily comprised European software developers, which limits representativeness of end users and local communities. Visualizations were created post-interview to enhance transparency and empower participants. These visualizations, inspired by the Soft Systems Approach and rich picture methodology (Monk & Howard, 1998), aimed to equalize the power dynamic between researcher and interviewee by providing visual feedback on mental models derived from the interviews.

Ethical considerations were integral to the research process. Interviewees were informed and gave their consent for documentation. Transparency and open dialogue were emphasized to address potential power imbalances inherent in qualitative research. Techniques such as visualizations and Authentic Relating (Kestano, 2022) were employed to enhance transparency and foster equitable interactions. These methods also aimed to mitigate researcher bias by reflecting emotions and responses back to interviewees, recognizing the two-way interpretive nature of interviews and the importance of non-verbal cues.

SCOPE

This study excludes infrastructural implementations managed by municipalities or governments, as their centralized structures and regulatory frameworks have limited relevance to the decentralized nature of distributed systems (Bodo & Trauthig, 2022). However, it acknowledges cases where regulations have disrupted projects, such as Napster, without impeding the underlying technology or systems themselves (Buford et al., 2009).

For the purposes of this study, "communities" may encompass municipalities, allowing for insights to be applied where relevant. The scope is restricted to offline- and local-first communication protocols, as these are directly linked to local communities through peer-to-peer data routing. Mesh-network communities were included in the analysis due to their alignment with local data-sovereignty principles. Specific communities focused exclusively on P4P infrastructure were not selected, as no representative examples fulfilling the study’s criteria were available.

The protocols examined in this paper are relatively new within the field of Information Communication Technologies (ICT). It is important to recognize that the adoption and implementation of these technologies depend on both the readiness of the technology and the end-user. While technological readiness is inherently tied to the maturity of a technology, this paper does not evaluate the readiness of the case projects. Instead, it explores the qualities—both technical and social—that can enable technological maturity.

6 THEORY & CONTEXT

COMPLEXITY THEORY

Complexity theory serves as the lens through which this paper examines the world, conceptualizing it as an interconnected web of nested systems. These systems consist of numerous small, relational, and deterministic components that collectively create an unpredictable whole. This section explores key aspects of complexity theory, focusing on self-organizing systems and their inherent resilience. It also presents a complexity theory perspective on the dynamic interplay between the global and the local (or micro and macro levels). The discussion concludes with an exploration of the Open-Source movement as an example of a self-organizing system.

Non-Linearity

Complexity theory is based on the principles of non-linearity (P. Anderson, 1999; Byrne & Callaghan, 2022; Gershenson & Heylighen, 2004; Heylighen, 2010; Jean Boulton et al., 2015). To better understand non-linearity we can look into the historical predecessor of linearity of which Newtonian physics is built on. Linear relations are seen when the results of a change to a causal element are predictable, the simplest form of a linear mathematical expression is that of:

$$Y = a + bX$$

In the example above, if X changes, the resulting Y can be predicted. A system is considered linear when the effects (outputs) are directly proportional to the original cause (inputs), reflecting a deterministic relationship (Gershenson &

Heylighen, 2004). In contrast, non-linear systems produce outcomes that are inherently unpredictable, with no definable formula to reliably forecast changes.

Non-linearity manifests in various forms, one of which is catastrophe theory. For instance, imagine a boat on steady yet oversized waves. Within certain limits, the relationship between the waves and the boat's movement remains linear—the boat tumbles back to the surface after each wave. However, once the pressure of the water exceeds a critical threshold, the boat capsizes. This exemplifies the shift from stability to a catastrophic outcome (Byrne & Callaghan, 2022). While catastrophe theory illustrates certain dynamics, this paper focuses on complex systems characterized by numerous small, independent, yet interconnected units.

The number of components in any given system, increases the systems complexity. Be these birds flying in a swarm (starling murmurations) (Jean Boulton et al., 2015), water molecules, or the economy. Complexity is found in the sum of their relationships and the relational characteristics. (Gershenson & Heylighen, 2004; Jean Boulton et al., 2015). In essence:

> *"We live as part of patterns of relationships."*
>
> (Jean Boulton et al., 2015 p. 9)

We have explored complexity theory and its foundational perspective of complex realism. This framework views the world as composed of small, independent, yet interrelated components—such as water molecules in a wave or birds flying in murmurations—that collectively form complex and inherently unpredictable systems. The following section delves into the layered interconnections among complex systems, examining how they influence one another across scales, from the local to the global and back again.

Local, Global and Complexity Theory

Let us revisit the example of Bart from Springfield introduced earlier. A television cartoonist, inspired by his family, names a character in his show after one of his siblings and sets the story in a fictional town called Springfield. The cartoon gains immense popularity, prompting marketing companies worldwide to leverage its appeal for their own brands. By associating with the cartoon, these companies aim to connect with local audiences through targeted campaigns. The term "glocalization" aptly describes this phenomenon, reflecting the blend of global influence and local adaptation. Two weeks later, a targeted advertising campaign, aimed at children, is launched.

This scenario illustrates the interplay between nested systems: a local event (parents choosing a name for their child) and its deterministic yet unpredictable ripple effects, culminating in a global impact. The targeted advertising campaign serves as a practical example of digital glocalization (Roudometof, 2023).

Another way to describe the interconnection between the global and the local is through the interactions of individual components that define complex systems. These interactions ripple through the system, influencing a broader scope than their immediate surroundings. A local event, therefore, can have far-reaching impacts on the global system.

For example, even the smallest change in a weather system can lead to dramatically different outcomes in a deterministically chaotic system, as illustrated by the well-known "butterfly effect." This phenomenon exemplifies the nested layers of complex systems and highlights how their interrelations often defy hierarchical structures, exhibiting unidirectional impacts (Byrne & Callaghan, 2022). To elaborate: a butterfly's wings may cause subtle changes in the weather, while the resulting winds simultaneously influence the butterfly’s flight. This intrinsic interconnection demonstrates how influences move from global to local and vice versa, forming a nested system as described by Byrne & Callaghan (2022).

By recognizing the feedback loops and nested structures of complex systems, we can better analyze the relational patterns that connect micro- and macro-states. These interactions underscore how local dynamics can ripple outward, shaping global outcomes (Miller & Page, 2007).

Did Bart’s parents foresee the ripple effects of naming their son? Likely not. According to complex realism, such outcomes are inherently unpredictable. All we can do is attempt to understand the deterministic and chaotic interplay of countless small actors, whose actions send ripples through the system, connecting the local to the global and back again (Byrne & Callaghan, 2022).

The next section examines self-organizing systems, continuing with the marketing bureau example. Once the "Bart from Springfield" campaign launched, the tagline quickly gained traction. The catchy tune “Bart Bart Bart Bartmobile,” funded by the automobile industry, resonated with young audiences. Leveraging the emergent dynamics of internet memes, the marketing team unknowingly sparked a new meme format. The self-organizing system of the internet amplified the campaign, significantly reducing marketing costs. This strategy highlights how self-organizing systems, such as the internet, can be harnessed—whether intentionally or not—to achieve widespread impact.

Self-Organized Systems and Complexity Theory

The internet serves as a prominent example of a self-organizing system. Within it, numerous small, independent actors interact to form emergent patterns without centralized authority or control. These patterns create a relatively stable context (e.g., sufficient oxygen or suitable temperatures) while the systems themselves thrive under chaotic and unstable conditions (Stacey, 1996).

Self-organizing systems are a subset of complexity theory (Anzola et al., 2017) and were introduced by the cyberneticist W. Ross Ashby in the 1940s. Ashby described decentralized and adaptable systems where organization emerges from the distributed interactions among components and their relationships (Gershenson & Heylighen, 2004). This concept was later adopted by physicists and chemists studying phenomena such as the spontaneous ordering of molecules (Heylighen, 2010). The process through which order arises in self-organizing systems is called *emergence* (Fuchs, 2006).

Stacey (1995) argued that for systems to foster creativity and innovation, they must operate at the "edge of instability." This perspective views organizations as dynamic entities, where adaptive qualities are enhanced when they balance near-equilibrium conditions. This outlook has strongly influenced the fields of organizational and social systems research (Drazin & Sandelands, 1992; P. Anderson, 1999; Lee & Edmondson, 2017; A. D. Meyer et al., 2005). Modularization is one practical approach to fostering innovation and adaptability in such systems (Chiles et al., 2010).

Interestingly, companies now intentionally introduce uncertainty into their structures to enable adaptability and competitiveness in dynamic market environments (Chiles et al., 2010; Stacey, 1996). This intentional embrace of instability reflects a strategic understanding of the principles of self-organization.

Self-organizing systems also exhibit *self-organized criticality*, a process where small events trigger cascading effects that lead to global impacts. For example, a meme can start as a minor event but grow into a cultural phenomenon. This concept was first introduced by Bak and colleagues in 1996 (Miller & Page, 2007).

Paradoxically, the criticality inherent in self-organizing systems contributes to their stability (Accard, 2019). This "chaotic stability" is closely tied to their resilience—a defining feature of self-organizing systems (Anzola et al., 2017; Jean Boulton et al., 2015; Tainter & Taylor, 2014). When disrupted, whether by natural disasters or other external changes, these systems adapt by reorganizing and forming new patterns of relationships. This adaptive response is what defines self-organization.

Expanding on resilience, self-organizing systems can go beyond merely adapting to disruptions. When these systems grow stronger and more capable in response to challenges, they exhibit a characteristic known as *antifragility*. This concept, introduced by Taleb (2016), highlights the capacity of some complex and self-organized systems to thrive under stress and uncertainty.

Self-Organized Systems in relation to open-source

The Open-Source movement exemplifies a self-organizing system. A 2002 study analyzing 39,000 Open-Source Software (OSS) projects identified non-linear characteristics within the movement, suggesting that it is inherently self-organizing (Madey et al., 2002). This voluntary-driven initiative plays a significant role in shaping internet standardization processes (Roscam Abbing et al., 2023), embedding itself within another complex system—the internet (Fuchs, 2003; Jean Boulton et al., 2015).

The Open-Source movement is guided by deeply embedded norms and principles, primarily emphasizing values of self-development and altruism (Oreg & Nov, 2008). Trust-based, interconnected networks among software developers provide the organizational foundation, and OSS projects are often decentralized in their structure. At a smaller scale, Open-Source teams can also be viewed as self-organizing, distributed teams (Crowston et al., 2012). More broadly, social movements, whether micro- or macro-level, frequently exhibit self-organizing characteristics (Fuchs, 2006; Tonellato et al., 2024).

OPEN-SOURCE SOFTWARE

The following section is structured like the weaving of a tapestry, where distinct threads come together to form a unified whole. The foundational thread represents the Open-Source movement, whose historical development and core principles provide the base pattern. Interwoven with this is the second thread, representing decentralized systems and the emergence of Peer-to-Peer (P2P) protocols. This thread traces the historical waves of P2P networks, emphasizing their adaptability and resilience. Binding these threads is Conway's Law, acting as the loom that shapes the organizational and architectural design of the system. Finally, the Local-First thread is added, emphasizing storage and locality. Together, these threads form a seamless tapestry, uniting Peer-to-Peer, Local-First, and Open-Source networks into a cohesive framework: Peer-4-Peer (P4P).

History of Open Source

The Open-Source movement traces its roots to the hacker culture of the 1960s, a time when software was freely shared among UNIX and C programming enthusiasts. One notable success during this era was the X Windows System, which thrived thanks to the open availability of its source code. However, over the following decades, the commercialization of software increasingly restricted access to source code, a shift celebrated by some but lamented by others (Ljungberg, 2000; Manteghi, 2017).

In response to this trend, Richard Stallman left his position at MIT in 1984 to create a free UNIX system called GNU, marking the birth of the Free Software Foundation (FSF). Stallman emphasized that “free” referred not to price but to values. The FSF outlined the four essential freedoms of free software (Stallman, 1999, via Ljungberg, 2000, p. 209):

- The freedom to run the program for any purpose.
- The freedom to modify the program to suit your needs (which requires access to the source code).
- The freedom to redistribute copies, either for free or for a fee.
- The freedom to distribute modified versions of the program to benefit the community.

To protect these freedoms, Stallman introduced the concept of "copyleft," a creative play on "copyright." As Ljungberg (2000, p. 209) explains:

> *“Copyleft uses copyright law but turns it the other way around: instead of a means of privatizing software, it becomes a means of keeping software free.”*

The GNU General Public License (GNU GPL) was the first major license to embody this principle and remains one of the most widely used licenses today, accounting for approximately 23% of OSS projects. It shares prominence with the

MIT License and Apache License as the three most popular licenses (Manteghi, 2017).

The Open-Source movement offers a collaborative alternative to proprietary, competitive software development models. In 1998, the term "open source" was coined, rebranding the movement in a way that softened its hacker-associated origins, making it more palatable to the commercial sector (Fitzgerald, 2006; Ljungberg, 2000). There's a Swedish saying, "A dear child has many names" meaning that it’s cherished by many, which for the Open-Source movement is visible in the many acronyms it has picked up over the years. The basis is "Free Libre Open Source Software", and common abbreviations are FLOSS, FOSS or OSS. (Crowston et al., 2012)

Initially, the notion that a volunteer-driven movement could challenge the proprietary software industry seemed absurd (Fitzgerald, 2006). Yet, Open-Source software is now ubiquitous, integral to both societal infrastructure and corporate tools (Crowston et al., 2012). Just as companies leverage the emergent dynamics of memes for marketing (Malodia et al., 2022), the commercial market has also capitalized on the collaborative efforts of Open-Source development. For instance, one could imagine a viral marketing agency storing their "Memetic Marketing" presentation on an Open-Source Apache Web Server—perhaps alongside a folder labeled “Voluntary Collaborative Efforts of Self-Organizing Systems.”

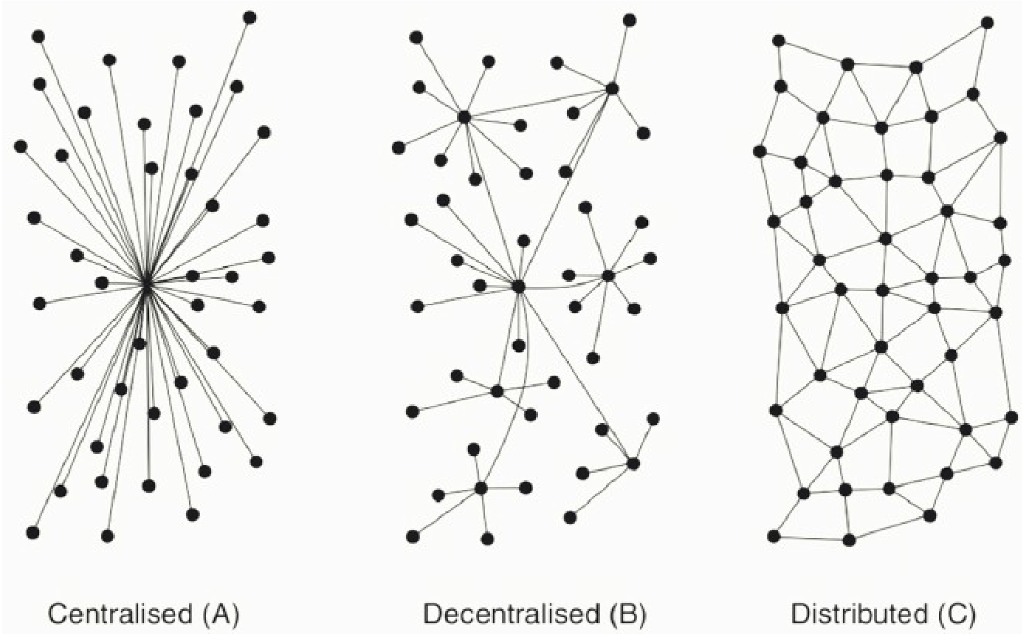
Despite some Open-Source companies adopting traditional organizational structures, the broader Open-Source scene remains unconventional. Motivations for participation often stem from values, personal development, and community engagement rather than financial incentives (Oreg & Nov, 2008). Typically, OSS projects feature a core group of developers with write-access to the code, supported by a community of contributors who provide input and help shape the project’s direction. Remarkably, the voices of peripheral contributors often carry as much weight as those of the core developers (Neulinger et al., 2016).

In summary, the Open-Source movement has evolved from its hacker-culture origins, becoming more commercialized over time while remaining largely volunteer-driven. Rooted in values and self-improvement, Open-Source development exemplifies a self-organizing system. So far, this discussion has focused on social self-organizing systems, such as memes and the Open-Source movement. In the next section, we turn our attention to technical self-organizing systems.

De/centralization and Distributed Systems

As part of the open-source movement there is a large field focused on decentralized and distributed software. Before we dive into what this kind of technology is comprised of, let's take a look at decentralization as a concept as it is quite diffuse and lacks clear definitions (Helmrich et al., 2021; Troncoso et al., 2017). The terms decentralization and distribution are commonly used interchangeably (Ackermann et al 2001, Alanne and Saari 2006, Makropoulos and Butler 2010 via Helmrich et al., 2021). For the sake of clarity, lets look at Figure 1 by Baran (1964) on centralized, decentralized and distributed systems.

BY (BARAN, 1964) – FIGURE 1



Centralization is when a node or actor in the system acts as the relay or storage for all others in the system, or in organizational structures, the focal point of decisions. Decentralized is characterized by multiple points acting as relay nodes or actors for the system. Federated systems are seen as decentralized as there are many potential relay points or servers users can connect to. Distributed is when each node can connect directly to another node, exchange stored data, make decisions or relay data, without the need for any middle-men. P2P systems are seen as technical implementations of Distributed systems. In contrast to (Troncoso et al., 2017), this paper does not view Decentralization as a subset of Distributed systems, nor Distributed systems as managed by a single root of authority (as this would be considered a centralization of authority) but rather adopts the view of "*de/centralization as a spectrum*", as put forth by Helmrich et al. (Helmrich et al., 2021 p. 9).

The difficulty in defining decentralization in part stem from the broad application possibilities of decentralization as a term. Infrastructure (Derrible, 2017; Helmrich et al., 2021), software (Korpal & Scott, 2022), organization theory (Ahuja & Carley, 2006), social science (Faguet et al., 2015) and business (Chen & Bellavitis, 2020) are just some realms in which decentralization appears, and the motivations for decentralization are equally many.

A reason for the many perspectives on decentralization is that the elements which are decentralized can vary; there can be decentralization of power and decision-making, decentralization of communication and localization, knowledge and data storage, production rights and resources, as some examples. In this paper the focus is on technical decentralization, (data storage and transfer) and organizational decentralization (communication and decision making).

Decentralization, much like modularity, is an aspect of self-organized systems. The amorpheus blob of sterlings flying in the sky is a natural example of a distributed system. Each bird is independant of the other, yet they sense each other through through sensory data and form a distributed relational network of self-organization. Decentralization is therefore seen as an aspect of self-organizing systems.

Peer-to-Peer and the Waves

Decentralized technical systems are widely regarded as more resilient than their centralized counterparts (M. Anderson, 2019; Troncoso et al., 2017). Distributed communication systems, in particular, demonstrate higher survivability against network attacks (Baran, 1964). Peer-to-Peer (P2P) systems are often described as the “natural self-organizing complement to the centralized organization of client/server computing” (Kini, 2002, p. 2).

Originally, the internet started as a fully distributed system, what is known as Peer-to-Peer (P2P). (Oram, 2001) The term 'peer' is at times interchangeable with the terms 'node', 'computer' and 'person'. In 1969, four computers located at universities in the US connected directly to each other constituted the origins of the internet. By 1977 there were 23 "nodes" in the network and by 1994, close to 4 million, an exponential growth. (Kini, 2002)

What distinguished P2P networks from centralized systems was their symmetry: each peer in the network could both request and store data. This symmetric relationship, where every node functioned equally as a client and a server, defined the early internet. However, this structure began to change in the mid-1990s.

In the complex cooperative system of the internet, every computer was equally a client and a server. It was around this time that the internet started to run out of each computer’s unique "street address" (IPv4) for the world wide web, what is known as IP addresses. A new system came into play with so called "local addresses", the system which facilitates this is called NAT (Network Address Translation) (Kleppmann et al., 2019). NAT along with firewalls and dynamic IPs descended upon the global visibility of the web like a dark fog, and individual nodes could no longer directly connect or see each other. While NAT and dynamic IPs solved the issues of scalability for the internet at the time, they weakened the infrastructure as a whole and created an enforced hierarchy of servers. (Oram, 2001) The client/server model is the current shape the internet is in and took form in parallel with the commercialization of the internet (Oram, 2001).

The first wave of re-decentralizing the internet came about with applications such as Napster, a music-sharing platform launched in 1999. (Daniel & Tschorsch, 2022). Napster was a music sharing platform launched in 1999 and was closely followed by projects such as Gnutella and Bittorrent technology which enables sharing of large packages of data in P2P networks by breaking these data-packages down into smaller components, enabling users to ask the network for the missing data packages and receive them from whomever had the data packages. Not long after Onion-routing emerged along with the privacy enhancing Tor network (Buford et al., 2009).

In response to the ongoing mass-surveillance (Ermoshina & Musiani, 2022; Troncoso et al., 2017) data leaks (examples such as the Facebook leak of 533 million users[2] or the Cambridge Analytica scandal (Wylie, 2019) the movement of re-decentralizing the internet started flourishing for a second time. This second wave of re-decentralization hit around 2008 (Daniel & Tschorsch, 2022). Building on the emergence of P2P-technologies came the wave of crypto currencies and blockchains, introducing decentralization both to the economy, away from centralized banking, as well as through the distributed data storage of blockchains and what's known as Distributed Ledgers (van Lier, 2019). This new era of

2 https://www.theverge.com/2022/11/28/23481786/meta-fine-facebook-data-leak-ireland-dpc-gdpr

computing is often referred to as Web 3.0, and the movement as the Decentralized Webs (DWebs) (M. Anderson, 2019; Korpal & Scott, 2022). The plurality here is important, because it's no longer a case of a single "world wide web" but of a plurality of webs, in some cases interoperable and in other cases, not.[3]

The centralization of the internet can be seen in the communication platforms of today. The realm is dominated by the few, Apple, Google and Facebook. Giants with control of users data (Salve et al., 2023), along with control over the algorithms that choose which kids gets to hear the “Bart Bart Bartmobile” song.

Among researchers, a paradigm shift has taken place, from Online Social Networks (OSNs) to Decentralized Online Social Networks (DOSNs), favouring the resiliency qualities and the personal ownership of own data, rather than automatic commodification (Chowdhury et al., 2015; Masinde & Graffi, 2020).

Decentralized, distributed, federated, and peer-to-peer solutions are being researched and while there has been considerable uptake with more than 3 million users on Mastodon and Diaspora (Masinde & Graffi, 2020) yet the movement is still in its early stages of development with considerable issues yet to be solved in relation to usability and scalability (Ermoshina & Musiani, 2022).

Sidenote: There are multiple different types of P2P systems. P2P computation and P2P networks. Distributed computation harnesses the idle processing time of networked computers (Kini, 2002). Distributed networks refer to how the computer nodes are connected to one another, as described above. For the purpose of this article we focus solely on Distributed networks.

In this section, we explored the origins of P2P systems, from the early days of the internet to their role in challenging centralized tech giants. The parallels between P2P technology and self-organizing systems highlight emergent patterns. As we transition to examining Peer-4-Peer (P4P), the next section focuses on the design principles and laws that have shaped the development of P2P systems.

3 This concept differs from the Spliternets, the ongoing nationalization and centrally controlled Internets run by nation states, such as in China (Hoffmann et al., 2020)

Conways Law and Systems Design

Another noteworthy aspect is that the development of the technologies mentioned above emerged largely through distributed collaborative efforts, often within the Open-Source movement. This phenomenon aligns with Conway's Law, which states:

> *"organizations which design systems... are constrained to produce designs which are copies of the communication structures of those organizations"*
>
> (Conway, 1968 p. 31)

This means that a group of software developers will, intentionally or not, repeat their own internal structures in the applications or protocols they produce.

In a beautifully crafted call for Decentralized and Complex Coordination, Anderson states:

> *“By this logic, a network of people trying to build software tools to facilitate decentralization ought to be decentralized themselves: diverse, interacting randomly, coalescing around projects, conducting experiments, cultivating or abandoning them in a fluid state of co-relation. The “participant design” Ito proposes, “design of systems as and by participants,” is, in fact, the core ethos of a decentralized ecosystem.”*
>
> (Anderson, 2019 p. 4)

It becomes clear that decentralization is not purely a technical system, yet nested with the social systems that create it.

This theory section has, step by step, introduced the components that form Peer-4-Peer (P4P) networks. These networks encompass all the categories discussed thus far: they are decentralized, distributed, peer-to-peer, open-source, complex, and self-organizing systems. However, P4P networks have an additional defining characteristic that sets them apart: they are Local-First.

Offline- and Local-First

Local-first software is a reaction to the inherent issues of cloud based services, namely, cloud based services don't function very well offline. Beyond this very blatant issue, the continuous maintenance is expensive and inefficient, (Haas et al., 2024) and they also have issues of the typical centralized type, if a cloud service shuts down, users lose access to all their data. (van Hardenberg & Kleppmann, 2020). In their article on P2P protocol exploration in 2020, Hardenberg & Kleppman list Local-First as their primary principle. The term Local-First was also popularized in an article 2017 where they also outline some ideals local-first software should strive for. In short the 7 ideals of local first software can be summarized as:

1. Primary copy of data stored locally on users device
2. Synchronization of data across users devices
3. Offline-First and possibly synched via other means (bluetooth, sneakernet etc)
4. Enables state conflict resolution, CRDTs
5. Data accessibility stretches into the future, even after a company has closed down, for example
6. No centralization of data, lessened risk of data breaches. End to end encryption.
7. You Retain Ultimate Ownership and Control - ownership in the sense of user agency, autonomy, and control over data.

(Kleppmann et al., 2019)

P4P Protocols

It’s time to celebrate the union of Peer-to-Peer (P2P) protocols, Local-First software, and Open-Source development!

In the absence of a unified name for this particular family of protocols, the term **Peer-4-Peer (P4P)** has been adopted. This designation emerged from collaborative discussions within P2P local-first communities and during a P2P local- and offline-first gathering in Berlin. The term "Peer-for-Peer" reflects the mutual-aid ethos inherent in these networks, a concept rooted in the natural law proposed by Kessler in 1880 and further developed by Kropotkin (1902).

Brimming with potential, P4P protocols represent a distributed, local-first paradigm. Daniel and Tschorsch (2022) describe them as "the new generation of network protocols." These protocols exhibit several unique characteristics:

- **Local data synchronization:** Data does not require the internet to synchronize and can instead be transferred via Bluetooth or mesh networks (local networks of routers).
- **Decentralized data storage:** Primary data is stored on the user’s device, with secondary storage distributed across other nodes in the network, rather than centralized on a server.
- **Minimal loading times:** The architecture reduces latency, enabling rapid data access.
- **Offline functionality:** Applications remain fully operational even without an internet connection.

The qualities P4P protocols exhibit are shared with those of self-organizing systems, resiliency and emergence, these same qualities which are desperately needed in the midst of the current ecological collapse, impacting humanity and ecosystems all across the world (Calvin et al., 2023; Garnaut, 2008).

Examples of protocols included in the P4P realm are: Scuttlebutt (Coretti et al., 2022; Mannell & Smith, 2022; Tarr et al., 2019; Tschudin, 2022), Hypercore as part of the dat ecosystem (Bikoff, 1992; Blähser et al., 2021; Daniel & Tschorsch, 2022; Hartgerink, 2019), P2Panda, Braid, Qaul, Willow based on work by A. Meyer, (2022), Cable related to work by Cobleigh (2020), Briar (Bramble) (Ermoshina et al., 2017; Ogden, 2017; Roscam Abbing et al., 2023; Song, 2023;

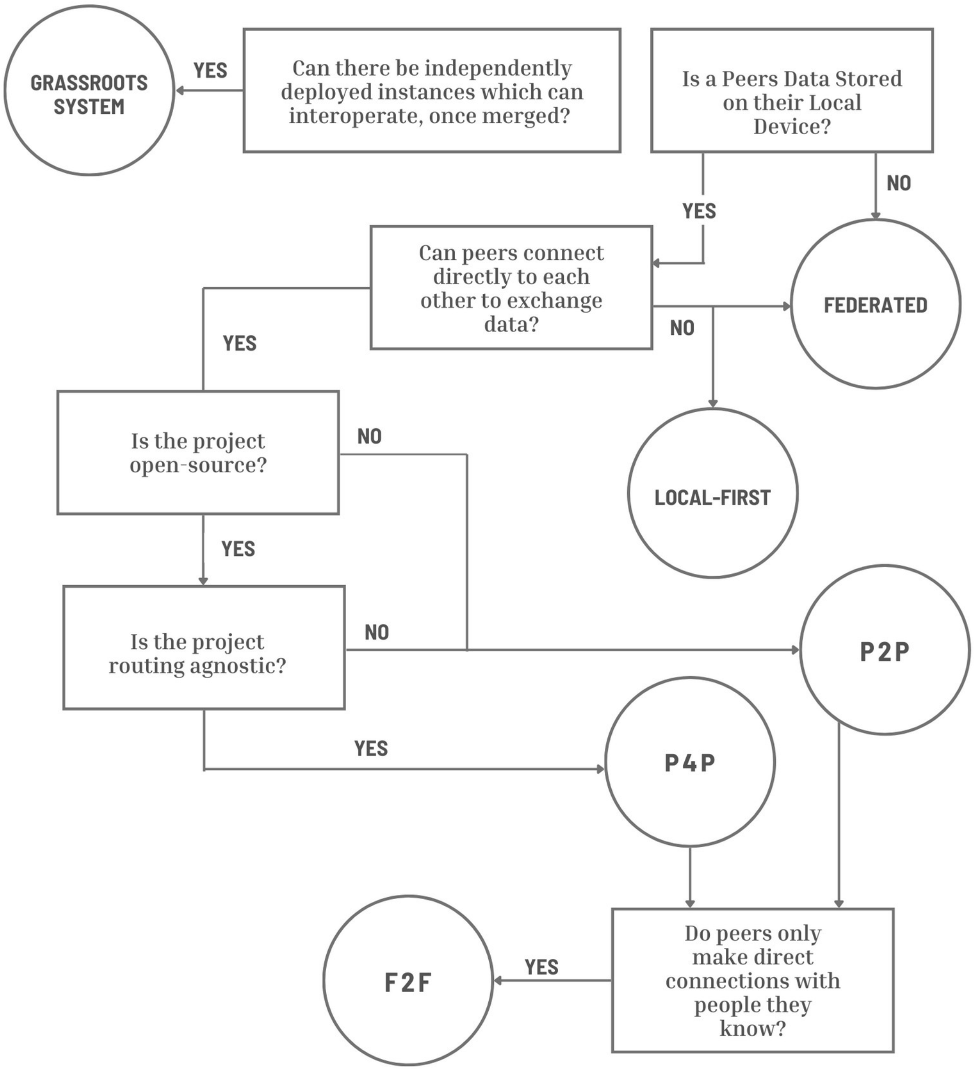
Troncoso et al., 2017; F. Yang et al., 2023; Y. Yang, 2021), IPFS and more, out of which IPFS is the by far most implemented protocol with implementations in 152 countries (Trautwein et al., 2022).

An even more specific definition is put forth by Shapiro in 2023 which would encompass some P4P systems as well as Friend-2-Friend networks (F2F) (Li & Dabek, 2006). Shapiro refers to these networks as Grassroots Systems and criteria goes as follows:

> *"Informally, a distributed system is grassroots if it can have autonomous, independently-deployed instances, geographically and over time—that can interoperate once interconnected."*
>
> (Shapiro, 2023 p. 2)

Protocols classified as Grassroots Systems include Scuttlebutt, Willow, P2Panda, and others. However, protocols such as IPFS and other systems relying on Distributed Hash Tables (DHTs) are excluded due to their inherent centralization aspects. In Shapiro's article (2023), Mastodon—a federated social network based on client/server infrastructure—is suggested as a potential Grassroots System. However, since Mastodon is not Peer-to-Peer (P2P), it does not qualify as a P4P system. A simplified overview of these terms and classifications is presented as a flow chart in Figure 2.

In conclusion, P4P refers to a family of networks that are defined by their Open-Source, P2P, and Local-First qualities. Within this broader classification, further distinctions can be made, such as Grassroots Systems or Friend-to-Friend (F2F) networks, depending on specific criteria and use cases.



FLOWCHART OF NETWORK TOPOLOGY – FIGURE 2

INFRASTRUCTURE

All P4P protocols are a form of infrastructure and society will be needing more resilient infrastructure, as mentioned in the problem statement. In the following section we look at self-organizing infrastructure as a field and how the decentralization of who designs the systems is essential.

Inverse Infrastructure

Information and Communication Technology (ICT)-enabled development generally falls into two categories: top-down development, driven by municipalities and governments, and community-driven development. A key downside of top-down development is its tendency to create dependency, which can undermine freedom-enhancing and sustainable initiatives (Leong et al., 2016).

In contrast, self-organized, bottom-up, grassroots, emergent, and decentralized infrastructures are referred to as "Inverse Infrastructures" by Egyedi and Mehos (2012). Their work highlights examples such as TV and radio systems, citizen-driven waste collection, wiki self-organization, e-government initiatives, wind energy development, community Wi-Fi, decentralized water supply, and rural telecommunications.

Micro-infrastructures, due to their localized nature, have several advantages: they attract private investment, utilize local resources, and alleviate governmental bodies of the burden of implementation, enabling them to focus on policy development (Warner, 2011, as cited in Heino & Anttiroiko, 2015). However, inverse and decentralized infrastructures face challenges stemming from the traditional, centralized nature of governmental organization and bureaucracy (Heino & Anttiroiko, 2015).

These adaptive, grassroots approaches are notable for their ability to respond to local circumstances more quickly than top-down models. Their adaptive qualities have been explored in the context of strategic processes, where balancing on the "edge of instability" sharpens innovation capabilities (Stacey, 1995). Adaptive approaches have also been discussed extensively in Peter M. Senge’s work on systems thinking, emphasizing their importance for fostering innovation and resilience (Senge, 1997).

Global to Local - Development of Infrastructure

On the notion of emergent qualities in society, let's look back on Conway's law which states that any system is shaped by the communication system of which it is created. From this it is clear that by who and where the systems are built matters, as they define what qualities the system will be imbued with. Most contemporary digital infrastructures are designed by western males working in IT. From a geographical perspective, the local is defining systems of infrastructure for the global. On a global scale, the decision-making power of global infrastructures is highly centralized, both vertically and horizontally. A specific demographic segment of society (approximately 0.4%)[4].

In their article on Glocalization and ICT, mapping how media content is localized, Roudometof brings forth a quote

> *“We are called to think of localizing in terms of social structure, not in terms of location... [T]he complexity of society just went up an order of magnitude”*

(Boyd 2005 via Roudometof, 2023 p.3)

In this regard, the internet architects are culturally and socially highly local to one-another while being globally distributed. This centralized social localization is shaping the values of society by designing the systems that societies utilize globally.

In an article on Value Sensitive Design, Friedman et al elaborate on values and technology:

> *"A given technology is more suitable for certain activities and more readily supports certain values while rendering other activities and values more difficult to realize."*

4 https://www.worldometers.info/world-population/#region, (Oceania,0.6+ Europe 9.2+ North Americas 4.7) / 2 sexes * 0.06 of the total work force https://www.comptia.org/content/research/state-of-the-tech-workforce

(Friedman et al., 2008 p. 4)

For a long time Internet infrastructures have been recognized as crucial sites in which power materializes (Musiani, 2022). The essence of what is described above can be summarized as ongoing infrastructural colonization (Iliadis et al., 2023) and de-colonizing thereby includes enabling infrastructures to be designed by the local for the local, in other words, decolonization includes a decentralization of the design process of infrastructure, not only the decentralization of the infrastructure itself.

Uhl-Bien and Arena 2018 dive further into this notion in relation to Complexity Leadership Theory and make an argument for vertical and horizontal decentralization. Vertical decentralization brings the decision-making power closer to the situation (to the local) and horizontal decentralization diversifies who has the ability to make decisions (inclusion)[5] (via Helmrich et al., 2021).

Decentralization in turn enables resilience through the opportunity for modularity. Continuing on the on the notion of decentralized infrastructure Helmrich et al. state:

> *“Decentralized infrastructure systems may limit cascading failures amongst infrastructure sectors by quickly recognizing and isolating the failure (Gleick 2003, Goldthau 2014, Zodrowet al 2017).”*

(Helmrich et al., 2021 p. 7)

It is clear that the cascading failures of the industrial society of the 20th and 21th century are increasing in prevalence. The systems which inform values of society are simultaneously being built by the same elite which embody the systems of industrialized society, and thus regurgitating the values and systems. De-colonization is intrinsically tied to environmentalism and decentralization is a means to this end. (De Santo & Domptail, 2023)

5 This concept of vertical and horizontal decentralization ties closely to the notion of vertical, horizontal and spatial complexity mapping to the number of levels in an organization, job titles in departments and geographic locations (P. Anderson, 1999).

7 METHODOLOGY

THEORY OF SCIENCE

This paper stands on the theoretical foundation of complexity theory. Complexity theory has its roots in the natural sciences, such as chemistry, physics and math, yet complexity theory in essence is an ontological perspective, a belief system about the existence of the world. (Allen et al., 2011; Byrne & Callaghan, 2022; Jean Boulton et al., 2015)

As an ontological perspective it is explored by Reed and Harvey (1992), and further developed by Byrne and Callaghan in 2022, under the term 'complex realism'. (Byrne & Callaghan, 2022) As the name suggests, it's a synthesis of critical realism and complexity. Critical realism is in turn associated with the work of Bhaskar (1989) and Archer (2003). Supporters agree with interpretivists, people's realities are socially constructed, yet simultaneously agree with positivists, who state that there is an observable external world. (Daymon & Holloway, 2010) Complex realism builds on this perspective as well as the notions of complex, non-linear deterministic relations. Complex Realism can be seen as a unification of the scientific practice of quantitative and qualitative research and thus are highly suitable for interdisciplinary scholarship. Research rooted in complexity theory aims to find small sets of laws (Holland, 1998 via Byrne & Callaghan, 2022) of qualitative nature:

> *...organizations are complex systems and complex systems are in general not mutable by degree but mutable in relation to kind – change is not incremental but qualitative.*

(Allen et al., 2011 p. 131)

RESEARCH DESIGN

The research design is based on multiple case studies which were investigated individually and later drawn parallels and comparisons to better understand the implementation process and development of P4P protocols. In total the research centred around 9 cases ranging from pure community projects such as the initiative Grobund, to pure protocols such as Holochain. In total 16 people were interviewed with a minimum of 1 person per project, 9 Rich Pictures were drawn depicting their immediate systems, 20 interviews were conducted (see Table 1 for more details) and 1 workshop was hosted during which 14 Peer-4-Peer (P4P) developers and representatives participated.

UN= Unstructured Interview SM= Semi Structured Interview FU = Follow–Up Interview

PROJECTS:	Āhau	Briar	Dat	Grobund	Holochain	Mapeo	Meli Bees	Scuttlebutt	Qaul	Willow
INTERVIEWS:	1 SM & 1 FU	1 SM & 1 FU	1 SM & 1 FU & 1 UN	1 SM & 1 FU	1 SM & 1 FU	1 SM & 1 FU	1 SM & 1 FU	1 SM & 1 FU	1 SM & 1 FU	1 US
PARTICIPANTS:	1	1	2	2	2	2	2	2	1	1

TABLE 1

The choice of multiple case studies was a natural selection as they support in granting a broader understanding of a field, in this case, an emerging field. The process of multiple case studies consists of studying each individual case in depth followed by combining the results to find similarities and differences. (Hunziker & Blankenagel, 2024). A significant advantage of multiple case studies is that researchers can compare their findings and are especially suited for inductive theory building. (Hunziker & Blankenagel, 2024)

The intellectual contribution of a multiple case study can be found in its ability to define relationships, elements and conditions, as well as adding to theory or differentiating from existing elements within the given theory. A common issue for multiple case studies is to simply make multiple single case studies in parallel, yet the expected result from a multiple case study research design goes beyond a collection of case studies and focuses on developing theory about the factors driving the similarities and differences (Hunziker & Blankenagel, 2024) This paper focuses on conditions and categories of P4P, and aims to contribute to complexity theory, specifically in relation to self-organizing systems.

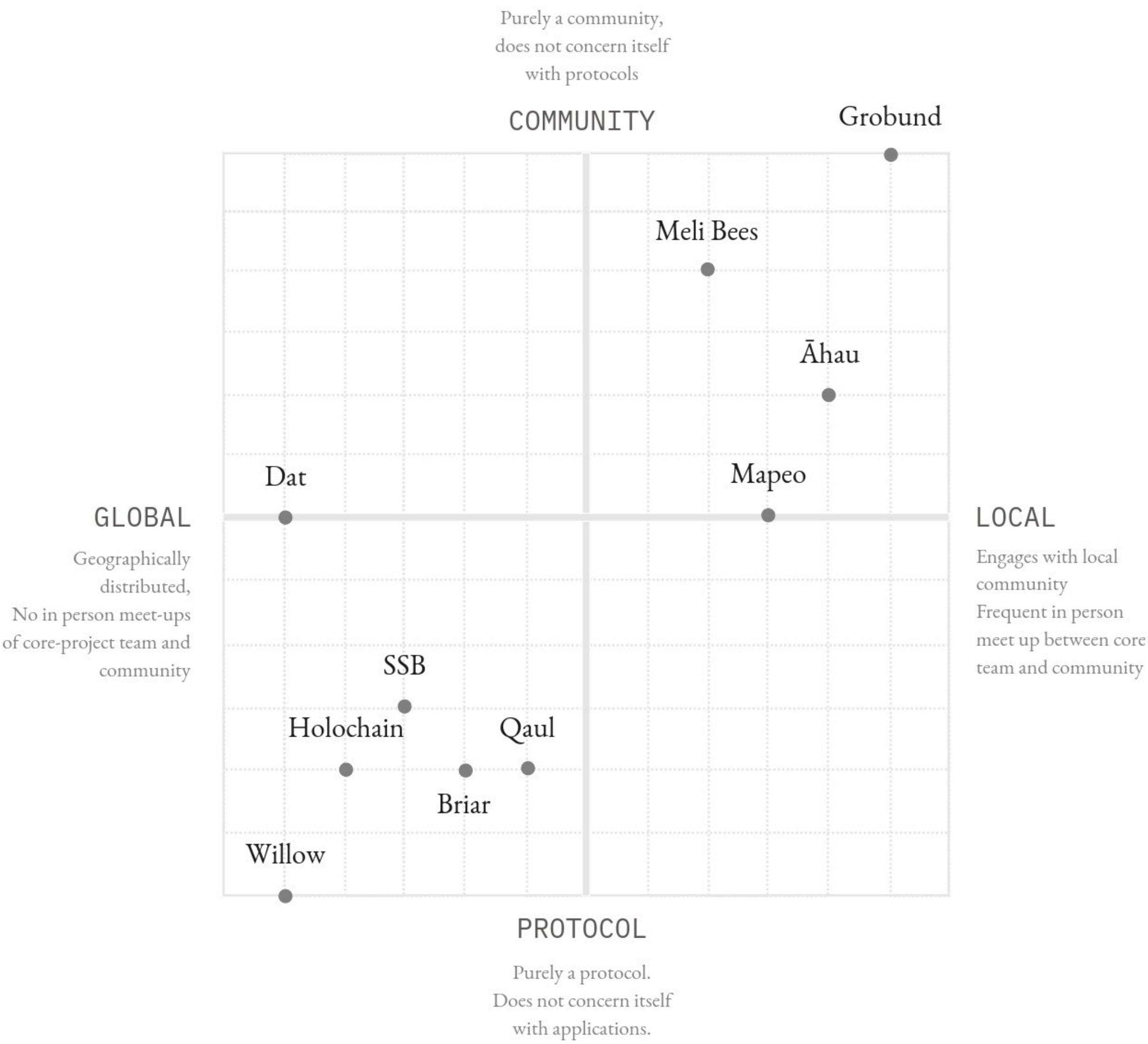


FIGURE 3

For the purpose mentioned above, contributing to complexity theory and the topology of P2P protocols, cases were selected based on the width of perspectives and layers they could provide, a way to “*Design Multilevel Research*” as recommended by Meyer et al. in 2005 p. 471, in their article on researching organizations and complexity (A. D. Meyer et al., 2005). For a layered perspective, geography was taken into consideration and cases from 4 different continents, South America, North America, Oceania and Europe were selected. Variety was also sought in relation to what type of project they were, from pure protocol (Willow) to pure community (Grobund). See Figure 3 for a depiction of the project’s distribution.

Out of the cases selected, five of the cases are stand-alone protocols - Hypercore, SSB, Holochain, Bramble and Qaul, with the addition of one case being closely related to a sixth protocol (P2Panda). Additionally Willow, also a protocol, was interviewed as a supplemental perspective. The other three cases consist of 2 applications built using existing protocol stacks, Āhau (SSB and Hypercore) and Mapeo (Hypercore) as well as one ecovillage, which shares values of off-grid principles, yet uses Web 2.0 stack.

Name	Type	Description	Founded	Developer Location	Core team	User Size	User Location	Technology
Āhau	Application	Application for Māori tribes to track family history	2018	Aoteroa (New Zealand)	~ 7	No data	Aoteroa (New Zealand)	SSB and Dat
Briar	Application and Protocol	Application and protocol for censorship resistance during internet shut-downs	2013	Primarily England, Germany and Brazil	6	1.8 million individual downloads	Primarily the global south with large uptakes in India and Iran	Bramble and Tor Network
Dat Ecosystem	Protocol and Application Ecosystem	An ecosystem of P4P applications and protocols originating from the formerly namned Dat protocol	2010	Primarily Europe	8	20 active projects	Dat ecosystem developers are primarily located in the global north, usrbases are found in the global south via Mapeo and Āhau	The Dat ecosystem, including Hypercore and the Cable Protocol
Grobund	Community	Co-owned factory and village with off-grid values	2015	Denmark	~ 40	600 people in the extended network	Denmark	Https and server. Zenzation?
Holochain	Protocol for application ecosystem	Distributed p2p protocol	2017	Primarily Northern America	No data	Not launched	Application devs, Global North. No user base.	Hypercore Protocol
Mapeo	Application	Application for Land Defenders globally, to map out territories.	2013	Primarily Global North	16	714 active users in X amount of	Globally, with largest uptake in South America	Hypercore, soon also Hyperswarm

						countries		
Meli Bees (P2Panda)	Organization	Organization focusing on supporting research as well as local and indigenous communities	2018	England and Germany	2	Not launched	South America, primarily Brazil	P2Panda
Scuttlebutt	Protocol and application ecosystem	Distributed p2p gossiping protocol	2014	Started in Aoteroa, spread globally with major uptake in Europe	3	25000 individual peers on main network. Active usage is around 200 per month. Seperate network keys are unknown.	Global	Secure Scuttlebutt (SSB)
Qaul	Protocol and Application	Application and protocol for censorship resistance during internet shut-downs	2011	Europe	4	unknown	Global South, specifically engagement in Syria	Qaul Protocol
Willow	Protocol architecture	Protocol architecture building on the Earthstar project	2023	Europe	2	Recently Launched	Recently Launched	Willow Protocol

CASE OVERVIEW – TABLE 2

PROCESS

The methodology approach for research gathering took an open approach and coding was done inductively. Literature was gathered in a focused manner at the very beginning of the project yet was continuous based on recommendations from chat forums and interviewees.

A general step in the research iteration process is outlined below:

1. Interview all cases
2. Data Harvest all cases
    1. Transcription of data
    2. Rich Picture interpretation drawing of system
    3. Inductive coding of transcriptions
3. Feedback on Rich Picture from participants

SEARCH STRATEGY

To better understand the environments in which P4P protocols exist, a framing of theory is helpful. For this paper the context is visualized in Figure 4.

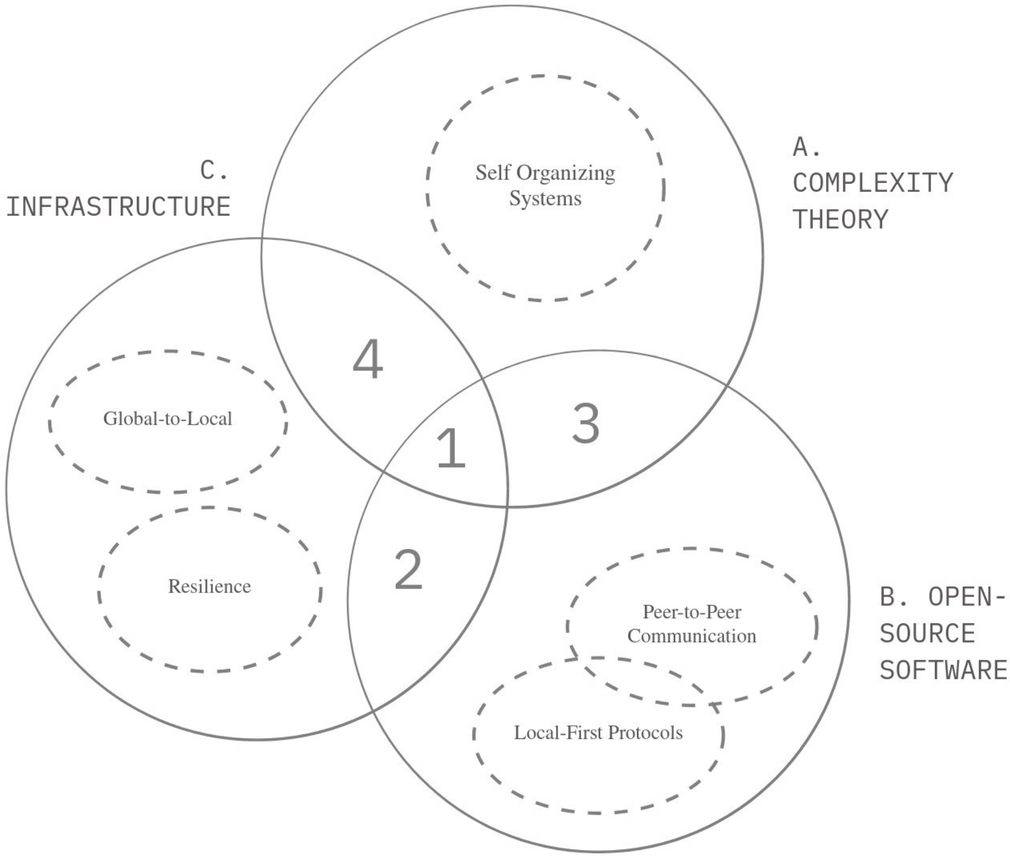


FIGURE 4

Figure 4 depicts the three main areas and their sub-categories, creating the boundaries of the scope of literature. This scope helped shape a process to better be able to answer the research question by creating a broad understanding of the fields and their overlaps.

The search terms that have been used are specified in Table 3 and in some cases a snowballing methodology was used to find additional articles, occasionally through the utilization of the application ResearchRabbit [6].

The main data sources were: the open web through search engines, journals, snowballing through references as well as a collection of grey literature gathered throughout the research period.

6 https://researchrabbitapp.com/

The three journals which were covered comprehensively was the Journal of Computer-Mediated Communication[7], The Journal of Information, Communication and Society[8] and the Journal of Peer Production[9]. The journal of Computer Mediated Communication was chosen due to its high rankings as an esteemed journal, as this paper concerns new internet infrastructure and networks it was a natural choice to include a well established journal with focus on computer mediated communication. The journal of Information, Communication and Society is also an esteemed journal and has an interdisciplinary focus, primarily on communication but also information exchange in society which is relevant to this paper as the P4P field goes beyond the technical and concerns itself with societal value based issues of data sovereignty, censorship, access to communication infrastructure and information flows. The journal is also associated with the AoIR community (the Association of Internet Researchers). Finally, the odd-one out is the Journal of Peer Production. Not only is it a fringe journal that is no longer active, but the focus can also be surprising to some. Peer Production is here seen as a supplemental perspective both from the intrinsic focus of P2P systems yet also in relation to the locality aspect as many articles in the Peer-Production journal focus on local production facilitated by global networks. The entirety of the journal's history of publications were manually screened for any potentially relevant articles, within the scope (Figure 4). Since this screening was done manually, no boolean search terms were used here. Search terms and boolean operators used for the two remaining journals are mapped out below using the SPIDER format (Cooke et al., 2012).

SPIDER — Search Table

Search Component	Description	Search Term and Synonym
Sample	P4P Protocols	(IPFS OR Briar OR Scuttlebutt OR Willow OR P2Panda OR Dat Protocol OR Hypercore OR Qaul OR Briar OR Bramble OR decentral*)
Phenomenon of Interest	Studies related to P4P networks, self-organizing systems, resilience infrastructure	(local-first AND p2p) OR (resilience AND infrastructure) OR (self-organizing systems AND

7 https://academic.oup.com/
8 https://www.tandfonline.com/journals/rics20
9 http://peerproduction.net/

		organ*)
Design	Mixed-methods, qualitative. Longitudinal studies or case studies, literature reviews .	(multiple-case studies OR OR case-study OR interviews OR longitudinal OR case-study OR literature review)
Evaluation	Maturity of P4P protocols	(topology OR architecture OR process* OR organi* OR participat*)
Research Type	No specification necessary	No specification necessary
Final Boolean Search	(IPFS OR Briar OR Scuttlebutt OR Willow OR P2Panda OR Dat Protocol OR Hypercore OR Qaul OR Briar OR Bramble OR decentral*) AND (local-first AND p2p) OR (resilience AND infrastructure) OR (self-organizing systems AND organ*) AND (multiple-case studies OR OR case-study OR interviews OR longitudinal OR case-study OR literature review) AND (topology OR architecture OR process* OR organi* OR participant*)	

TABLE 3

Excerpts and highlights were made in relevant papers with a particular focus on the findings and main messages of the articles. All types of methodologies were included, quantitative and qualitative, yet the vast majority were articles based on qualitative approaches.

The criteria for selection of literature is limited to English as the written language and the literature was scoped to papers which fit the overlapping topic areas mapped out in Figure 4 above. Exceptions have been made for articles which examine the overarching fields for the purpose of laying a theoretical and contextual foundation. If the field was related to technical topics, newer articles took priority while the publication dates for the selection of theoretical articles were of less concern.

DATA GATHERING

Data gathering was done in four ways, the three primary data sources were interviews, a workshop, and visualizations. In addition the fourth source was secondary data in the form of participant supplied documents.

Interviews

Semi-structured interviews were chosen as the primary data collection method due to their flexibility in capturing in-depth insights while allowing for some predetermined structure. Additionally, the semi-structured format enabled the researcher to adapt questioning based on participants' responses, thus accommodating emergent themes and nuances in the data (Gubrium & Holstein, 2001).

The semi-structured interviews were primarily audio-recorded with participants' consent to ensure accuracy in data capture and subsequent analysis. In 3 cases the consent for audio recording was not given and an in-person interview, with notes, was held instead. Out of the total of 20 interviews, 13 were audio based, in person or online, and 5 interviews were conducted via asynchronous text exchange, either over email or over Signal, the private (and centralized) messaging platform.

Comprehensive audio based interviews occurred primarily in the first round of interviews, and each case represented in the research participated in at least one audio based interview with the exception of Willow. The second round of interviews were meant to fill in gaps from the first round. The second rounds interviews were less structured, some were in person and others completely text based over chat mediums such as messengers and e-mails, depending on the availability and necessity to set up a second meeting.

Initially, two interview guides were created (one for communities and one for protocols) but these were discarded in favour of a single interview guide, already by the time of the first interview. The reason being that the binary categorization of "protocol or community" enforced a limiter on what the interviewee embodied, restricting the space of the gray-zones through a biased narrative and excluding the possibility that the interviewee represented both. By adopting a single interview guide consisting of a merge of the two previous interview guides, the semi-structured interviews could be conducted in a manner where the representative category could be set by the interviewee themselves, or not at all for that matter.

The questions in the interview guide were focused on the process of maturity, in relation to a protocol's development, community relations with developers and infrastructure, with specific emphasis on the initial stages in adoption. These questions assist in attaining a deeper understanding of the maturity of a project and its relations. The guide also included questions relating to use-cases, in local communities and in general. Emphasis was made on the relational interactions between developers and community members as well as developer to developer to further understanding of the systems nested aspects, informing perspectives on self-organizing systems. The follow up questions filled in the gap of organisational systems, non-technical and technical, which were missing from the original interview guide. The aim of the questions were to uncover the different layers of the system and how they evolved over time, from technical and geographical to organisational and relational.

The interview guide was formulated based on the principles of Kvale and Brinkmann in 2015 (Kvale & Brinkmann, 2015) and further inspiration was sourced from the Appreciative Inquiry approach for crafting meaningful questions and locating gaps of understanding. (Vogt et al., 2003)

Workshop

To complement the semi-structured interviews, an in-person workshop was hosted with participants from the peer-to-peer and offline-first protocol realm. This workshop was hosted in Berlin at Offline Space, a community hub meant for cultural and technical exploration [10]. The workshop had 14 participants out of which 2 had previously been interviewed.

Workshops were employed as a methodological approach to engage participants in collaborative activities and group discussions aimed at eliciting diverse perspectives and generating collective insights about the field as a whole.

Drawing on the principles of participatory action research (PAR), the workshop was designed as interactive sessions where participants could actively contribute to

10 https://offline.place/

the research process, specifically through Appreciative Inquiry (Reason & Bradbury, 2013). While appreciative inquiry is commonly thought of as a methodology which focuses on the positive Priest et al, in 2013, highlight that it's also about learning from the difficult. (Priest et al., 2013).

> *"Like other action research approaches, appreciative inquiry invites the researcher to wholeheartedly engage with the complex, messy, and emergent nature of organizational and societal life."*
>
> (Reason & Bradbury, 2013 p. 191)

The workshop was designed based on the frameworks developed by Bliss Browne as part of the Imagine Chicago[11] initiative, an applied Appreciative Inquiry project. (Reason & Bradbury, 2013)

Steps of the process are outlined as follows:

1. Mapping of the realm by drawing a visual map of Distributed P2P and local-first scenes. This helps give focus to the topics at hand.
2. Question: "*What question is most alive in your life and work right now… a growing edge of curiosity you would love the chance to discuss with others here?*" The participants write the questions on an A4 and hold them up in front of themselves.
3. On the back of the A4, the participants write how their work contributes to solving their own question.
4. Participants mingle and find questions they resonate with that others have written.
5. Groups of questions form based on similarity and documentation is made of what questions are in what groups.
6. Participants are asked to look at other groups' questions and nominate a selection of 3-6 questions for open discussion.
7. The selected questions are numbered and a speed dating process proceeds where participants represent the selected questions. The individuals split up and

11 https://www.imaginechicago.org/

represent the different questions. Each interviewer takes notes by hand which are later harvested by the researcher.

The speed dating process specifically was inspired by Bliss Brown's write up on the process on Imagine Chicago’s website[12].

Workshop materials were prepared in advance to support participation in the research process and an announcement was made in the description of the workshop as well as in the beginning of the session to enhance participants' understanding of the data gathering taking place. All participants were anonymous and the workshop involved 14 people as part of the P4P unconference in Berlin. Workshop description and schedule can be seen on the unconferences organizing platform[13].

Document Gathering

As part of each interview participants were asked if they had any documents they would like to share which may support the research process. In total 35 documents were shared and a selected few were also coded as part of the data analysis.

To supplement the documents sourced from participants, document gathering also occurred through the use of chat-groups with focus on, or tangential to, P4P as well as the federated social media platform Mastodon.

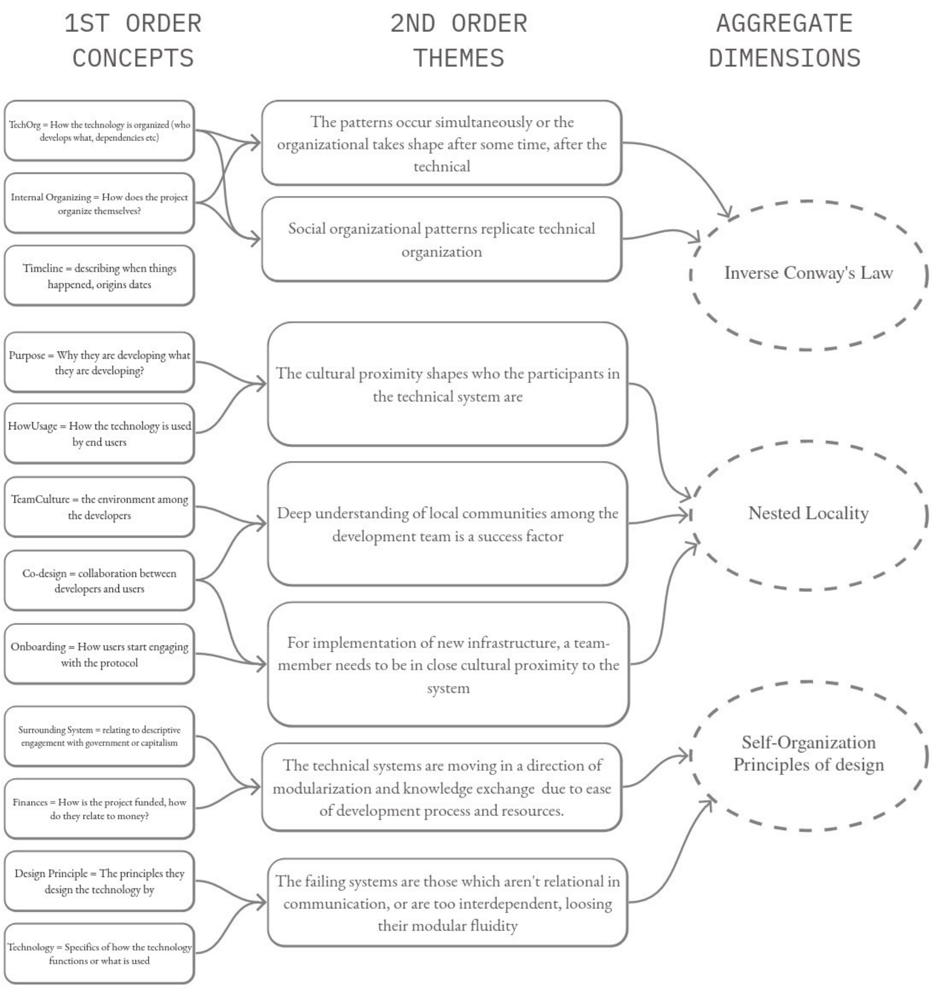
DATA ANALYSIS

Coding of Interviews

Inductive coding took place for all interviews, including those in the second round. The coding process was done by extracting highlights from the transcriptions of the interviews and thematically coding these based on recurring concepts without

12 https://www.imaginechicago.org/creative-engagement-activities?rq=speed%20dating
13 https://p4p.offline.place/

premade codes, thus inductive and open-coding (Gibbs, 2007). Once the first round of coding had taken place, the second round was initiated, along with the new data from the interviews and rich picture interpretations. The "5W-1H" method inspired the formation of codes (Williams & Moser, 2019). Once the previous code themes were re-organized into new and more concise themes, the whole data-set was re-coded. Sentences describing the codes were produced in the second round of coding to ensure coherence over time. The goal of the iterative coding process included moving towards more analytical coding rather than descriptive or categories. (Gibbs, 2007)



CODING – FIGURE 5

Workshop Analysis

Data Analysis of results from the Workshop were done by gathering the questions and answers provided by the workshop participants and digitizing them. Participants themselves had made categories as part of the workshop process and these remained in the data analysis as a means of informing the problem areas and solutions. The results were then analyzed in relation to the coding analysis as a complementary perspective of the context and the issues and solutions within. It is of importance to note that the participants in the workshop were primarily software developers from various european countries, and their perspectives are only a representation of their positions in the context, therefore not representative of the end users or local communities.

Visualizations

Visualizations were drawn directly after an interview or after reading or listening to an interview, by the researcher. The purpose was to increase transparency between the researcher and interviewee and empower the interviewee to change the mental picture the researcher had painted through visualization. The images were drawn on a drawing pad and shared with the interviewees for feedback. The drawings were then adjusted based on feedback from the interviewees, unless there were no requests for adjustments.

The method drew inspiration from the common practice of rich pictures originated in the Soft Systems Approach to better understand human activity systems. Important elements of developing a rich picture include: 1. Structure, 2. Process, 3. Concerns of the depicted actors (these can be supplemented in text form) 4. Using the language of the people depicted in the Rich Picture, and lastly 5. Use whatever means of drawing that suits your work best. (Monk & Howard, 1998)The purpose in this case was less to model the systems or understand the process but rather one of balancing the power dynamic of interviewer and interviewee. To clarify, in coherence with a complexity theory approach, a complex system can't be truly modelled:

> *...It is a recognition that exact representation cannot be achieved by anything which is less complex than the system itself and with the added implication that the representation would have to possess all the dynamic potentials of the original system.*
>
> (Byrne & Callaghan, 2022 p. 65)

However, restrictions on accurate representation does not mean that one can't communicate aspects of a system through modelling, and describe concepts more easily grasped visually than through words. It is important to declare that the visual representations are in no way meant to be accurate depictions of the systems at hand, and an attempt to do so would be in vain.

ETHICAL CONSIDERATIONS

All interviewees were informed and asked to give consent for documentation of the conversations. Brinkmann & Kvale wrote on the topic of Confronting Ethics of Qualitative Research in 2005 (Brinkmann & Kvale, 2005) where they explored the power imbalance of the interview format. Suggestions to combat this ethical conundrum include transparency and dialogue.

To further balance power and enable transparency, the interviewer used the approach of visualizations, as described above, and Authentic Relating (Kestano, 2022) in the interviews. Specifically the researcher actively aimed to reflect back the emotions and reactions of the researcher to the interviewee. This was done to increase the transparency of the interviewer and balances the power between the interviewer and interviewee.

In relation to the methodology of the interviews there are challenges of transparent and dialogue approach. The challenges include situations in which the interview may be influenced by the researchers active responses by swaying the interviewee, either emotionally or towards certain conclusions, this is however the case for any interview as 93% of communication is non-verbal (Mehrabian & Ferris, 1967). In traditional one-way dialogues, the bias of the researcher may sway an interview either way - the difference is in the transparency of the researchers bias. (Thompson & Thompson, 2022). An interpretive understanding of interviews acknowledges that they consist of two-way interpretations and communication. (source?)

8 RESULTS

Mapping of projects

An overview of the projects are presented below, along with some honorable mentions of cases not part of the whole research process. Following the presentations comparisons, relations and an overview of the results are portrayed as well as a depiction of the timelines in Figure 6.

ĀHAU

Āhau[14] is an application founded by and for Maori, the indigenous of Aoteroa (New Zealand) to map out tribe heritage. The team consists of around 7 people and the technical basis is a combination of Scuttlebutt for establishing connections between peers, relationships and linking out to larger files and media which is stored using hyperdrive. They also have their own private group encryption, unique to Āhau. The organizational structure is in a transitional stage from a limited liability company (based on the predecessor Matau) towards a coop model and was founded by Ben Tairea in 2018.

BRIAR

Briar[15] is an offline-first communication protocol and app. Made for censorship resistance and private messaging it bypasses central servers to establish connections via Bluetooth, Wi-Fi or Tor built primarily in Java. It has been downloaded 1.8 million times and has had 40+ contributors to the code, testing and design throughout its existence. The application runs over the protocol

14 https://Āhau.io
15 https://briarproject.org/

Bramble, specifically developed for Briar, and was launched in 2018. It was founded in London by Michael Rogers in 2010 in reaction to the internet shutdowns during the Arab Spring.

DAT ECOSYSTEM

The Dat ecosystem[16] is a network of applications and software modules which center around the dat stack which was founded in 2013. The main components are currently maintained by the company Holepunch. The organizational aspects have evolved considerably in the past years as the origins was a centralized organization focused on the protocol and is now considered an ecosystem of independent yet collaborating companies, projects and applications. There are 20 active projects in the dat ecosystem, including Āhau and Mapeo, with 8 more in the periphery. The dat ecosystems organizational structure centers around a 501c3 public charity and a consortium consisting of 6 project representatives.

GROBUND

Grobund[17] is an association which coordinates around a factory, land and local infrastructure. Founded in 2015 outside in the east of Denmark, Ebeltoft, they crowdsourced the funding to collectively buy a factory which they now run through sociocracy. Their internal data infrastructure is based on a traditional server running ‘Synologic’ over https and the only case in this study not utilizing P4P technology. The community is around 400 people with 40 actively involved in the organizing. With local-first and off-grid values they strive for in-house production of all things from vegetables to houses. Grobund is also in the process of expanding with satellite sites in two other locations in Denmark.

HOLOCHAIN

Holochain[18] describes itself as a framework for building distributed p2p applications. It was initiated by Arthur Brock and Eric Harris-Braun in 2017 under

16 https://dat-ecosystem.org/
17 https://www.grobund.org/
18 https://www.holochain.org/

the banner of the MetaCurrency Project and the development is continued as part of the company. The core development is centred in North America and while there are multiple applications under development, from discord like applications to collaboration tools. While usable the protocol has, as of June 2024, yet to launch a stable version resulting in a lacking uptake among end-users. Central to the design is the idea of membranes, functioning similarly to private group functionality for the applications. Technically it shares a lot of similarities to the hypercore protocol, using DHTs and hashing of data.

MAPEO & AWANA DIGITAL

Mapeo[19] started in Ecuador around 2013 with the Waorani tribe as a means to "*create a map full of things that don't have a price*" to represent their territories in fighting the sale of their lands[20]. The founder of Awana Digital is Emily Jacobi and the founder of Mapeo is Gregor MacLennan. MacLennan, in dialogue with the Waorani tribe, understood the importance of mapping and decided to learn how to code. Since then Mapeo has grown and is now used around the globe to support land-heritage mappings with 714 active users in 38 countries. Mapeo is a p2p local-first protocol which utilized the hypercore protocol[21]. Mapeo is likely to be the biggest active local use-case of a P4P application to date. Unique among the P4P cases interviewed here, Awana Digital have developed a co-design process which informs the development of the application Mapeo.

MELI BEES

Meli Bees[22] is an independent organization that engages with indigenous communities and researchers to support grassroots processes of environmental regeneration of ancestral territories. They engage with +60 indigenous and local communities and function as a network facilitator for indigenous communities. Founded by Ana Rosa in 2020 in collaboration with researchers and the Kayapo community. They are currently collaborating with P2Panda[23], a P4P protocol

19 https://www.digital-democracy.org/mapeo
20 https://www.earthdefenderstoolkit.com/community/mapping-waorani-ancestral-lands-in-ecuador/
21 https://docs.mapeo.app/
22 https://www.meli-bees.org/
23 https://p2panda.org/

developed primarily in Europe and set to launch an application in July 2024 in support of Meli Bees collaborative endeavour of documenting bee species in the Amazonas.

SCUTTLEBUTT

Secure Scuttebutt (SSB)[24] is a social network, and gossiping protocol with around 20,000 individual identifiable nodes on the main network key and approximately 200 monthly users. Founded in 2014 (and started in 2012[25]) by Dominic Tarr in Aotearoa (New Zealand) it has a relatively unique network architecture and is a F2F-P2P-P4P network, as well as a Grassroots System. The protocol is built in Javascript with Go and Rust implementations. The data is replicated across mutual trust relations of "friends" on the network in a 2-distance hop, that means that each user stores the data of their friends and their friends’ friends. Scuttlebutt as a protocol has approximately 20 different applications developed to run over it, from chess to variations of different social network layouts, and a user of different applications will automatically connect to the same social network as they work on the same user key-pairs.

QAUL

Qaul[26] is an internet-independent wireless mesh communication app. Launched by two artists based in Europe, as an art project in 2011 during the Arab Spring, similarly to Briar, Qaul seeks to enable communication during internet shut-downs. Qaul has been inspired by research showing that the majority of communication primarily occurs in geographically local context. Technically Qaul uses end-to-end encryption and a their own distance-vector based gossip protocol. The two artists didn't originally see themselves as fit for the highly technical task, yet with their background in user research continued the process and collaboration with communities, especially in Syria. Currently the code is owned by the association "The Open Community Project Association" which was launched in 2018.

24 https://scuttlebutt.nz/
25 https://web.archive.org/web/20180429021039/http://gwenbell.com/dt-interview/
26 https://qaul.net/

"...Maybe it's also a reflection on expertise in that one could say, during uprisings and so on, the people themselves are not experts, but they are still doing it. Because they are in the situation, and they want to change their own situations."

- Qaul Interviewee

Honourable Mentions

The following network projects were not interviewed as extensively compared to the dual semi-structured interviews of the other case, but will be mentioned for their significance to the realm of p4p:

CABAL

Cabal[27] started in 2018 as a p2p group chat project in the dat ecosystem and has now transitioned into its own protocol, Cable. Cable is a peer-to-peer protocol for private group chats where users collaborate with each other to exchange data[28]. One of the unique features of the project is their implementation of content moderation, wherein users decide whom to delegate authority in a subjective manner, as inspired by TrustNet, a novel system for p2p moderation (Cobleigh, 2020). It is a volunteer-run project that was started when multiple individuals in the p2p space came together and combined efforts.

INTERPLANETARY FILE SYSTEM (IPFS)

InterPlanetary File System (IPFS) is a peer-to-peer hypermedia protocol. It was started by Juan Benet and his team at Protocol Labs in 2015 (Benet, 2015). IPFS is a P4P protocol with files stored across nodes. (Benet, 2015). Since its inception, IPFS has gained considerable attention in both academic and technical communities. As of 2024, thousands of articles and research papers have been written mentioning IPFS, reflecting its growing influence and application in fields such as decentralized storage, blockchain integration, and content delivery

27 https://cabal.chat/
28 https://github.com/cabal-club/cable-docs/blob/main/introduction.md

networks (Barbara Guidi et al., 2021; Daniel & Tschorsch, 2022; Trautwein et al., 2022)

WILLOW

Willow is a protocol that was started in 2023 building on the foundation laid by Cinnamon who developed Earthstar in 2020. Developed by Sam Gwilym and Aljoscha Mayer it utilizes Range-based Set Reconciliation as outlined by Meyers paper by the same name (A. Meyer, 2022). Sponsored by NGI Assure it has measurable and achievable goals and is considered complete with guidelines for how to design a P4P network architecture while leaving the specifics of how data is stored and how connections are made open for defining by the implementations themselves, such as Iroh who are developing on Willow. Primary programming languages are Typescript and Javascript, there is currently a Rust implementation in development.

Other projects to mention are: Braid[29] who focus on Interoperable State Synchronization and PZP[30], the recently launched protocol developed by André Staltz and Jacob Karlsson and Iroh[31], a toolkit for building distributed apps.

Parallels of Organizing and Technology

In the cases below we see examples in which the organisational shape, over time or immediately, embodies the patterns of the technology with which they work with. This can be considered a reverse of Conway’s Law.

To start off, let's have a look at Dat and SSB which had very similar journeys all the way back to their origin points, in the IRC channel of Mad Wizards. While sharing similar origin stories from the Node JS community, the journeys evolved in very different directions.

29 https://braid.org/
30 https://pzp.wiki/
31 https://iroh.computer/

SCUTTLEBUTT

SSB is organized as a social network, with little to no defined structures of governing, flat structure organizing. Starting as a social network, so it continued, with trust building functioning as an essential glue, socially and technically. Dominic Tarr, the founder of Scuttlebutt, took a very hands-off stance in relation to organizing and preferred to let things evolve naturally through community design. Over time organizing structures emerged and collapsed, ranging from facilitated grant voting structures to different Scuttlebutt consortium which pledged to dissolve themselves once their tasks were completed, as was the case with the Handshake Council on SSB. This flat-structure naturally lends itself to the Tyranny of the Structurelessness (Freeman, 1970) where the few who are well connected socially, and know how to navigate the social spheres, end up being the people who make unofficial decisions, and become in-official centralization points. Organizationally active SSB participants created private group chats and co-ordinated over these, yet these were sporadic in nature and there was never a formalized private group chat.

Technically SSB is modular in its structure. As with dat, it was inspired by the node JS communities modularity principles. In contrast to dat, SSBs modules relate to each other in a more intertwined form. It makes it so that a programmer, when setting out to learn about one SSB module, ends up having to follow the paths and understand more of the system of how the modules interrelate. The modularity can be said to be visual rather than systemic. While the modules are stored separately in different folders, changing one may affect another. One interviewee referred to this as having to "crawl the spider web of SSB to understand". While this intertwining of modules and their dependencies hinders engagement from all but the most dedicated, socially inquisitive and knowledgeable. A positive aspect was pointed out by the interviewee. Due to the intertwining of both the technical and the social it hinders commercial actors from entering the space and using the technology, as the social dissemination of information combined with complicated tech stack, acts as guardians of knowledge.

"But to some degree, you have to have like the right... Have kind of like special interest and technical capabilities to be able to use it so far. Which is a shame"

- SSB Interviewee

This "crawling of the web" was related also to the organizational structures, in which the dynamics of organizing were governed by the ability of the individual to understand the social web. In this regard, SSB's structure, organizationally and technically, largely resembled each other.

In this day and age, multiple generations of developers have tried to carry the burden of maintaining SSB, both front-end clients and the back end code. Today few are left and have continued the relations they built, along with the knowledge of how to build P4P networks forward, and many of the protocols we see today stem from SSB.

DAT

From an organizational perspective, dat started in the other end of the de/centralization spectrum from SSB, and as it grew, became relatively centralized and hierarchical, something new participants vowed to change on a quest for democratization.

"In 2019, the consortium was formed. So that these are like first steps towards more decentralization also in the organizational sense, because before that, that was very hierarchical structure, in a way it was producing peer to peer, but as an organization was a very top down. And there were many problems because of this. Rae McKelvey, who was then a director, or whatever, he pushed into this direction to make the ecosystem more decentralized and formed a consortium of around 10 members."

- Dat Interviewee

The organizational dissonances reached a culmination point and what used to be known as the dat-protocol, maintained largely by Max Ogden and Mathias Buus, separated and renamed itself to hypercore. Holepunch as a company, where Mathias Buus works, continues the development of Hypercore and related software. The surrounding community, applications building on hypercore and adjacent, were in momentary disarray until a new approach emerged, that of an ecosystem rather than a protocol. The dat-ecosystem came about with a website and narrative, and the consortium continued, yet no longer tied to the specific part of the tech stack known as hypercore.

The technological organization of the dat-ecosystem is highly modular. Each module can be understood as an isolated building block which has enabled an easy entry way for developers to engage with the tech stack as they don't need to understand the whole to engage with the software. Some of the modules have dependencies but for a P4P network its fairly modularized.

Interestingly enough, while hypercore started as a more centralized and hierarchical organizational structure it soon came to be more and more distributed until it consisted of a number of independent actors connected in a relational manner, sometimes technically and other times socially. What is seen here is an organizational structure which effectively replicated the technical structure.

MAPEO

Mapeo has also, over time, adopted a more distributed internal structure. Recent changes of Mapeos internal system included a shift from stricter team divisions in which different co-workers were categorized into teams based on their roles. The new internal structure of Mapeo is one in which there are general domains of work such as Product Support, Community Engagement, App Development and Deep Accompaniment. These domains no longer serve as strict divisional factors of the teams but rather means of which the co-workers themselves can use to describe the type of work they do. Some of the co-workers of Mapeo also move around and shift domains, in a fluid and adaptive form.

ĀHAU

A similar organizational journey is happening with Āhau. Their original organizational structure is one which was relatively hierarchically centered around the founder, Ben Tarea, who made most of the decisions and was legally the owner of the company, as based on the successor company to Āhau, Matou (Āhau = I am, Matou = we are in Maori). Āhau is now in the process of researching new organizational models to reshape into a coop format, distributing the power within the organization and following in the footsteps of the technical infrastructure architecture.

Āhau is also collaborating across domains a lot, with knowledge exchanges between Mapeo and Āhau as well as knowledge exchanges with the network protocol P2Panda (who in turn collaborate with Meli Bees). In a quote about this collaboration an Āhau developer elaborates:

> *“[P2Panda] chose one path and [Āhau] chose the other path. And we don't know which one is the right path yet. But now I know that we've got colleagues have made a different decision. Because we've had that conversation, we can track how the system behaves, having made that decision, because that's one of the challenges of being in such a new space is we don't know what the shortcomings are and what the strengths are of each of our decisions yet.”*

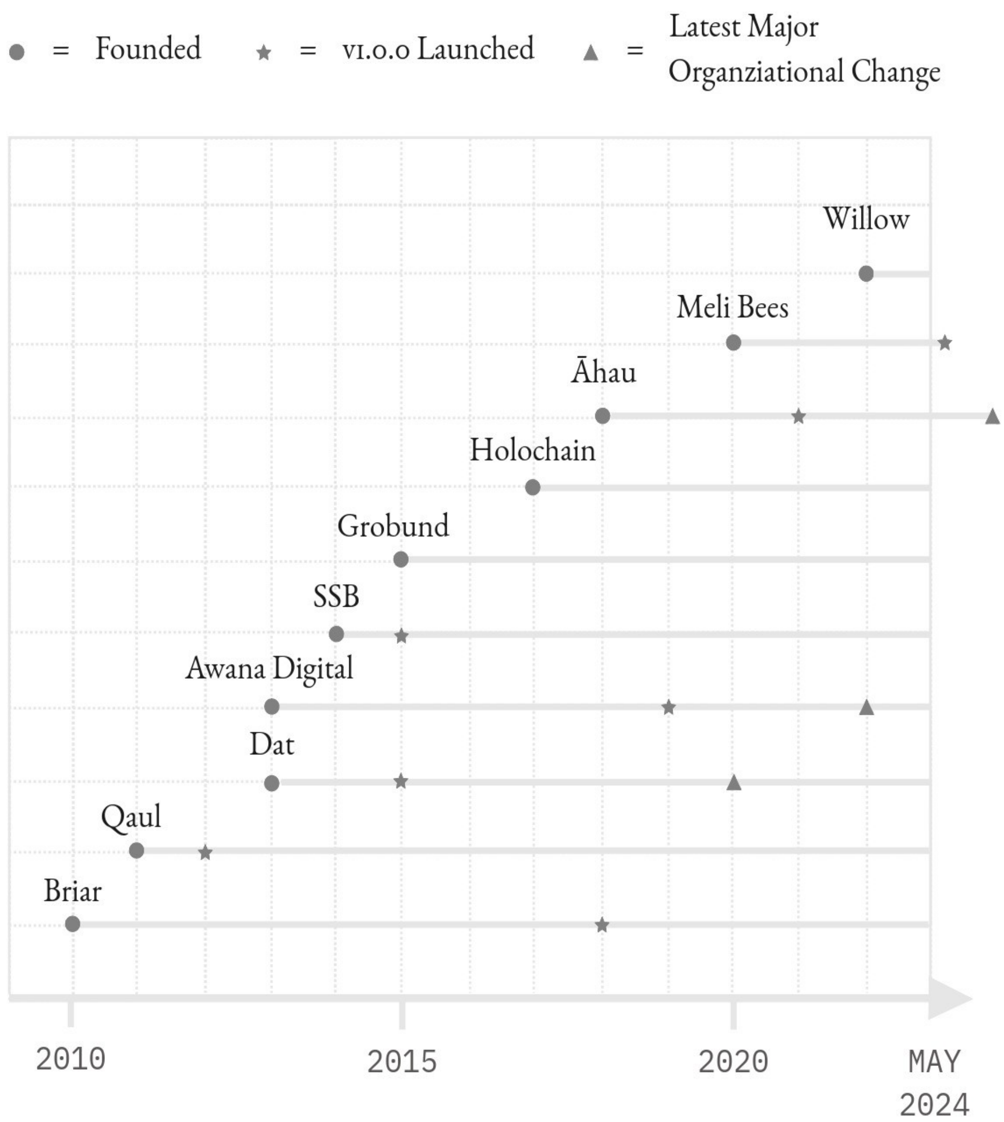
- Āhau Interviewee

BRIAR AND QAUL

Briar and Qaul, the applications most similar to one another in regards to purpose, also organize in similar ways, both the projects consist of a core group of western developers with their private chats in which decisions are made collaboratively. They each have a matrix chat the public can access, along with git repos. User research is occasionally done, and in Qauls case, visits to local communities as well, while Briar has focused on primarily getting feedback from community security experts who work directly with at-risk communities instead of directly from the communities. Each protocol has one main application and welcomes contributors with open arms, from all across the world.

HOLOCHAIN

Holochains development organization is also quite centralized, with the core protocol developers partaking in private chat spaces along with a public discord, similar to Briar and Qaul. It does however have the approach towards applications in common with SSB and Dat, in which multiple applications are built on top of the protocol, enabling (in theory) a seamless shift between applications from an end-users experience. Funded by its sibling Holo, a token project. Holochain has emphasized B2B adoption more than the other protocols yet the long development time has led to frustrations among its application developers. The distinction between core-developers and application developers seems to be exacerbated by the divide of who is hired by Holo and "inhouse" and who is "external". Interestingly enough a core design concept in Holochain is that of "membranes", in practice these membranes can be seen as Network keys, separating one group from receiving the data of another group. One could theorize that the mental model of distinct group separations may have contributed to the slow release due to lacking cross-community connections, yet while design parallels can be drawn between the mental models of the technology design to the organizational, no conclusion can be made as there wasn't enough data gathered during the research project in relation to internal organizational design to clarify the relations of the parallel.



TIMELINE OF PROJECTS — FIGURE 6

Modularity - Social and Technical

Here we look at the impact of the systems qualities on the development process. The results indicate importance of locality and bridging, socially yet also technically. We end with a note on the correlation between locality, bridging and who develops.

LOCALITY AND BRIDGING

Mapeo, Meli-Bees, Grobund, and Āhau are some of the more communally oriented projects which participated in this multiple-case research project. The projects shared some commonalities. A distinct commonality was how specific of an issue they each solved, or required to be solved in Grobunds case. Mapeo is a mapping of territory project (for mapping of sighted ecosystem species or fighting legal battles with oil companies), Meli-Bees started as an ecological project on bee-species in the Amazonas and have broadened their perspective as the organization and geographical regions grew, Āhau focuses on Family Trees. A representative from Grobund came with a lot of different highly specific application needs, such as being able to locate where people were on the large premise when they weren't answering their phones, finding who needs a lift into town, that the applications worked on the mobile phone.

It would seem that infrastructural issues are closely linked to the geographic perspective. The more zoomed out the geographic perspective is, the more general the problem becomes. From an application perspective it is clear that local issues require local solutions, something easier said than done for today's developers.

Locality can however be seen as disconnected from spatial and geographical locality, as an interviewee from Dat pointed out:

> *"I feel local to me is like a little bit broader. I mean, one is definitely the geographically local sense. But if I'm thinking I feel I'm part of many communities that are all local, in the sense of we have close proximity in terms of interests, or skills, or maybe certain political ideals, or whatever it is."*

Another common ground for each of them was the importance of bridges. In this regard bridges are the cases in which a person acts as a connecting point to another community or towards an infrastructure. Some case examples are listed below.

Meli-Bees explicitly utilize social bridges in their process of connecting to local communities. This is done by fostering closer relations to what they call "pollinators" or in relation to connecting to new communities who live in lush nature, in low-connectivity regions.

> *“Yesterday I was giving a presentation about about the pollination regeneration program... we brought a kind of a structure of ideation and support them to do an ideation basically “Okay, which project do we want and what we want to do?” ...And I was very surprised because there was a new community. They joined our network because they were better structured than most of the communities that we work with are less established, this community had access to larger funds. And during the ideation session she came to me and said "wow, that was impressive. Nobody ever asked us what we want to do." And that was very shocking for me.”*

Meli-Bees embody the role of bridging between communities, a large part of their purpose derives from facilitating these networks of indigenous communities, also in relation to researchers and infrastructure, such as in the collaboration with P2Panda.

Mapeo also utilizes bridging organizations in their collaborations, similarly to Meli-Bees, when working with new communities Mapeo often collaborates with local organizations who facilitate the connections. Mapeo's success may also be attributed to their unique focus on how to craft these relations and ensure that they are mutual and in service of the community, a process they refer to as the co-design process, carried out by the Awana Digital employees whom are part of the Deep Accompaniment domain.

> *“we have a process we call co-development or co-design. And that is, you know, our main pillar”*

For grobund this was expressed in relation to adopting new infrastructure, or organizational approaches. It was of essence that there was an existing member as part of the core who had a connection to the new system. An interviewee elaborates in the following quote:

> *"they should know about Grobund. And it knowledge and they should know what [we] want. And not think what [we] want. Yeah, actually. Yeah, or being part of [Grobund]. Yeah. So deep"*

All of the above can be considered modularizations of relational facilitation, to use a language that can describe both the technical and social patterns. These patterns follow principles of self-organization as the modularization can be re-configured as appropriate. If a connection doesn't work, another might, and the burden of success is distributed and no longer a single point of failure.

DEVELOPERS – BRIDGING AND LOCALITY

The ideal, which is also expressed by a Mapeo representative, is when the social-proximity of the developers and the community overlap, in other words, when the people developing also are representatives of the project. Co-design may still be important but the intrinsic understanding of the context, culture and needs are part of the developer already. Enabling them not only to hear but to reproduce the systems. As the saying goes, teach them how to fish.

Building Small, Concrete and Relational Components

From a technical perspective, Āhau is also a fascinating case as it is the only application, out of the ones which have been researched in this paper, that combines the technical capabilities of two different protocols, specifically Scuttlebutt and hypercore. Āhau uses scuttlebutt for most aspects of its network, from coordination and linking out to larger media files, which in turn are stored using hyperdrive and hyperswarm from the dat ecosystem. They reportedly use old versions of hyperdrive and hyperswarm though due to lacking documentation. Beyond the SSB and dat sections of the stack, Āhau has also implemented private groups, which are unique to Āhau.

From both a social and technical perspective, modularity can increase the adaptive capabilities of a network, breaking apart and reforming as necessary, as part of a self-organizing process. Technically though, modularity is easily misjudged as simply plugging together two pieces of software and having them work, yet as a participant at P4P exclaimed "It's not like Lego you know! The pieces don't just fit together.", an exclamation rooted in hours upon hours of hard work coding to get pieces (which should easily fit together, theoretically) to fit together. To enable modular software to be built, the ill fitting metaphor of Lego blocks would need to be discarded and rather replaced with a metaphor which includes bridges or adaptors, for software doesn't automatically fit, it needs translators, just like social systems need people who can bridge between communities.

Another example of technical modularity is Willow and Iroh. Iroh is, as mentioned, a toolkit for building distributed apps. It is currently in the process of implementing Willow. Iroh is distributing the access to building distributed applications by enabling a more easily accessible way for developers to make P4P applications, without having to do the heavy lifting of back-end code. Willow, in turn, is modularizing protocol design by building the skeleton of the protocol design and offering different parts as potential ways to continue on protocol build, without requiring developers to choose a certain approach. This approach is more similar to that of the dat-ecosystem in which different projects can solve different things, yet still relate to each other.

The importance of modularity was brought up in an interview with Briar in which they referenced a report brought forth by a team member, highlighting the importance of re-usability:

> *"One of the things that came out of the discussions with Ellinor early in the project was to try and build a reusable protocol stack....So in theory, we have a protocol stack called Bramble, which you can take and build another app on top of. But I say in theory, because although you can do that the design of Bramble has often been driven by the needs of Briar... ...if you wanted to build a, you know, a peer to peer app with a totally different security model before that, you couldnt really use bramble. So that's a kind of question about... you know, it's reusable in the sense that it's got an API in there. but what could you actually build with it?"*

- Briar Interviewee

Enabling building blocks, and the ability of breaking down software into smaller components, is an essential principle for networked self-organization as modularization enables the adaptable qualities of self-organization. A shift in the approach towards building P4P protocols includes a shift in terminology. Rather than protocols, it seems plausible that the near future of P4P is shifting away from "complete protocols" and instead moving into the direction of networked protocol components. Protocols are somewhat tied to use-cases while networks are not. Network components can be re-organized to serve particular use-cases, and as seen above, communities require specific use cases to their unique circumstances, being able to move protocol components around to enable more local solutions, and more local uptake.

A shift from the big and bulky software protocols into lean and small components of networks can take shape as described above, yet it is already taking place for applications as well. An emergent developers paradigm is that of applications "protocol agnosticism", such as the case of for example Element[32] or recent developments of Delta Chat[33], in which the application interface combines multiple different back-end networks. The resulting ecosystem is one in which both the protocol layers and the application layer consist of small, relational, and achievable components, be these parts of a communication protocol design or the front end applications - connecting to the same or multiple protocols.

Problem areas and challenges

During the P4P gathering in Berlin a workshop was hosted with the purpose of researching what questions were alive in the community. Three main areas were uncovered:

1. Systemic Capitalism and Sustainable Development
2. Longevity of P4P development

32 https://element.io/
33 https://delta.chat/en/

3. Collaboration

Questions within the group of systemic capitalism and sustainable development were the most common, with a total of 7 questions. Some of the questions were "*How can the p2p movement flourish under circumstances of low financial support?*" and "*How to unmask surveillance capitalism and destroy it?*", including, "*How to find more time and energy to read more?*". These questions related to the category of Longevity, such as "*How can I make a cool, interesting and complete thing without it being so exhausting?*". It's clear that sustainability in relation to funding and energy are present among P4P developers. The third category of collaboration was the smallest, with three questions. Here a desire for collaboration was expressed as "*How can we have more direct collaboration between projects?*" and "*How do we get good standards?*".

Speed-dating interviews, based on a selection of the questions, enabled some light to be shed on potential solutions:

SOLUTIONS FOR COLLABORATION

For collaboration, meeting in person, active communication and human connection in various forms such as listening and playing games, was mentioned a number of times. Coincidentally topics of locality, coalitions, tribes and cross-connections were also mentioned as a potential solution for collaboration. Specifically in relation to standards, shifting away from the global system of standards, in which large bodies of internet enthusiasts (often sponsored) set one truth for the system as a whole, enabling the multitude of truths, local standards between coalitions was proposed.

SOLUTIONS FOR SUSTAINABILITY OF P4P DEVELOPMENT

Completing a project, along with complete specifications, was proposed as a solution to sustainability in development of P4P software. This again relates to modularity as one aspect of building smaller, yet complete, blocks of network software, is that of making the development process more manageable. A smaller project requires less people to complete and also less maintenance. Therefore, beyond contributing to the self-organizing ecosystem (as mentioned in the previous section on modularity) it also contributes towards solving one of the main issues within the field of open-source; maintenance.

> *However, even widely used tools are often not promoted in traditional digital security resources for fear that they may lack longevity, as unmaintained tools pose a significant security risk for those who continue to use them.*
>
> - Report on Open Source Digital Safety Tool Ecosystem - Basics, 2020[34]

When the project parts are smaller, and with less dependencies, it becomes easier for new maintainers to step in, since the knowledge threshold is lower compared to a big project. Smaller components thus alleviate the stressors of solving potential issues that come over time, as seen here in the comparative results of Dat (more modular) and SSB (more interconnected). Another illustration of this approach can be seen in terms of team and financial size. Scuttlebutt and Briar are two projects which combined have received several hundred thousand euros in funding over the years, each of the projects has had over 60 contributors each. Willow was developed in one round of funding by a team of two, while standing on the shoulders of relative giants, Earthstar and Scuttlebutt as examples in Willow's case. The necessity of larger projects such as Scuttlebutt and Briar has passed and the time for networked ecosystems of P4P components is arriving.

Unexpectedly, building small, measurable and achievable projects also relates to issues of commercial seizing of Open-Source projects. Mozilla Firefox stands as a case example with deep roots in the Open-Source movement yet is reliant on Google for funding. In 2010 84% of Firefox's revenue came from Google, and that was before their google contract more than tripled in funding[35]. In essence, Google's stakes in Mozilla are so high they can control its destiny. The challenge of maintaining a browser ensuring coherence with the amounts of web standards[36]

34 https://internews.org/wp-content/uploads/2022/05/BASICS-report-on-health-of-open-source-digital-safety-tool-ecosystem.pdf
35 https://www.zdnet.com/article/firefox-hits-the-jackpot-with-almost-billion-dollar-google-deal/
36 https://www.w3.org/TR/

is such a huge task that in today’s society, it is difficult to ensure adherence to Open-Source values.

For sustainable P4P development, rather than repeating the systems of standard bodies defining the space for all participants, which has been an important aspect of the “world” part of world-wide-web, the P4P movement will have to find ways of creating local standards, partial bridges and fluid forms of connection. Evading centralization, censorship and lock-in through liquid patterns of network, built up by small, relational and independent components. This means that there will be multiple webs, to various scales and degrees. A major difference between the multiple webs of P4P, in contrast to that of the Splinternet, is that the network separation is disconnected from nationality as it operates on a peer-to-peer level, hence its usefulness in avoiding censorship or the walled gardens of splinternets.

9 DISCUSSION

This study aimed to explore the development of Peer-4-Peer (P4P) networks and their interplay with self-organizing systems, modularity, and sustainable practices. The findings contribute to understanding the relationships between technical and organizational systems and provide theoretical and practical insights into fostering decentralized, community-driven infrastructures.

KEY RESULTS

The primary results of this study can be summarized as follows:

1. **Organizational Patterns and Self-Organizing Systems:** Self-organizing systems working with technology may, over time, adopt organizational patterns from the technology itself, suggesting a symmetrical bi-directional relationship between technical and organizational systems.
2. **Modularity as a Catalyst for Emergence and Sustainability:** Social and technical modularity enable adaptable, emergent properties in self-organizing systems while addressing challenges related to financial and organizational sustainability.
3. **Defining the P4P Field:** The term Peer-4-Peer (P4P) was proposed to encompass P2P offline- and local-first communication protocols, positioning this field within broader technological and social contexts.

NESTED SYSTEMS AND ISOMORPHIC SYSTEMS DYNAMICS

The observation that organizational systems mirror technical patterns supports the concept of Isomorphic Systems Dynamics. Traditionally, Conway's Law posits that organizational communication shapes system design. This study extends that idea, proposing that system design also influences organizational structures. In complexity theory terms, this reflects the isomorphic nature of nested self-organizing systems:

Nested self-organizing systems develop structurally similar patterns.

This finding aligns with earlier work by Friedman et al. (2008), which suggested that information systems influence organizational values. The concept of Isomorphic Systems Dynamics builds on this idea by proposing that patterns embedded in technical systems shape not only organizational structures but also the values they embody.

The precise mechanisms driving this symmetry remain unclear. Key questions include:

- Does a shared mental model of the project mediate this reciprocal influence?
- Are collective experiences shaped by technical patterns, leading to organizational reconfiguration?
- Do these patterns repeat across scales, from small working groups to broader networks?

Further research is needed to confirm these dynamics. Mixed-methods and longitudinal studies, such as those conducted by Neulinger et al. (2016), could shed light on the interrelations between technical and organizational systems, particularly in highly adaptable, nested self-organizing environments.

DESIGN PRINCIPLES: SOCIAL AND TECHNICAL MODULARITY

This study highlights key principles for designing P4P software infrastructures, emphasizing specific, modular, small, and achievable projects. Modularity—both social and technical—emerged as a critical enabler of adaptability, emergence, and sustainability within self-organizing systems. In this context, modularity refers to the division of work into small, independent, yet interconnected components, a principle that applies to both technical systems and team dynamics in a networked ecosystem.

The advantages of modularity include:

- **Encouraging emergence:** Smaller components foster the self-organizing dynamics of systems.
- **Lowering knowledge barriers:** Developers can engage more easily with manageable and focused projects, enabling broader participation.
- **Supporting reusability:** Modular components can be repurposed across projects, ensuring resource efficiency.
- **Reducing the maintenance burden:** Smaller, self-contained modules minimize the risk of perpetually ongoing projects and energy drains.
- **Ensuring project completion:** Modular projects are more achievable and avoid stagnation.
- **Mitigating financial risks:** Smaller projects reduce financial pressures that could compromise project values.

From a complexity theory perspective, modularity fosters adaptability by enabling small, independent components to ripple change through the system. Stacey (1995, p. 483) observes:

> *"When it is at the edge of instability, a system is far easier to change because small actions of [actors] within the system can escalate into major outcomes."*

This modular approach is reflected in the emerging developer paradigm within the P4P field. Developers are increasingly favoring small, completable, and relational projects that form a networked ecosystem, rather than attempting to build monolithic "one-size-fits-all" protocols. This paradigm challenges centralized infrastructure and fosters grassroots, community-driven digital sovereignty. Successful examples, such as Willow, Iroh, and the Dat ecosystem, demonstrate how smaller, interconnected projects form resilient and adaptive ecosystems of mutual aid.

These principles align with broader efforts to harmonize local needs with global infrastructure development. By fostering localized control and autonomy, modular P4P systems support both technical innovation and community-driven knowledge exchange, ensuring long-term sustainability.

Further Exploration:
This study provides several avenues for future research:

1. Network Theory: Comparative network modeling could reveal deeper connections between technical and social systems, advancing our understanding of modularity in P4P networks.
2. Organizational Structures: Exploring distributed organizational models, such as liquid democracy (Blum & Zuber, 2016), sociocracy, and microsolidarity, may offer insights into aligning technical and organizational patterns. TrustNet (Cobleigh, 2020) and similar initiatives provide valuable case studies for these approaches.
3. Identity in P4P Systems: Future work should address the challenge of managing identity within distributed ecosystems. Disassociating identity from specific protocols or applications could enable seamless interoperability, a goal already partially realized through technologies like ed25519 key-pairs.

IMPLICATIONS

This study contributes to the fields of complexity theory and decentralized infrastructure design by:

- Implicating that nested self-organizing systems develop structurally similar patterns.
- Highlighting the critical role of modularity in fostering adaptable, emergent, and sustainable systems.
- Defining and naming the field of P4P networks, establishing a foundation for future research and development.

By prioritizing small, specific, documented and acheivable projects, P4P systems can foster a resilient and adaptable ecosystem while addressing key challenges. Modular designs are not only a technical innovation but also a socio-technical framework that aligns with the principles of self-organizing systems. These principles empower communities to co-create infrastructures that reflect their needs and values, supporting a transition toward decentralized and sustainable digital sovereignty.

10 CONCLUSION

This research set out to explore the maturity and development of Peer-4-Peer (P4P) networks, seeking to define their unique characteristics, design principles, and theoretical contributions. The findings provide insights into the social and technical dimensions of P4P networks, offering pathways to foster their growth as resilient, adaptive systems.

KEY FINDINGS AND THEORETICAL CONTRIBUTIONS

1. **Ordering Theory: Defining P4P Networks**
   The study defines P4P as a distinct family of networks that are Open-Source, Local-First, and Peer-to-Peer (P2P). By naming and framing this field, the paper establishes a foundation for further exploration, distinguishing P4P from related concepts like Local-First software (Kleppmann et al., 2019) and Grassroots Systems (Shapiro, 2023). A topology of the field was outlined, emphasizing the importance of interoperability and the capacity for independently deployed instances to merge seamlessly—an essential characteristic of Grassroots Systems within the P4P realm.

2. **Design Principles: Empirical Findings**
   The research highlights key principles for designing P4P software infrastructures, emphasizing small, documented, specific, and achievable projects. These principles enable quicker development cycles, minimize maintenance burdens, and align with self-organizing systems. Modular designs allow developers to adapt to local needs while challenging colonial

internet structures by fostering localized control and autonomy. Successful examples, such as Willow, Iroh, and the Dat ecosystem, demonstrate the power of smaller, interconnected projects to form resilient, networked ecosystems of mutual aid. These principles not only support technical development but also encourage community-driven knowledge exchange, ensuring long-term sustainability.

3. **Theory Contribution: Enacting Theory**
   This paper contributes to complexity theory by proposing the notion of a bi-directional Conway's Law. Findings suggest that nested self-organizing systems—both technical and social—develop isomorphic patterns over time. Organizational structures in projects like Mapeo, the Dat ecosystem, and Āhau reflect the influence of their distributed technical architectures. These cases illustrate how social and technical systems co-evolve, reinforcing each other's design principles. Further research is needed to explore the extent of this isomorphic relationship.

Humanity is navigating a period of profound technical, social, and environmental change. P4P networks offer a model for adaptivity and resilience, addressing these challenges through decentralized, collaborative, and modular approaches. This study charts a vision for a future where technology empowers communities, fosters mutual aid, and strengthens local autonomy in an increasingly unpredictable world.

REFLECTIONS ON THE RESEARCH PROCESS

The research journey was iterative, dialogical, and deeply collaborative. The scope of the study evolved through repeated cycles of feedback and refinement, allowing for a fractal understanding of nested systems to emerge. Grounded theory heavily influenced the process, ensuring that insights were shaped by theory, practice, and context alike. Each step was designed to remain open, inviting diverse perspectives to contribute to the final work.

As this work concludes, it carries forward the seeds of future possibilities for P4P networks. The research has been both a joy and an inspiration, and the findings reflect a collective effort to imagine and build resilient, adaptive infrastructures for the challenges ahead. On a final note:

THE INTERNET IS DEAD, LONG LIVE THE INTERNETS!

11 REFERENCE LIST

Accard, P. (2019). Criticality: How Changes Preserve Stability in Self-Organizing Systems. *Organization Studies*, *40*(11), 1613–1629. https://doi.org/10.1177/0170840618783342

Ahuja, M. K., & Carley, K. M. (2006). Network Structure in Virtual Organizations. *Journal of Computer-Mediated Communication*, *3*(4), 0–0. https://doi.org/10.1111/j.1083-6101.1998.tb00079.x

Allen, P., Maguire, S., & McKelvey, B. (2011). *The Sage Handbook of Complexity and Management*. SAGE Publications Ltd. https://doi.org/10.4135/9781446201084

Anderson, M. (2019). Exploring Decentralization: Blockchain Technology and Complex Coordination. *Journal of Design and Science*.

Anderson, P. (1999). Perspective: Complexity Theory and Organization Science. *Organization Science*, *10*(3), 216–232. https://doi.org/10.1287/orsc.10.3.216

Anzola, D., Barbrook-Johnson, P., & Cano, J. I. (2017). Self-organization and social science. *Computational and Mathematical Organization Theory*, *23*(2), 221–257. https://doi.org/10.1007/s10588-016-9224-2

Archer, M. S. (2003). Structure, Agency and the Internal Conversation. *Cambridge University Press*, 370.

Axelsson, V., & Larsson, F. (2023). *Understanding the Software Bill Of Material for supply-chain management in Open Source projects*.

Baran, P. (1964). *On Distributed Communications: I. Introduction to Distributed Communications Networks*. RAND Corporation. https://doi.org/10.7249/RM3420

Barbara Guidi, Guidi, B., Andrea Michienzi, Michienzi, A., Laura Ricci, & Ricci, L. (2021). *Data Persistence in Decentralized Social Applications: The IPFS approach*. 1–4. https://doi.org/10.1109/ccnc49032.2021.9369473

Benet, J. (2015). *IPFS - Content Addressed, Versioned, P2P File System*.

Bhaskar, R. (1989). Reclaiming Reality: A Critical Introduction to Contemporary Philosophy, London: Verso, 1989. *History of the Human Sciences*, *3*(3), 443–457. https://doi.org/10.1177/095269519000300309

Bikoff, E. K. (1992). Formation of complexes between self-peptides and MHC class II molecules in cells defective for presentation of exogenous protein antigens. *Journal of Immunology (Baltimore, Md.: 1950)*, *149*(1), 1–8.

Blähser, J., Göller, T., & Böhmer, M. (2021). Thine—Approach for a fault tolerant distributed packet manager based on hypercore protocol. *2021 IEEE 45th Annual Computers, Software, and Applications Conference (COMPSAC)*, 1778–1782. https://doi.org/10.1109/COMPSAC51774.2021.00266

Blum, C., & Zuber, C. I. (2016). Liquid Democracy: Potentials, Problems, and Perspectives. *Journal of Political Philosophy*, *24*(2), 162–182. https://doi.org/10.1111/jopp.12065

Bodo, L., & Trauthig, I. (2022). *Emergent Technologies and Extremists: The DWeb as a New Internet Reality?* GNET (Global Network on Extremism & Technology).

Brinkmann, S., & Kvale, S. (2005). CONFRONTING THE ETHICS OF QUALITATIVE RESEARCH. *Journal of Constructivist Psychology*, *18*(2), 157–181. https://doi.org/10.1080/10720530590914789

Brozović, D. (2023). Societal collapse: A literature review. *Futures*, *145*, 103075. https://doi.org/10.1016/j.futures.2022.103075

Buford, J. F. K., Yu, H. H., & Lua, E. K. (2009). *P2P networking and applications*. Elsevier/Morgan Kaufmann.

Byrne, D., & Callaghan, G. (2022). *Complexity Theory and the Social Sciences: The State of the Art* (2nd ed.). Routledge. https://doi.org/10.4324/9781003213574

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Péan, C. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Cazenave, A., & Nerem, R. S. (2004). Present-day sea level change: Observations and causes. *Reviews of Geophysics*, *42*(3), 2003RG000139. https://doi.org/10.1029/2003RG000139

Chacon, S. (2014). *Pro Git* (Second edition). Apress.

Chen, Y., & Bellavitis, C. (2020). Blockchain disruption and decentralized finance: The rise of decentralized business models. *Journal of Business Venturing Insights*, *13*, e00151. https://doi.org/10.1016/j.jbvi.2019.e00151

Chiles, T. H., Tuggle, C. S., McMullen, J. S., Bierman, L., & Greening, D. W. (2010). Dynamic Creation: Extending the Radical Austrian Approach to Entrepreneurship. *Organization Studies*, *31*(1), 7–46. https://doi.org/10.1177/0170840609346923

Chowdhury, S. R., Roy, A. R., Shaikh, M., & Daudjee, K. (2015). A taxonomy of decentralized online social networks. *Peer-to-Peer Networking and Applications*, *8*(3), 367–383. https://doi.org/10.1007/s12083-014-0258-2

Cobleigh, A. (2020). *TrustNet: Trust-based Moderation Using Distributed Chat Systems for Transitive Trust Propagation*.

Conway, M. E. (1968, April). *How Do Committees Invent?* F. D. Thompson Publications, Inc.

Cooke, A., Smith, D., & Booth, A. (2012). Beyond PICO: The SPIDER Tool for Qualitative Evidence Synthesis. *Qualitative Health Research*, *22*(10), 1435–1443. https://doi.org/10.1177/1049732312452938

Coretti, S., Kiayias, A., Moore, C., & Russell, A. (2022). The Generals' Scuttlebutt: Byzantine-Resilient Gossip Protocols. *Proceedings of the 2022 ACM SIGSAC Conference on Computer and Communications Security*, 595–608. https://doi.org/10.1145/3548606.3560638

Crowston, K., Wei, K., Howison, J., & Wiggins, A. (2012). Free/Libre open-source software development: What we know and what we do not know. *ACM Computing Surveys*, *44*(2), 1–35. https://doi.org/10.1145/2089125.2089127

Daniel, E., & Tschorsch, F. (2022). IPFS and Friends: A Qualitative Comparison of Next Generation Peer-to-Peer Data Networks. *IEEE Communications Surveys & Tutorials*, *24*(1), 31–52. https://doi.org/10.1109/COMST.2022.3143147

Daymon, C., & Holloway, I. (2010). *Qualitative Research Methods in Public Relations and Marketing Communications* (0 ed.). Routledge. https://doi.org/10.4324/9780203846544

De Santo, M. K., & Domptail, S. E. (Eds.). (2023). *Degrowth Decolonization and Development: When Culture Meets the Environment*. Springer International Publishing. https://doi.org/10.1007/978-3-031-25945-6

Derrible, S. (2017). Urban infrastructure is not a tree: Integrating and decentralizing urban infrastructure systems. *Environment and Planning B: Urban Analytics and City Science*, *44*(3), 553–569. https://doi.org/10.1177/0265813516647063

Dietz, T., Shwom, R. L., & Whitley, C. T. (2020). Climate Change and Society. *Annual Review of Sociology*, *46*(1), 135–158. https://doi.org/10.1146/annurev-soc-121919-054614

Drazin, R., & Sandelands, L. (1992). Autogenesis: A Perspective on the Process of Organizing. *Organization Science*, *3*(2), 230–249. https://doi.org/10.1287/orsc.3.2.230

Egyedi, T. M., & Mehos, D. C. (2012). *Inverse Infrastructures: Disrupting Networks from Below*. Edward Elgar Publishing. https://doi.org/10.4337/9781781952290

Ermoshina, K., Halpin, H., & Musiani, F. (2017). Can Johnny build a protocol? Co-ordinating developer and user intentions for privacy-enhanced secure messaging protocols. *Proceedings 2nd European Workshop on Usable Security*. European Workshop on Usable Security, Paris, France. https://doi.org/10.14722/eurousec.2017.23016

Ermoshina, K., & Musiani, F. (2022). *Concealing for Freedom*. Mattering Press. https://doi.org/10.28938/9781912729227

Estrada-Jimenez, L. A., Pulikottil, T., Peres, R. S., Nikghadam-Hojjati, S., & Barata, J. (2021). Complexity theory and self-organization in Cyber-Physical Production Systems. *Procedia CIRP*, *104*, 1831–1836. https://doi.org/10.1016/j.procir.2021.11.309

Faguet, J.-P., Fox, A. M., & Pöschl, C. (2015). Decentralizing for a Deeper, More Supple Democracy. *Journal of Democracy*, *26*(4), 60–74. https://doi.org/10.1353/jod.2015.0059

Fitzgerald, B. (2006). The Transformation of Open Source Software. *MIS Quarterly*, *30*(3), 587. https://doi.org/10.2307/25148740

Freeman, J. (1970). *The tyranny of structurelessness.pdf*.

Friedman, B., Kahn, P. H., & Borning, A. (2008). *Value Sensitive Design and Information Systems*.

Fuchs, C. (2003). The Internet as a Self-Organizing Socio-Technological System. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.458680

Fuchs, C. (2006). The Self-Organization of Social Movements. *Systemic Practice and Action Research*, *19*(1), 101–137. https://doi.org/10.1007/s11213-005-9006-0

Garnaut, R. (2008). *The Garnaut climate change review: Final report*. Cambridge University Press.

Gershenson, C., & Heylighen, F. (2004). How can we think the complex. *arXiv: Adaptation and Self-Organizing Systems*.

Gibbs, G. (2007). *Analyzing Qualitative Data*. SAGE Publications, Ltd. https://doi.org/10.4135/9781849208574

Glasze, G., Cattaruzza, A., Douzet, F., Dammann, F., Bertran, M.-G., Bômont, C., Braun, M., Danet, D., Desforges, A., Géry, A., Grumbach, S., Hummel, P., Limonier, K., Münßinger, M., Nicolai, F., Pétiniaud, L., Winkler, J., & Zanin, C. (2023). Contested Spatialities of Digital Sovereignty. *Geopolitics*, *28*(2), 919–958. https://doi.org/10.1080/14650045.2022.2050070

Gubrium, J., & Holstein, J. (2001). *Handbook of Interview Research*. SAGE Publications, Inc. https://doi.org/10.4135/9781412973588

Haas, J., Mogk, R., Yanakieva, E., Bieniusa, A., & Mezini, M. (2024). LoRe: A Programming Model for Verifiably Safe Local-first Software. *ACM Transactions on Programming Languages and Systems*, *46*(1), 1–26. https://doi.org/10.1145/3633769

Hartgerink, C. (2019). Verified, Shared, Modular, and Provenance Based Research Communication with the Dat Protocol. *Publications*, *7*(2), 40. https://doi.org/10.3390/publications7020040

Heino, O., & Anttiroiko, A.-V. (2015). Inverse infrastructures: Self-organization in the water services. *Water Policy*, *17*(2), 299–315. https://doi.org/10.2166/wp.2014.095

Helmrich, A. M., Markolf, S. A., Li, R., Carvalhaes, T., Kim, Y., Bondank, E., Natarajan, M., Ahmad, N., & Chester, M. (2021). Centralization and decentralization for resilient infrastructure and complexity. *Environmental Research: Infrastructure and Sustainability*, *1*(2), 021001. https://doi.org/10.1088/2634-4505/ac0a4f

Heylighen, F. (2010). *Complexity and Self-Organization*. 1215–1224. https://doi.org/10.1081/e-elis4-120043869

Hoffmann, S., Lazanski, D., & Taylor, E. (2020). Standardising the splinternet: How China’s technical standards could fragment the internet. *Journal of Cyber Policy*, *5*(2), 239–264. https://doi.org/10.1080/23738871.2020.1805482

Hunziker, S., & Blankenagel, M. (2024). Multiple Case Research Design. In *Research Design in Business and Management* (pp. 171–186). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-42739-9_9

Iliadis, A., Siapera, E., & Lokot, T. (2023). Decolonising the internet: An introduction to the #AoIR2022 special issue. *Information, Communication & Society*, *26*(12), 2369–2375. https://doi.org/10.1080/1369118X.2023.2262554

Jean Boulton, Peter M. Allen, & Cliff Bowman. (2015). *Embracing Complexity: Strategic Perspectives for an Age of Turbulence*. https://doi.org/10.1093/acprof:oso/9780199565252.001.0001

Kestano, R. (2022). *Authentic Relating: A Guide to Rich, Meaningful, Nourishing Relationships*. ART International.

Kini, R. B. (2002). Peer-To-Peer Technology: A Technology Reborn. *Information Systems Management*, *19*(3), 74–84. https://doi.org/10.1201/1078/43201.19.3.20020601/37173.10

Kleppmann, M., Wiggins, A., Van Hardenberg, P., & McGranaghan, M. (2019). Local-first software: You own your data, in spite of the cloud. *Proceedings of the 2019 ACM SIGPLAN International Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software*, 154–178. https://doi.org/10.1145/3359591.3359737

Korpal, G., & Scott, D. (2022). *Decentralization and web3 technologies* [Preprint]. https://doi.org/10.36227/techrxiv.19727734.v1

Kropotkin, P. A. (with Jackson, J.-D.). (1902). *Mutual aid: A factor of evolution*. Verlag nicht ermittelbar.

Kvale, S., & Brinkmann, S. (2015). *InterViews: Learning the craft of qualitative research interviewing* (Third edition). Sage Publications.

Lee, M. Y., & Edmondson, A. C. (2017). Self-managing organizations: Exploring the limits of less-hierarchical organizing. *Research in Organizational Behavior*, *37*, 35–58. https://doi.org/10.1016/j.riob.2017.10.002

Leong, C., Pan, S. L., Newell, S., & Cui, L. (2016). The Emergence of Self-Organizing E-Commerce Ecosystems in Remote Villages of China: A Tale of Digital Empowerment for Rural Development. *MIS Quarterly*, *40*(2), 475–484. https://doi.org/10.25300/MISQ/2016/40.2.11

Li, J., & Dabek, F. (2006). F2F: reliable storage in open networks. *In 5th International Workshop on Peer-to-Peer Systems (IPTPS '06).*

Ljungberg, J. (2000). Open source movements as a model for organising. *European Journal of Information Systems*, *9*(4), 208–216. https://doi.org/10.1057/palgrave.ejis.3000373

Madey, G., Freeh, V., & Tynan, R. (2002). *Understanding OSS as a Self-Organizing Process*.

Malodia, S., Dhir, A., Bilgihan, A., Sinha, P., & Tikoo, T. (2022). Meme marketing: How can marketers drive better engagement using viral memes? *Psychology & Marketing*, *39*(9), 1775–1801. https://doi.org/10.1002/mar.21702

Mannell, K., & Smith, E. T. (2022). Alternative Social Media and the Complexities of a More Participatory Culture: A View From Scuttlebutt. *Social Media + Society*, *8*(3), 205630512211224. https://doi.org/10.1177/20563051221122448

Manteghi, M. (2017). Understanding Open Source and Free Software Licensing Mechanism: A Close Review of the Alternative Approach to Traditional Notions of Software Licensing. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3082313

Marley, T. L. (2019). Indigenous Data Sovereignty: University Institutional Review Board Policies and Guidelines and Research with American Indian and Alaska Native Communities. *American Behavioral Scientist*, *63*(6), 722–742. https://doi.org/10.1177/0002764218799130

Masinde, N., & Graffi, K. (2020). *Peer-to-Peer-Based Social Networks: A Comprehensive Survey*. *1*(5), 1–51. https://doi.org/10.1007/s42979-020-00315-8

Mehrabian, A., & Ferris, S. R. (1967). Inference of attitudes from nonverbal communication in two channels. *Journal of Consulting Psychology*, *31*(3), 248–252. https://doi.org/10.1037/h0024648

Meyer, A. (2022). *Range-Based Set Reconciliation* (Version 2). arXiv. https://doi.org/10.48550/ARXIV.2212.13567

Meyer, A. D., Gaba, V., & Colwell, K. A. (2005). Organizing Far from Equilibrium: Nonlinear Change in Organizational Fields. *Organization Science*, *16*(5), 456–473. https://doi.org/10.1287/orsc.1050.0135

Miller, J. H., & Page, S. E. (2007). *Complex adaptive systems: An introduction to computational models of social life*. Princeton Univ. Press.

Monk, A., & Howard, S. (1998). Methods & tools: The rich picture: a tool for reasoning about work context. *Interactions*, *5*(2), 21–30. https://doi.org/10.1145/274430.274434

Musiani, F. (2022). *Infrastructuring* digital sovereignty: A research agenda for an infrastructure-based sociology of digital self-determination practices. *Information, Communication & Society*, *25*(6), 785–800. https://doi.org/10.1080/1369118X.2022.2049850

Neulinger, K., Hannemann, A., Klamma, R., & Jarke, M. (2016). A Longitudinal Study of Community-Oriented Open Source Software Development. In S. Nurcan, P. Soffer, M. Bajec, & J. Eder (Eds.), *Advanced Information Systems Engineering* (Vol. 9694, pp. 509–523). Springer International Publishing. https://doi.org/10.1007/978-3-319-39696-5_31

Ogden, M. (2017). *Dat—Distributed Dataset Synchronization And Versioning*. https://doi.org/10.31219/osf.io/nsv2c

Oram, A. (Ed.). (2001). *Peer-to-peer: Harnessing the benefits of a disruptive technology* (1. ed). O'Reilly.

Oreg, S., & Nov, O. (2008). Exploring motivations for contributing to open source initiatives: The roles of contribution context and personal values. *Computers in Human Behavior*, *24*(5), 2055–2073. https://doi.org/10.1016/j.chb.2007.09.007

Parasuraman, A. (2000). Technology Readiness Index (Tri): A Multiple-Item Scale to Measure Readiness to Embrace New Technologies. *Journal of Service Research*, *2*(4), 307–320. https://doi.org/10.1177/109467050024001

Priest, K. L., Kaufman, E. K., Brunton, K., & Seibel, M. (2013). Appreciative Inquiry: A Tool for Organizational, Programmatic, and Project-Focused Change. *Journal of Leadership Education*, *12*(1).

Reason, P., & Bradbury, H. (2013). *The SAGE handbook of action research: Participative inquiry and practice* (2. ed., paperback ed). SAGE.

Roscam Abbing, R., Diehm, C., & Warreth, S. (2023). Decentralised social media. *Internet Policy Review*, *12*(1). https://doi.org/10.14763/2023.1.1681

Roudometof, V. (2023). Digital glocalization: Theorizing the twenty-first-century ICT revolution. *Frontiers in Communication*, *8*, 1244614. https://doi.org/10.3389/fcomm.2023.1244614

Salve, A. D., Mori, P., Ricci, L., & Pietro, R. D. (2023). *Content privacy enforcement models in decentralized online social networks: State of play, solutions, limitations, and future directions*. *203*, 199–225. https://doi.org/10.1016/j.comcom.2023.02.023

Sandberg, J., & Alvesson, M. (2021). Meanings of Theory: Clarifying Theory through Typification. *Journal of Management Studies, 58*(2), 487–516. https://doi.org/10.1111/joms.12587

Senge, P. M. (1997). THE FIFTH DISCIPLINE. *Measuring Business Excellence, 1*(3), 46–51. https://doi.org/10.1108/eb025496

Shapiro, E. (2023). *Grassroots Systems: Concept, Examples, Implementation and Applications* (Version 4). arXiv. https://doi.org/10.48550/ARXIV.2301.04391

Song, Y. (2023). *Cryptography in the Wild: Briar*.

Stacey, R. D. (1995). The science of complexity: An alternative perspective for strategic change processes. *Strategic Management Journal*, *16*(6), 477–495. https://doi.org/10.1002/smj.4250160606

Stacey, R. D. (1996). *Complexity and creativity in organizations*. Berrett-Koehler.

Tainter, J. A., & Taylor, T. G. (2014). Complexity, problem-solving, sustainability and resilience. *Building Research & Information*, *42*(2), 168–181. https://doi.org/10.1080/09613218.2014.850599

Taleb, N. N. (2016). *Antifragile: Things that gain from disorder* (Random House trade paperback edition). Random House.

Tarr, D., Lavoie, E., Meyer, A., & Tschudin, C. (2019). Secure Scuttlebutt: An Identity-Centric Protocol for Subjective and Decentralized Applications. *Proceedings of the 6th ACM Conference on Information-Centric Networking*, 1–11. https://doi.org/10.1145/3357150.3357396

Thompson, W., & Thompson, M. (2022). *Pulling Back the Curtain on Qualitative Research* (1st ed.). Routledge. https://doi.org/10.4324/9781003320760

Tonellato, M., Tasselli, S., Conaldi, G., Lerner, J., & Lomi, A. (2024). A Microstructural Approach to Self-Organizing: The Emergence of Attention Networks. *Organization Science, 35*(2), 496–524. https://doi.org/10.1287/orsc.2023.1674

Tranos, E. (2013). *The geography of the Internet: Cities, regions and Internet infrastructure in Europe*. Edward Elgar.

Trautwein, D., Raman, A., Tyson, G., Castro, I., Scott, W., Schubotz, M., Gipp, B., & Psaras, Y. (2022). Design and evaluation of IPFS: A storage layer for the decentralized web. *Proceedings of the ACM SIGCOMM 2022 Conference*, 739–752. https://doi.org/10.1145/3544216.3544232

Troncoso, C., Isaakidis, M., Danezis, G., & Halpin, H. (2017). *Systematizing Decentralization and Privacy: Lessons from 15 Years of Research and Deployments*. https://doi.org/10.48550/ARXIV.1704.08065

Tschudin, C. (2022). A connectionless grow-only set CRDT. *Proceedings of the 3rd International Workshop on Distributed Infrastructure for the Common Good*, 25–30. https://doi.org/10.1145/3565383.3566110

van Hardenberg, P., & Kleppmann, M. (2020). *PushPin: Towards production-quality peer-to-peer collaboration*. https://doi.org/10.1145/3380787.3393683

van Lier, B. (2019). *Blockchain Technology: The Autonomy and Self-Organisation of Cyber-Physical Systems*. 145–167. https://doi.org/10.1007/978-3-319-98911-2_5

Vogt, E. E., Brown, J., & Isaacs, D. (2003). *The art of powerful questions: Catalyzing, insight, innovation, and action*. Whole Systems Associates ; Pegasus Communications [distributor].

Weking, J., Mandalenakis, M., Hein, A., Hermes, S., Böhm, M., & Krcmar, H. (2020). The impact of blockchain technology on business models – a taxonomy and archetypal patterns. *Electronic Markets*, *30*(2), 285–305. https://doi.org/10.1007/s12525-019-00386-3

Williams, M., & Moser, T. (2019). *The Art of Coding and Thematic Exploration in Qualitative Research*.

Wylie, C. (2019). *Mindf*ck: Cambridge Analytica and the plot to break America* (First edition). Random House.

Yang, F., Ding, Z., Yu, Y., & Sun, Y. (2023). Interaction mechanism between blockchain and IPFS. *Blockchain*. https://doi.org/10.55092/blockchain20230007

Yang, Y. (2021). *A secure Mesh Messaging service over Android Wi-Fi Aware capabilities*.

12 APPENDIX

A) Interview Guide

B) Interview Transcripts & Notes

C) Coding Results

D) Visualizations

E) Workshop Results