Liquid Democracy for Rating Systems

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Acknowledgements

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Abstract

Liquid democracy is a hybrid decision-making model that allows individuals to either vote directly or delegate their vote to a trusted peer. This project integrates a comprehensive liquid democracy system into vodle, a web-based group decision-making platform, to support more flexible and inclusive participation.

The implementation introduces several key features: transitive delegation, ranked delegation with fall back options, per-option delegation, and a novel vote splitting mechanism based on a trust matrix model. This trust matrix approach – originally proposed by co-supervisor Jobst Heitzig – allows users to express nuanced trust across multiple delegates and was selected as the final vote splitting algorithm for its high expressivity and alignment with vodle's goals of autonomy and transparency.

By combining technical innovations with an intuitive interface, this project enables vodle to adapt to users' varying levels of engagement and expertise. The resulting system empowers users to participate meaningfully in collective decisions without requiring constant direct input, making liquid democracy practical for real-time, web-based environments.

Keywords – liquid democracy, vote delegation, real-time voting, web development, decision-making systems

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Chapter 1

Introduction

1.1 Context and Motivation – TODO

In group settings ranging from online communities to organisations, collective decision making is both essential and difficult to scale. Direct democracy empowers individuals by letting everyone vote on every issue, but struggles with engagement as participation grows. Representative democracy improves scalability but often reduces accountability and flexibility (Ford, 2002; Blum and Zuber, 2016)

Liquid democracy is a hybrid model that aims to balance these trade-offs. It allows individuals to either vote directly or delegate their voting power to others they trust. This approach combines the transparency and agency of direct democracy with the scalability of representation, offering a dynamic alternative for participatory systems.

This project applies liquid democracy within vodle, a web-based platform for group decision making. Vodle allows users to express nuanced preferences across decision options and promotes open, participatory decision making. However, it inherits a common limitation: users may lack the time, interest, or confidence to engage with every decision, leading to underrepresentation and disengagement.

By integrating liquid democracy into vodle, the project aims to give users more flexibility in how their preferences are represented. Delegation features allow users to stay involved even when they choose not to vote directly, making the platform more scalable, inclusive, and responsive to varying levels of user engagement – all while maintaining transparency and user control.

1.2 Project Goals

The goal of this project is to design and implement a liquid democracy system within vodle. This involves building flexible delegation mechanisms that support diverse

participation styles and address the limitations of traditional direct voting.

The system introduces several key features:

- **Ranked delegation**, allowing users to specify trusted delegates in order of preference.
- **Per-option delegation**, enabling different delegates for different decision topics.
- **Vote splitting**, using a trust-based model to distribute voting power across multiple delegates.

These features are designed to enhance participation, reduce the concentration of voting power, and improve the resilience of the platform. The project focuses on creating an intuitive and efficient implementation that aligns with vodle's existing architecture and emphasises user autonomy.

1.3 Structure of This Report

The remainder of this report is structured as follows:

- Chapter 2 outlines the theoretical and technical background, including research into delegation models and related systems.
- Chapter 3 defines the core and extension objectives of the project, along with detailed requirements.
- Chapter 4 presents the architecture and implementation of the delegation features.
- Chapter 5 evaluates the system through testing and feedback.
- Chapter 6 reflects on the planning, risks, and methodology used during development.
- Chapter 7 offers a summary of the project outcomes and directions for future work.

Chapter 2

Background Research

This chapter provides the necessary foundation for designing and implementing a liquid democracy system within vodle. It begins by comparing liquid democracy to traditional models (direct and representative democracy) highlighting its potential to balance participation and scalability through transitive and revocable delegation.

The chapter then examines key limitations of liquid democracy in practice, including delegation cycles, abstentions, and the emergence of super-voters. These issues are explored in detail, alongside the strategies proposed in the literature to mitigate them.

Additionally, real-world deployments of liquid democracy are considered, drawing lessons from systems such as LiquidFeedback and Google Votes. These examples inform both the technical feasibility and design challenges of integrating delegation mechanisms into online platforms.

Finally, the chapter outlines the technical foundations of vodle, including its architecture and existing (incomplete) delegation features. These constraints play a key role in shaping the design choices presented in later chapters.

2.1 Liquid Democracy

While liquid democracy was briefly introduced in Chapter 1, this section provides a more detailed rationale for its relevance – particularly in the context of decision-making systems like vodle.

Direct democracy maximises personal agency and transparency by allowing individuals to vote on every issue. It is often viewed as the most egalitarian form of governance, as it ensures that all participants have a direct say in decisions. However, it becomes impractical at scale. Expecting all users to remain consistently informed and engaged across all issues is unrealistic, particularly in large or heterogeneous groups (Ford, 2002). As Ford observes, the assumption that the majority can or will make

consistently well-informed decisions across a broad range of topics does not hold in practice. This can lead to voter fatigue, low turnout, and uninformed or irrational decision-making.

Representative democracy addresses the scalability problem by allowing users to elect officials who vote on their behalf. This model is forms the basis of most modern democracies, enabling stable governance in large populations. It allows representatives to develop expertise and reduces the decision-making burden on the general population. However, the model has key limitations: between elections, representatives may act without sufficient accountability, and voters have limited influence over individual decisions (Blum and Zuber, 2016). As a result, decision-making can become misaligned with the evolving preferences of the electorate.

Liquid democracy attempts to reconcile these competing trade-offs. It allows each participant to either vote directly or delegate (entrust) their vote to another participant (a delegate). Delegates can in turn delegate their votes, forming chains of trust. This is known as *transitive delegation*: a vote is passed along the chain until it reaches a user who casts it. Delegations are also *revocable*, allowing users to reclaim and reassign their vote at any time.

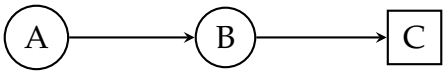


Figure 2.1: Example of transitivity in action: Voter A delegates to Voter B, who delegates to Voter C. Voter C then casts a vote with the weight of three individuals (A, B and C).

By supporting both direct and delegated participation, liquid democracy allows users to engage at varying levels depending on their interest, expertise, or availability. This flexibility makes it a promising model for decision making in online platforms such as vodle, where participation levels naturally fluctuate.

2.1.1 Issues With Liquid Democracy

While liquid democracy offers an elegant compromise between agency and scalability, it introduces several non-trivial implementation challenges. This section identifies three core issues that threaten its robustness and fairness in practice: cycles in delegation chains, vote loss due to abstentions, and the disproportionate influence of super-voters.

To support this discussion, the following diagram legend is used to visually distinguish between voter behaviours:

Role	Description	Symbol
Delegated voter	Has delegated their vote and does not cast one directly	Circle
Casting voter	Casts their own vote and has not delegated	Square
Abstaining voter	Neither delegates nor casts their own vote	Triangle

Table 2.1: Diagram legend showing symbols used for different voter behaviours in a liquid democracy context.

Delegation Cycles

Delegation cycles occur when a vote is delegated in such a way that it ends up forming a loop (Brill et al., 2022), preventing the vote from reaching a final casting voter. For example, if Alice delegates her vote to Bob, Bob delegates to Charlie, and Charlie delegates back to Alice, the votes become trapped in a cycle (see Figure 2.2) and can be treated as a loss of representation (Christoff and Grossi, 2017).

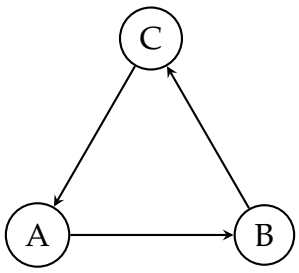


Figure 2.2: Delegation cycle: A delegates to B, B to C, and C back to A.

This issue is particularly problematic because it can nullify votes without the affected users becoming aware of it. In systems where cycles are not explicitly detected and handled, these votes could be discarded silently, potentially changing the final outcome of the votes.

A simplistic method to prevent cycles is to check whether a delegation would create a cycle before allowing it. For example, if Alice tries to delegate her vote to Bob, the system checks whether Bob has already directly or indirectly delegated their vote to Alice. If so, the delegation is rejected. However, this approach can be cumbersome and may lead to a poor user experience, as users may not understand why their delegation was denied.

Delegation cycles are particularly likely to emerge in dynamic, real-time voting systems like vodle, where users can add, remove, or modify delegations at any time. Even delegation chains that are initially valid may later form part of a cycle as other participants update their preferences. This makes cycle detection not just a one-off validation step, but an ongoing requirement for maintaining consistency and ensuring vote resolution remains reliable.

Abstentions

A voter abstains by neither casting a vote nor delegating it to another user (Brill et al., 2022). This includes both deliberate abstention, where a voter knowingly chooses not to participate, and passive abstention, where a voter may be unaware of an ongoing poll or are unable to engage with it.

Abstentions are especially impactful when they occur at the end of a larger delegation chain (see Figure 2.3), as all votes passed along the chain to that voter are effectively lost (Brill et al., 2022). Additionally, the voters whose decisions were passed along the chain may also be unaware that their votes have been nullified, worsening the effect of the abstention.

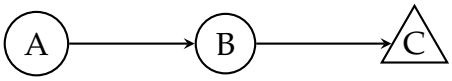


Figure 2.3: Delegation chain ending in abstention: A delegates to B, B to C. C abstains, causing the votes of A and B to be lost.

Super-Voters

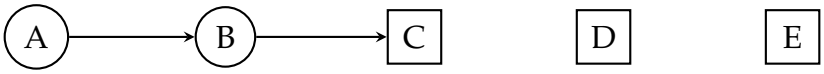


Figure 2.4: Super-voter: A delegates to B, B to C. No matter which vote D or E cast, C's vote will always determine the outcome as it has a weight of 3.

In liquid democracy, a *super-voter* is a user who receives a large number of delegations, thereby accumulating significant voting power (Kling et al., 2015). While such concentration may arise from genuine trust, it risks creating imbalances that contradict the egalitarian goals of the system. Super-voters can effectively act as unelected representatives – potentially swaying results with little accountability.

Even when systems allow voters to revoke delegations at any time, many users may not actively monitor how their vote is used. This can lead to persistent power structures where a small number of users hold substantial, often unnoticed, influence over outcomes.

This phenomenon is not just theoretical. In the German Pirate Party's use of LiquidFeedback, some participants became so dominant that their votes carried decree-like weight, even though they were not formally elected (Sven Becker, 2012; Kling et al., 2015). While Kling et al. (2015) observed that these super-voters generally aligned with majority opinion, contributing to system stability rather than distorting it, their disproportionate influence still raises concerns about transparency and the extent to which individual voters retain meaningful control over their vote.

Super-voting is not confined to traditional political platforms. In decentralised autonomous organisations (DAOs), which use token-based voting on blockchains, similar patterns emerge. Hall and Miyazaki (2024) found that in many DAOs, voting power was highly concentrated among a few delegates due to low overall participation. In some cases, such as Gitcoin, over 90% of votes cast were controlled by the top five delegates.

These examples underscore the importance of delegation mechanisms that can curb excessive power accumulation. Techniques such as vote splitting and delegation caps are essential to preserving fairness, especially in systems like vodle that prioritise inclusivity and trust-based participation.

2.1.2 Variations of Liquid Democracy

This section explores several proposed extensions to liquid democracy that address the limitations outlined above. While many models offer theoretical advantages, particular attention is paid to ranked delegation and vote splitting – two techniques that are not only promising from a fairness and robustness perspective, but also feasible to implement within vodle's existing architecture.

The challenges discussed in the previous section, such as delegation cycles, vote loss due to abstentions, and the emergence of super-voters, highlight inherent vulnerabilities in the standard liquid democracy model. To mitigate these issues, enhancements have been proposed that modify how delegations function. These include techniques that allow voters to specify multiple delegates or distribute their vote to multiple casting voters. Each approach introduces different trade-offs and requires algorithmic support to ensure sound and interpretable outcomes.

The following subsections present several such variations, along with the algorithms that can be used to implement them.

Ranked Delegation – TODO: ADD DIAGRAMS

Ranked delegation improves liquid democracy by allowing voters to list several trusted delegates in order of preference. Instead of choosing just one delegate, a voter can specify a ranked list so that if their top choice is unavailable (e.g. due to abstention or being a part of a delegation cycle) the system can use the next delegate specified.

Implementing ranked delegation requires a mechanism to decide among multiple possible delegation paths – a route that a vote can take through the delegation graph to reach a casting voter. This is done through a *delegation rule*, a function that, given a ranked delegation instance and a delegating voter, selects a unique path leading to a *casting voter* (Brill et al., 2022).

The following key properties help evaluate these delegation rules:

- **Guru Participation:** Ensures that a voter accepting delegated votes (a "guru") is never worse off by doing so. Receiving additional delegations should not decrease their influence over the final outcome (Kotsialou and Riley, 2020).
- **Confluence:** Guarantees that each delegating voter ends up with one clear and unambiguous delegation path. This property simplifies vote resolution and enhances transparency (Brill et al., 2022).
- **Copy Robustness:** Prevents strategic manipulation where a voter might mimic their delegate's vote outside the system to gain extra influence. A copy-robust rule makes sure that duplicating a vote externally does not yield more combined power than a proper delegation (Brill et al., 2022; Behrens and Swierczek, 2015).

The literature considers several delegation rules, each with distinct trade-offs:

Depth-First Delegation (DFD): Selects the path beginning with the highest-ranked delegate, even if the resulting chain is long. Although it prioritises individual trust preferences, DFD can violate guru participation (Kotsialou and Riley, 2020).

Breadth-First Delegation (BFD): Chooses the shortest available delegation path and uses rankings only to resolve ties. This approach usually produces direct, predictable chains and satisfies guru participation, although it might sometimes assign a vote to a lower-ranked delegate (Kotsialou and Riley, 2020; Brill et al., 2022).

MinSum: Balances path length and delegation quality by selecting the path with the lowest total sum of edge ranks. Due to this, MinSum avoids both unnecessarily long chains and poorly ranked delegations (Brill et al., 2022).

Diffusion: Constructs delegation paths in stages by assigning votes layer by layer based on the lowest available rank at each step. This method tends to avoid poor delegations but can sometimes produce unintuitive outcomes due to its tie-breaking procedure (Brill et al., 2022).

Leximax: Compares paths based on their worst-ranked edge. This ensures that especially low-ranked delegations are avoided early in the path while maintaining confluence (Brill et al., 2022).

BordaBranching: Takes a global view of the delegation graph by selecting a branching that minimises the total rank across all delegation edges. It satisfies both guru participation and copy robustness, though it is more computationally intensive (Brill et al., 2022).

In summary, ranked delegation enhances liquid democracy by reducing the risk of lost votes. The choice of delegation rule not only affects system efficiency but also

influences fairness and robustness. While simpler methods such as DFD and BFD are easier to implement, advanced rules like MinSum, Leximax, and BordaBranching offer stronger guarantees and are better suited for practical deployment in platforms such as vodle.

Based on these considerations, the project adopts the MinSum rule. It offers a clear trade-off between delegation quality, computational efficiency, and user interpretability, making it well-suited for deployment within vodle. By selecting the path with the lowest total rank sum, MinSum prioritises higher-ranked delegates while avoiding unnecessarily long or indirect chains. This supports user trust and clarity by ensuring that final delegation paths reflect stated preferences in an understandable way.

Vote Splitting – TODO: ADD DIAGRAMS

Traditional delegation systems, which require voters to delegate their entire vote to a single individual, introduce significant risks such as vote loss through delegate abstentions, delegation cycles, and excessive concentration of voting power in the hands of a few super-voters. To mitigate these issues, vote splitting allows voters to divide their voting power among multiple delegates, rather than assigning it entirely to one. This approach provides greater flexibility and robustness while preserving voter intent more accurately.

Vote splitting offers several key advantages:

- **Increased resilience:** Distributing votes across multiple delegates mitigates the effect of abstentions by individual delegates.
- **Reduced concentration of power:** Allowing partial votes to different delegates decreases the likelihood of any single delegate becoming a super-voter.
- **Enhanced voter expression:** Voters can more precisely express their preferences and trust levels by allocating voting power proportionally to multiple individuals.

Several methodologies for implementing vote splitting have been explored in the literature, each with its strengths and weaknesses:

Equal Vote Distribution (Degrave, 2014)

Degrave's approach allows voters to distribute their votes evenly among multiple delegates. Voters select a group of delegates, and their vote is equally distributed amongst those that do not abstain. Although this system is intuitive and reduces the

impact of abstentions, it lacks flexibility as voters cannot express differing trust levels towards each delegate. Additionally, a critical limitation is the inability for voters to allocate any portion of their vote to themselves, meaning voters are forced to either delegate their entire voting power or none of it, severely limiting personal control over a user's final vote.

Fractional Delegation (Bersetche, 2024)

Bersetche et al. introduce fractional delegation, allowing voters to explicitly assign different weights to each chosen delegate, including themselves. Delegates each receive a specified fraction of the voter's total voting power, reflecting the voter's nuanced trust and preference levels. This approach captures detailed voter preferences accurately and allows for greater personal agency compared to equal vote distribution. However, fractional delegation introduces additional complexity in managing and tracking these weighted delegations. Users must explicitly manage multiple numerical allocations, which may increase cognitive load and complicate user interfaces.

Trust Matrix Model (proposed by Heitzig) – TODO: convergence + performance implications

This model was originally proposed by Jobst Heitzig, co-supervisor of this project, as a novel and highly expressive approach to vote splitting. It allows voters to define trust values $\text{trust}_{i,j}$ for multiple delegates, including themselves, and combines these into an effective rating via an iterative computation:

$$\text{eff}_i = \text{trust}_{i,i} \cdot \text{self}_i + \sum_{j \neq i} \text{trust}_{i,j} \cdot \text{eff}_j \tag{2.1}$$

Here, each voter's trust values (including self-trust) must sum to at most 1. The iterative computation continues until the change in effective ratings between iterations falls below a predefined threshold ϵ. This approach offers the highest granularity and expressive power, allowing voters to precisely articulate nuanced trust relationships among multiple delegates. However, it comes with considerable computational complexity and potential convergence issues, especially in large networks with dense delegation relationships. Additionally, users may find it challenging to specify and manage such detailed trust matrices, potentially impairing system usability.

Summary of Approaches

- **Equal Vote Distribution (Degrave)** excels in simplicity and ease of implementation, ensuring robustness through straightforward delegation. However, it sig-

nificantly limits voter expression and prohibits voters from allocating votes to themselves.

- **Fractional Delegation (Bersetche)** provides greater flexibility, permitting detailed voter preference expression, including self-allocation of votes. This method increases both computational complexity and interface complexity.
- **Trust Matrix Model** offers the highest expressivity and detail in delegation relationships, capturing complex trust dynamics. However, this method entails substantial computational overhead and introduces complexity in terms of usability and understanding for voters.

Each vote-splitting method balances voter expressivity, computational complexity, and ease of implementation differently. After evaluating these trade-offs, this project selects the trust matrix model for its high expressiveness and compatibility with vodle's principles of autonomy and transparency. While more computationally intensive, it captures nuanced trust relationships and enables fine-grained participation – both essential for resilient, inclusive decision-making at scale.

2.2 Existing Implementations of Liquid Democracy

To understand how liquid democracy can be integrated into vodle, it is important to examine how similar systems have been implemented in real-world contexts. This section explores two implementations, LiquidFeedback and Google Votes, that offer valuable insights into the technical, social, and usability challenges associated with applying liquid democracy at scale.

2.2.1 LiquidFeedback

LiquidFeedback is one of the earliest and most influential real-world implementations of liquid democracy. Developed as an open-source platform, it was notably adopted by the German Pirate Party in 2010 to facilitate internal policy-making through online participation (Behrens et al., 2014). The platform allowed members to submit proposals, debate them in structured phases, and vote either directly or via transitive delegation.

In LiquidFeedback, users could choose different delegates for different topics, allowing them to assign their vote to someone they trusted on a specific issue. These choices remained in place until the user changed them, which meant that certain individuals could gradually accumulate more influence if others did not update their delegations.

When multiple proposals were put forward, the system used a ranking-based voting method (such as the Schulze method) to decide which one should win. This approach compares each proposal against the others and selects the one that would win the most head-to-head match ups. Importantly, the system only accepted a proposal if it clearly beat the alternative of doing nothing, helping to avoid unnecessary or unpopular changes.

In practice, the Pirate Party's use of LiquidFeedback revealed several key dynamics relevant to this project. The platform was successful in enabling large-scale participation and crowd sourced policy formation, but it also demonstrated common risks of liquid democracy. Such as the existence of super-voters, as discussed previously.

Another practical issue was the complexity of the system. LiquidFeedback was difficult to understand for many users, especially those unfamiliar with concepts like transitive delegation or multi-stage voting which limited its accessibility and contributed to declining engagement over time (Kling et al., 2015).

For a platform like vodle, the experience of LiquidFeedback highlights several important design considerations. First, user interfaces must be intuitive enough to allow voters to participate without needing deep technical knowledge. Second, the user must know the status of their delegation at a glance - improving the understanding of the platform. Finally, ensuring that votes lead to visible and actionable outcomes is critical for maintaining user engagement.

2.2.2 Google Votes

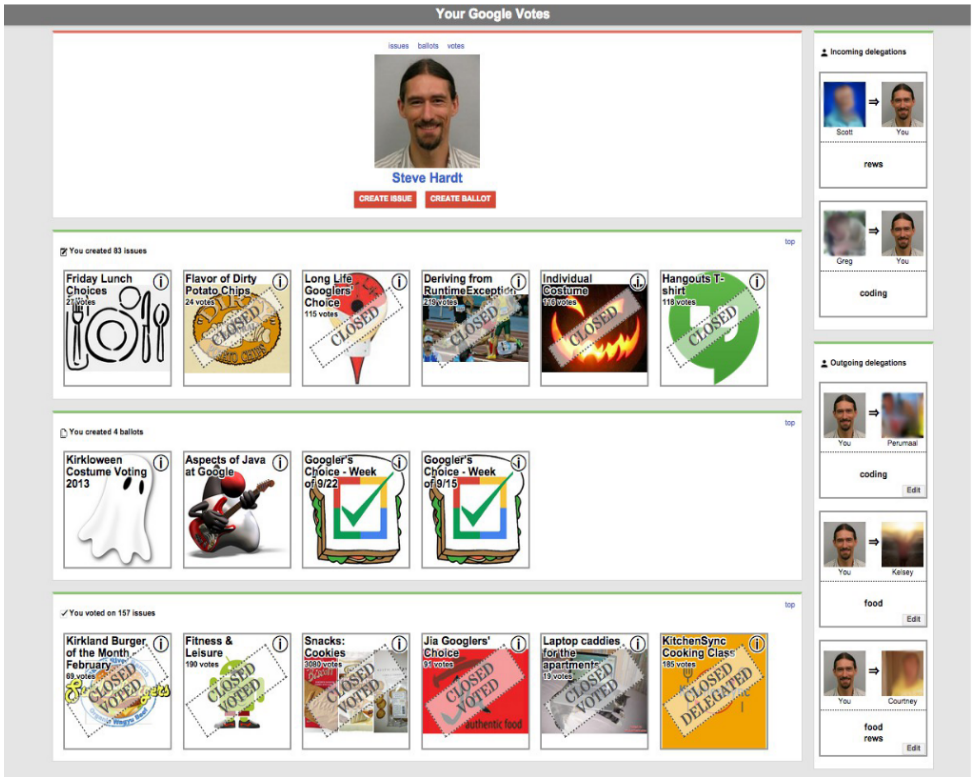


Figure 2.5: Screenshot taken from Hardt and Lopes (2015) showing the user interface of Google Votes.

Google Votes was an internal experiment at Google designed to explore the practical application of liquid democracy within a corporate environment. Built on top of the company's internal Google+ social network, it operated between 2012 and 2015 and allowed employees to participate in decision making by either voting directly or delegating their vote to a colleague (Hardt and Lopes, 2015).

Delegations in Google Votes were category-specific, meaning that users could choose different delegates for different areas of interest, such as food, events, or technical infrastructure. These delegations were persistent but could be overridden at any time, giving users flexibility to either rely on trusted experts or vote independently as needed. The system supported transitive delegation and allowed users to reclaim control by casting their own vote, even after delegating.

The platform placed strong emphasis on usability and transparency. Delegation features were rolled out incrementally, with additional tools such as voting power estimates and delegation advertisements helping users understand their influence. One key design principle was what the authors called the "Golden Rule of Liquid Democracy": if a user delegates their vote, they should be able to see how it is being used. To accomplish this, users received notifications when their delegate voted, and all

votes were visible to the relevant group. This encouraged accountability and gave voters confidence that their delegated votes were being used appropriately.

While Google Votes was never made publicly available, it served as a successful demonstration of liquid democracy in a structured, real-world setting. It showed that being able to delegate votes could improve engagement and decision making within large organisations, especially when designed with attention to user experience. For vodle, the system provides a concrete example of how features like topic-specific delegation, transparency tools, and real-time voting feedback can make liquid democracy more practical and accessible.

2.3 Agent Based Modelling

Agent-based modelling (ABM) is a computational approach used to simulate the actions and interactions of autonomous agents in order to assess their effects on a system as a whole. It is particularly suited for exploring complex, dynamic systems where behaviour emerges from local interactions between individual entities (agents) rather than being dictated by central control. ABM has been widely applied in domains such as economics, sociology, and ecology to study decentralised systems, market dynamics, and collective behaviours (Bonabeau, 2002).

The need to explore ABM arises due to the project's goal of introducing a vote-splitting mechanism that hasn't been explored before into vodle. Traditional analysis alone may not effectively capture the dynamic interactions or unintended consequences that can emerge from this novel feature. Through ABM, it is possible to simulate realistic voting scenarios, track delegation chains, identify potential power imbalances, and anticipate challenges. These simulations can reveal performance insights and inform design decisions before implementing the mechanisms within the live platform.

Several widely used ABM frameworks exist, each with their own strengths and drawbacks relevant to this project:

- **NetLogo** (Tisue and Wilensky, 2004) is a highly accessible and widely adopted modelling platform known for its user friendly graphical interface and ease of learning. It offers rapid prototyping capabilities and excellent visualisation features, allowing clear communication of results. However, very complicated models are not compatible with it.
- **Repast** (Collier, 2003) provides a powerful and versatile suite of tools for building large scale, computationally intensive simulations. It supports distributed

computing, which is beneficial for extensive delegation networks with potentially thousands of agents. However, Repast has a steep learning curve, which could hinder its compatibility with this heavily time restricted project.

- **Mesa** (Kazil et al., 2020) is an open source framework written in Python and specifically designed for agent based modelling. Its advantage lies in its integration with Python's ecosystem of data science libraries. Simulations built with Mesa can easily make use of tools such as NumPy and pandas for efficient data processing, and Matplotlib or Seaborn for visualising model outputs. This compatibility allows for rapid analysis and iteration, while also significantly lowering the learning curve for developers already familiar with Python. Mesa offers a practical balance between usability and computational flexibility, making it well suited for customisable and moderately large simulations.
- **Agents.jl** (Vahdati, 2019) is a high-performance agent-based modelling framework written in Julia. Due to Julia's speed and efficiency, it is suitable for large-scale and computationally demanding simulations. The framework is designed to be user-friendly, with a syntax that is approachable for those familiar with scientific computing. However, the Julia ecosystem is less mature compared to Python's, which may limit the availability of additional libraries and resources. However, this trade off may be acceptable for highly performance driven solutions.

Given the time constraints of this project, Mesa offers a practical and efficient solution. Its Python-based interface and straightforward setup allow for rapid development without the overhead of learning a new framework. This ease of use enables more time to be spent designing meaningful experiments and analysing results, rather than configuring tooling.

2.4 Vodle

To effectively explore and implement liquid democracy mechanisms, it is essential to understand the design and technical context of the platform into which they are being integrated. Vodle is a web based decision-making tool developed to support participatory group processes through interactive polls and transparent aggregation methods. Its goal is to provide users with flexible, fine grained input mechanisms that encourage compromise between voters, while maintaining accessibility and usability across a broad and diverse user base.

This section introduces the core architecture of vodle, including its underlying rating system (MaxParC) and the technologies that support its operation. These technical

foundations were instrumental in shaping the design and feasibility of the advanced delegation features developed in this project. In addition, the platform's design philosophy is examined, providing a basis for the principles that guided the implementation of new components.

2.4.1 MaxParC

MaxParC (Maximum Partial Consensus) is the rating system used in vodle to aggregate user preferences and determine poll outcomes. Introduced by Heitzig et al. (2024), MaxParC was designed to address common limitations of traditional voting systems, particularly the tendency for majority rule to overlook minority preferences. Its goal is to balance fairness, consensus, and efficiency in collective decision making.

In MaxParC, each user rates an option on a scale from 0 to 100. This rating reflects the user's willingness to approve that option based on how many other users also support it. Specifically, a rating of x means that the voter will approve the option if fewer than x% of participants disapprove. A rating of 0 means the option is never approved, while 100 means it is always approved regardless of others' opinions. This structure transforms a simple rating into a conditional approval, allowing for a more nuanced expression of preferences with the potential for compromise.

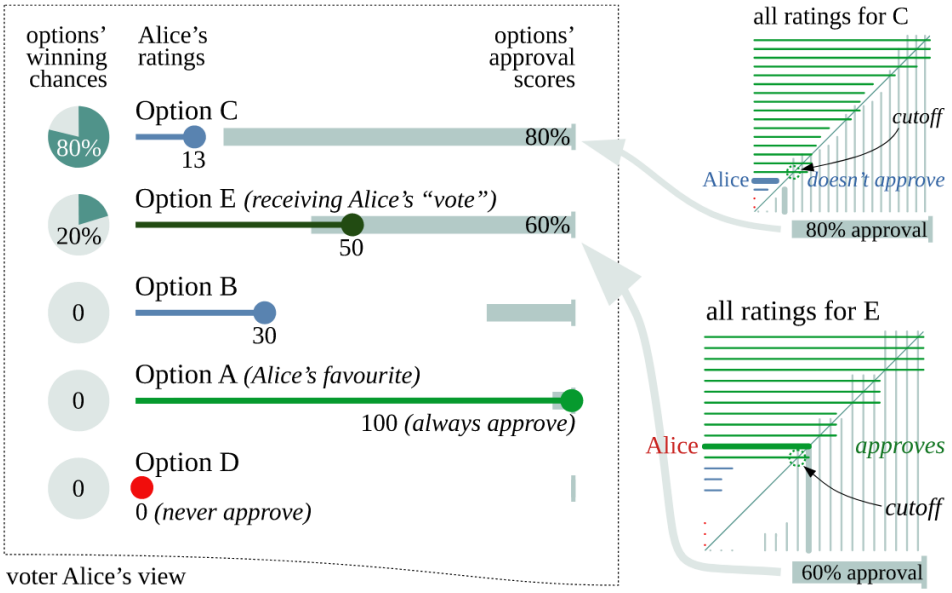


Figure 2.6: Visual representation of MaxParC from the perspective of a voter (Alice). Ratings represent conditional approval thresholds. An option is counted as approved by Alice if the approval bar (light grey) overlaps with her rating needle. Graphic from Heitzig et al. (2024).

Understanding how MaxParC processes ratings is essential for this project, as the proposed vote splitting mechanism must operate within its conditional approval frame-

work. When a user splits their vote among multiple delegates, the system must ensure that their own rating continues to contribute appropriately. Specifically, if a user delegates $x\%$ of their rating to others, their final rating must not fall below $(100 - x)\%$ of their original input. This constraint guarantees that the user's approval remains proportionally represented, even when part of their voting power is passed on to others.

Integrating liquid democracy into vodle therefore requires careful design to align with MaxParC's logic, ensuring both technical compatibility and conceptual consistency.

2.4.2 Technical Architecture and Implementation Constraints

Understanding vodle's technology stack is crucial to successfully integrate liquid democracy features into the existing platform. Since the project involves adding complex delegation and voting logic, it's important to appreciate the constraints and benefits of the technologies currently used in vodle, as they directly influence the design and implementation choices.

Angular

Vodle is built with Angular (Angular Team, 2024), a TypeScript based frontend framework created by Google. Angular's modularity and structured component system provides a strong foundation for incremental development, essential when introducing new features such as ranked delegation that build upon existing components. Its clear separation of concerns helps maintain readable and maintainable code, simplifying debugging and future enhancements. This is particularly beneficial as the delegation logic is expected to grow in complexity and build upon existing components as the project progresses.

Ionic Framework

The Ionic (Ionic Team, 2024) framework complements Angular by enabling the creation of responsive, mobile-compatible applications from a single codebase. Given vodle's goal of broad user participation, Ionic ensures that its functionalities remain consistent and accessible across both desktop and mobile devices. For this project, new delegation features must be designed to work seamlessly within the existing Ionic framework, ensuring that they are visually appealing and user-friendly on all platforms, including mobile devices.

CouchDB

CouchDB (Apache CouchDB Project, 2024) is vodle's primary data storage method and communicates directly with the client through HTTP requests, meaning there is no dedicated backend. This architecture places significant computational responsibilities on the client-side Angular application, including the handling of delegation chains, cycle detection, and the computation of final vote outcomes. Furthermore, since CouchDB stores data exclusively as JSON-formatted strings, complex delegation structures and voting relationships must be serialised and de-serialised on the client side.

The lack of server-side computation means the delegation algorithms must be designed with client-side efficiency in mind, ensuring performance remains acceptable even as delegation complexity increases. Thus, the choice of algorithms for liquid democracy features, such as those to resolve conflicting delegation paths, is directly influenced by CouchDB's architectural constraints.

These technological considerations (covered in more detail in Section 4.1) strongly shaped the practical implementation of liquid democracy in vodle. They necessitated a focus on efficient client-side logic as well as careful management of data flow.

2.4.3 Partially Implemented Delegation in Vodle

Vodle contained an incomplete implementation of vote delegation at the beginning of the project. While this functionality was not exposed to end users and had never been deployed in a working state, several components of a delegation system were already present in the codebase. These included an invitation based mechanism for creating delegations, along with the user interface elements required for it to function.

This implementation also attempted to prevent delegation cycles, but its behaviour was inconsistent. Because delegation graphs were stored only in local memory and not synchronised across clients, different browsers could have divergent views of the delegation state. As a result, delegation actions that passed cycle checks on one client could fail on another, undermining the reliability of the system.

Although inactive and incomplete, this partial implementation helped clarify some of the challenges involved in integrating liquid democracy into vodle – in particular those related to consistency, synchronisation, and user experience. It also provided a foundation of interface patterns and conceptual models that were built upon the development of the project.

Further discussion of the issues with this implementation as well as how it was adapted, improved, or replaced can be found in Chapter 4.

2.4.4 Design Philosophy – TODO

2.5 Summary

The background research presented in this chapter has provided the necessary foundation for designing and implementing advanced delegation features within vodle. Initially, the research highlighted critical limitations in traditional liquid democracy systems, such as the formation of delegation cycles, the risks associated with abstentions, and the disproportionate influence of super-voters. These insights showed the need for implementing delegation mechanisms that are capable of addressing these challenges effectively.

Research into these mechanisms revealed several promising methods. Ranked delegation was found to be an effective approach for reducing the risk of lost votes, with the MinSum delegation rule being particularly suitable due to its clear balance of efficiency, interpretability, and fairness. Vote splitting was identified as a valuable strategy to allow voters greater flexibility by distributing their influence among multiple trusted delegates. Additionally, the concept of delegating different options to distinct delegates was supported by practical experiences from Google Votes, where topic-specific delegations improved user engagement and representation accuracy.

Among the vote splitting methods explored, the trust matrix model stood out for its expressiveness and alignment with vodle's goals of user autonomy and flexibility. By allowing voters to articulate nuanced trust relationships across multiple delegates, including themselves, the model offers a compelling balance between representation quality and individual control. While more computationally intensive than simpler approaches, it presents a viable strategy for robust vote splitting within a real-time voting system.

The technological constraints of vodle itself, especially the reliance on client-side processing due to the CouchDB architecture, demonstrated the need for efficient, lightweight implementation strategies.

These insights collectively define the project's objectives, which are formalised in the following chapter. The objectives are designed explicitly to address the limitations uncovered in the research, ensuring the integration of liquid democracy into vodle is practical, user-friendly, and aligned with established best practices.

Chapter 3

Project Objectives

This chapter outlines the milestones of the project. These objectives were derived from the background research and are designed to address the technical and theoretical challenges identified with traditional delegation systems.

To manage the project effectively, the objectives are divided into two categories: **core objectives**, which form the backbone of the implementation and are essential to meeting the project's main goals, and **extension objectives**, which provide additional insight or value.

Later in the chapter, each objective is broken down into specific functional and non-functional requirements. This structure helps to clarify expectations, guide implementation, and provide clear criteria for evaluating whether each objective has been met.

Core Objectives:

1. **Implement a Core Delegation Model into Vodle:** Build upon the existing, partially implemented delegation code within the vodle platform to create a fully functional system, including resolving key challenges such as cyclic delegations.
2. **Implement Ranked Delegation into Vodle:** Add a backup delegation mechanism to vodle, allowing users to specify up to 3 delegates.
3. **Implement a Vote Splitting Delegation Mechanism into Vodle:** Add functionality to vodle to delegate fractions of their rating to different delegates. Use the *will come back to when research written up* system to calculate final ratings.
4. **Implement the Ability to Delegate Individual Options to Different Users**: Allow users to delegate the ratings of specific options to different delegates.

Extension Objective:

1. **Simulate Delegation Mechanisms:** Perform agent-based modelling to analyse the effectiveness of various delegation systems, including those outlined in Objectives 1, 2 and 3.

3.1 Project Requirements

The project objectives represent high-level goals that must be translated into specific, actionable requirements. This process is essential for clarifying the scope of the work, ensuring comprehensive coverage of each objective, and establishing a structured foundation for both implementation and evaluation.

To support this, requirements are organised into two categories: functional (F) and non-functional (NF). Functional requirements describe the core behaviours and features the system must support, while non-functional requirements define performance, usability, and other quality-related constraints (Sommerville, 2016). Distinguishing between these categories helps ensure that both the system's functionality and overall user experience are properly addressed.

Each requirement is formulated to be measurable and testable. This allows for objective evaluation during development, facilitates verification against the project goals, and helps identify areas for improvement as the system evolves.

3.1.1 Implement a Core Delegation Model into Vodle

Functional Requirements

- **FR1:** The system shall correctly handle the delegation process from invitation to acceptance.
  - **FR1.1:** The system shall allow users to invite others to act as their delegate.
  - **FR1.2:** The system shall allow invited users to accept delegation requests.
  - **FR1.3:** The system shall prevent users from accepting their own delegation invitations.
  - **FR1.4:** The system shall detect and prevent the formation of delegation cycles.
- **FR2:** The system shall provide users with a clear view of their current delegation, including the ability to revoke it at any time.
- **FR3:** The system shall resolve delegations transitively, such that if User A delegates to B and B delegates to C, User C is the final casting voter for A's vote.

- **FR4:** The system shall allow users to override a delegate's decision for specific poll options by submitting a direct vote.
- **FR5:** The user interface for delegation shall be intuitive and accessible, with clear instructions and minimal friction to perform delegation actions.

Non-Functional Requirements

- **NFR1:** All delegation-related data must be stored in a JSON-encoded format, ensuring compatibility with the existing vodle CouchDB database.
- **NFR2:** Any changes to the database schema must be backward compatible, ensuring that existing data is not lost or corrupted during the upgrade process.
- **NFR3:** Any additional data stored in the database must be encrypted, using the same encryption method as the existing data, to ensure user privacy and consistency with the existing system.
- **NFR3:** The system shall preserve user privacy by ensuring that individual voting preferences and delegation choices are not visible to other users. The only information visible to a delegated user shall be the final vote cast on their behalf.

3.1.2 Implement Ranked Delegation into Vodle

Functional Requirements

- **FR1:** The system shall allow users to specify a ranked list of up to 3 delegates for each poll, with the ranking applying to all options within that poll.
- **FR2:** The system shall apply the MinSum delegation rule to resolve each voter's delegation path based on their ranked list of delegates.
- **FR3:** The system shall allow users to override the ranked delegation by submitting a direct vote for specific poll options.
- **FR4:** The system shall provide users with a clear view of their ranked delegation choices, including the ability to alter their rankings or revoke them at any time.

Non-Functional Requirements

- **NFR1:** The system shall ensure that the ranked delegation process does not introduce significant latency in the voting process, maintaining a response time of less than 2 seconds for delegation-related actions when the number of delegates is less than 100.

- **NFR2:** The user interface for ranked delegation shall be intuitive and accessible, with clear instructions and minimal friction to perform delegation actions.
- **NFR3:** The system shall ensure that any data related to ranked delegation is stored in a JSON-encoded format, ensuring compatibility with the existing vodle CouchDB database.

3.1.3 Implement a Vote Splitting Delegation Mechanism into Vodle

Functional Requirements

- **FR1:** The system shall allow users to delegate their vote to multiple delegates simultaneously for a single poll.
- **FR2:** The system shall allow users to assign a weight to each delegate such that the total weight does not exceed 0.99.
- **FR3:** The system shall use the algorithm described in subsection **??** to calculate the final rating for each option based on the weights assigned to each delegate.
- **FR5:** The system shall provide users with a visual interface to edit the weights assigned to each delegate, with either sliders or numeric inputs for easy adjustment.

Non-Functional Requirements

- **NFR1:** The system shall ensure that vote-splitting calculations are performed entirely on the client side to comply with vodle's CouchDB architecture.
- **NFR2:** All related data must be serialised as JSON strings to ensure compatibility with the CouchDB backend.
- **NFR3:** The user interface for vote splitting shall be intuitive and allow users to adjust weights easily, using sliders or numeric inputs.

3.1.4 Implement the Ability to Delegate Individual Options to Different Users

Functional Requirements

- **FR1:** The system shall allow users to assign different delegates for each individual option or subset of options within a poll.

- **FR2:** The system shall ensure that each delegated option is resolved independently, using the appropriate delegate's vote for that option.
- **FR3:** The system shall allow users to override a delegate's vote for a specific option by submitting their own rating.
- **FR4:** The system shall provide a user interface for viewing or revoking each individual delegation.

Non-Functional Requirements

- **NFR1:** The delegation interface must be intuitive and clearly indicate which delegate is assigned to each option, ensuring ease of use.
- **NFR2:** The delegation data must be serialised in a format compatible with CouchDB (e.g., JSON-encoded) to maintain compatibility with vodle's storage system.

3.1.5 Simulate Delegation Mechanisms

Functional Requirements

- **FR1:** The simulation system shall model individual agents representing voters, each capable of voting, abstaining, or delegating their vote according to a selected delegation rule.
- **FR2:** The system shall support multiple delegation mechanisms, including standard transitive delegation, ranked delegation (with the MinSum delegation rule), and vote splitting.
- **FR3:** The system shall allow configuration of simulation parameters such as number of agents, delegation probabilities and abstention rates.
- **FR4:** The system shall track and record key metrics such as vote concentration, number of super-voters, average chain length, vote loss due to abstentions or cycles, and decision quality.
- **FR5:** The system shall output simulation results in a structured format (e.g. CSV or JSON) for further analysis.

Non-Functional Requirements

- **NFR1:** The simulation framework must be lightweight and easy to extend, enabling rapid experimentation with new delegation rules or metrics.
- **NFR2:** The system shall be developed using Mesa to take advantage of existing data science libraries such as NumPy, Pandas, and Matplotlib for analysis and visualisation.
- **NFR4:** The simulation design shall support reproducibility by enabling fixed random seeds and storing configuration settings alongside output data.

Chapter 4

Design and Implementation

This chapter describes the design and implementation of the delegation mechanisms integrated into vodle, detailing both the technical approach and practical decisions made throughout development. It begins by outlining vodle's existing system architecture, clarifying how this influenced the integration of new delegation features.

Each subsequent section aligns directly with one of the project objectives defined previously, explaining the rationale behind key design choices, algorithms, and interface elements. Emphasis is placed on the critical design trade-offs and challenges encountered, highlighting how constraints such as the serverless architecture and client-side computation informed implementation decisions.

4.1 System Architecture Overview

Vodle is built as a serverless web application that emphasises accessibility, client-side performance, and ease of deployment. Its architecture comprises two components:

1. **Frontend:** Implemented using Angular and the Ionic framework, the frontend provides a responsive and modular interface that works across both desktop and mobile devices. The use of Angular facilitates the creation of component-based user interfaces, essential for introducing interactive features such as the ranked delegation UI and vote splitting sliders.
2. **Backend:** Vodle uses CouchDB as its database. There is no custom backend logic or middleware; instead, the frontend application communicates directly with CouchDB over HTTP.

Implications of This Architecture

Vodle's serverless architecture has several implications for the design and implementation of the delegation mechanisms, especially due to the absence of a traditional data processing backend. The following points summarise the key considerations:

- All vote delegation logic, including transitive resolution, cycle detection, and vote splitting calculations, must be executed in the browser. This places constraints on performance and requires careful optimisation of algorithms used.
- CouchDB's document-based storage model means that all data must be serialised and deserialised in JSON format. This affects how data structures are designed and manipulated, as well as how they are stored and retrieved from the database.

4.1.1 CouchDB Storage and Write Constraints

Vodle store all data in CouchDB in two types of databases: the _users database and poll databases. The _users database is a standard CouchDB database that stores user documents, while the poll databases are created dynamically for each poll and contain all relevant data for that poll.

1. **_users Database.**
   - Each document ID is `org.couchdb.user:<username>`.
   - Only the account owner or an administrator may modify or delete their user document.
2. **Poll Databases.**
   - Databases are named `poll-<POLLID>`.
   - Stores:
     - The immutable poll definition (`poll.json`).
     - One vote document per voter (`vote-<user>`).

Document-Level Security CouchDB enforces security at the level of entire documents. This means that access control decisions are made based on the identity of the user attempting to write a document and the document's ID – there is no support for restricting access to individual fields within a document. Additionally, CouchDB does not support merging concurrent changes; updates must replace the entire document in a single write operation. As a result, all write operations are either fully accepted

or fully rejected by the database's `validate_doc_update` function. This strict model simplifies validation logic but introduces important constraints in the context of implemented liquid democracy, which are discussed in the remainder of this section.

Poll-DB Validation

When a client writes to a poll database, the `validate_doc_update` enforces:

1. **User Documents:** IDs are prefixed with `vodle.user.`, and only the owner may modify them:

```
if (!id.startsWith(`~{userCtx.name}Â§`)) {
  throw({ forbidden: 'Only the document owner may modify this user doc.' });
}
```

Figure 4.1: Code to prevent a user from modifying another user's document.

2. **Immutable Poll Artefacts:** Documents like `poll.json` or results cannot be updated once created:

```
if (oldDoc && isPollArtifact(id)) {
  throw({ forbidden: 'Poll documents are immutable once created.' });
}
```

Figure 4.2: Code to prevent modification of poll artefacts.

_users-DB Validation

In the _users database, a similar validation function is used to prevent users from modifying other users' documents, including the `vodle` service account.

```
if (id !== `org.couchdb.user:{userCtx.name}`) {
  throw({ forbidden: 'Users may only modify their own user document.' });
}
if (userCtx.name === 'vodle' || isPollService(userCtx.name)) {
  throw({ forbidden: 'Service accounts are immutable.' });
}
```

Figure 4.3: Code to prevent a user from modifying another user's document.

4.1.2 Summary of Storage and Validation Constraints

The architecture of vodle, particularly its reliance on CouchDB and the absence of a custom backend, imposes important constraints on how delegation features are designed and implemented.

- **User autonomy is strictly enforced.** Each user can only modify documents that are explicitly associated with their own identity. This guarantees that vote and delegation data cannot be tampered with by other clients but also eliminates the possibility of directly setting or managing another user's vote.
- **Issues with sharing a document.** The current database design does not support the modification of a single document by multiple users. As a result, features that require a global view – such as a delegation graph – require a rework of the database schema.
- **Validation logic is structural, not contextual.** Since CouchDB validation functions can only inspect the document being written, they cannot reason about relationships across documents. This prohibits logic such as resolving delegations server-side, enforcing uniqueness of votes, or validating delegation cycles at the point of write.
- **Client-side logic carries the burden.** Due to previous point, all logic for delegation resolution, cycle checking, and vote splitting must be implemented in the client. This requires careful design to ensure that the frontend can handle complex delegation scenarios without overwhelming the user or causing performance issues.

Together, these constraints shape some of the design and implementation choices of the delegation features in vodle, which will be discussed in detail in the following sections.

4.1.3 Existing Implementation of Liquid Democracy

As mentioned in the background research (see Section 2.4.3), vodle already contained a partial implementation of liquid democracy prior to this project. This early version was not activated in production and was ultimately left incomplete due to stability and design issues. Despite this, it included a basic delegation model that served as a foundation for completing objective 1.

The following subsection outline the key features of the original implementation, including its strengths and issues, which were addressed in the redesigned system.

Delegation Interaction Flow

The original delegation mechanism in vodle was built around an explicit, opt-in invitation model. Under this model, a user could not be designated as a delegate without their knowledge or consent, thereby preserving both vote privacy and user autonomy.

Delegation was initiated by one user (the *delegator*) and required an explicit response (either acceptance or rejection) from the other party (the *delegate*) before it became active.

Figure 4.4 illustrates the standard interaction sequence. In step 1, user A generates and shares a unique delegation link with user B. This link encodes A's intent to delegate and provides B with a prompt to either accept or reject the invitation. If B accepts (step 2), A adopts B's vote as their own (shown by a dashed arrow), while B proceeds to cast their vote independently. Crucially, the delegation only becomes effective upon B's confirmation.

If B instead rejects the invitation (Figure 4.5), both users cast their votes independently. In either case, the process is explicit and reversible: B can update their decision at any time, and A can cancel or resend the delegation request as needed.

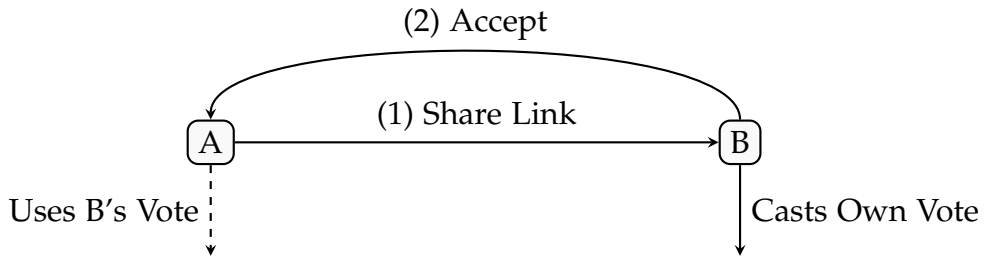


Figure 4.4: Sequence for a delegation to be initiated. User A shares a link with user B, who accepts the delegation.

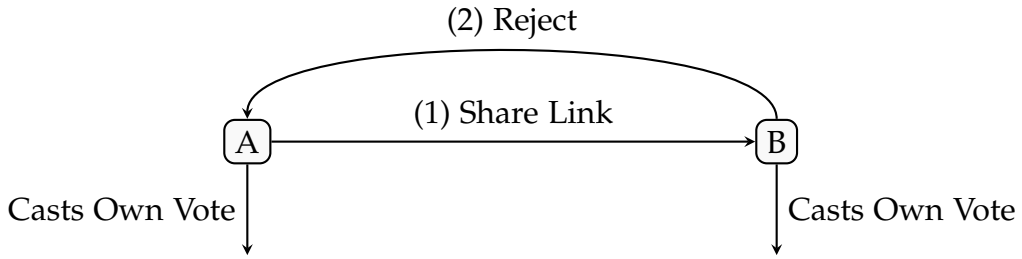


Figure 4.5: Sequence for a rejected delegation. User A shares a delegation link with user B, who rejects the delegation.

This interaction flow has two key strengths. First, it ensured that delegations could not be made unilaterally - a voter could never become a delegate without their knowledge. Second, it provided a simple and intuitive interface for forming delegation links (which could be shared via email, social platforms, or by copying the link), lowering the barrier to entry for new users.

However, while this implementation excelled at user autonomy and privacy, it lacked critical safeguards such as a consistent mechanism to prevent delegation cycles. The following section discusses the limitations of the original cycle-checking logic and outlines how these issues were addressed in the redesigned system.

Cycle Checking

Cycle prevention is necessary to ensure that delegated votes always reach a valid casting voter. If a cycle forms – such as A delegating to B, B to C, and C back to A – then no vote is cast at the end of that chain, causing all involved votes to be nullified. This can seriously undermine the integrity of the final result.

The original implementation in vodle attempted to prevent such cycles but applied this logic inconsistently. Cycle detection relied on the local view of the delegation graph cached in each user's browser. Since there was no mechanism for synchronising delegation state between clients, different users could have contradictory views of the system. This meant that a delegation rejected on one device (due to a perceived cycle) might succeed on another. The lack of real-time propagation also led to user interface inconsistencies, where delegation controls displayed outdated or misleading information.

Internally, the system attempted to detect cycles when a user received a delegation request by checking for existing direct or indirect delegations back to the requester. The code used a combination of local delegation maps, including the `direct_delegation_map` and `effective_delegation_map`, to approximate whether a cycle might form. The logic for determining if a cycle or two-way delegation would occur can be seen in the following code snippet:

```
const effdel_vid = effdelmap.get(oid).get(myvid) || myvid;
if ((dirdelmap.get(oid) || new Map()).get(myvid) == client_vid) {
  two_way = true;
} else if (effdel_vid == client_vid) {
  cycle = true;
}
```

Here, the code checks if the effective delegate (casting voter) of the responder (`effdel_vid`) is equal to the original requester (`client_vid`). If so, it flags the possibility of a cycle.

Despite these precautions, the absence of a global, shared delegation graph meant that cycle prevention was never fully reliable. Cycles could still occur due to race conditions or stale client views. This instability, coupled with the challenge of maintaining consistent cycle detection across browsers, was a key reason why delegation features were disabled in production at the time.

In the redesigned system, these issues are addressed through a shared, synchronised data structure that tracks delegation across all users. This enables consistent validation of new delegations and real-time detection of cycles regardless of which client initiates or accepts a delegation. The design and implementation of this new cycle detection mechanism (as part of completing Objective 1) are described in Section 4.2.1.

Inconsistent User Interface

4.2 Implement a Core Delegation Model into vodle

This section describes the design and implementation of the core delegation mechanism in vodle, which allows users to delegate their votes to others. It covers how the issues and constraints outlined in the previous section were addressed, including the design of the data structures used to represent delegations, the algorithms for preventing delegation cycles, and the user interface changes made to support the new delegation features.

4.2.1 Cycle Checking

Robust cycle detection is a core requirement for any system implementing transitive delegation. In liquid democracy, cycles render votes unresolved and potentially lost, directly undermining the integrity of the outcome. Given vodle's dynamic and client-driven architecture, it was crucial to implement an efficient, client-side mechanism that could detect and prevent cycles in real time, without requiring server-side intervention or excessive computation.

As previously discussed in Section 4.1.3, the original cycle detection relied on unsynchronised local state and was prone to failure. To resolve this, the new system introduces a shared, synchronised representation of the delegation graph, enabling consistent client-side validation of delegation requests. This redesign ensures that cycles are reliably detected and blocked in real time, regardless of which device initiates the delegation.

The remainder of this section details the algorithmic choices, data structures, and UI modifications used to implement reliable cycle detection in vodle.

Algorithm Design

The current delegations in a system can be represented as a directed graph where each user is represented as a node and each delegation is represented as a directed edge (u, v), where u is the delegator and v is the delegate. The goal of the cycle-checking algorithm is to ensure that a proposed delegation does not create a cycle in this directed graph.

A new delegation $X \to Y$ is valid if and only if Y is *not* reachable from X in that DAG – if Y is not a descendant of X.

Instead of checking for this condition directly using a depth-first search (DFS) or breadth-first search (BFS), a more efficient approach is to maintain a list of all descendants for each user. This allows us to check if Y is in the list of descendants of X in constant time. The implementation of this algorithm is detailed in the next section.

Implementation Details

A hashmap is used to store the descendants of each user. The keys are user IDs, and the values are sets of user IDs representing the direct delegates of that user. In the code, this hashmap is referred to as "`inverse_indirect_map`".

```
inverse_indirect_map = {
  "B": {"A"},
  "C": {"B", "A"},
  "D": {"C", "B", "A"}
}
```

Figure 4.6: Example of a hashmap for users A, B, C, and D. User A has delegated to B, user B has delegated to C, and user C has delegated to D. Consequently, the descendants of user D are A, B and C.

This map enables several key operations required for maintaining a consistent and cycle-free delegation graph:

- **Check Delegation Validity:** To determine whether a delegation $X \to Y$ would create a cycle, the system checks if Y already appears in the set of descendants of X. If so, the new delegation is invalid. This check takes $O(1)$ time.

```
const inverse_indirect_map = this.G.D.get_inverse_indirect_map(pid);
const descendant_set = inverse_indirect_map.get(delegate_vid);
if (descendant_set.has(myvid)) {
  cycle = true;
}
```

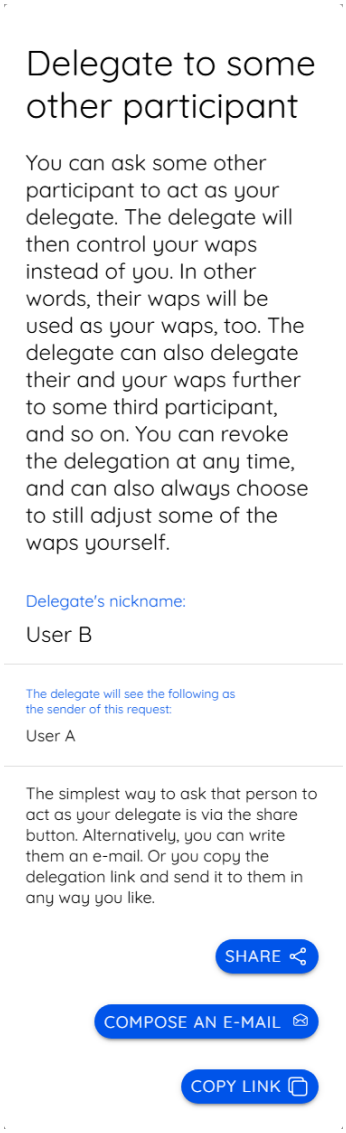
Figure 4.7: Code for checking if a delegation is valid. This check is triggered when a user clicks on a delegate link. The map is retrieved from the synchronised local cache, and the set of descendants is used to confirm that a cycle would not be formed.

- **Add Delegation Edge:** When a new delegation $X \to Y$ is accepted, the system must ensure that the descendant relationship is updated consistently. Specifically, for Y and every user u such that $Y \in \texttt{desc}(u)$, their descendants must be updated to include both X and all of X's current descendants.

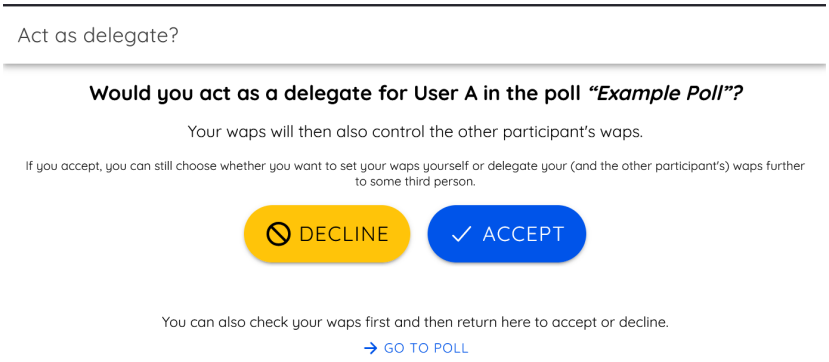
- **Remove Delegation Edge:** When a delegation $X \to Y$ is removed, the system must ensure that the descendant relationship is updated consistently. Specifically, for Y and every user u such that $Y \in \texttt{desc}(u)$, their descendants must be updated to remove both X and all of X's current descendants.

User Interface – TODO: add screenshots and actually fill in

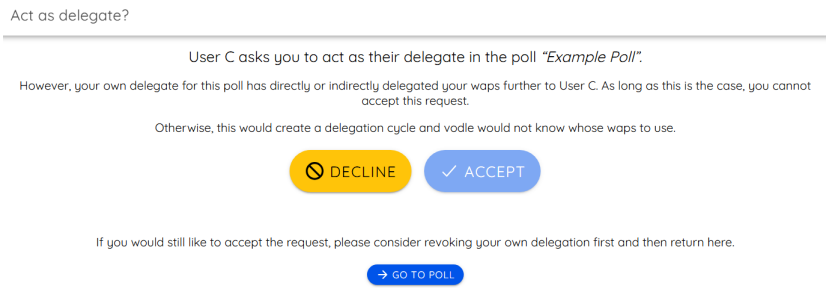
- Create delegation invite line
- Accept screen
- Accept screen when there is a cycle
- UI from user A POV (votes are being controlled)
  - Note Fixes:
  - controls some-all-none of your votes
  - your vote is used for n-other delegates
- UI from user B POV (Is a delegate)



(a) User A's invitation screen.



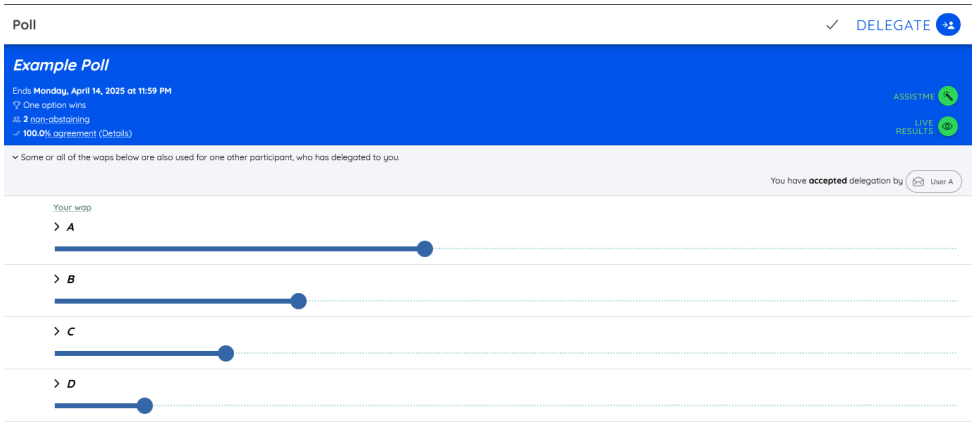
(b) User B's delegation acceptance screen when there is no cycle.



(c) User A's screen after opening a delegation link from User C (who User B has delegated to).

Figure 4.8: Screens shown to Users A and B during the delegation invitation and response process.

(a) User A (delegator) can now see that their waps are controlled by User B.



(b) User B (delegate) can see that their vote also determines the outcome for one other user (User A).

Figure 4.9: Delegate's (bottom) and delegator's (top) screens after a delegation has been accepted.

4.2.2 Summary – TODO

4.3 Implement Ranked Delegation into Vodle

This feature introduced ranked delegation using the MinSum rule, allowing users to list fallback delegates in case their primary choice was unavailable.

- UI for setting delegate rankings
- make sure you can't delegate the same rank twice

- UI for re ordering delegations
- New UI when making a poll to allow user to select ranked delegation.
- `direct_delegation_map`: maps user IDs to list of ranked delegates [[delegationid, rank, status]...]
- Explanation and application of the MinSum rule
- How do we determine who is a casting voter?
- Implementation of ranked path resolution
- Illustrations and code snippets

Challenges

The MinSum rule had to be implemented efficiently using only browser-based resources. Ranking resolution had to preserve user intent while avoiding delegation ambiguity. Providing visual feedback to help users understand how rankings would resolve added an additional layer of design complexity.

4.4 Implement a Vote Splitting Delegation Mechanism into Vodle

Vote splitting was implemented to allow users to distribute fractional influence to multiple delegates.

- UI for assigning weights
- modify`direct_delegation_map`to include weights [[delegationid, weight, status]...]
- Computation of weighted vote outcomes
- Constraints:
  - Weight sum limit (`< 1.0`)
  - Error handling
- Optimisations to limit database writes.
- Algorithm integration and frontend testing

Challenges

The vote splitting logic needed to maintain consistency with the MaxParC aggregation model, while ensuring intuitive user experience. Edge cases (e.g., partially overlapping delegate chains or missing data) introduced complexity during testing. Rendering weight distributions clearly in the UI while keeping the interface lightweight was a recurring challenge.

4.5 Implement the Ability to Delegate Individual Options to Different Users

This feature enabled per-option delegation, allowing users to assign a different delegate for each item in a poll.

- Per-option delegate selection interface
- Independent resolution of each delegated option
- talk about nested map - need to take care to serialise.
- `direct_delegation_map`: `option_id` -> `user_id` -> [delegationid, null, status]
- `inverse_indirect_map`: `option_id` -> `user_id` -> list of users who have delegated to them, either directly or indirectly.
- Storage schema modifications

Challenges

This mechanism required updates to the internal delegation logic to handle resolution at the option level. The user interface also had to be adapted to display multiple concurrent delegate selections without overwhelming the user. Debugging resolution logic for hybrid delegation modes (e.g., one direct, one split, one ranked) was non-trivial.

4.6 Simulate Delegation Mechanisms – Can Remove?

The simulation objective was de-scoped due to time constraints and prioritisation of implementation work. While initial planning and framework selection (Mesa) were completed, no functional simulation code was delivered. The decision to drop this extension is discussed further in the Project Management chapter.

4.7 Design Decisions and Trade-offs

- All logic had to run client-side due to the serverless CouchDB architecture, limiting complexity and computational resources.
- A consistent JSON format was required for all data models, impacting flexibility in data design.
- Trade-offs were made between expressive delegation types and usability, particularly in the option-specific and vote splitting interfaces.

4.8 Summary

- Each objective was successfully implemented within the constraints of the vodle platform.
- Challenges were primarily technical (client-side performance, real-time resolution) and design-oriented (clarity and control for users).
- The final implementation offers a modular, extensible delegation system that addresses the key theoretical and practical limitations outlined in earlier chapters.

Chapter 5

Evaluation

The following

5.1 Testing

- unit testing for delegation algorithms (minsum, vote splitting and test cycle checking for standard delegation)
-
- make sure all requirements are done (can format as table)

5.2 Requirements Evaluation - TODO After Requirements are 100% Done

The following section evaluates the project against the requirements set out in section 3. For each objective, their corresponding requirements are listed, along with a brief description of how they were/ were not met.

5.2.1 Core Objective 1: Implement a Core Delegation Model into Vodle

5.2.2 Core Objective 2: Implement Ranked Delegation into Vodle

5.2.3 Core Objective 3: Implement a Vote Splitting Delegation Mechanism into Vodle

5.2.4 Core Objective 4: Implement the Ability to Delegate Individual Options to Different Users

5.2.5 Extension Objective 1: Simulate Delegation Mechanisms

5.3 Feedback From Customer

get quote from Jobst: what he likes and dislikes about the implementation. also include specifications about what the final delegation implementation will be (vote splitting).

Chapter 6

Project Management

This chapter outlines the project's management approach, including the development methodology, planning, and reflections on the process. It also considers legal and ethical issues and assesses key risks associated with the project.

6.1 Methodology

The project adopted an agile methodology, chosen for its flexibility, iterative development cycle, and emphasis on frequent customer feedback. The work involved incrementally building a series of interdependent features into vodle – starting with a core delegation mechanism, and progressively expanding functionality to include ranked delegation, vote splitting, and finally, per-option delegation. This iterative approach allowed each new feature to build directly upon the last, ensuring ongoing compatibility and adaptability in design decisions as the system evolved.

Agile methodology was particularly suitable for this project due to the involvement of an active "customer" figure: Jobst Heitzig, co-supervisor and original creator of vodle. Heitzig played a crucial role in defining system expectations and guiding design decisions based on practical, real-world considerations. Regular meetings, held fortnightly with both Jobst Heitzig and Markus Brill, facilitated continuous feedback and review of progress, enabling rapid adaptation of development plans. This feedback cycle closely reflects the Agile Manifesto's principles of early and continuous delivery, as well as close collaboration between developers and stakeholders (Beck et al., 2001).

Other project management approaches, such as Waterfall, were also evaluated but ultimately dismissed due to their inherent rigidity. Although Waterfall initially appeared attractive due to clearly defined phases and comprehensive documentation at each stage, its requirement to specify the complete project scope upfront was incompatible with the evolving nature of the project. Given the shorter time frame and the

dynamic nature of feature requirements, the flexibility afforded by agile was critical to the project's success.

Scrum, one of the most widely adopted agile frameworks (used by approximately 63% of agile teams (VersionOne, 2020)), was also considered. Its structured, sprint-based cycles, clear team roles, and structured ceremonies such as sprint planning and reviews were appealing for maintaining focused implementation and streamlined communication. However, the project's constraints – limited availability due to academic commitments and a small team size – made Scrum's daily stand-up meetings and fixed sprint lengths impractical. As a result, the project adopted an adapted agile approach: progress was reviewed every two weeks, effectively maintaining the advantages of frequent feedback without the constraints and scheduling pressures imposed by full Scrum ceremonies.

Each iteration of development produced a functional, testable feature that could be immediately evaluated and integrated into the broader system. This method significantly reduced the risk of late-stage integration issues and ensured steady, measurable progress throughout the project's duration. Overall, the agile methodology's iterative, feedback-oriented structure proved highly effective, meeting both the technical complexity and collaborative needs inherent in this work.

6.2 Plan

The project plan was organised into objectives (see Section 3) that built on one another in sequence:

- **Core Objective 1:** Implement a Core Delegation Model into Vodle.
- **Core Objective 2:** Implement Ranked Delegation into Vodle.
- **Core Objective 3:** Implement a Vote Splitting Delegation Mechanism into Vodle.
- **Core Objective 4:** Implement the Ability to Delegate Individual Options to Different Users.
- **Extension Objective 1:** Simulate Delegation Mechanisms.

This objective-led structure was well-suited to the agile approach, allowing each milestone to be treated as an iteration with a deliverable at the end. A Gantt chart (see below) was created to visualise the project timeline and to track dependencies and progress.

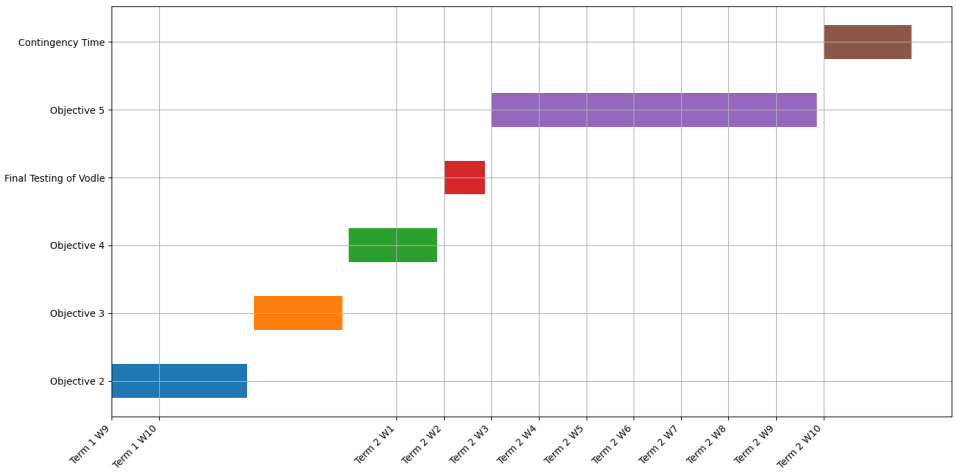


Figure 6.1: Gantt chart illustrating the project plan from the progress report.

6.3 Changes to the Project Plan

The original project plan, illustrated in the Gantt chart (Figure 6.1), outlined a linear progression through the core objectives. However, several adjustments were made during the course of the project to reflect evolving priorities and unforeseen technical challenges.

The most significant change was the decision to de-scope the extension objective (simulating delegation mechanisms). This was prompted by two main factors. First, implementing the core objectives proved more technically demanding than initially anticipated – particularly ranked delegation and vote splitting. These challenges required more time and attention than expected, leaving limited capacity to complete the extension objective without compromising the quality of the core deliverables.

Second, during the background research phase, it became clear that similar investigations into delegation behaviour had already been conducted – most notably by Brill et al. (2021). Although their study did not use agent based modelling, instead using networks from synthetic and real-world networks (such as partial networks from Facebook, Twitter, Slashdot, etc.), it provided a comprehensive empirical evaluation of ranked delegation rules using various metrics such as maximum vote path length, average vote path rank, the number of isolated voters (voters without a delegation path) and many more.

Given the depth and relevance of these findings, replicating the analysis through agent-based modelling, especially within the project's limited timeframe, was deemed unnecessary. Instead, the project focused on fully delivering and refining the core objectives, which aligned more directly with vodle's platform goals and would have a better impact on the user experience of vodle.

A second change involved reversing the development order of objectives 3 and 4. Originally, objective 3 (vote splitting) was scheduled to follow objective 2. However, during the Christmas development period, it became clear that objective 4 (per-option delegation) could be completed more quickly and required fewer algorithmic dependencies. To maintain development momentum, objective 4 was brought forward.

This adjustment helped mitigate project risk. Objective 4 involved minimal changes to the database schema and integrated easily with UI components developed for earlier objectives. In contrast, objective 3 introduced more complex computational logic and performance concerns, which demanded additional design, testing and changes to the database. Tackling objective 4 earlier helped avoid potential cascading delays and ensured a smoother integration process later in development.

6.3.1 Actual Timeline vs Planned Timeline

While the original project plan provided a clear sequence for implementing each objective, the actual progression deviated in several key areas due to technical challenges, interface considerations, and evolving priorities. Figure 6.2 (below) shows the actual timeline of the project, which can be compared to the original plan (Figure 6.1).

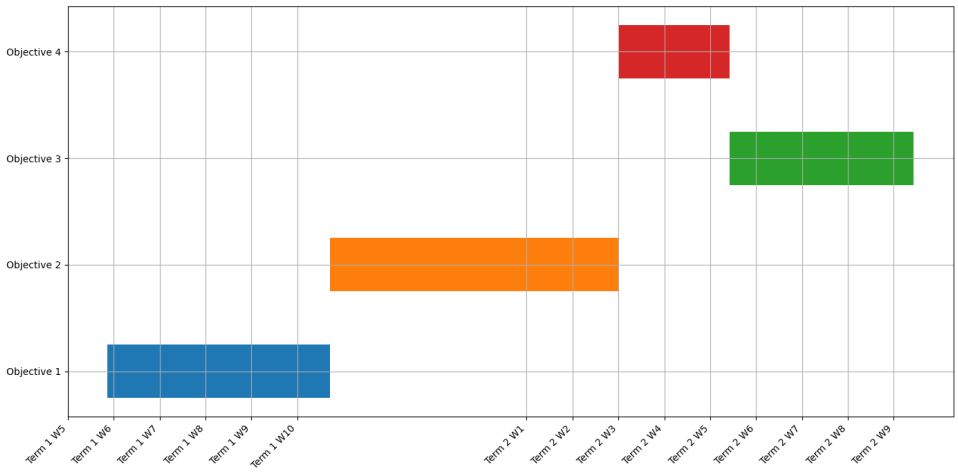


Figure 6.2: Gantt chart illustrating the actual timeline of the project.

The most significant deviations from the original plan included:

- **Objective 1 (Core Delegation Model)** commenced approximately one week later than planned. This delay stemmed from the need for deeper familiarization with vodle's existing codebase, particularly its database schema and frontend architecture. Understanding these components was essential to ensure that new delegation features could integrate seamlessly without disrupting existing functionality. This initial exploration phase, while time consuming, was crucial for establishing a solid foundation for subsequent development.

- **Objective 2 (Ranked Delegation)** extended significantly beyond its initial timeframe. Originally scheduled for completion during the Christmas break, development continued until Term 2, Week 3. This extension was primarily due to the unforeseen complexities (as discussed in Section 4.3) which required both sophisticated transitive resolution logic and intuitive user interface feedback mechanisms, which proved more challenging than initially estimated.
- **Objectives 3 and 4**'s order was swapped, as discussed earlier in this section. While the original plan positioned Objective 3 (Vote Splitting) to follow Objective 2, development logistics and dependency considerations prompted a shift to implement Objective 4 (Per-Option Delegation) first. This decision minimised integration risks, as Objective 4 required fewer schema modifications and built more directly on existing UI components, in particular those developed for Objective 2 (Ranked Delegation).
- **Extension Objective (Simulation)** was ultimately descoped from the project plan. This decision reflected both time constraints imposed by the extended development periods for core objectives and the discovery of existing comprehensive research on delegation behavior by Brill et al. (2021). Focusing resources on delivering robust implementations of the core objectives was deemed more valuable than duplicating existing research.

Despite these deviations, the overall project structure remained intact and successful. The buffer period allocated at the end of Term 2 served its intended purpose as contingency time, effectively absorbing the delays in Objectives 1 and 2. This strategic planning ensured that despite timeline adjustments, the project remained on track for completion with all core objectives delivered to high quality standards.

The ability to adapt the project plan while maintaining focus on delivering the core functionality demonstrates the value of the chosen agile methodology. Rather than rigidly adhering to potentially unrealistic timelines, the flexible approach allowed for continuous reassessment and prioritisation based on evolving technical insights and stakeholder feedback.

6.4 Risk Assessment

The following section provides a detailed analysis of the risks identified in the risk assessment table below (see Table 6.1). Each risk is discussed individually in detailed later on in the section, outlining its implications and the strategies proposed to mitigate potential issues.

Risk	Likelihood	Mitigation Strategy
Breaking the live vodle site during development	Medium	Use Git branching to isolate development from production environments. Conduct local testing before deployment.
Feature complexity exceeds estimates	High	Prioritise core objectives and maintain flexibility in scope.
Lack of engagement from supervisors or stakeholders	Low	Maintain regular communication through scheduled meetings.
Data loss or corruption	Low	Use Git for version control and take regular local backups.

Table 6.1: Key risks identified and their mitigation strategies

Breaking the Live Vodle Site During Development

Likelihood: Medium

Description: Modifications to the existing vodle platform could unintentionally introduce downtime or impair existing functionality on the live website. Any disruptions could negatively impact real users' interactions, leading to dissatisfaction and loss of trust in the platform.

Mitigation: Development activities will utilise Git branching to isolate new code from the production environment. Features will be developed and rigorously tested in local or staging environments before integration with the live deployment. Incremental rollouts and thorough pre-deployment testing will further help identify potential problems early, allowing quick remediation or rollback.

Feature Complexity Exceeds Estimates

Likelihood: High

Description: Advanced features such as ranked delegation and vote splitting may prove more complex than initially anticipated. Unexpected complexity can lead to delays, reduced functionality, or incomplete implementations, potentially affecting the project's timeline and deliverables.

Mitigation: Core objectives have been clearly defined and prioritised, ensuring focus remains on essential functionality. In cases of higher than anticipated complexity, resources will be redirected towards completing critical core features first, while the extension objective (agent based modelling) can be scaled back or postponed as needed. Regular agile reviews will monitor progress closely, facilitating early identification and management of complexity-related issues.

Lack of Engagement from Supervisors or Stakeholders

Likelihood: Low

Description: Regular feedback and engagement from supervisors and stakeholders are crucial to ensure alignment with project goals, requirements, and user expectations. Insufficient feedback could result in misaligned implementations or objectives that do not fully meet user needs.

Mitigation: Fortnightly meetings have been scheduled with both the primary supervisor (Markus Brill) and the co-supervisor (Jobst Heitzig), who also fulfils the role of the project customer. This structured schedule ensures consistent opportunities for input and feedback. Additionally, a Telegram group chat is available to handle urgent queries and maintain ongoing dialogue.

Data Loss or Corruption – Code

Likelihood: Low

Description: Development activities pose a risk of code loss or corruption due to accidental deletion, unintended changes, or version conflicts. Such incidents could significantly delay development and necessitate additional time for recovery.

Mitigation: Version control will be rigorously maintained using Git, with frequent commits and descriptive commit messages ensuring traceability. Regular backups of the repository will be taken to safeguard against accidental loss, providing straightforward recovery paths when needed.

Data Loss or Corruption – Database

Likelihood: Low

Description: While unlikely, corruption of the CouchDB database during development could occur due to improper schema modifications or accidental changes.

Mitigation: No mitigation – in the event of data corruption, the development database will be reset to its original state. As all data in the database is poll and user specific, it does not impact development as no important data is stored in the production environment.

6.5 Risk Management Reflection

This section evaluates how effectively the project's risk management strategies addressed both anticipated and unforeseen challenges. It examines which risks were

realised, how mitigation strategies performed in practice, and identifies lessons learned that could inform future projects.

Breaking the Live Vodle Site During Development

The use of Git branching strategies and comprehensive local testing successfully prevented any disruption to the live site. The separation between development and production environments ensured stability throughout the project lifecycle. This disciplined approach proved valuable despite adding some overhead to the development process.

Feature Complexity Exceeds Estimates

This materialised as the most significant risk, particularly during the implementation of ranked delegation (Objective 2) and vote splitting mechanisms (Objective 3). The algorithmic complexity and UI considerations extended development beyond initial estimates. The strategy of prioritising core objectives proved invaluable, allowing the project to successfully deliver all essential functionality. The decision to descope the extension objective demonstrates effective risk management balancing ambition with practical constraints. In hindsight, breaking complex features into smaller subtasks during planning might have improved estimation accuracy, though the agile methodology compensated through its inherent flexibility.

Lack of Engagement from Supervisors or Stakeholders

This risk did not take place. The fortnightly meetings and additional communication channels maintained strong engagement throughout the project. Jobst Heitzig's dual role as co-supervisor and customer representative provided crucial domain expertise and timely feedback on design decisions.

Data Loss or Corruption

No significant data loss incidents occurred. Git version control provided reliable tracking of code changes, while the lightweight approach to database management proved appropriate as no critical data was compromised.

Summary

Overall, the risk management approach proved effective in supporting project delivery despite several challenges. The most significant risk – feature complexity exceeding estimates – did occur and required timeline adjustments, but the contingency buffer and flexible scope management successfully mitigated its impact. The disciplined development approach prevented any disruption to the live site, while strong stakeholder engagement and version control systems effectively addressed the remaining identified risks. The experience highlighted the importance of integrating contingency time into project schedules and maintaining flexibility when dealing with technically complex features.

6.6 Legal and Ethical Considerations

As vodle may eventually be used to gather votes on sensitive topics, particular attention was paid to ensuring user privacy and system fairness throughout development.

Delegation chains are resolved internally within the browser and are never publicly exposed. A key design feature is that a delegation only becomes active when the invited user explicitly accepts the invitation. This ensures that no information about a user's voting intentions or delegation preferences is shared without their consent. The delegate only becomes aware of the relationship once they actively confirm it, and the delegator retains full control to revoke or modify the delegation at any time.

This mechanism protects the confidentiality of voter relationships and ensures that vote flows remain private unless both parties agree to the delegation. As such, even in a scenario where a vote is passed through multiple users, no individual along the chain gains access to the full path unless explicitly authorised.

Furthermore, no personal data was collected or processed for the purposes of this project. All stored information relates strictly to poll participation and delegation structures, with no link to identifiable personal attributes. As a result, no changes to vodle's terms of service were required, and the project remains compliant with relevant data protection and ethical standards.

6.7 Overall/Self Reflection - TODO

Chapter 7

Conclusions

7.1 Author's Assessment of the Project

"It can be a useful exercise for you (and a point of consolidation for the reader) to put together a brief summary of what you have achieved. This is not a compulsory section, but a self-assessment is welcome. A suggested format for this is to include a short section entitled 'Author's Assessment of the Project' consisting of brief (up to 100 words) answers to each of the following questions.

- What is the (technical) contribution of this project?
- Why should this contribution be considered relevant and important for the subject of your degree?
- How can others make use of the work in this project?
- Why should this project be considered an achievement?
- What are the limitations of this project?

"

What is the (technical) contribution of this project?

Why should this contribution be considered relevant and important for the subject of your degree?

How can others make use of the work in this project?

Why should this project be considered an achievement?

What are the limitations of this project?

7.2 Future Work

- More algorithms for ranked delegation
- Global Delegations – like liquid feedback

Bibliography

Angular Team, . *Angular - Web Framework*. Google, 2024. URL `https://angular.io/`. `https://angular.io/`.

Apache CouchDB Project, . *Apache CouchDB*. The Apache Software Foundation, 2024. URL `https://couchdb.apache.org/`. Accessed April 2025. `https://couchdb.apache.org/`.

Beck, Kent & Beedle, Mike & van Bennekum, Arie & Cockburn, Alistair & Cunningham, Ward & Fowler, Martin & Grenning, James & Highsmith, Jim & Hunt, Andrew & Jeffries, Ron & Kern, Jon & Marick, Brian & Martin, Robert C. & Mellor, Steve & Schwaber, Ken & Sutherland, Jeff & Thomas, Dave. Manifesto for agile software development, 2001. URL `https://agilemanifesto.org`. Accessed: 2025-04-21.

Behrens, Jan & Swierczek, Björn. Preferential delegation and the problem of negative voting weight. *The Liquid Democracy Journal*, 3:6–34, 2015.

Behrens, Jan & Kistner, Axel & Nitsche, Andreas & Swierczek, Björn. *The Principles of LiquidFeedback*. Interacktive Demokratie, 2014.

Bersetche, Francisco M. Generalizing Liquid Democracy to multi-agent delegation: A Voting Power Measure and Equilibrium Analysis, April 2024.

Blum, Christian & Zuber, Christina Isabel. Liquid Democracy: Potentials, Problems, and Perspectives. *Journal of Political Philosophy*, 24(2):162–182, June 2016. ISSN 0963-8016, 1467-9760. doi: 10.1111/jopp.12065. URL `https://onlinelibrary.wiley.com/doi/10.1111/jopp.12065`.

Bonabeau, Eric. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, 99:7280–7287, 2002.

Brill, Markus & Delemazure, Théo & George, Anne-Marie & Lackner, Martin & Schmidt-Kraepelin, Ulrike. Liquid Democracy with Ranked Delegations, December 2021.

Brill, Markus & Delemazure, Théo & George, Anne-Marie & Lackner, Martin & Schmidt-Kraepelin, Ulrike. Liquid Democracy with Ranked Delegations. *Proceedings of the AAAI Conference on Artificial Intelligence*, 36(5):4884–4891, June 2022. ISSN 2374-3468. doi: 10.1609/aaai.v36i5.20417. URL https://ojs.aaai.org/index.php/AAAI/article/view/20417. Number: 5.

Christoff, Zoé & Grossi, Davide. Liquid democracy: An analysis in binary aggregation and diffusion, 2017. URL https://arxiv.org/abs/1612.08048.

Collier, Nick. Repast: An extensible framework for agent simulation. *The University of Chicago's social science research*, 36:2003, 2003.

Degrave, Jonas. Resolving multi-proxy transitive vote delegation. (arXiv:1412.4039), December 2014. doi: 10.48550/arXiv.1412.4039.

Ford, Bryan Alexander. Delegative Democracy. May 2002. URL https://infoscience.epfl.ch/handle/20.500.14299/156450.

Hall, Andrew B. & Miyazaki, Sho. What Happens When Anyone Can Be Your Representative? Studying the Use of Liquid Democracy for High-Stakes Decisions in Online Platforms. Technical report, 2024.

Hardt, Steve & Lopes, Lia. Google Votes: A Liquid Democracy Experiment on a Corporate Social Network. *Defensive Publications Series*, June 2015.

Heitzig, Jobst & Simmons, Forest W. & Constantino, Sara M. Fair group decisions via non-deterministic proportional consensus. *Social Choice and Welfare*, May 2024. ISSN 1432-217X. doi: 10.1007/s00355-024-01524-3. URL http://dx.doi.org/10.1007/s00355-024-01524-3. Publisher: Springer Science and Business Media LLC.

Ionic Team, . *Ionic Framework - Cross-Platform Mobile App Development*. Ionic, 2024. URL https://ionicframework.com/. Accessed April 2025. https://ionicframework.com/.

Kazil, Jackie & Masad, David & Crooks, Andrew. Utilizing Python for Agent-Based Modeling: The Mesa Framework. In Thomson, Robert & Bisgin, Halil & Dancy, Christopher & Hyder, Ayaz & Hussain, Muhammad, editors, *Social, Cultural, and Behavioral Modeling*, pages 308–317, Cham, 2020. Springer International Publishing. ISBN 978-3-030-61255-9.

Kling, Christoph Carl & Kunegis, Jerome & Hartmann, Heinrich & Strohmaier, Markus & Staab, Steffen. Voting behaviour and power in online democracy: A study of liquidfeedback in germany's pirate party, 2015. URL https://arxiv.org/abs/1503.07723.

Kotsialou, Grammateia & Riley, Luke. Incentivising Participation in Liquid Democracy with Breadth-First Delegation. *New Zealand*, 2020.

Sommerville, Ian. *Software Engineering*. Always Learning. Pearson, Boston Columbus Indianapolis New York San Francisco Hoboken Amsterdam Cape Town Dubai London, tenth edition edition, 2016. ISBN 978-1-292-09613-1 978-1-292-09614-8.

Sven Becker, DER SPIEGEL. Liquid Democracy: Web Platform Makes Professor Most Powerful Pirate - spiegel.de, 2012. URL `https://www.spiegel.de/international/germany/liquid-democracy-web-platform-makes-professor-most-powerful-pirate-a-818683.html`.

Tisue, Seth & Wilensky, Uri. Netlogo: A simple environment for modeling complexity. In *International Conference on Complex Systems*, volume 21, pages 16–21. Citeseer, 2004.

Vahdati, Ali. Agents.jl: Agent-based modeling framework in Julia. *Journal of Open Source Software*, 4(42):1611, October 2019. ISSN 2475-9066. doi: 10.21105/joss.01611.

VersionOne, . 14th annual state of agile report. `https://stateofagile.com`, 2020. Accessed: 2025-04-09.