

NANYANG TECHNOLOGICAL UNIVERSITY

**NEXT-GEN GENERATIVE SEARCH ENGINE FOR CODE
BASE**

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College of Computing and Data Science

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Abstract

This report presents the design, implementation and evaluation of CodeOrient, an Artificial Intelligence (AI) Search tool, designed to accelerate developer onboarding. This application leverages Natural Language Processing (NLP), code graph visualisation and vector-based retrieval to help new developers understand unfamiliar codebases and reduce the time to first commit.

CodeOrient integrates semantic code search using embedding models, structural analysis through dependency graphs and generative user interfaces (UI) to provide context-aware feature cards. Through the use of Retrieval-Augmented Generation (RAG) with source grounding, the application eliminates hallucination, commonly seen in AI code assistants. Preliminary testing suggests that by externalising the mental model of a codebase through a unified graph-and-card interface, the system significantly reduces the cognitive load associated with onboarding and system discovery in large-scale repositories.

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Chapter 1

Introduction

Software Engineering is undergoing a fundamental shift with the rise in Large Language Models (LLMs), Agentic Artificial Intelligence (AI), and generative user interfaces (GenUI). As the complexity of current software architectures (distributed systems) and codebases grow, the challenge of developers learning a new repository has become a significant bottleneck for engineering productivity. I propose CodeOrient, an autonomous AI-driven developer onboarding platform that leverages Retrieval-Augmented Generation (RAG) with dynamic graph visualisation. Deployed as an interactive onboarding assistant, CodeOrient combines the reasoning capabilities of LLMs with the structural insights of code graphs to transform how developers understand and navigate unfamiliar codebases.

1.1 Motivation and Problem Statement

The rapid advancement of AI-assisted coding tools, such as GitHub Copilot and Cursor, has prioritised code generation over code comprehension. However, for a developer joining a new organisation, the primary hurdle is not writing new code, but understanding the existing codebases tied within complex architectures. Current onboarding processes face three critical issues:

1. **The Hallucination Problem:** LLMs often generate plausible-sounding but incorrect explanations of code structure, leading to confusion and mistrust.

2. **The Context Window Constraint:** Large codebases exceed the input limits of LLMs, resulting in fragmented or incomplete answers.
3. **Cognitive Overload in Navigation:** Static documentation fails to capture the dynamic relationships within code, forcing developers to mentally map text-based

1.2 Research Objectives and Goals

The primary goal of this research is to create a citation-grounded, visually adaptive system that reduces the time required for a new developer to familiarise with the codebases. The specific objectives are:

1. **Develop a Retrieval-Augmented Generation (RAG) Framework:** Moving beyond keyword/fuzzy search to a hybrid system that queries semantic embeddings to capture user intent.
2. **Implement a Generative UI for Code Visualisation:** Leveraging libraries like React Flow to dynamically render interactive graphs that adapt to the user's specific natural language intent.
3. **Minimise AI Hallucinations through Citation Grounding:** Ensuring every architectural claim made by the LLM is backed by code snippets or graph nodes from the actual repository.
4. **Evaluate the Impact of Visual Context on Onboarding:** To explore how dynamic graph visualisations affect developer comprehension and cognitive load compared to traditional text-based documentation.

1.3 Key Contributions

CodeOrient introduces several innovations that distinguish it from conventional AI coding assistants:

- **Dynamic Graph Synthesis:** Instead of text-based answers, Generative UI is used to create custom visualisations for each query. If a developer asks about

“authentication flow,” the UI creates a graph focused strictly on those related modules, rather than a cluttered, static diagram.

- **Citation-Grounded RAG Pipeline:** By integrating citation mechanisms into the RAG framework, CodeOrient ensures that all LLM outputs are verifiable against actual code segments, significantly reducing misinformation.
- **Agentic LLM Integration:** CodeOrient utilises agentic LLMs capable of autonomously deciding when to query the vector database, generate visualisations, or seek clarifications. This autonomy allows for a more fluid interaction between the developer and the system.

1.4 Report Structure

This report is organised to guide the reader through the theoretical foundations and technical implementation of CodeOrient:

- **Chapter 2:** Literature Review explores the intersection of software complexity metrics, semantic code search, and the emerging technologies of Generative UI.
- **Chapter 3:** System Design and Architecture details the technical stack, including the integration of Agentic LLMs with vector databases and React Flow-based frontend.
- **Chapter 4:** Implementation Details discusses the challenges of grounding AI outputs in the source code and the development of the RAG pipeline.
- **Chapter 5 & 6:** Evaluation and Results will analyse the tool’s effectiveness in reducing cognitive load and improving search precision.
- **Chapter 7:** Discussion discusses the implications of the findings, limitations of the current approach, and potential avenues for future research.
- **Chapter 8:** Conclusion summarises the contributions of this research and reflects on the broader impact of AI-driven developer onboarding tools.

Chapter 2

Literature Review

Understanding unfamiliar and large codebases poses significant challenges for software developers, especially those new to a project or organisation. Different organisations have various ways to onboard new developers, yet these approaches to codebase exploration remains inefficient. As AI adoption increases, the problem of accurate code comprehension becomes paramount. Often, AI-assisted tools hallucinate information that is not grounded in actual source code. Furthermore, large codebases make it harder for AI to comprehend due to its limited context window.

This literature review examines five interrelated research domains critical to the proposed AI Search Tool - CodeOrient:

1. Software Complexity Metrics and Code Quality Measurements
2. Semantic Code Search and Natural Language Query Processing
3. AI Hallucination and Grounded Code Comprehension
4. Code Visualisation and Dependency Analysis
5. Generative User Interfaces

The combination of these areas provides the theoretical foundation for building an AI application that reduces developer onboarding time while maintaining citation accuracy and reliability.

2.1 Software Complexity Metrics and Code Quality Measurements

2.1.1 Cyclomatic Complexity as Foundation

Thomas J.M McCabe introduced cyclomatic complexity, a quantitative measure of program complexity based on control graph flow analysis [1]. His work established that cyclomatic complexity directly correlates with code maintainability and testing. The formula $M = E - N + 2P$, where E represents edges, N represents nodes, and P represents the number of connected components in a control flow graph, represents the complexity as the number of linearly independent paths through a program's source code [1]. As shown in Fig.1, a simple control flow graph of a function below yields a complexity of 2, where $P = 1$.

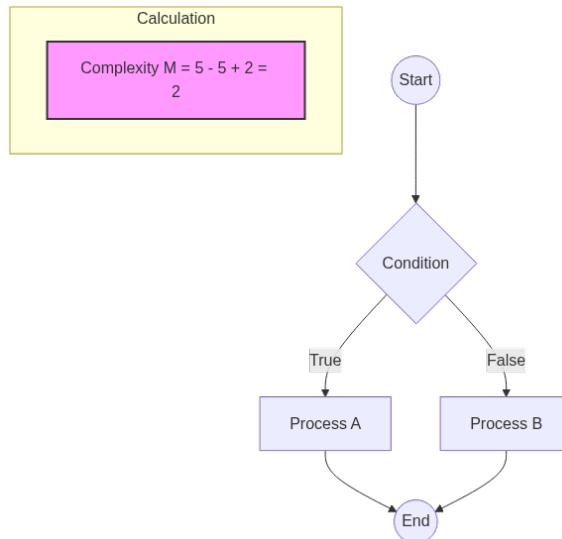


Figure 2.1: *Control flow graph of a simple if-else statement.*

McCabe's complexity measure allows developers to identify highly complex functions and recognise problematic code sections that require refactoring. When implementing the code graph visualisation feature in a code search application, cyclomatic complexity serves as one signal among many to highlight high-risk or critical code sections.

2.1.2 Modern Complexity in Distributed Systems

Kafura's recent reflection on McCabe's work in 2025 acknowledges that cyclomatic complexity has proven durable for the last 50 years. However, modern software architectures, such as distributed systems and microservices, require additional metrics beyond control flow analysis [2]. This observation directly motivates the integration of code graph visualisation in modern development tools, as visual representation of information flow across procedures becomes just as important as understanding control flow within individual functions.

2.2 Code Search and Natural Language Query Processing

2.2.1 Semantic Code Search Through Embeddings

With the recent advancements in neural networks and embedding models, the field of semantic code search has evolved significantly from traditional keyword-based search. Cambronero et al. demonstrated that the use of neural embeddings could bridge the semantic gap between natural language queries and code snippets [3]. By transforming both code and queries into a shared vector space, and code snippets relevant to the query can be retrieved by calculating the cosine similarity between their embedding vectors, given by the formula:

$$\text{cosine_similarity}(\vec{a}, \vec{b}) = \frac{\vec{a} \cdot \vec{b}}{\|\vec{a}\| \|\vec{b}\|}$$

where \vec{a} and \vec{b} are the embedding vectors of the query and code snippet, respectively.

In the figure below, developers can express their intent through natural language, which is then mapped into the same embedding space as code snippets. This technique supplements existing searches, such as fuzzy search or keyword-based approaches that often miss semantically relevant results. This motivates the use of natural language search in modern code repositories like GitHub.

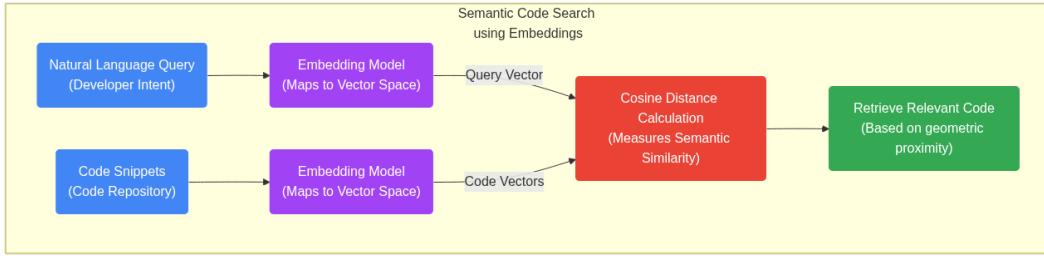


Figure 2.2: *Semantic code search in a shared embedding space for retrieval [3]*.

2.2.2 Structural Code Search with Domain-Specific Languages

Recent research by Limpanukorn et al. (2025) introduces structural code search by translating natural language queries into Domain-Specific Language (DSL) queries for more precise code retrieval [4]. This approach leverages the architectural information embedded in a codebase rather than just its textual meaning. This method achieved a precision score of 55-70% and outperformed semantic search baselines by up to 57% on F1 scores [4].

This research presents a critical missing link in developer tools, such as tracing an "authentication flow", where the relationships between modules are more informative than the functions' names themselves. The findings provide a strong validation for the code graph visualisation tool, providing syntactic and architectural information for developers to understand complex problem spaces.

2.2.3 Code Embedding Models for Retrieval

In 2025, Qodo introduced specialised code embedding models (Qodo Embed-1) that achieved state-of-the-art performance in Codebase Understanding Gartner® 2025, with a product score of 3.72/5. Their approach directly encodes code semantics without an intermediate language description step [5]. By avoiding the overhead of the intermediate step, Qodo Embed-1 has proved to be computationally efficient while maintaining high retrieval accuracy.

2.3 AI Hallucination and Grounded Code Comprehension

2.3.1 The Hallucination Problem in Code-Generating LLMs

With the rise in AI-assisted code generation tools such as GitHub Copilot and ChatGPT, the problem of hallucination becomes increasingly critical. Hallucination refers to generated information that seems plausible but is fabricated or factually incorrect. Spracklen et al.'s (2025) research revealed that package hallucinations are a systemic issue across state-of-the-art code-generating models [6]. They analysed over 576,000 generated code samples across 16 Large Language Models (LLMs) and found that the LLMs consistently hallucinate package names. More critically, they regenerate the same false package name across 43% of repeated prompts [6].

This poses a critical issue in agentic workflow as the hallucination is exploitable via "slopsquatting", creating risks in the software supply chain [6]. The figure below showcases how an attacker can exploit hallucinations from LLMs. This research highlights the urgent need for citation-grounded code comprehension systems that can verify all claims against actual source code.

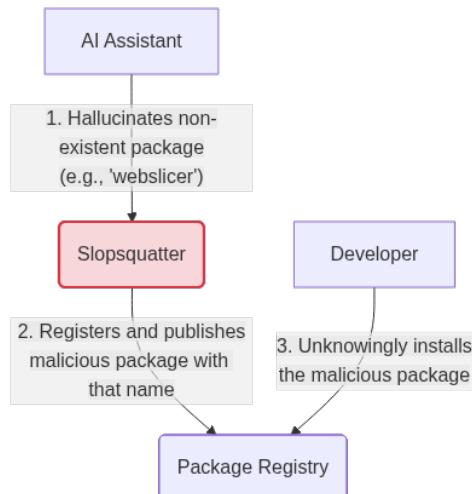


Figure 2.3: *Exploiting LLM hallucinations through slopsquatting.*

2.3.2 Citation-Grounded Code Comprehension

Arafat et al.’s recent work on citation-grounded code comprehension directly addresses the hallucination problem [7]. They conclude that code comprehension systems must ground all claims in verifiable source code citations. Their proposed hybrid retrieval system with Neo4j graph database to provide import relationships, achieved a 92% citation accuracy with zero hallucinations. Moreover, the graph component discovered richer cross-file relationships that purely text-based retrieval missed, 62% of architectural queries [7].

2.3.3 Retrieval-Augmented Generation

The broader principle emerging from hallucination research is Retrieval-Augmented Generation (RAG). As it is not possible to train new information into LLMs at scale, RAG provides a mechanism to ground LLM outputs with real-time data via a retriever [8]. The use of a retriever reduced hallucination rates across all categories from a baseline high of 21% to below 7.5% [8]. In the context of code comprehension, RAG refers to a retriever that fetches relevant code snippets, which are then passed to an LLM as a context to generate grounded explanations with source citations.

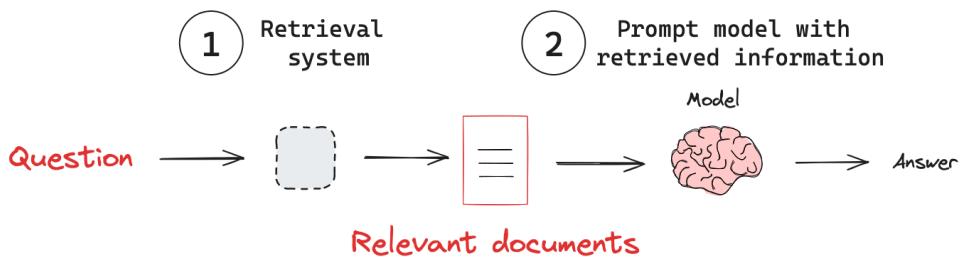


Figure 2.4: *Retrieval-Augmented Generation to reduce hallucinations [7]*.

2.4 Code Visualisation and Dependency Analysis

2.4.1 Static Analysis and Dependency Graphs

To understand the real structure of a codebase, dependency graphs are essential. Using entities as nodes and relationships as edges, code graphs provide a visual representation

of how different components interact with each other [9]. Without this visualisation, it is inherently difficult for developers to grasp the complex relationships present in modern software architectures like microservices. In particular, for CodeOrient, visualising dependencies helps developers trace data flows and control flows across modules, which helps them understand unfamiliar codebases faster.

2.4.2 Interactive Visualisation Tools

React Flow is a popular open-source library for building interactive, node-based User Interfaces (UIs) in React applications [10]. This interactivity is crucial for developers to understand the linkage between nodes and edges and how they interact. Rather than traditional static diagrams, developers can explore relationships dynamically by hovering over nodes and their related code snippets.

2.5 Generative User Interface (UI)

2.5.1 Generative UI as a Paradigm

Google’s recent research on Generative UI introduces a paradigm shift in interface design [11]. Traditionally, LLMs can only generate text-based outputs, but Generative UI extends this capability by generating dynamic user interfaces at runtime based on user prompts. This strengthens the capability of LLMs by giving them the tools to generate dynamic code graphs for visualisation, with their structure and content optimised for each specific query.

2.5.2 Task-Driven Data Models for Adaptive Interfaces

Recent research by Cao et al. showcases the use of task-driven data models as the foundation for Generative UI [12]. By allowing LLMs to generate a data model representing the core task, then mapping it to UI specifications, the resulting interfaces were more adaptive and aligned with user intent than direct UI code generation. This also ensures that the generated UI is grounded in actual data structures rather than arbitrary code snippets.

2.6 Related Systems and Tools

Based on current semantic search tools like RAG [8] and interactive graph visualisation tools [10], there is a clear gap in integrating these capabilities into a unified developer onboarding experience. This addresses the onboarding challenges faced by developers when exploring unfamiliar codebases. The integration of LLMs, semantic search, code graph visualisation, and generative UI into a single application allows developers to search for relevant code snippets, understand their relationships via dynamically generated graphs, while ensuring trust through citation grounding [7].

2.7 Research Gaps and Motivation

While the individual domains of semantic search, graph analysis, and Generative UI have matured significantly, their integration into a developer tool reveals two critical research gaps that CodeOrient aims to address:

2.7.1 Bridging Semantic and Structural Code Search

Current tools typically favour either semantic search (finding code that looks right) or structural analysis (finding code that is connected). As noted by Limpanukorn et al. (2025), structural search outperforms semantic baselines, yet most AI tools like GitHub Copilot still relies primarily on text-based RAG. There is a lack of research into how Generative UI can bridge this gap by dynamically synthesising a visual graph that represents both the user’s natural language intent and the codebase’s physical architecture.

2.7.2 The ”Black Box” of Generative UI in Software Engineering

Research by Leviathan et al. [11] and Cao et al. [12] establishes the framework for task-driven UIs. However, these studies focus on general tasks such as education or shopping, as shown below. In the high-stakes domain of software engineering, it is unknown how a constantly changing, generative interface affects a developer’s productivity.

CodeOrient provides an experimental platform to observe whether generative graphs reduce cognitive load during onboarding or if the lack of visual consistency hinders comprehension.

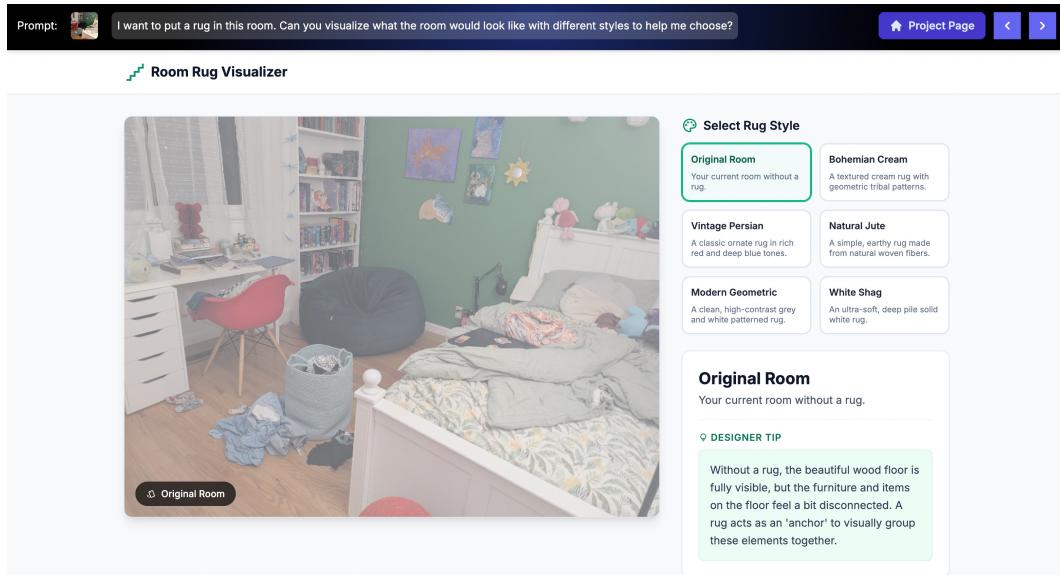


Figure 2.5: *Generative UI for a Room Rug Visualiser [11]*.

2.8 Conclusion

Improving developer onboarding requires addressing code comprehension at multiple levels. Recent research in cyclomatic complexity [1], semantic code search [3], citation-grounded AI [7], and Generative UI [12] provides a comprehensive foundation. By integrating these approaches together, CodeOrient has the potential to accelerate developer onboarding while being reliable and accurate.

Chapter 3

System Design and Architecture

3.1 System Overview

This section provides a high-level overview of CodeOrient's system architecture on how it transforms a user's query into a citation-backed technical response with relevant code snippets and visualisations.

3.1.1 Core Components

The main components of CodeOrient include:

- **User Interface:** Built with Next.js and React Flow. It provides an end to end experience to input queries, visualise code dependencies, and view generated responses.
- **LLM Integration:** Utilises Vercel AI SDK and OpenAI for natural language processing, autonomous tool calling, and response generation.
- **Code Discovery Engine:** Leverages GitHub Search API to find relevant code snippets and index them for semantic retrieval.
- **Storage Solutions:** PostgreSQL for structured data, Upstash Redis for caching and Upstash Vector for embedding storage.

3.1.2 Data Flow Architecture

CodeOrient handles user interaction through a multi-stage pipeline that is optimised for speed and quality of responses. Figure 3.1 illustrates the data flow architecture where the lifecycle is split into two phases: *Code Indexing Cycle* and *Query-Response Cycle*.

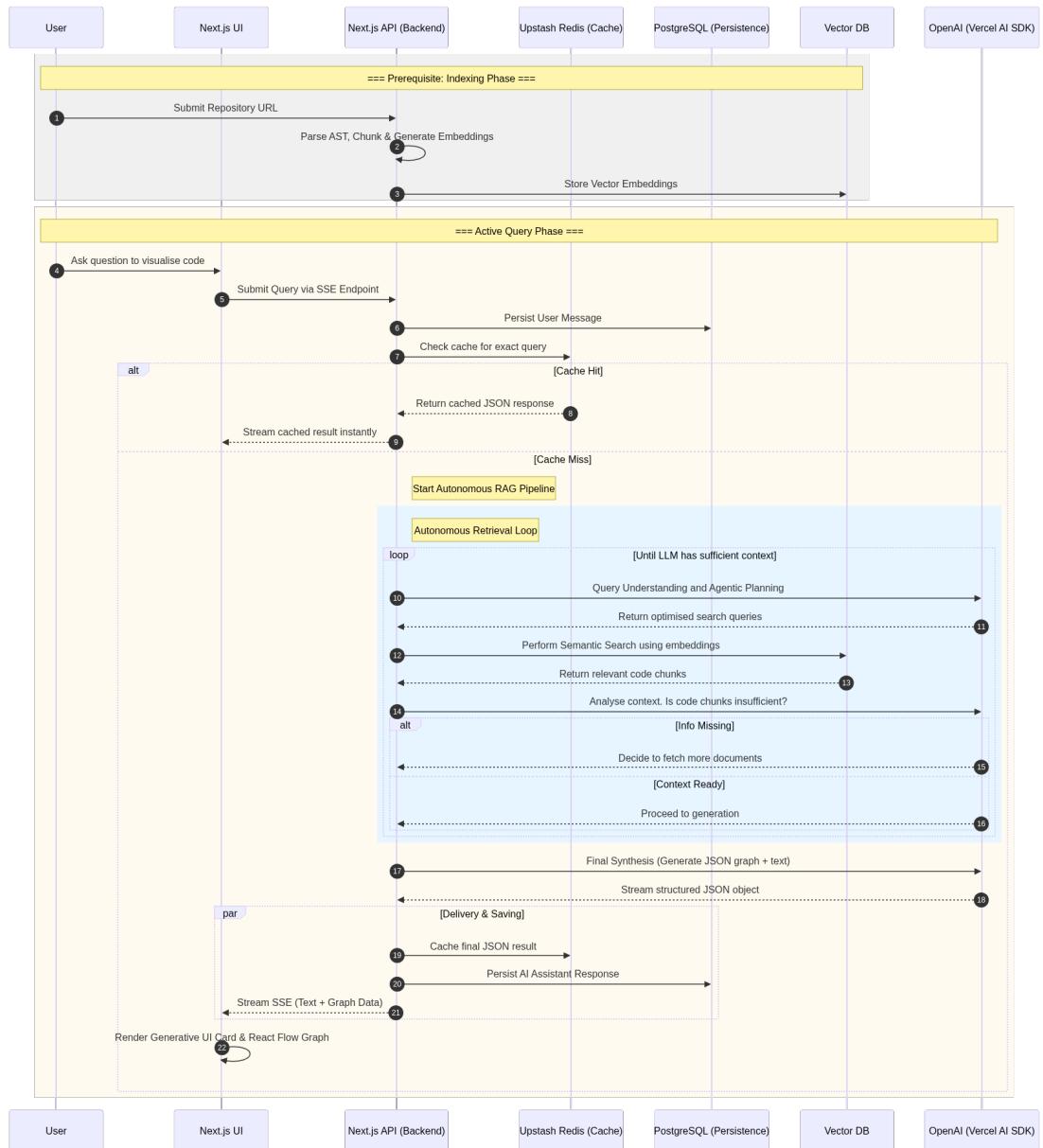


Figure 3.1: Data Flow Architecture of CodeOrient

3.1.3 Code Indexing Cycle

This phase is responsible for ingesting code repositories via GitHub API. This is a prerequisite step which parses the source code files, chunks them, generates semantic embeddings, before storing them into a vector database for efficient retrieval.

3.1.4 Query-Response Cycle

When a user asks a question, the system goes through the following steps:

1. **Input with Persistence** The user submits query via the frontend built with Next.js. The message is saved to PostgreSQL for chat history persistence.
2. **Cache Layer** The backend will first check Upstash Redis for an identical query in the same session:
 - **Cache Hit:** If a cached response exists, the stored JSON response is retrieved and streamed back to the UI, which cuts down latency over 90%.
 - **Cache Miss:** If no cached response is found, the system initiates the Retrieval-Augmented Generation (RAG) pipeline.
3. **Autonomous RAG Pipeline** This pipeline serves as the core reasoning engine:
 - **Query Understanding & Planning:** The LLM first understands and rephrases the user's natural language query. This step is crucial to fix potential errors such as typos, ambiguous terms, or lack of context. Next, the LLM generates a plan to decompose the query into sub-tasks, generating up to 3 sub-queries for retrieval.
 - **Semantic Retrieval:** Each sub-query is converted into embeddings and the system retrieves the top-K relevant code chunks from the vector database.
 - **LLM Evaluation Loop:** The LLM evaluates the retrieved content. If the

context is deemed insufficient, it autonomously triggers further searches in a loop until it gathers sufficient context to confidently answer the original query.

4. **Citation-Grounded Response:** Once sufficient context is gathered, the LLM generates a structured JSON object that contains the required nodes, edges, code snippets (citations) and explanation required for visualisation and response generation. Furthermore, the LLM is prompted to perform inline citations for each code snippet used in the response to mitigate hallucinations.
5. **Message Persistence & Caching:** The final result is stored in PostgreSQL for chat history and also cached in Upstash Redis for future identical queries. Simultaneously, the response is streamed via Server-Sent-Events (SSE) back to the frontend for real-time rendering.
6. **Interactive Rendering:** Next.js parses the streamed JSON response to render as a Generative UI card that contains an interactive graph visualisation built with React Flow, along with citation-backed explanations and code snippets.

3.1.5 Serverless Service Architecture

CodeOrient utilises Next.js API Route Handlers to create a modular, serverless backend. This separates logical concerns while maintaining the codebase as a monorepo for quicker development cycles. Additionally, when it is deployed in a serverless environment (Vercel), each Route Handler (e.g., `/api/search` vs `/api/index`) scales independently based on traffic. Even as a monorepo, the backend logic is divided into specialised services that operate independently:

- **Ingestion Service:** Handles the ingesting of code repositories from GitHub API asynchronously through background jobs, allowing the frontend to remain responsive.
- **Vector Orchestration Service:** Manages the communication with the vector database which handles embedding generation and semantic search.
- **RAG Agent:** Specialised agent that has access to various tools such as Code

Search, Graph Generation, etc. It maintains the state of the search by deciding if the retrieved content is sufficient to answer the query or if more code snippets are required.

- **Code Search Service:** Interfaces with GitHub Search API to discover relevant code snippets based on user queries.
- **Persistence & Cache Service:** Prisma, a dedicated Object Relational Mapping (ORM) service is used to interact with PostgreSQL for persistence chat history and Redis client to interact with Upstash Redis for caching frequent queries.

3.2 Frontend Architecture

3.2.1 Technology Stack

- **Framework:** The framework of choice is Next.js App Router with Typescript. This framework allows to mix Server Components (RSC) and Client Components seamlessly, optimising for performance and developer experience.
 - **Server Components:** Used for static content that does not require interactivity, such as the landing page and documentation pages. This reduces the amount of JavaScript sent to the client, improving load times.
 - **Client Components:** Used for interactive elements such as the chat interface and graph visualisation. These components can leverage React hooks and state management libraries. To create a Client Component in Next.js, the file must include the directive "`use client`" at the top.
- **Styling:** Tailwind CSS & Shadcn UI are used for the application's design system, providing a consistent and responsive user interface.

3.2.2 User Interface Design

This section discusses the key design principles and layout of the chat page of CodeOrient application. Figure 3.2 showcases the chat page layout which features a split-pane

design that prioritise the chat interface with the AI assistant and the source code.

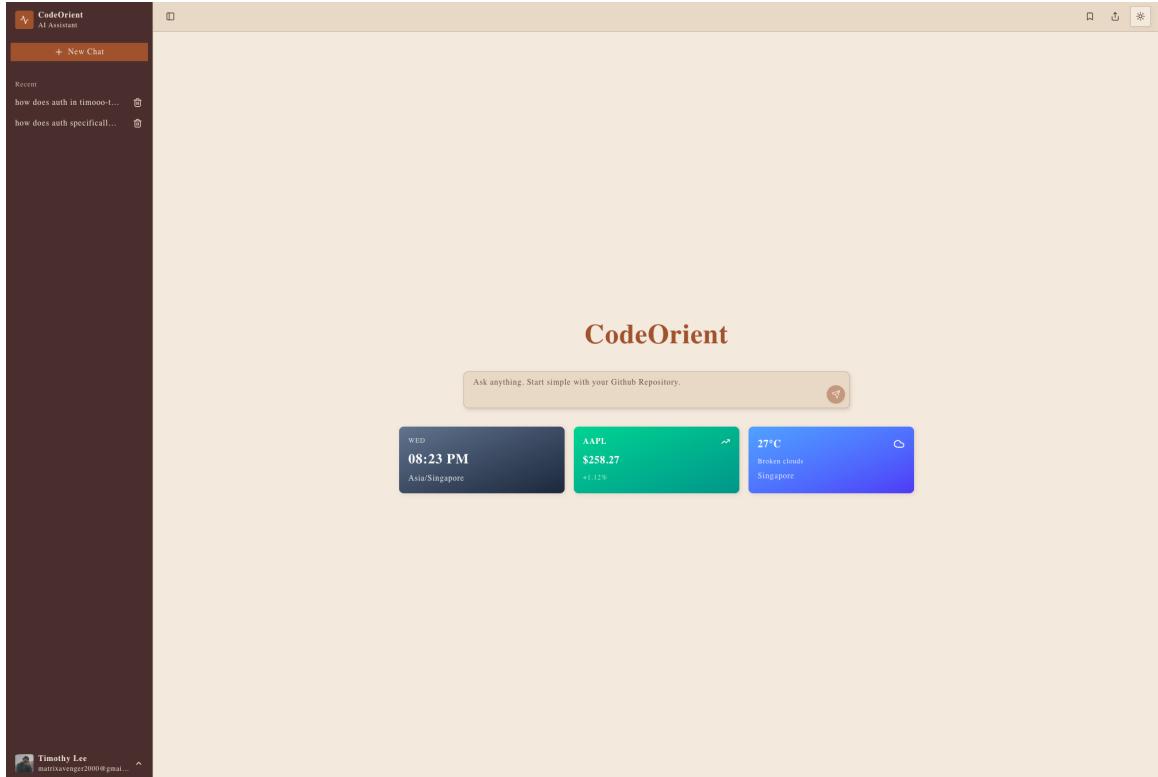


Figure 3.2: *CodeOrient Chat Page Layout*

- **Persistent Sidebar:** Contains a collapsible left sidebar that manages user context, providing quick access to their conversation history in chronological order. It also includes a user profile section at the bottom for account settings and logout.
- **Navigation Bar:** The top navigation bar includes sharing options, bookmarking and toggling of light/dark mode for user convenience.
- **Main Chat Area:** The central area occupies the main viewport, where the AI assistant interacts with the user via Generative UI or text-based responses.
- **Responsive Design:** The layout adapts to different screen sizes, ensuring usability across laptops, tablets, and mobile devices.

3.2.3 Interactive Graph Visualisation with React Flow

Static architecture diagrams often disconnect users from the actual source code. This makes it hard to navigate and update dynamically as a user explores various parts of

the repository. To combat this pain point, CodeOrient integrates React Flow to create a dynamic canvas that visualises a subset of the code repository. Hence, this allows for a real-time and interactive exploration of the codebase.

1. **Nodes as Entities:** High-level code entities such as files, functions, classes, and components are represented by individual nodes. Each node carries metadata including the entity type, file path, code snippet and description.
2. **Edges as Relationships:** Dependencies are presented as directed edges between nodes. These illustrate how data and logic flow between different parts of the codebase. Common relationship types include imports, calls, extends, and uses. For example, Component A imports Function B would be represented as an edge from Node A to Node B.
3. **Interactive Features:** Users can pan, zoom, and click or hover over nodes to reveal additional information such as code snippets, code language, file path and description. This interactivity enhances understanding and navigation within the codebase.

3.2.4 Generative UI Card Components

Standard LLM responses are limited to text or markdown formats. Often, this is insufficient to convey complex code structures or relationships. To address this, CodeOrient adopted a Generative UI architecture where the LLM is able to generate structured JSON objects that renders as functional React components. This allows for richer and more interactive responses.

With the structured JSON object, the frontend acts as an orchestrator, parsing the JSON and mapping it to a React component. For example, a JSON block describing a graph visualisation would be rendered as a "Graph Card" component rather than a bulleted list.

To achieve this, CodeOrient leverages Vercel AI SDK and its `streamObject` function. Based on the user's query, the LLM autonomously decides which component to generate. For example, if the user asks about their list of repositories, the LLM would

generate a "Repository Card" component. The component data is streamed into the UI, which the card to populate incrementally. This creates a smooth user experience by reducing perceived latency.

3.3 Backend Architecture

3.3.1 API Design

The backend of CodeOrient is built on a RESTful Serverless architecture using Next.js API Route Handlers.

1. **Stateless Functions:** Each API endpoint is implemented as a stateless function. This allows the system to scale horizontally, as each function can be invoked independently based on demand.
2. **Endpoint Categories:** The API is divided into four primary domains:
 - **Authentication API:** Manages user login, registration, and session management.
 - **Ingestion API:** Manages the lifecycle of ingesting and indexing code repositories from GitHub API.
 - **Search & Retrieval API:** Interfaces with the vector and structured databases to perform semantic search, retrieval of code snippets and chat persistence.
 - **Streaming Chat API:** Orchestrates the Vercel AI SDK to handle LLM generation via SSE to the client.

3.3.2 Code Search Engine

Traditional keyword-based or fuzzy search methods fail to capture the intent behind a user's query, especially in a large and complex code repository. To overcome this problem, CodeOrient utilises a semantic Code Search Engine for vector-based retrieval of relevant code snippets.

1. **GitHub Octokit:** The engine uses GitHub’s Octokit library to fetch private repository contents from the user’s account. This allows the system to access up-to-date codebases for indexing.
2. **Hybrid Retrieval Strategy:** The engine utilises `bge-large-en-v1.5`, an embedding model to perform semantic search in Upstash Vector. Furthermore, it conducts a sparse search to find documents based on keyword frequency and term importance. This hybrid approach allows the engine to find relevant code even if the user’s query does not explicitly match the code’s keywords or function names. Apart from the code itself, the engine leverages the docstrings and comments extracted during the indexing phase to improve context matching.
3. **Scoping and Filtering:** The engine partitions searches by repository and user ID to prevent cross-project contamination. Additionally, the engine supports metadata filtering, such as file type or entity type, to refine search results.
4. **Ranking Mechanism:** Retrieved code snippets are ranked using Distributed-Based Score Fusion (DBSF), which combines results from dense and sparse indexes. For CodeOrient, DBSF was chosen because it balances semantic meaning with exact keyword match effectively. This ranking ensures that the most contextually relevant code snippets are prioritised for retrieval.

3.3.3 LLM Integration and RAG Pipeline

Creating an autonomous RAG pipeline allows the LLM to move beyond simple search and retrieval patterns. Instead, the LLM follows a more complex reasoning process:

1. **Query Rephrasing:** The LLM first rephrases the user’s query into multiple optimised sub-queries to improve recall during retrieval.
2. **Autonomous Reasoning Loop:** The pipeline implements a loop where the LLM will evaluate the initial search results. If a certain context is missing, the LLM will autonomously generate secondary searches before finalising the response. For example, if the LLM finds a function call but is missing the definition, the agent identifies the missing piece and triggers another search specifically for that

function definition.

3. **Hallucination Mitigation:** To eliminate hallucinations, the LLM is prompted to only cite the relevant code snippets that are used to formulate the response. Each citation includes the file path, URL and code snippet for user verification. This ensures higher precision and trustworthiness of the generated content.

3.4 Data Pipeline

This pipeline transforms a raw GitHub code repository into a structured and searchable knowledge base through a four-stage process:

3.4.1 Repository Ingestion

To bypass GitHub API rate limits and ensure efficient ingestion, the system uses a streaming ingestion strategy.

1. **Tarball Archive:** The system fetches the entire repository as a compressed `.tar.gz` archive in a single request using Octokit.
2. **In-memory Extraction:** The system utilises `RecursiveCharacterTextSplitter` from LangChain to extract code chunks from the archive without writing to disk. This reduces I/O overhead and speeds up processing.
3. **Indexing with Filtering:** The pipeline whitelists indexable file types (e.g., `.ts`, `.py`, `.go`) and ignores binary or large files (e.g., `node_modules`) to optimise storage and retrieval efficiency.

3.4.2 Chunking Strategy

Instead of indexing entire files, the engine breaks code files into smaller semantically “logical” chunks to ensure the LLM receives the most relevant context.

1. **Language-Specific Parsers:** The system uses `RecursiveCharacterTextSplitter` with its `.fromLanguage()` method to parse code files based on their programming language. Unlike generic text splitters, this prioritises splitting at language

specific constructs such as function blocks or method signatures.

2. **Chunk Size Optimisation:** Each chunk is limited to a maximum of 1,500 tokens with a chunk overlap of 200 tokens. This overlap is key for maintaining context across chunk boundaries, ensuring that related code segments are not lost during retrieval.

3.4.3 Metadata Extraction

To assist LLM with context understanding, each code chunk is enriched with relational metadata:

1. **Docstring Extraction:** The parser scans for docstrings or comments immediately preceding code entities. These high-level summaries provide a natural language description of what the code does.
2. **Source Attribution:** Each chunk is tagged with its `filePath`, `repoFullName`, and specific `startLine/endLine`. This creates the ground truth for the citation mechanism during response generation.

3.4.4 Indexing and Storage

The final stage involves storing the processed code chunks for low-latency retrieval.

1. **State Persistence:** The system uses Prisma ORM and PostgreSQL to track the indexing lifecycle of each repository (e.g., CLONING → PARSING → INDEXING → COMPLETED). This allows for resumable indexing in case of interruptions. Additionally, it allows the UI to show real-time progress updates to the user.
2. **Batch Vector Upsert:** Code chunks are converted into embeddings using `bge-large-en-v1.5` model and upserted into Upstash Vector in batches of 100. This strategy optimises throughput and ensures the indexing process is resilient to transient API issues.

3.5 Technical Stack Summary

Category	Technology	Engineering Justification
Framework	Next.js 16	Enables a unified architecture of Server Components for data safety and Client Components for complex React Flow interactivity.
AI Framework	Vercel AI SDK	Provides native primitives for <code>streamObject</code> , enabling real-time Generative UI rendering and SSE-based communication.
Database & ORM	PostgreSQL & Prisma	Ensures robust relational integrity for managing complex user, repository, and chat-session hierarchies via Prisma ORM.
Vector Store	Upstash Vector	A serverless vector database that allows for high-dimensional semantic indexing with native metadata filtering for multi-repo isolation.
Caching	Upstash Redis	Acts as a high-speed buffer to intercept repeated semantic queries, reducing LLM token consumption and decreasing latency by over 90%.
Visualisation	React Flow	Offers the capability of rendering dynamic nodes and edges derived from code analysis.
Ingestion	Octokit (GitHub)	Facilitates secure fetching of code repositories from GitHub.
Analytics	Sentry	Provides real-time error monitoring and performance tracking for both frontend and backend components.

Table 3.1: Summary of Technical Stack and Rationale

Chapter 4

Implementation Details

4.1 Development Methodology

4.1.1 Iterative Development Process

CodeOrient was developed using an iterative approach, which allowed for continuous refinement and integration of feedbacks. Key stages included:

1. **Requirement Analysis:** Initial requirements were gathered based on the pain points of new developers navigating unfamiliar codebases.
2. **Prototyping:** Early prototypes of the search and Generative UI systems were built to validate core concepts. In particular, a simple weather card UI was created to test the dynamic card generation capabilities in Figure 4.1.

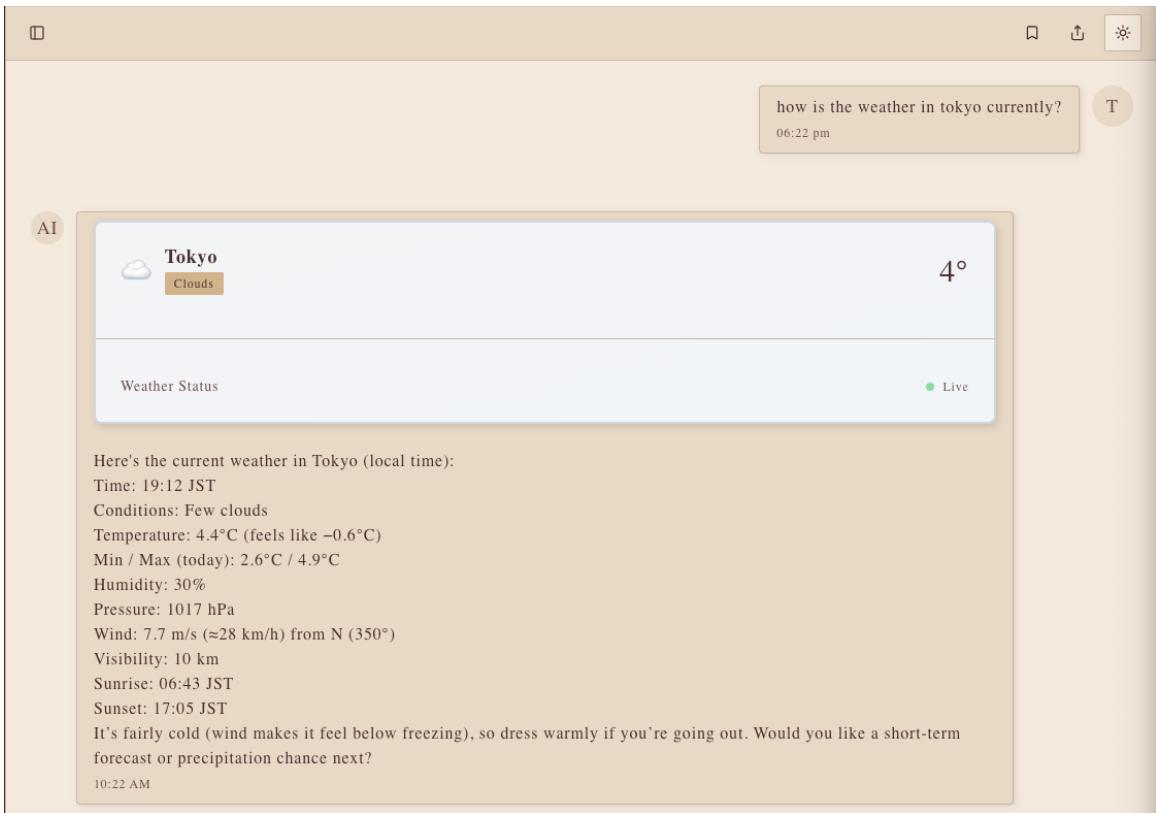


Figure 4.1: *Prototype of Dynamic Card Generation for Weather App*

3. **Incremental Development:** Development was done based on the priority features identified during prototyping. The search module, code graph analysis, and RAG pipeline were built in successive iterations.
4. **User Feedback Integration:** Feedback from preliminary user testing was incorporated to enhance usability and functionality of the chat application.
5. **Final Testing and Optimisation:** The system underwent rigorous testing to ensure performance, reliability, and accuracy before and after deployment.

4.1.2 Version Control and Branching Strategy

The project utilised Git for version control, hosted on GitHub. A feature-branching strategy was employed to isolate the development of core features (e.g. search module, chat interface) while ensuring a stable main branch for continuous deployment via Vercel. Figure 4.2 illustrates the branching strategy which squashed feature branches into the main branch after code reviews and testing.

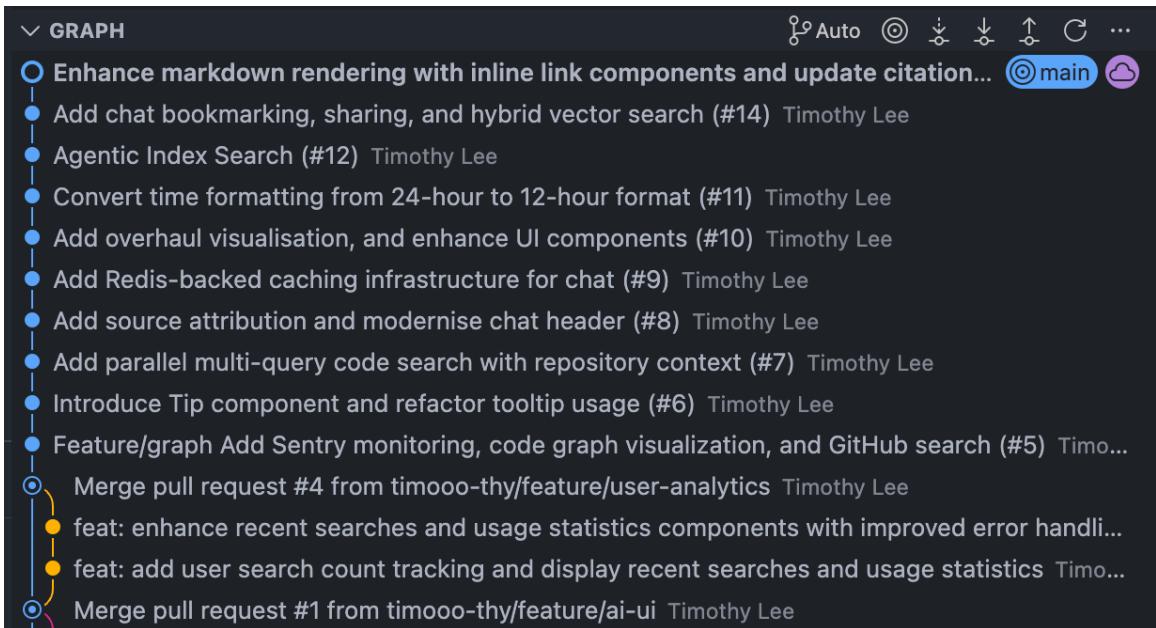


Figure 4.2: *Git Branching Strategy for CodeOrient Development*

4.2 Core Implementation Components

4.2.1 Search Module

BM25 Sparse Retrieval

To handle keyword-based searches, the system implements the Best Matching 25 (BM25) algorithm. The BM25 score for a document D given a query Q is computed as:

$$\text{BM25}(D, Q) = \sum_{q_i \in Q} \text{IDF}(q_i) \cdot \frac{f(q_i, D) \cdot (k_1 + 1)}{f(q_i, D) + k_1 \cdot (1 - b + b \cdot \frac{|D|}{avgdl})}$$

where:

- $f(q_i, D)$ is the term frequency of query term q_i in document D .
- $|D|$ is the length of document D .
- $avgdl$ is the average document length in the corpus.
- k_1 and b are hyperparameters, typically set to $k_1 = 1.5$ and $b = 0.75$ for general text.

- $IDF(q_i)$ is the inverse document frequency of term q_i , calculated as:

$$IDF(q_i) = \log \frac{N - n(q_i) + 0.5}{n(q_i) + 0.5}$$

where N is the total number of documents and $n(q_i)$ is the number of documents containing term q_i .

CodeOrient utilise this retrieval method as it is effective in retrieving exact variable or function names in the codebase.

Dense Embedding Retrieval

For semantic search, the system leverages the bge-large-en-v1.5 embedding model. Each chunk of code is converted to a 1024-dimensional vector and stored in Upstash Vector. This allows the engine to retrieve code snippets based on semantic similarity to the user query. The similarity between the query vector Q and document vector D is computed using cosine similarity:

$$\text{cosine_similarity}(\vec{a}, \vec{b}) = \frac{\vec{a} \cdot \vec{b}}{\|\vec{a}\| \|\vec{b}\|}$$

Hybrid Search Integration

The final ranking is achieved through Distributed-Based Score Fusion. The normalised score is computed as:

$$Score = \frac{s - (\mu - 3\sigma)}{(\mu + 3\sigma) - (\mu - 3\sigma)}$$

where:

- s is the score.
- μ is the mean of the scores.
- σ is the standard deviation.
- $(\mu - 3\sigma)$ represents the minimum value (lower tail of the distribution).
- $(\mu + 3\sigma)$ represents the maximum value (upper tail of the distribution).

This approach takes into account the distribution of scores which is more sensitive to variation in score ranges from the different retrieval methods.

4.2.2 Code Graph Analysis

This section details the transformation of the codebase into an interactive graph seen in Generative UI System (Figure ??).

Dependency Extraction

Rather than using AST for traversal, the system utilise a recursive language aware splitting strategy. This approach breaks down code files by identifying structural boundariees based on the programming language syntax. The algorithm is outlined in Algorithm 1.

Algorithm 1: Language-Aware Recursive Code Splitting Algorithm

Input: File Content C , File Extension E , ChunkSize S , Overlap O

Output: List of Semantic Chunks K

$K \leftarrow \emptyset$

$Language \leftarrow \text{MapExtensionToLanguage}(E)$

if $Language$ is supported **then**

$Splitter \leftarrow \text{InitialiseLangChainSplitter}(Language, S, O)$

end

else

$Separators \leftarrow \{\backslash\text{n}class\text{ }, \backslash\text{n}def\text{ }, \backslash\text{n}\backslash\text{n}, \backslash\text{n}, \text{ } \}$

$Splitter \leftarrow \text{InitialiseRecursiveSplitter}(Separators, S, O)$

end

$Documents \leftarrow Splitter.createDocuments(C)$

foreach Doc in $Documents$ **do**

$Chunk \leftarrow \text{ExtractContentAndMetadata}(Doc)$

Add $Chunk$ to K

end

return K

Graph Construction Algorithm

The extracted entities and their relationships are mapped to a JSON structure compatible with React Flow. In Listing 1, the node and edge schemas are defined to represent code entities and their interactions.

```
1  /**
2   * Metadata schema for Code Graph Nodes
3   * Represents logical code entities within the React Flow canvas.
4   */
5  export type CodeGraphNode = {
6    id: string; // Unique identifier: userId::repo::path::type::name
7    label: string; // The display name of the entity (e.g., function name)
8    type?: "file" | "function" | "class" | "component";
9    filePath?: string; // Original source file path
10   codeSnippet?: string; // The raw source code associated with the entity
11   description?: string; // Extracted docstring or JSDoc comment
12 };
13
14 /**
15  * Metadata schema for Code Graph Edges
16  * Defines the directional relationships between code entities.
17 */
18 export type CodeGraphEdge = {
19   id: string; // Composite ID: sourceID->targetID
20   source: string; // ID of the originating node
21   target: string; // ID of the destination node
22   label?: string; // Relationship type for UI display
23   type?: "imports" | "calls" | "extends" | "uses";
24   animated?: boolean; // Visual indicator for active data/logic flow
25 };
```

Listing 1: TypeScript interfaces for CodeOrient graph entities.

4.2.3 Generative UI System

The Generative UI system dynamically creates interactive UI cards based on user queries. The implementation involves several key components:

Toolkit Selection

To enrich the LLM's capabilities, external tools are integrated. The available tools available for selection based on the user query are:

- **Code Graph Tool:** Retrieves and visualises code entities and their relationships.
- **Repository Search Tool:** Fetches all repositories associated with the user.
- **GitHub Search Tool:** Fetches specific files or code snippets from GitHub directly.
- **Vector Search Tool:** Interacts with the hybrid search module to fetch relevant code snippets.

Dynamic Card Generation

Based on the user query, the LLM intelligently selects the appropriate tool(s) to fulfill the request. It then generates a structured JSON object based on the tool(s) chosen which results in different card visualisations. It is dynamically streamed to the frontend for real-time rendering. The different visualisations supported are:

- **Repository Card**



Figure 4.3: Example of Repository Card in Generative UI

- **Code Graph Card**

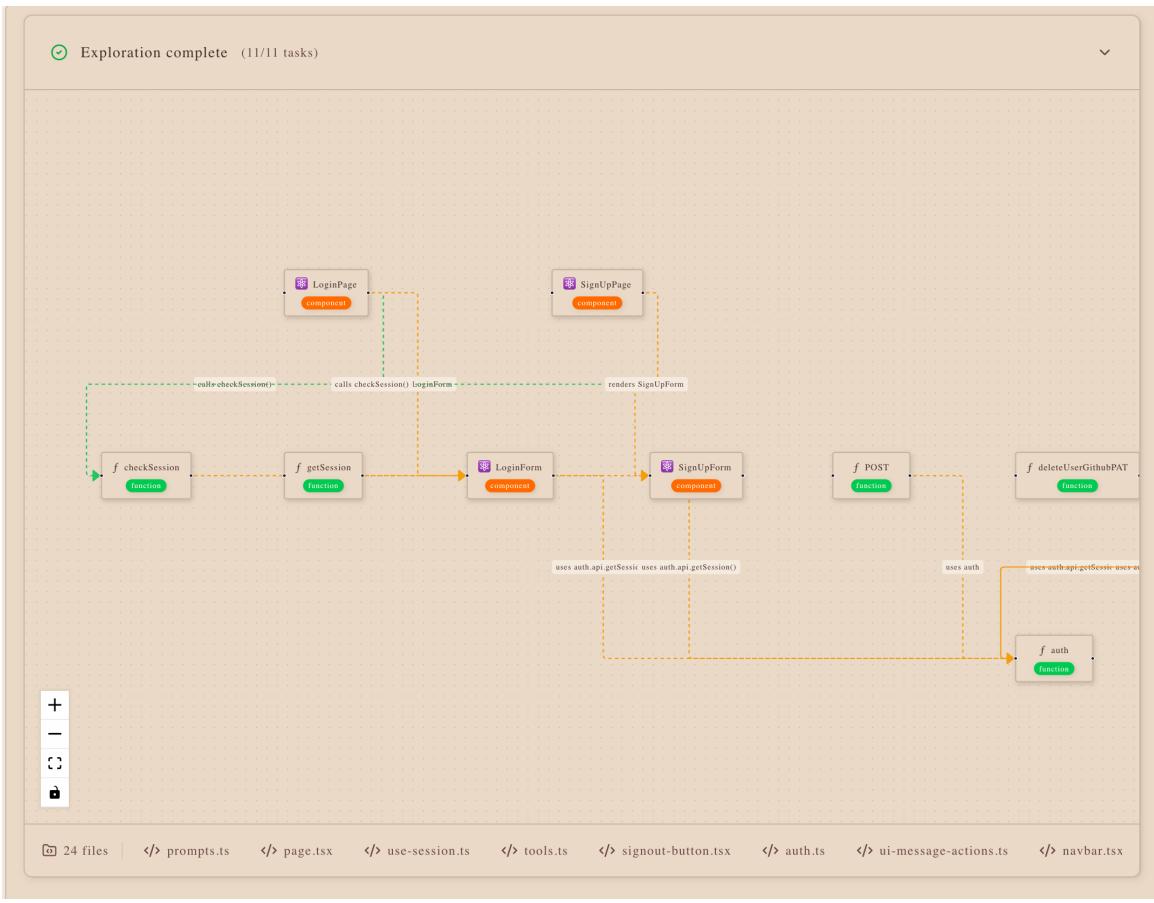


Figure 4.4: Example of Code Graph Card in Generative UI

4.2.4 Large Language Model Integration

CodeOrient is model agnostic and can integrate with any LLM providers that support tool-calling.

Model Selection and Justification

In this implementation, CodeOrient utilises OpenAI's GPT-4.1-mini model due to its advanced reasoning capabilities and large context window, which prevents "lost in the middle" degradation. Furthermore, the latency and cost-effectiveness of the mini variant make it suitable for real-time applications compared to State-Of-The-Art reasoning models.

Prompt Engineering Strategies

To optimise the performance of the LLM and reduce hallucinations during code exploration, a Multi-layered Prompting Strategy is employed with specialised personas for different stages of the RAG pipeline:

- **Search Architect Persona:** This persona’s responsibility is to decompose a user’s query into a structured search plan. The plan entails the steps it will take before generating a graph. The most important responsibility is to break down complex queries into non-overlapping sub-queries that target different parts of the codebase. Additionally, the repository’s tree is provided as context to guide the planning process. This reduces the hallucination of non-existent files or functions. In Figure 4.5, the step by step breakdown of the planning process is illustrated to the user.

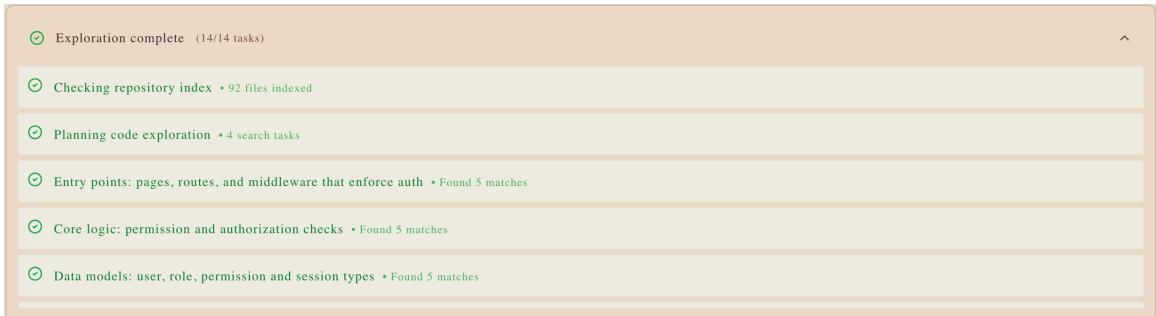


Figure 4.5: Example of Multistep Planning by Search Architect Persona

- **Gap Analyser Persona:** To give the LLM autonomy in exploring the codebase, this persona acts as a quality control layer to identify gaps in the retrieved context. If there are any missing pieces of information, it will trigger an additional search iteration with refined queries. This iterative process continues until sufficient context is gathered to answer the user’s query accurately. Figure 4.6 illustrates an example of gap analysis performed by this persona.

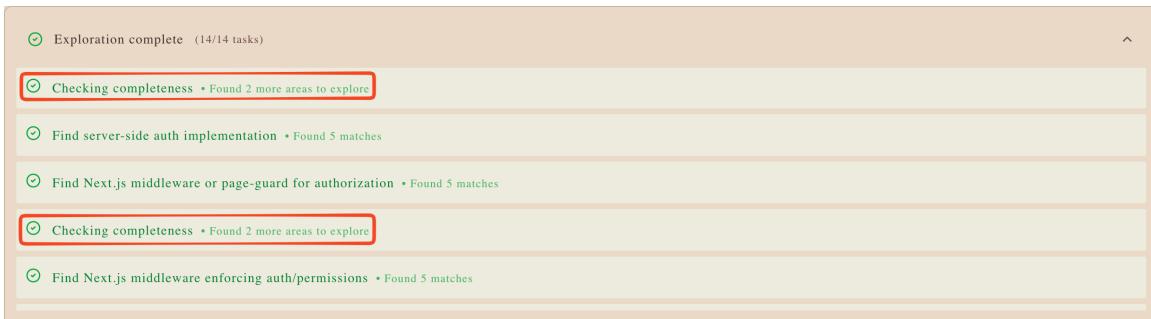


Figure 4.6: Example of Gap Analysis by Gap Analyser Persona

- **Graph Architect Persona:** This persona is responsible for translating the retrieved context into a graph object required for React Flow. It identifies the relevant code entities and their relationships, ensuring that the graph accurately represents the code structure and logic flow.

4.2.5 RAG Pipeline Implementation

This pipeline iteratively retrieves relevant code snippets to ground the LLM's responses. The key components are outlined below:

Query Processing

Raw user queries are usually ambiguous and require refinement. The pipeline first rephrases the query into technical search queries that align with the codebase's terminology and structure. This is achieved using the Search Architect persona described earlier.

Multistep Planning & Exploration

Mentioned previously, the Search Architect persona decomposes complex queries and conducts a breadth-first exploration.

Retrieval & Ranking

The refined queries are used to fetch relevant code chunks from the hybrid search module, with `userId` and `repoFullName` used as filters to ensure strict multi-tenancy.

K-Nearest Neighbour with $K = 10$ is used to retrieve the most similar chunks based on cosine similarity. The retrieved chunks are then ranked using the Distributed-Based Score Fusion method to ensure the most relevant snippets are prioritised.

Context Assembly

The top-ranked code chunks are assembled and wrapped in XML-style tags containing metadata for the LLM to accurately reference the sources during the response phase.

An example of the assembled context is shown in Listing 2.

```
1 <chunk file="lib/auth.ts" lines="12-45" url="...>
2   [Code Snippet]
3 </chunk>
```

Listing 2: Example of Assembled Context with Source Metadata.

Citation Extraction and Grounding

To increase the credibility of the generated answer, all sources retrieved from the RAG pipeline are shown to the user in Figure 4.7. To further reduce hallucination in the response, the LLM is prompted to provide inline citations using markdown format `[file_path](link_to_source_code)`. The frontend parses these citations to create clickable links that direct users to the exact source code locations. An example of inline citations is shown in Figure 4.8.

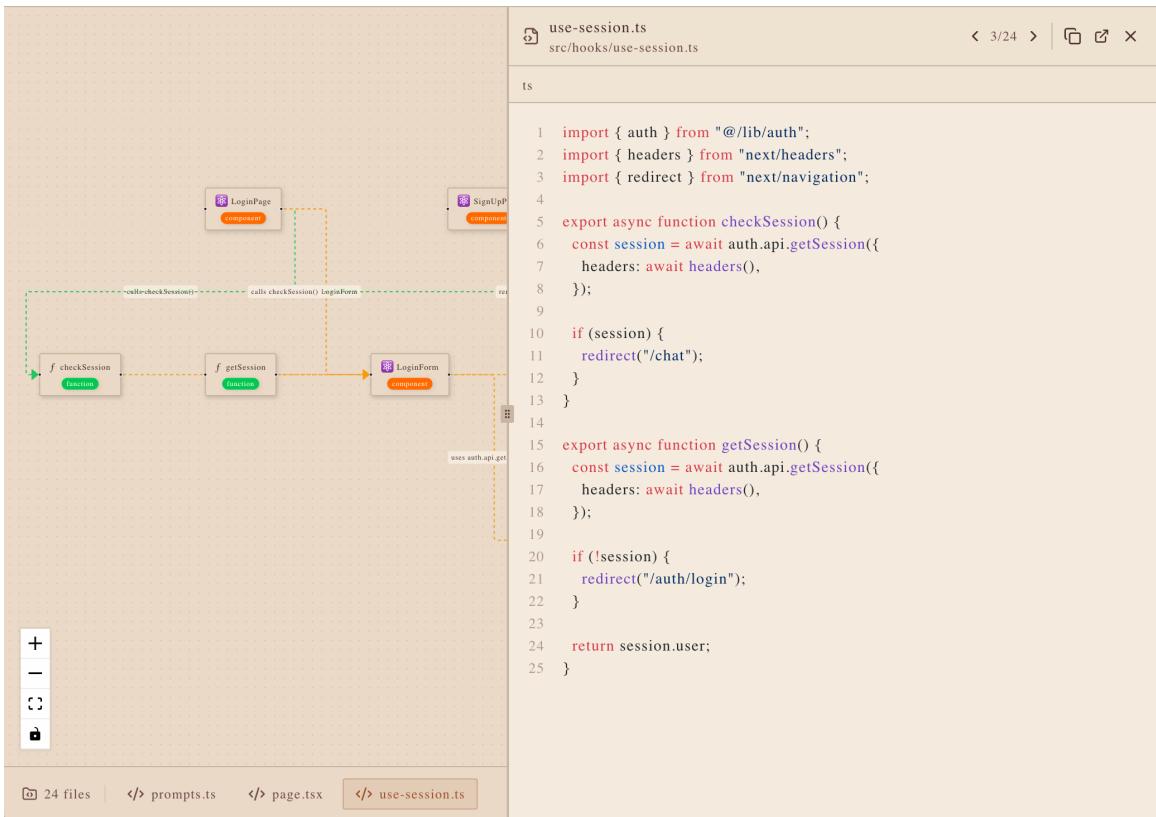


Figure 4.7: Example of sources retrieved from RAG pipeline

In the "timooo-thy/ai-search" repo, authentication is implemented primarily using the better-auth library with Prisma as the database adapter.

Core Auth Setup:
In [src/lib/auth.ts](#), an auth instance is created using `betterAuth()`. This configures authentication to use Prisma as the adapter, tying auth data to the Prisma-managed database.

Client-side Auth:
The client-side uses an `authClient` created with `createAuthClient()` from better-auth's React integration in [src/lib/auth-client.ts](#). This `authClient` handles functions like signing in and signing out from the UI.

Session Management:
The `checkSession()` and `getSession()` functions in [src/hooks/use-session.ts](#) interact with the `auth.api.getSession()` to verify if a user session is active. `checkSession()` redirects to login if no session exists, while `getSession()` redirects to the chat if a session is found.

Authentication Pages:
The login page ([src/app/auth/login/page.tsx](#)) checks the session and then renders a login form component.
Similarly, the signup page ([src/app/auth/signup/page.tsx](#)) checks the session and renders a signup form.

API Route:
Authentication requests (like sign-in, sign-out, session retrieval) are handled by API route handlers defined in [src/app/api/auth/\[...all\]/route.ts](#), which delegates to the better-auth instance.

Sign Out:
There is a sign-out button component ([src/app/chat/components/signout-button.tsx](#)) that signs the user out via the `authClient` and redirects to login.

Figure 4.8: Example of inline citations in LLM response

4.3 Database Schema

CodeOrient utilises PostgreSQL for relational data storage, managed via Prisma ORM.

The schema is organised into three primary clusters:

- **User Identity & Session:** Tables to manage user authentication and GitHub Personal Access Tokens (PATs).
- **Conversation State:** Tables storing Chat, Message, and Part models to support Generative UI and tool-calling outputs.
- **Indexing Lifecycle:** Table to track the asynchronous indexing jobs for user repositories, used in the RAG pipeline.

The complete Prisma schema is provided in Listing 3.

```

1 // Core User and Repository Models
2 model User {
3   id          String    @id
4   name        String
5   email       String    @unique
6   githubPAT  String?   // Encrypted token for repository access
7   chats       Chat[]
8   createdAt   DateTime  @default(now())
9   @@map("user")
10 }
11
12 model IndexedRepository {
13   id          String    @id @default(cuid())
14   userId      String
15   repoFullName String    // Format: "owner/repo"
16   status      IndexingStatus @default(PENDING)
17   progress    Int       @default(0)
18   totalFiles  Int       @default(0)
19   indexedFiles Int      @default(0)
20   lastIndexedAt DateTime?
21
22   @@unique([userId, repoFullName])
23   @@map("indexed_repository")
24 }
25
26 // Conversational State with Generative UI Support
27 model Chat {
```

```

28     id      String      @id @default(cuid())
29     title   String
30     messages Message[]
31     userId   String?
32     User     User?      @relation(fields: [userId], references: [id])
33     @@map("chat")
34   }
35
36 model Message {
37     id      String      @id @default(cuid())
38     chatId  String
39     chat    Chat        @relation(fields: [chatId], references: [id],
40                                     → onDelete: Cascade)
40     role    MessageRole
41     parts   Part[]      // Supports multi-modal and tool-call outputs
42     @@map("message")
43   }
44
45 model Part {
46     id      String      @id @default(cuid())
47     messageId String
48     message  Message      @relation(fields: [messageId], references: [id],
49                                     → onDelete: Cascade)
49     type    MessagePartType
50
51     // Generative UI and Tool Metadata
52     tool_toolCallId   String?
53     tool_visualiseCodeGraph_output Json? // Stores React Flow graph data
54     data_codeGraph     Json?
55
56     @@map("part")
57   }
58
59 enum IndexingStatus {
60   PENDING
61   CLONING
62   PARSING
63   INDEXING

```

```

64    COMPLETED
65    FAILED
66 }

```

Listing 3: Prisma Database Schema.

4.4 UI/UX Enhancements

This section highlights the various UI/UX features implemented to enhance user experience in CodeOrient.

4.4.1 Account Dashboard

The account dashboard allows users to monitor their interaction with the platform. As shown in Figure 4.9, users can view statistics such as:

- Recent Activities
- Usage statistics (e.g., lifetime searches, total repositories analysed)

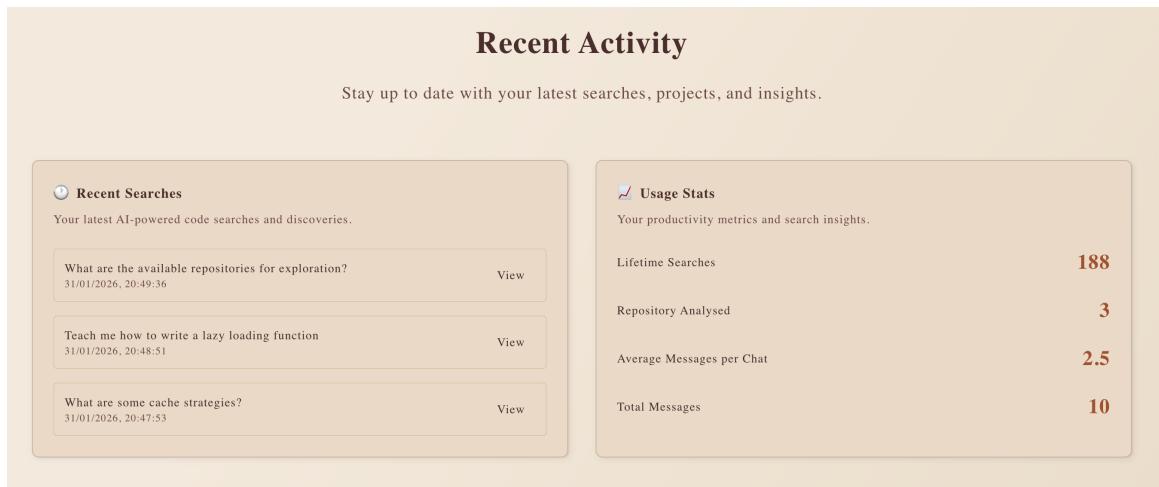


Figure 4.9: Example of Account Dashboard

4.4.2 Sharing of Conversations

To facilitate collaboration, CodeOrient supports the sharing of conversations via unique read-only links. Figure 4.10 illustrates the shared chat view where authorised users can

view the conversation history in a read-only format.



Figure 4.10: *Example of Sharing Conversation Link*

4.4.3 Setting Preferences

This interface allows users to customise their experience. As illustrated in Figure 4.11, this tab of the settings page focuses on data integration. Users can securely connect their GitHub accounts via Personal Access Tokens (PATs) to enable repository indexing and analysis. Furthermore, users can index any private repositories they have access to. The entire indexing process is asynchronous, and real-time progress updates are provided. By enabling indexing, the LLM will prioritise searching the vector database over GitHub to reduce latency and cost.

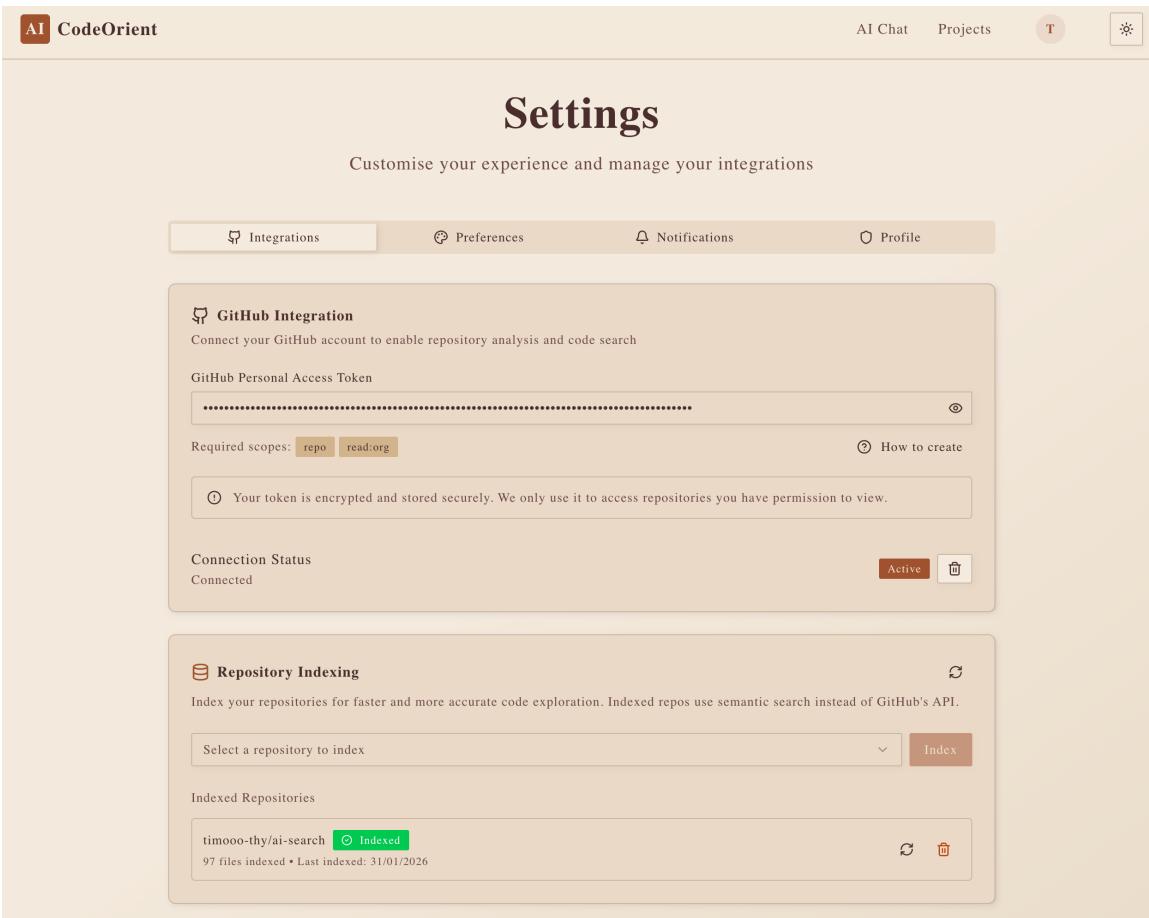


Figure 4.11: *Example of User Preferences Settings*

4.5 Challenges and Solutions

4.5.1 Handling Large Codebases

To overcome GitHub API rate limits, the system implements a **Streaming Tarball Strategy**. By fetching a single compressed `.tar.gz` archive, the system reduces network calls by over 90% and processes repository data entirely in-memory.

4.5.2 Real-Time Graph Updates

To ensure a smooth user experience, the system utilizes Server-Sent Events (SSE) to stream graph data. This allows the React Flow canvas to begin rendering nodes as they are discovered by the RAG agent, rather than waiting for the entire process to complete.

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