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Anoma: a unified architecture for full-stack decentralised applications

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Abstract

Programmable settlement architectures do not enable counterparty discovery and solving, both of which are necessary to build the majority of interactive multi-party applications. The architectural constraints of programmable settlement result in contemporary application protocols that have at least one Web2 component, which becomes the centralisation point. We present Anoma, a unified architecture for full-stack decentralised applications. Anoma is designed following the principles of intent-centricity and homogeneous architecture / heterogeneous security, together constituting a declarative paradigm for building decentralised applications. In this paper, we first outline the Anoma architecture, provide an intuition for the design rationale, and describe how Anoma disentangles the choices of protocol and security. We then define the Anoma application programming model and enumerate several existing and novel decentralised applications that can be built using the novel primitives. Finally, we outline the current components used to instantiate Anoma and list future research directions.

Keywords: Anoma ; Intent-Centricity and Homogeneous Architecture ; Full-Stack Decentralised Applications ; Counterparty Discovery ; Programmable Settlement Architectures ;

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Contents

1. Background and motivations

The release of the Bitcoin protocol in 2008 marked the beginning of *scriptable settlement*, a category of distributed ledger architectures that is suitable for cryptocurrencies with discrete properties and monetary policies. Although it is not Turing-complete, Bitcoin Script Bitcoin Wiki (2021) is able to support applications beyond currencies, such as Namecoin and Colored Coins. As discussed in the Ethereum Whitepaper Buterin (2014), while applications built on scriptable settlement are functional, this architecture requires too many trade-offs that resulted in constrained properties and usability.

The introduction of the Ethereum protocol in 2014 set the precedent for *programmable settlement*, a new category of architectures for constructing decentralised applications that leverage Turing-complete virtual machine execution, which adds substantially more expressivity to the settlement layer. Programmable settlement paved the way for improved versions of applications that scriptable settlement is not able to support, such as fungible tokens (ERC20) or Ethereum Name Service (ENS), which are today well-established versions of the Colored Coin and Namecoin ideas, respectively – in addition to many other desirable applications, such as non-fungible tokens (NFTs), Decentralised Autonomous Organisations (DAOs), or the recently introduced Soulbound Tokens (SBTs) Weyl et al. (2022).

Proposed and deployed blockchain protocols since Ethereum's release have brought significant improvements to specific architectural components, for instance: consensus mechanisms (Tendermint Buchman et al. (2018), Avalanche Rocket (2018)), Sybil-resistance mechanisms (proof-of-stake, proof-of-storage), scaling solutions (sharding, rollups), and cryptographic schemes (zero-knowledge proofs) – but these improvements to constituent primitives do not change the basic architecture of programmable settlement.

While programmable settlement is sufficient for certain applications, many contemporary applications have further requirements. Settlement suffices when the involved parties have already decided what and with whom to settle, but contemporary applications often also require infrastructure for helping potential counterparties discover each other and decide with whom and on what to settle. As a workaround, existing applications have usually adopted an architecture that relies on one or many permissioned or centralised components (such as provers, solvers, or sequencers), usually implemented as Web2 services, in their stack.

Examples include decentralised exchanges for fungible assets (0x, CoWSwap, Uniswap), for non-fungible assets (Wyvern, LooksRare, OpenSea), novel voting/funding mechanisms (quadratic voting/funding, Gitcoin), and rollups (Optimism, Arbitrum, Starknet, zkSync) – their architectures involve at least one centralised component that often results in a loss of permissionlessness, fault-tolerance, censorship-resistance, or privacy.

One emerging approach for applications seeking to avoid centralisation points in their architecture is to deploy an application-specific sovereign chain to replace a specific component in the stack. Even though this approach can solve the immediate centralisation problem, it comes with substantial trade-offs, such as the loss of network effects (application composability and software re-use) or the addition of disproportionate complexity to developers and users, who need to reason about multi-layered security, privacy, and latency domains.

In this paper we present Anoma. Anoma is a unified architecture for full-stack decentralised applications – characterised by its intent-centricity, decentralised counterparty discovery and computational outsourcing of NP search problems to solvers which compute valid state transitions. With this architecture, contemporary applications can be built without compromising permissionlessness, fault-tolerance, censorship-resistance, or privacy.

Anoma's architecture also exposes novel primitives, such as composable privacy, which enables applications to handle transparent, shielded, and private state and operations; and multi-chain atomic settlement, which allows users and applications with different security preferences to obtain atomicity. These and other novel primitives pave the way for the development of applications that cannot be built with existing architectures, several of which we enumerate in **Section 5: Applications**.

2. Architectural design philosophy

Anoma's architecture is driven by two design principles: first, intent-centricity; second, a homogeneous protocol architecture with a heterogeneous security model. Beyond these two design principles, all other architectural choices are a matter of modularisation and runtime configuration parameters.

2.1. Intent-centricity. An *intent* is an expression of what a user wants to achieve whenever they interact with a protocol, for instance "transfer X from A to B" or "trade X for Y". Practically, an intent is an off-chain signed message that encodes which state transitions a user wants to achieve. Unlike transactions, intents are partial, so one can think of intents as parts of transactions that require other direct or indirect parts as complements in order to form a final balanced transaction which satisfies all users' constraints.

Existing protocols are designed with *transactions* as their most fundamental unit. Anoma takes a radically different approach: the architecture of Anoma is centred around programmatic *intents*.

An intent-centric architecture is necessary to enable counterparty discovery, which is crucial for compelling applications, since they require multiparty coordination and to enable full-stack decentralised applications. Anoma vertically integrates counterparty discovery, solving, and settlement, and is able to interpret and process intents natively and generically. Contemporary applications, as described earlier, require both counterparty discovery, solving, and settlement. Intents are the point at which users interact with such applications, and an intent-centric design captures the requirements of applications which need these two processes to work in tandem and satisfy censorship-resistance, privacy, and fault-tolerance properties.

Intent-centric design also constitutes a *declarative paradigm* for building applications, since Anoma is designed to settle intents *as defined* by the users – an intent is either settled as defined, or not settled at all. This declarative model gives users a significantly higher degree of control, *without* requiring them to understand the underlying protocol primitives and execution flows, which is crucial in order for decentralised applications to reach mass adoption. This paradigm presents a radically different approach as compared to existing *transaction-centric* architectures that default to an *imperative model* for applications. In the latter, users are required to understand the full execution trace to benefit from security and privacy guarantees, because instead of authorising a specific state change, they authorise specific execution paths. In practice, this is so difficult that users commonly interact with applications without understanding the risks.

For application developers, Anoma's intent-centric architecture enables them to build *safer by construction applications* by leveraging the combination of intents and *validity predicates*. Validity predicates are an architecture for smart contracts which separate out cleanly the task of computing state transitions and the task of verifying correctness of state transitions, as compared to message-passing VM execution models (pervasive in current programmable settlement architectures) which interleaves computation and verification. Validity predicates allow application developers to reason about the invariants which they would like their application to satisfy without worrying about how other applications interact with it, since the validity predicate of their application expresses these invariants directly.

2.2. Homogeneous architecture, heterogeneous security. The Anoma protocol, just like the TCP/IP protocol stack, follows the principle of homogeneous architecture and heterogeneous security. In TCP/IP, the various layers of the internet protocol are standardised, but the choice of whom to connect to and what data to entrust them with is left to the user, and different users can make different choices while using the same protocol stack. In Anoma, the various layers of counterparty discovery, solving, and settlement are similarly standardised, but the choice of what security domains to trust and what data to send to whom are left to the user, and different users can make different choices while using the same protocol stack.

In this framework, protocols can be analysed along two dimensions: architecture and security.

- **Architecture**: the abstractions and relations constituting the structure of a system. An architecture is syntactical, possessed of properties and syntaxes but with no particular semantics in relation to the exterior world. Convergence on a singular architecture saves time and verification costs without constraining users to particular choices.

- **Security**: the choice of whom and how to trust in the operation of a distributed system. Security is a decision inseparable from the particular semantics of a specific context of use. While security can be economically abstracted to a certain degree by limiting the information available to and consequent choice-making capabilities of system operators, operators will always have choices of: how and from whom to accept messages; when to elect to include them in blocks or other aggregations over which they vote; and when to cease voting or otherwise alter normal operational procedures in response to exceptional circumstances. Whom to trust with these responsibilities depends on what the state in the database *represents* in the real world, and alignment with the interests of users of the database requires mutual interests beyond the purely economic ones.

2.2.1. Analysis of platforms. Consider distributed ledger platforms, from the perspective of applications running on top of them, along these two dimensions: protocol architecture and security model, and whether they are *homogeneous* or *heterogeneous* for different applications running on the same platform.

Protocol architecture refers to the state layout, virtual machine, language support, sharding mechanisms, cross-contract messaging model, etc. An architecture determines what is required to write an application for a platform, and applications are specific to a particular architecture.

- Platforms with a *homogeneous* architecture require that all applications are written in a certain format (e.g. EVM bytecode or WASM).
- Platforms with a *heterogeneous* architecture allow applications to be written in different formats, perhaps with some agreement at the edges, such as cross-chain communication protocols.

Security model refers both to security *in theory*, such as fault tolerance properties of the consensus, fork detection and handling; and security *in practice*, i.e. which miners or validators operate the deployed instances of these architectures.

- Platforms with a *homogeneous* security model have the same security for all applications.
- Platforms with a *heterogeneous* security model have different security characteristics for different applications.

For illustration, Section 2.2.1 situates several platforms on these two axes:

Platform	Architecture	Security Model
Bitcoin	Homogeneous	Homogeneous
Ethereum	Homogeneous	Homogeneous
Ethereum 2.0	Homogeneous	Homogeneous
Polkadot	Heterogeneous	Homogeneous
Near	Homogeneous	Homogeneous
Cosmos	Heterogeneous	Heterogeneous
Multichain	Heterogeneous	Heterogeneous
Anoma	Homogeneous	Heterogeneous

Table 1: An analysis of platforms based on their architecture and security model

As the table suggests, these dimensions are generally quite correlated: homogeneous architectures come with homogeneous security models, and heterogeneous architectures come with heterogeneous security models. It is easier to design a system where they are correlated. If everything is homogeneous, protocols can be fit together neatly, and functionalities including cross-contract communication are easy; whereas if everything is heterogeneous, protocols just agree on the edges of interaction, for instance via the Inter-Blockchain Communication protocol (IBC) Goes (2020), and handling the complexity of security is up to the users and application developers.

2.2.2. Why decouple these dimensions?. Anoma's fractal instance architecture is designed to decouple these dimensions and build a platform which is architecturally *homogeneous* and with a *heterogeneous* security model. This is more complicated, but it separates out the question of what the best *protocol architecture* is, where there may be a "benevolent monopoly" (à la Git or TCP/IP), from the question of what is the best *security model*, where there is almost certainly not.

Applications written for fractal instances can standardise on the architecture Anoma offers, which is sufficiently well-defined to allow for complex interoperability, automatic scaling, etc., without agreeing on any single security model. Furthermore, in some cases, this flexibility of choice can be extended all the way to users of the applications, who can choose independently.

User interfaces for Anoma instances can support the same applications deployed with different security models, and communicate that latter difference to users in a way which allows them to choose their trust assumptions while retaining the network effects of using the same protocol.

Noteworthily, Anoma's architecture is not homogeneous like a straitjacket, as it supports multiple deployment models. The components in the protocol are layered so that fractal instances can pick and choose which parts they participate in, even if it involves leveraging Anoma for specific functionalities, such as decentralised counterparty discovery and solving, whilst anchoring the final settlement on another platform, such as Ethereum. Nonetheless, a unified and vertically integrated architecture allows developers and users to benefit from standardisation.

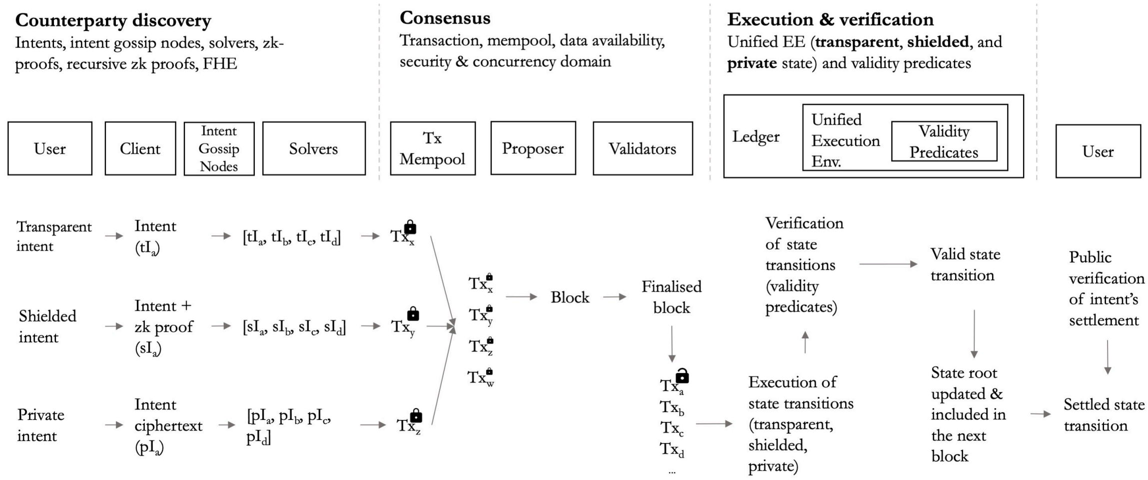

Fig. 1: The lifecycle of a transparent, shielded, and private intent in the Anoma architecture

3. Architectural topology

Anoma's architectural topology consists of a set of logical abstractions delineated by their role in dataflow, independent of particular forms of representation, deployment models, choices of cryptographic implementation, etc, **Figure 1** provides an overview of the architectural topology. Particular instantiations carry different concrete performance and security implications and should be chosen according to requirements of the specific deployment in question. We offer a sketch of our choices for different deployments in **Section 5: Applications**.

3.1. Nodes and network layer. The architectural topology of Anoma operates on a substrate of networked Turing machines, which we refer to as *nodes*. Nodes may take on different operational *roles*, such as gossiping intents, searching for solutions, and voting in consensus. Although different roles will have different hardware requirements, nodes are a single class and runtime configuration settings determine which roles a node performs.

All nodes compute deterministically, with the ability to generate local randomness (which may be used, for example, as secret values in cryptography) and have read and write access to local storage. The set of nodes is unbounded and dynamic with nodes entering and exiting at any times. Nodes are partially connected on an open network, where different roles require different connections. The network layer is assumed to be unreliable (messages may be arbitrarily dropped, duplicated, or reordered) and untrustworthy (unencrypted data is not secret). Specific roles may have more stringent network assumptions such as partial synchrony.

3.2. Intents. An *intent* is a signed message that describes a partial state transitions. Semantically, intents contain information about state preferences, such as that Alice wishes to swap X for Y, or any X with property T for any Y with property U, or Z for some asset A, but only if A was previously owned by Bob, and only if Bob provides an additional signature. More generally intents are arbitrary code that is evaluated at runtime by the settlement layer.

Intents are partial and hence specific counterparties are not required, albeit they can also be complete (complete state transitions are a subset of partial state transitions). For example, an intent may express that Alice wishes to send asset A to Bob, a state change which requires no one except Alice to agree in order to be enacted. Such intents may still require solvers, if certain information is unknown by Alice. For example, Alice could express that she wishes to set a bounty value in proportion to the current temperature in Berlin, a value which she does not know but knows an oracle key for, and which a solver with oracle data access could provide. Intents which need neither counterparties nor solvers can be immediately converted into transactions. The particular syntax of representation of assets, properties, etc. is fixed at the application level. At the architectural level, intents are opaque bytestrings.

3.3. Intent gossip layer. The *intent gossip layer* is a virtual sparse overlay network for dissemination of intents, counterparty discovery, and solving (when a solver combines multiple intents to craft a valid transaction). The intent gossip layer consists of sparsely networked *intent gossip nodes*, where *intent gossip* is a role any node can play. When a client authors an intent which requires solving, it broadcast the signed intent to an *intent gossip node*, which further relays the intent over the intent gossip layer. This broadcast can be directed, where the node picks specific other nodes based on privacy, solving specialisation or other criteria, or undirected, where the node broadcasts the intent as widely as possible. Intents can contain a settlement-conditional fee, to be paid only if the intent is satisfied, settled and confirmed by consensus. Furthermore this fee can be split between all nodes involved in the gossip and the ultimate solver. Intents can pay a fee for confirmation and ordering of the (likely encrypted) intent in a data availability domain where solvers compete to find the best match for each batch of intents.

3.4. Solver. A *solver* is a node which chooses to observe all or a subset of intents and computes solutions over the set of intents. It achieves this by running one or many *solver algorithms*. These algorithms are local and different solvers compete with each other to satisfy the presented constrain system. In practice, solvers will likely specialise in certain applications, such as fungible token trading or computing rollup states. Solvers are permissionless and anyone can act as the role of solver. Solvers can decide which intents to accept and should generally only consider those that are worth the storage and bandwidth costs, perhaps due to a fee or an expected spread from a trade. The solver algorithm searches the space of possible solutions based on the current state of the settlement layer and the known intent pool with the aim of finding subsets of combinable intents to generate transactions which are accepted by the settlement layer.

3.5. Transaction. A *transaction* is complete state transition which acts as a function from the current state to a new state. Transactions follow the declarative programming model and describe the desired end state rather than the imperative steps to compute it. As a result, submitters of transactions, such as solvers or ordinary users, do not have to consider the execution steps when reasoning about the behaviour of their transaction. In existing systems, such as Ethereum or other programmable settlement architectures, submitters have to be aware and trust all intermediary execution steps, including as proxy contracts, since they can modify the imperative computation and change the final state result. With Anoma's declarative approach submitters only have to accurately specify the desired end state without worrying about the compute done in the middle.

Submitters encrypt transactions against the Ferveo Distributed Key Generation (DKG) public key Bebel and Ojha (2022). Nodes receive and gossip only encrypted transactions. After consensus has ordered the encrypted byte strings a $\frac{2}{3}$ majority of consensus nodes decrypts and reveals the original transactions. Ferveo is non-interactive, which means that there are no extra economic security guarantees required in order to enforce the revelation of the original transactions.

3.6. Mempool. The *mempool* is a virtual dense partitioned overlay network for transactions. The mempool is partitioned on the basis of security and concurrency domains (fractal instances), where nodes participating in the mempool gossip only transactions for fractal instances which they are interested in. By contrast to the intent gossip network, the mempool is dense in the sense that validators of a particular fractal instance must receive all of the transactions destined for that instance. The mempool is opaque since it only receives, stores and gossips encrypted byte strings rather than transparent transactions.

3.7. Data availability domain. A *data availability domain* is a logical clock and data availability layer. These data availability domains are programmable by all applications. It allows applications to specify batches of intents that are decrypted all at once at the same time after a particular time interval has passed. Intents can be submitted in encrypted form (using Ferveo) to the nodes in a particular batch. After the batch is complete the validators decrypt all intents in a batch and add the decrypted content to the state. These intents are not directly executed by the state machine, but rather are available to solvers who compete to offer the best solution by a measurable criterion defined by the application.

3.8. Security domain. A *security domain* is a set of cryptographically identified nodes executing a particular state transition function in consensus, for which finality and correctness hold under a particular assumption of a certain fraction of nodes behaving according to protocol, generally: $n \geq 3f + 1$. Different Sybil-resistance mechanisms can be used to select the set of nodes, such as proof of stake (PoS), proof of work (PoW), proof of identity (PoI) or proof of authority (PoA).

3.9. Concurrency domain. A *concurrency domain* is a total ordering over a set of transactions within the domain which may be partially ordered or unordered with respect to other concurrency domains. Concurrency domains always operate within particular security domains, since the total order is enforced by the consensus of the security domain.

3.10. Consensus. *Consensus* is an algorithm for agreement between many parties (some possibly Byzantine) that forms a security domain and quantizes time. The consensus algorithm is responsible for grouping transactions into blocks which are agreed upon by consensus participants.

3.11. Execution. An *execution environment* is an algorithm for taking the current state and a set of transactions and applying those transactions to the state resulting in a new state. Anoma provides a *unified execution environment* which can handle transparent, shielded, and private state transitions.

- *Transparent* data is public to execution nodes and observers.
- *Shielded* data is private to execution nodes and observers, but known to a single user, who can prove properties of it using ZKPs.
- *Private* data is known by no one independently and is computed and stored in encrypted form using various forms of homomorphic encryption (HE).

Anoma provides a general framework for reasoning about the privacy of data independently of the kind of verification performed, but performance characteristics of the underlying cryptographic schemes will determine the practical feasibility and execution costs of various applications. It is important to note that the delineation here is purely on the basis of state privacy. Technologies such as zero-knowledge or optimistic rollups can be used with transparent, shielded, and private state transitions.

3.12. Application. An *application* is a semantic domain governing the form and logic of a particular partition of state which many users may interact with. **Figure 2** illustrates the interfaces for end-users in Anoma. An application consists of:

- *State*, which may be partitioned across multiple fractal instances and shards within those instances;
- *application validity predicates*, which govern changes to the application's state;
- *user validity predicate components*, which can be included by the user in order to authorise certain interactions with the application;
- *intent formats*, which allow intents to be created by clients, reasoned about by solvers, and processed by application validity predicates;
- *solver algorithms*, which allow solvers to craft transactions satisfying intents from a specific application or possibly from many other applications;, - - and *interfaces*, which provide users visual, spatial, and temporal abstractions for interacting with the application.

Fig. 2: End-user interfaces of applications on Anoma

3.13. Fractal instance. A *fractal instance* is an instance of the Anoma consensus and execution protocols operated by a set of networked validators. In general, fractal instances are security domains, in that they are operated by a particular set of validators, of which the user must trust a quorum; concurrency domains, in that they maintain a full order of only the transactions which they execute; and data availability domains, in that external observers can query the fractal instance to retrieve parts of its state. Fractal instances are sovereign, in that they do not depend on any other part of the fractal instance graph for continued correct execution, although their validator sets may overlap, a property which can be exploited in certain cases to provide multi-chain atomic settlement. Fractal instances, in order to be compatible with all features of the network, must implement the Anoma consensus and settlement protocols according to the specification, but they can vary in their chosen sybil-resistance mechanisms, execution pricing, and local governance of protocol versioning, economic distribution regime, and irregular state transitions handling.

4. Programming model

Considering the architecture of Anoma from the perspective of users with preferences over states of the system, one might ask the question: why are there applications at all? Cannot users merely articulate their preferences and the system enact them, without further component intermediation? In principle, they can, but the search space of solvers and difficulty of coordinating the relations between the state of the ledger and state of the world would be computationally intractable without coordination on particular forms of representation and particular logics of preference expression and settlement. Applications describe these particular forms, on which it is necessary to coordinate in order to express, match, and settle intents, and in order to provide simple and accurate interfaces for users.

4.1. Application components. An application on the Anoma architecture consists of intent formats, an application state validity predicate, user validity predicate components, solver algorithms, and one or many user interfaces.

- *Intent formats* describe the form and semantics of particular intents utilised by the application, which must be created by the user interfaces, understood by intent gossip nodes, matched by solvers, and validated by the application's validity predicates.
- The *application state validity predicate* encodes the relation governing valid state transitions of the application's state.
- *User validity predicate components* encode the relations which users can approve in order to allow for safe interactions with this application.

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- *Solver algorithms* instruct a solver how to match this application's intents and form valid transactions.
- Finally, *user interfaces* present users with a graphical or textual view of and controller for the application in question.

4.2. Application portability. By default, applications are portable across fractal instances, and application state validity predicates may also reason about security and concurrency domains in order to allow for safe interaction between users of an application across these domains.

Although nothing ties a particular interface to a particular application, Anoma's intent gossip network is capable of acting as a data availability layer for interface code, in a way which allows secure synchronised interface and application versions.

4.3. Application security model. In Anoma, users distrust applications. Applications are never granted un-restricted access to modify a user's state. All state entries carry an explicit owner, and the validity predicate associated with that owner must authorise all changes to that state. Instead of authorising à la `transferFrom`, users add components to their validity predicates which allow for specific interactions with a specific application, which can then be performed non-interactively from the perspective of the user, if they have granted the application license to do so. These components can be altered or revoked at any time, and allow for "defence-in-depth", e.g. prevent transfers of more than X within time bound `t`.

4.4. Application state model. Anoma assumes clients are *stateful* - they are treated as components of the distributed system. Messages will only be sent once, and can be marked as delivered, in which case they will not be kept around. Message history can be reconstructed by reprocessing historical transaction archives.

5. Applications

The architecture of Anoma is suitable for any application desiring to provide counterparty discovery, solving, and settlement for particular forms of preferences over a particular semantic domain. Here we enumerate several primitives that Anoma exposes to application developers. We then list several examples of contemporary decentralised applications and how they would benefit from Anoma's architecture. Followed by the description of novel decentralised applications which have hitherto been impractical or impossible to develop due to the constraints of existing architectures.

5.1. Novel primitives for applications. Anoma exposes several new primitives to application developers:

- Incentivised data availability, for data which is expected to be used in the creation of future transactions, provided by the intent gossip layer (see **Section 6: Architectural instantiation**).
- Programmable solvers, provided by intent gossip nodes running solver algorithms, to which can be outsourced the computational task of finding an atomic state transition (transaction) involving many parties which simultaneously satisfies all of their preferences.
- Programmable threshold decryption, provided by Ferveo Bebel and Ojha (2022), which can be used to implement on-demand batching and enforce configurable fairness properties on the processing of application-specific state transitions submitted within a quantised period of logical time.
- Programmable privacy, provided by ZKP systems and fully homomorphic encryption (FHE), which can be used to separate verification of properties of data from knowledge of the data itself. Application developers can leverage programmable privacy to build applications that handle transparent, shielded, and private state in the same application.

These primitives taken together provide the flexibility required to build complex user-friendly applications which provide the desired game-theoretic, privacy, and latency properties, such as decentralised quadratic voting and quadratic funding, voting through incentivised data availability, settlement through solvers, privacy & receipt-freeness through ZKPs and HE.

5.2. Application examples.

5.2.1. Contemporary decentralised applications. Here we list example of collections of contemporary applications that follow the intent, counterparty discovery, and solving design pattern, but that are at the moment application specific and rely on at least one single-operator component.

Decentralised exchanges Contemporary decentralised exchanges for both fungible and non-fungible tokens, such as 0x, CoWSwap, Uniswap, Wyvern, and Seaport, require both counterparty discovery, solving, and settlement, besides other requirements such as batched/fair execution. At the moment, such projects either use the blockchain itself for counterparty discovery (Uniswap) or operate single-operator orderbooks controlled by specific parties (0x, Wyvern, Seaport, CoWSwap), which tend to be trusted for fair ordering and optimal execution. Using Anoma, these parties could be replaced by the peer-to-peer intent gossip and distributed solving layer, which generalises through arbitrary trades. Orders to buy or sell particular assets would instead be broadcasted across the intent gossip network as intents, matched by a solver, who could collect any number of intents in order to balance a trade, and submitted for settlement to the fractal instance holding the assets in question. Threshold decryption can be used for fairness across batches.

Rollups Existing rollup architectures, both optimistic ones such as Arbitrum, Optimism; and zero-knowledge ones, such as ZkSync or StarkNet, operate with a single-operator sequencer and solver responsible for ordering transactions, calculating state updates, and submitting updated states to the root chain, in these cases, Ethereum. This sequencer is trusted with fair ordering and optimal solving, and can selectively omit transactions, so some projects have expressed a desire to decentralise the sequencer. As a decentralised sequencer is simply a consensus instance, such rollups could instantiate an Anoma fractal instance, using Typhon consensus, to operate their sequencer, and submit zero-knowledge or optimistic proofs of execution to Ethereum as they currently do.

Public goods funding Quadratic funding (QF), as implemented by Gitcoin, requires both counterparty discovery, solving (as the funding provider's payouts depend on individual donations), and settlement. Using Anoma, QF can be implemented in a manner which preserves individual privacy and provides excellent UX (e.g., donating to projects carries no fees). The funding provider, project creators, and all individual donators each author intents reflecting their willingness to commit funds, execute on a project, and donate, respectively. A solver algorithm matches these intents and creates a single transaction to settle at the end of the QF round, while the funding provider can pay the settlement fees. Amounts of donations must be public in order to perform the QF calculations, but individual identities can be kept private using Anoma's private execution environment. Expressive intents can also capture additional dimensionality which is difficult to represent in a simpler QF model - for example, many projects require a certain amount of funding in order to do anything at all, and only wish to receive funding (and commit to action) should a certain threshold be met. This can be expressed as a constraint in the intent, and the solver must either find enough funding to meet the threshold or omit the project, as desired, in order for the final settlement transaction to be valid.

5.2.2. Novel applications.

Here we sketch some novel decentralised applications that can be built using Anoma's architecture: DAOs 2.0, runtime rollups, multiparty multivariate bartering, private auctions, and local episodic games.

DAOs 2.0 Decentralised autonomous organisations (DAOs) hold the twin promises of organisational *operational transparency*, in that the rules for decision-making are articulated and executed in the same code, which anyone can read, and *operational verifiability*, in that any past actions of the organisation can be proven to a third party to be consistent with this rule set. In present instantiations, however, they obtain transparency and verifiability by execution on a public blockchain, which comes at the cost of privacy.

Operational privacy allows organisations to present, and prove with verifiability, specific data about the organisations inputs and outputs (e.g. quarterly funding disclosure for a non-profit) without revealing every aspect of decision-making, which is a lot of data from which someone can easily cherry-pick to misrepresent what's really happening, or which members of the public with other agendas (perhaps operating a competing organisation, or with a personal bone to pick with a member of the one in question) can use to start bike-shedding debates or otherwise interfere with organisational operations.

Anoma's architecture allows for the creation of private DAOs which need make no such compromise: they can keep both decision-making rules and data private, visible only to parties within the organisation, but prove arbitrary properties of each to the world as they choose.

In particular, this system could be used to instantiate something like the plural money system Prewitt (2022). Communities could themselves create private DAOs, controlled by members of the community, with internal community currencies, community-owned SALSA-allocated assets, and limitations/taxes on wealth transfer outside the community.

Runtime rollups Let us take a "rollup" to be the separation of computation and verification such that the verification can be suitably replicated for improved fault-tolerance while the computation need not be. In systems which rely on imperative semantics, and where end-users are signing particular imperative execution paths, rollups are long-lived and must be specifically specified by users. In Anoma's declarative architecture, since users sign intents expressing properties which the execution is required to satisfy rather than any particular execution path, rollups can be created at runtime depending on dynamic demand, and markets for compute may be used rather than replication where doing so is cheaper.

Multiparty, multivariate private bartering Consider three friends, Alice, Bob, and Charlie, a hotel operator David, a festival producer Eve, and a train company Deutsche Bahn. The festival runs for three weekends in July near Potsdam. Alice, Bob, and Charlie wish to attend the festival together, on the same weekend, and take trains from their respective home towns of Berlin, Zurich, and Amsterdam. They're flexible about the particular weekend, and would like the combined price of train tickets, hotel rooms, and festival passes to be as low as possible. Eve wants to sell tickets to his festival, which are fixed-price based on his costs plus markup, but sometimes resold by parties who purchase them early on then later realise that they cannot attend. Deutsche Bahn sells train tickets with variable prices based on demand, David likewise for hotel rooms (and she has both single rooms suitable to host one person and quadruple rooms suitable to host four). Alice, Bob, and Charlie are happy to room with another person, as long as they are also attending the festival (they view this as good evidence of a likely friendship).

In the world today, Alice, Bob, and Charlie might go to the festival's website to look for ticket availability, then try to check hotel and train prices across the three possible weekends and compile a spreadsheet in order to figure out what their costs might be. Of course, while they're busy compiling the spreadsheet, someone else looking to travel could book their hotel room or train seat, and they'd be out of luck. Worse, they could book a hotel room for a particular weekend, then find out that the train tickets are unavailable and be unable to change the hotel room (at least without paying a cancellation fee).

Alice, Bob, Charlie, David, Eve, and Deutsche Bahn could all use Anoma as a substrate for multiparty private bartering. Each party would author an intent with their preferences, and all intents would either be matched atomically (meaning that train tickets, hotel rooms, and festival passes are booked for all of Alice, Bob, and Charlie in correspondence at once) or not at all. Using private bartering, *what* all parties want is public, but *who* they are need not be revealed.

This can also be used for simpler cases, such as fungible tokens. Users can author intents capturing the semantics of market & limit orders, and also more complex algorithms such as an AMM. Expressed in intent form, an AMM order is simply a price curve along which one is willing to swap two assets (`xy = k`). Users can author AMM intents for the full price range or any subrange (similar to Uniswap v3). Unlike on-chain AMMs, this does not require sending transactions or locking any assets up.

Private auctions Independent of more long-term reasons, auctions often benefit from privacy for game-theoretic reasons: a sealed-bid second-price auction gives bidders reason to bid their true value, but requires bid privacy in order to work. Using Anoma, such auctions could be conducted privately, in two different ways. The first and most immediately feasible way is to use programmable threshold decryption to keep all bids encrypted until the auction deadline has passed, then decrypt them all at once, select the highest bidder as the winner and charge them the second-highest price. This can be combined with other privacy techniques for concealment of identity. FHE can also be used to implement private auctions, by performing the bid selection directly as operations on the bids submitted as ciphertexts.

Local episodic private games Consider a digital re-enactment of a game of poker. Games of poker are episodic, in that (even if bets are being placed and winners reported to a leaderboard) no interaction or ordering takes place between different games - if users are submitting actions, actions taken by users within the same game must be ordered with respect to actions taken by other users in that game, but not with respect to actions taken by any others. Anoma's fractal instance architecture can instantiate this structure efficiently: players, when they start a poker game, launch a temporary consensus instance (simply operated between themselves) to order state transitions within that game, then submit the results at the end to a poker tracking/statistics application on a more long-running fractal instance. This fractal instance can be run on LAN for low-latency, and transactions need not have any cost (since the set of who can submit them is restricted to the players).

Poker also requires privacy, primarily keeping a private hand and periodically revealing cards, and randomness (for the deck shuffle), which can be provided by the private execution system and threshold signatures from the threshold cryptosystem in Anoma, respectively.

6. Architectural instantiation

The Anoma architecture requires many individually intricate subcomponents which can be instantiated in a variety of ways with different performance, complexity, and ergonomic trade-offs. Here we sketch the abstract interfaces required of necessary subcomponents and summarise our current development directions in instantiating them.

6.1. Gossip. The Anoma gossip system is a pseudonymously identified, path-authenticated, fault-accountable sparse overlay network. In contrast to conventional peer-to-peer gossip networks, this system is designed to operate privately by default, with optional attestations. Nodes are identified by cryptographic keys and all messages are encrypted to their recipient and signed by their sender. Nodes craft & enforce local rules around message validity, rebroadcast, and retention. Combined with a settlement ledger and path-authentication-based fees, this provides an incentivised data availability layer for transaction-relevant data, which is used within the Anoma architecture by users to broadcast intents, which are sent around until solvers find counterparties, create transactions, and submit them to fractal instances for settlement. Nodes maintain a local trust graph and ruleset around message content validity and rebroadcast criteria. The Anoma gossip system uses an explicit trust model, where the underlying physical network is distrusted, new nodes bootstrap with a set of trusted peer public keys, and nodes maintain trust relations over time, keeping track of who introduced them to whom and applying changes in trust recursively along the trust graph.

6.1.1. Node model. Nodes in the gossip network are assumed to possess a private key, the corresponding public key to which is used as identification. Nodes must totally order and sign all messages which they send, which are unique. Signing two messages with the same nonce is an accountable fault.

In traditional P2P gossip systems, nodes are primarily identified by their IP address, which refers to a physical network destination and is assumed to be long-lived. By contrast, in the Anoma gossip system, nodes are primarily identified by their public key, which can list and periodically rotate IP addresses at which it could potentially be reached (but which a sender does not necessarily need to know in order to send messages). This can be seen as a sort of virtual gossip network, with identity persistence based on secret information (the private keys) which can be freely moved across physical substrates. Local caches of physical routing latency are kept in order to maintain a relatively efficient mapping of the spatially non-local virtualised network into the spatially local physical one.

This choice of structure also allows for a conceptually elegant virtualisation of fault-tolerant subsystems: a threshold cryptosystem in combination with consensus (in order to provide ordering) effectively virtualises many nodes as one node, with the threshold key used for incoming and outgoing messages and shares for threshold decryption and threshold signing internally rebroadcast around for reconstruction (encrypted to individual node public keys for privacy). In contrast to other blockchain systems, Anoma's gossip network is not sharded on the basis of security domains (compare to independent blockchain mempools), but rather simply sparse, where real-time demand can inform connection choices and routing tables.

6.1.2. Path authentication. Anoma's gossip system provides *path authentication*: the receiver of a message can verify a chain of signatures recursively back all the way to the original sender, such that each party in the message chain can be verified to have authorised the next send, and can be both potentially paid for participating in gossip and held accountable for inconsistent ordering across messages. This is accomplished simply by keeping an ordered list of signatures in the message header, which can all be checked by the recipient for correctness and linkage consistency. For efficiency and privacy, validity checks may be compressed and inner path identities may be hidden using ZKPs, which the recipient then verifies as a part of receiving the message.

6.1.3. Gossip incentives. The path authentication system described above can be used to provide a form of gossip incentive whereby a user can broadcast an intent and offer payment to any nodes who participate in a chain of gossip which leads to its eventual settlement. The user simply includes a small fee (the semantics of which are chosen at runtime) which they allow gossip nodes to malleate, so that each node, when forwarding the message, can choose to take a portion of the fee for themselves. If the node can settle the intent by combining it with others, crafting a valid transaction, and submitting it to the appropriate fractal instance, they can claim the fee immediately. If not, the node can choose how much fee to take for themselves before they forward the message. Of course, they can take all the fee, but then there would be no reason for other nodes to rebroadcast or settle the intent, so the node would receive nothing. Nodes can thus be expected to rebroadcast intents taking only enough of the fee such that the expected benefits of potential settlement outweigh the opportunity cost of potentially being able to settle it themselves (but the user can broadcast their intent to many parties, so an individual node who cannot immediately settle it is unlikely to be the first to be able to).

6.2. Consensus. The consensus component is an algorithm by which many nodes can be abstracted as one virtual node, which will be correct subject to certain assumptions about the correctness of the constituent nodes (generally $\frac{2}{3}$). Just as individual nodes operate a deterministic state machine and send and receive messages in a local total order, virtual nodes created by use of the consensus algorithm operate a deterministic (replicated) state machine and send/receive messages in a total order. The consensus algorithm is responsible for abstracting many nodes into this virtual node by gossiping, ordering, and executing transactions (incoming messages), then finalising the updated states (outgoing messages) in a verifiable manner.

At present, the consensus component in Anoma is instantiated by Typhon Heliax (2022), which draws substantially from Heterogeneous Paxos Sheff et al. (2021), Narwhal Danezis et al. (2022), and Tendermint Buchman et al. (2018).

6.2.1. Ordering. The ordering component of consensus is responsible for ordering transactions prior to execution, where nodes participating in consensus must agree on the ordering and ensure that all transactions so ordered are available to them for execution.

6.2.2. Execution. The execution component of consensus is responsible for executing transactions on which an order has already been agreed, updating the state to reflect the results of transaction execution, and finalising the updated state so that external parties can inexpensively verify properties of it.

6.3. Execution environments. The execution environment of Anoma is a runtime responsible for partitioning and permissioning state and code to allow for safe interoperation of mutually distrusting programs, abstracting transparent, shielded, and private state changes and providing appropriate primitives for cryptographic operations, and handling cross-fractal instance state verification as well as synchronous and asynchronous cross-fractal-instance messaging. These three responsibilities of abstraction are orthogonalised into three components: the validity predicate subsystem, the unified transparent/shielded/private execution environment (Taiga), and the transparent execution environment (Typhon EE).

6.3.1. Validity predicate subsystem. The validity predicate (VP) subsystem is responsible for partitioning and permissioning state and code in order to allow for safe interoperation of mutually distrusting programs. This is accomplished by splitting the keyspace of transparent, shielded, and private state into mutually exclusive prefix spaces, where the first part of a key corresponds to ownership by a specific validity predicate, stored at a sentinel key within that prefix. Whenever state within a particular prefix is altered, the validity predicates associated with that prefix are called, and they can choose to accept or reject the transaction. Validity predicates can also choose to require that other validity predicates also accept.

The validity predicate subsystem is itself implemented as a validity predicate and can in principle be instantiated recursively. The subsystem is also responsible for enforcing limitations on what data is accessible to VPs.

6.3.2. Taiga Unified EE. The Taiga unified execution environment is responsible for handling transparent, shielded, and private data access and operations.

Data privacy domains Transparent data is represented as a mutable key-value tree, where keys can be read, written, and deleted, and prefixes can be iterated over.

Shielded data is represented as an immutable append-only note set, where each note can be either consumed once or many times. Each note includes a key, value, and owner key, to which an encryption of the note contents must be available.

Private data is represented as a mutable key $\rightarrow$ ciphertext mapping, where keys can be read, written, and deleted, and ciphertexts can be operated on using special homomorphic instructions.

Cross-domain transit Conversion between the three data realms is handled as follows:

- Transparent $\rightarrow$ Shielded: Transparent data can be read or computed over in the course of execution, and then written into a shielded note.
- Transparent $\rightarrow$ Private: Transparent data can be read or computed over in the course of execution, and then encrypted to the threshold key.
- Shielded $\rightarrow$ Private: Shielded data can be computed over in zero-knowledge, and then encrypted to the threshold key, where correct encryption is proved in zero-knowledge and only the encrypted value is revealed to the operator.
- Shielded $\rightarrow$ Transparent: Properties of shielded data can be proved in zero-knowledge and then revealed to the operator along with the proof.
- Private $\rightarrow$ Transparent: Private ciphertexts can be decrypted using threshold decryption. This process is asynchronous.
- Private $\rightarrow$ Shielded: Private ciphertexts can be re-encrypted to another public key and thus become shielded data. This process is asynchronous.

6.3.3. Typhon Transparent EE. The Typhon execution environment is the lowest-level execution environment, designed to impose only the minimal requirements and structure required by Typhon for transaction ordering and concurrent execution.

The Typhon execution environment has only transparent state, which is organised in a key-value tree. Transactions declare parents of all subtrees of keyspace within which they will read and write. Using this information, Typhon can identify transactions which touch only non-overlapping regions of state and thus order transactions for concurrent execution. This execution environment does not itself have any state semantics for private data or state/code partitioning. Further structure is specified by a root validity predicate, stored at a particular sentinel key, which is called as a part of all transactions.

The Typhon EE is also responsible for handling asynchronous message passing across fractal instances and synchronous (atomic) message passing within chimera chains. The EE handles transport, ordering, and verification, while message semantics are left to higher execution abstraction layers.

6.4. Compilation stack. In order to provide a unified black-box application development interface, the Anoma implementation includes a new language, Juvix, and a compiler stack, designed in tandem to allow developers to write formally verified, privacy-preserving, fault-tolerant distributed applications.

A great deal of research work into the compiler stack remains and this section should be considered a work in progress. Several components described herein are only partially implemented and alternatives are still under active consideration.

6.4.1. Juvix. Juvix is a high-level function language which compiles to a variant of the simply typed lambda calculus. Programs written in Juvix can express and reason about public, shielded, and private data and operations. Juvix's lambda calculus output language can be compiled to RISCV or WASM through C, or can be compiled to the abstract categorical operations of the AVM which can in turn be instantiated as polynomials, the input language of VampIR.

6.4.2. AnomaVM. The AnomaVM (AVM) is a distributed abstract categorical virtual machine. The AVM is designed to capture information theoretic semantics of multiparty interactions and compute without fixing concrete cryptographic representations/instantiations or operational execution semantics. An AVM program directly references agents by role, who can reason about each others state transitions and states through proofs of execution and authentication, and who can send and receive messages to and from each other.

An AVM program itself specifies agents only abstractly, but it can be executed (or compiled, then executed) by any agent, who must specify the role they wish to play (this is a sort of local naming system). The AVM can be compiled through LLVM for transparent execution, and through VampIR for circuits suited to ZKP or FHE execution.

As an operationally neutral abstract representation, the AVM is also the level at which the Anoma architecture defines cost semantics and identity of programs, e.g. different parties may compile AVM programs to different concrete cryptographic and transparent backends for execution.

6.4.3. VampIR. VampIR is a language and compiler designed to provide an abstract representation of polynomials, circuits, and constraint systems which can be compiled to different concrete proof systems. The IR is designed to capture the denotational semantics of circuits while remaining agnostic to operational semantics of instantiation in various proof systems and cryptographic backends, including ZKP and FHE.

6.5. Fractal instance components.

6.5.1. Sybil resistance. Fractal instances must provide a Sybil resistant mechanism in order to assign voting power in consensus. This can be proof-of-stake, proof-of-authority, hybrid (partially fungible) proof-of-stake, or some form of liquid democracy based on the cryptographic identity substrate.

6.5.2. Governance. Fractal instances may provide a governance mechanism for enacting irregular state changes by a (somewhat) more regular process than what would take place without any such system. This governance mechanism itself requires Sybil resistance, which can be the same as used in consensus or a slight variant.

6.5.3. Resource pricing. Fractal instances must provide a Sybil resistance mechanism for performing expensive computational operations upon the receipt of messages which can be sent by anyone in an open network. This Sybil resistance mechanism could be based on fees paid in a network token, identity-based quotas or subscriptions of compute, storage, etc., or low flat per-message limits in combination with network-based rate limiting.

7. Future directions

7.1. Private counterparty discovery. The trade-off axis between counterparty discovery, fairness, and privacy is quite fundamental: in order to find a counterparty in any way more efficient than random testing, you must provide some information about your preferences, which entails a corresponding loss of privacy, and in order to provide fairness across a larger set of parties in cases of uncertain information (e.g. variable prices), you must make your preferences public to a larger set of solvers who can see more intents at once and compete to find the fairest solutions.

Encrypted solving (solving intents which are completely private to the solver), while possible in principle, pairs the already NP problem of solving with the overhead of heavy-duty HE, and is likely to remain infeasible in the near future, but research into improved algorithms, application-specific solutions, and dedicated hardware could bring these overhead costs down over time.

7.2. End-to-end behavioural verification. Anoma's architecture covers the domain from (abstract) Turing machines operating node software to (abstract) users authoring intents, and provides guarantees for the behaviours of the system with respect to the latter given certain assumptions about the behaviours of the former. In practice, safe usage of a deployment of Anoma depends not only on the correctness of this system but also on the correctness of the hardware utilised by nodes and the correctness of interfaces utilised by users. Eventually, this verification could be extended further into the interface and hardware domains.

8. Acknowledgements

References

Bitcoin Wiki. Bitcoin Script, 2021. URL https://en.bitcoin.it/wiki/Script. [Online; accessed 29-July-2022]. (cit. on p. 2.)

Vitalik Buterin. Ethereum: A Next-Generation Smart Contract and Decentralized Application Platform, 2014. URL https://ethereum.org/669c9e2e2027310b6b3cdce6e1c52962/Ethereum_Whitepaper_-_Buterin_2014.pdf. [Online; accessed 29-July-2022]. (cit. on p. 2.)

E Glen Weyl, Puja Ohlhaver, and Vitalik Buterin. Decentralized society: Finding web3's soul. *Available at SSRN 4105763*, 2022. (cit. on p. 2.)

Ethan Buchman, Jae Kwon, and Zarko Milosevic. The latest gossip on bft consensus. *arXiv preprint arXiv:1807.04938*, 2018. (cit. on pp. 2 and 11.)

Team Rocket. Snowflake to avalanche: A novel metastable consensus protocol family for cryptocurrencies. *Available [online].[Accessed: 4-12-2018]*, 2018. (cit. on p. 2.)

Christopher Goes. The interblockchain communication protocol: An overview. *arXiv preprint arXiv:2006.15918*, 2020. (cit. on p. 4.)

Joseph Bebel and Dev Ojha. Ferveo: Threshold decryption for mempool privacy in bft networks. *Cryptology ePrint Archive*, 2022. (cit. on pp. 6 and 8.)

Matt Prewitt. PLURAL MONEY: A NEW CURRENCY DESIGN, 2022. URL https://www.radicalxchange.org/media/blog/plural-money-a-new-currency-design/. [Online; accessed 29-July-2022]. (cit. on p. 9.)

Heliax. Typhon, 2022. URL https://specs.anoma.net/master/architecture/consensus/typhon.html. [Online; accessed 29-July-2022]. (cit. on p. 11.)

Isaac Sheff, Xinwen Wang, Robbert van Renesse, and Andrew C Myers. Heterogeneous paxos. In *OPODIS: International Conference on Principles of Distributed Systems*, number 2020, 2021. (cit. on p. 11.)

George Danezis, Lefteris Kokoris-Kogias, Alberto Sonnino, and Alexander Spiegelman. Narwhal and tusk: a dag-based mempool and efficient bft consensus. In *Proceedings of the Seventeenth European Conference on Computer Systems*, pages 34–50, 2022. (cit. on p. 11.)

Lukasz Czajka. Juvix to vampir pipeline, August 2023. URL https://doi.org/10.5281/zenodo.8246535. This document is based on Juvix v0.4.1, Geb v0.4.0, and VampIR v0.1.3.

Artem Gureev and Jonathan Prieto-Cubides. Geb Pipeline. *Anoma Research Topics*, August 2023. doi:10.5281/zenodo.8262815. URL https://doi.org/10.5281/zenodo.8262815. This document is based on Geb v0.4.1.