Chapter 1: Introduction

1.1 Purpose and Motivation

The digital landscape is undergoing a profound transformation, driven by the rapid proliferation of autonomous agents and sophisticated Artificial Intelligence (AI) model integrations. These intelligent entities, possessing the capacity for independent action, complex decision-making, and economic interaction, are poised to revolutionize industries ranging from decentralized finance (DeFi) and supply chain logistics to personalized healthcare and distributed scientific research. Agents can automate complex workflows, manage digital assets, interact with decentralized applications (dApps), and provide specialized services, creating a dynamic and potentially vast digital economy [1, 4].

However, this burgeoning ecosystem of autonomous agents and AI-driven services faces a significant infrastructural challenge: the lack of standardized mechanisms for discovery, verification, and interoperability within decentralized networks. As the number and heterogeneity of agents increase, locating trustworthy and capable agents or specialized AI services, such as those adhering to the Model Context Protocol (MCP) [5], becomes increasingly difficult. This fragmentation impedes the formation of a cohesive, efficient, and reliable AI ecosystem, hindering the realization of its full potential. Without robust registries and discovery protocols, developers struggle to integrate disparate AI components, users face uncertainty when interacting with agents, and the overall growth of decentralized AI is constrained.

This research document directly addresses this critical infrastructure gap by proposing a comprehensive design for two interconnected, Solana-based program protocols: an **Agent Registry** and an **MCP Server Registry**. These on-chain registries are conceived as foundational pillars for a thriving decentralized AI ecosystem on the Solana blockchain. Their purpose is threefold:

1. **Enable Robust Discoverability:** To provide standardized methods for agents and users to find and identify relevant AI components (other agents or MCP servers) based on their capabilities, identity, and operational status.
2. **Foster Trust:** To offer a platform for storing verifiable information about registered entities, allowing participants to assess the credibility and reliability of agents and servers before interaction.

3. **Promote Interoperability:** To establish common data structures and interaction patterns that facilitate seamless communication and collaboration between diverse AI components, regardless of their underlying implementation or origin.

By leveraging the unique high-performance architecture of the Solana blockchain—characterized by its low transaction fees, high throughput, and scalability [7]—these proposed registry protocols aim to deliver a scalable, efficient, and secure framework for managing the lifecycle and discovery of AI services within a decentralized environment. This work seeks to lay the groundwork for a more organized, trustworthy, and interconnected future for AI on the blockchain.

1.2 Scope of the Research

This document provides an in-depth technical specification and implementation guide for the Solana program protocols governing the proposed Agent Registry and MCP Server Registry. The research encompasses the following key areas:

- **Foundational Solana Concepts:** A detailed exploration of core Solana blockchain concepts essential for understanding the registry design, including Program Derived Addresses (PDAs), the account model, Borsh serialization, rent mechanics, and on-chain data limitations.
- **Registry Protocol Design:** Comprehensive specifications for both the Agent Registry and MCP Server Registry protocols. This includes:
    - **Data Structures:** Precise definitions for the on-chain data structures (e.g., `AgentRegistryEntryV1`, `MCPServerRegistryEntryV1`) stored within PDA accounts, balancing on-chain efficiency with descriptive richness through hybrid storage models.
    - **Program Instructions:** Detailed outlines of the Solana program instructions required for managing the lifecycle of registry entries (registration, updates, deregistrations) and enforcing access control.
    - **Alignment with Standards:** Ensuring the Agent Registry design incorporates principles from established frameworks like the Autonomous Economic Agent (AEA) [1, 9] and Google's Agent-to-Agent (A2A) protocol [3], and that the MCP Server Registry adheres to the official MCP specification [5].
- **Discovery and Querying Mechanisms:** Analysis of various strategies for discovering registered entities, including direct on-chain lookups, secondary indexing patterns, and the crucial role of off-chain indexing infrastructure powered by on-chain event emission.
- **Implementation Guide:** Practical guidance on developing, testing, and deploying the registry programs using Rust and the Anchor framework [10], including

environment setup, program structure, instruction handling, client integration, and testing strategies.

- **Security Considerations:** A thorough examination of potential security vulnerabilities specific to Solana programs and the registry context, along with best practices for secure development, auditing, and mitigation strategies.
- **Performance Optimization:** Techniques for optimizing the compute usage, data storage, and transaction throughput of the registry programs on the Solana network.
- **Deployment and Maintenance:** Strategies for deploying the registry programs, managing upgrades, and ensuring ongoing monitoring and maintenance.
- **Diagrams and Examples:** Inclusion of illustrative diagrams (in a 90s ASCII grayscale style as requested) and code examples to clarify complex concepts and implementation details.

The research aims to be comprehensive, providing not only the theoretical design but also practical implementation details and considerations, structured in a manner that facilitates understanding for developers building or interacting with these foundational AI infrastructure components on Solana.

1.3 Key Objectives

The principal objectives guiding the design and specification presented in this research document are:

1. **Define Precise On-Chain Specifications:** To establish clear, unambiguous, and technically sound on-chain data structures for both Agent and MCP Server registry entries, optimizing for Solana's storage model and ensuring data integrity through Borsh serialization.
2. **Outline Secure and Efficient Program Logic:** To detail the Solana program instructions necessary for the complete lifecycle management (create, read, update, delete) of registry entries, emphasizing security, gas efficiency, and adherence to Solana development best practices [11].
3. **Propose Robust Discovery Mechanisms:** To design a multi-layered discovery strategy that effectively combines the strengths of direct on-chain lookups (for essential, verifiable data) with the flexibility and power of off-chain indexing systems (for complex, multi-faceted queries), enabled by standardized on-chain event emission.
4. **Ensure Alignment with Relevant Standards:** To explicitly integrate concepts and requirements from the AEA framework [1, 9] and Google's A2A protocol [3] into the Agent Registry design, and to ensure the MCP Server Registry strictly adheres to the

official MCP specification [5], particularly regarding the advertisement of tools, resources, and prompts.

5. **Provide Practical Implementation Guidance:** To offer actionable insights and examples for developers implementing these registry programs or building clients to interact with them, covering development, testing, security, optimization, and deployment.
6. **Foster a Foundational Infrastructure:** To contribute a robust, open, and extensible design that can serve as a cornerstone for a thriving ecosystem of interoperable AI agents and services on the Solana blockchain.

1.4 Document Structure

This document is structured to guide the reader progressively from foundational concepts to detailed implementation and advanced topics, resembling a comprehensive guide or book:

- **Chapter 1: Introduction:** Sets the stage, outlining the motivation, scope, and objectives.
- **Chapter 2: Foundational Solana Concepts:** Covers the essential Solana blockchain mechanics relevant to the registry design.
- **Chapter 3: Agent Registry Protocol Design:** Details the specific design for the Agent Registry.
- **Chapter 4: MCP Server Registry Protocol Design:** Details the specific design for the MCP Server Registry.
- **Chapter 5: Discovery and Querying Mechanisms:** Explores on-chain, off-chain, and hybrid approaches to finding registered entities.
- **Chapter 6: Implementation Guide:** Provides practical steps and examples for building the registries and clients.
- **Chapter 7: Security Considerations:** Discusses potential vulnerabilities and security best practices.
- **Chapter 8: Performance Optimization:** Focuses on optimizing the registries for the Solana environment.
- **Chapter 9: Deployment and Maintenance:** Covers the lifecycle of the registry programs post-development.
- **Chapter 10: Case Studies and Examples:** Illustrates potential applications and integration patterns.
- **Chapter 11: Future Directions:** Discusses potential evolution, integrations, and research areas.
- **Chapter 12: Conclusion:** Summarizes the key takeaways and recommendations.
- **Chapter 13: References:** Lists all cited sources.

- **Chapter 14: Appendices:** Includes supplementary materials like glossaries and code snippets.

Each chapter builds upon the previous ones, aiming to provide a thorough understanding of both the 'what' and the 'how' of building decentralized AI registries on Solana.

References will be compiled and listed in Chapter 13.

Chapter 10: Case Studies and Examples

This chapter explores practical applications and scenarios where the Agent and MCP Server Registries can be utilized. These case studies illustrate how the registries facilitate discovery, interaction, and coordination within a decentralized agent ecosystem built on Solana.

10.1 Example: Autonomous Travel Agent

10.1.1 Scenario Overview

Imagine an Autonomous Economic Agent (AEA) designed to act as a personalized travel planner. This "TravelAgent" AEA needs to discover and interact with various service providers (flight booking agents, hotel reservation agents, local tour guide agents) to fulfill user travel requests.

User Goal: Book a round-trip flight from London to Tokyo and a 5-night hotel stay for specific dates.

TravelAgent AEA Role: 1. Understand the user request. 2. Discover relevant service provider agents using the Agent Registry. 3. Interact with discovered agents (potentially using A2A or MCP) to get quotes and availability. 4. Compare options and present the best choices to the user. 5. Execute bookings upon user confirmation.

10.1.2 Registry Usage

1. **Service Provider Registration**: Agents offering flight booking, hotel reservation, or tour guide services register themselves on the Agent Registry.
    - **Flight Booker Agent**: Registers with `agent_id: flight-booker-alpha`, `skill_tags: ["flight-booking", "airline-tickets",`

`"travel"]`, `supported_protocols: ["a2a-v1"]`, `service_endpoints: [...]`.
  - **Hotel Booker Agent**: Registers with `agent_id: hotel-booker-beta`, `skill_tags: ["hotel-reservation", "accommodation", "travel"]`, `supported_protocols: ["a2a-v1", "mcp-v1"]`, `service_endpoints: [...]`.
  - **Tour Guide Agent (Tokyo)**: Registers with `agent_id: tokyo-tours-gamma`, `skill_tags: ["local-tours", "tokyo", "sightseeing"]`, `supported_protocols: ["a2a-v1"]`, `service_endpoints: [...]`.

2. **TravelAgent Discovery**: The TravelAgent AEA queries the Agent Registry to find suitable service providers.

   - **Query 1 (Flights)**: Search for agents with `skill_tags` containing "flight-booking" and potentially filter by reputation or supported protocols.
   - **Query 2 (Hotels)**: Search for agents with `skill_tags` containing "hotel-reservation" and potentially filter by location (implicitly, as hotels are global) or preferred protocols.

3. **Interaction**: The TravelAgent uses the `service_endpoints` and `supported_protocols` information from the registry entries to initiate communication (e.g., A2A requests for quotes) with the discovered agents.

```
+-------------------+     +-------------------+
+------------------------+
|                   | --> |                   | -->
|                        |
| User Request      |     | TravelAgent AEA   |     | Agent
Registry (Solana)|
| (Flight & Hotel)  |     |                   |
|                        |
|                   | <-- | 1. Query Flights  | <-- | - Flight
Booker Agent |
+-------------------+     | 2. Query Hotels   | --> | - Hotel
Booker Agent  |
                        |                   |     | - Tour

Guide Agent    |
                        | 3. Get Endpoints  | <--
|                       |
                        +---------+---------+
+------------------------+
                                  |
                                  | 4. Interact (A2A/MCP)
                                  v
      +----------------------+     +----------------------+
      | Flight Booker Agent |     | Hotel Booker Agent  |
      +---------------------+     +---------------------+
```

10.1.3 Benefits

- **Decentralized Discovery**: TravelAgent doesn't rely on a central directory; it uses the on-chain registry.
- **Dynamic Service Integration**: New flight or hotel booking agents can join the ecosystem simply by registering.
- **Interoperability**: Standardized registration information (protocols, endpoints) facilitates communication.

10.2 Example: Decentralized Scientific Computing Platform

10.2.1 Scenario Overview

Consider a platform where researchers can submit complex computational tasks (e.g., protein folding simulations, climate modeling) to be executed by a network of specialized compute provider agents. An MCP Server acts as the orchestrator for task distribution and result aggregation.

Researcher Goal: Run a protein folding simulation requiring significant GPU resources.

Platform Role: 1. Researcher submits task specifications to the MCP Server. 2. MCP Server needs to find agents capable of executing the task. 3. MCP Server queries the Agent Registry for compute provider agents with specific capabilities (e.g., GPU availability, specific software installed). 4. MCP Server distributes task chunks to suitable agents via MCP. 5. Agents execute tasks and return results to the MCP Server. 6. MCP Server aggregates results and provides them to the researcher.

10.2.2 Registry Usage

1. **Compute Agent Registration**: Agents offering computational resources register on the Agent Registry.

    - **GPU Compute Agent**: Registers with `agent_id: gpu-compute-delta`, `skill_tags: ["gpu", "cuda", "simulation", "protein-folding"]`, `capabilities_flags: TASK_EXECUTION`, `supported_protocols: ["mcp-v1"]`, `service_endpoints: [...]`.

    - **CPU Compute Agent**: Registers with `agent_id: cpu-compute-epsilon`, `skill_tags: ["cpu", "simulation", "climate-modeling"]`, `capabilities_flags: TASK_EXECUTION`, `supported_protocols: ["mcp-v1"]`, `service_endpoints: [...]`.

2. **MCP Server Registration**: The orchestrating MCP Server registers on the MCP Server Registry.
    - **MCP Server**: Registers with `server_id: science-compute-mcp`, `name: "Decentralized Science Compute Hub"`, `supported_models: ["protein-folding-v2", "climate-sim-v1"]`, `endpoint_url: "https://mcp.science-compute.org"`, `status: Active`.
3. **MCP Server Discovery (Agent -> Server)**: Compute agents might query the MCP Server Registry to find active orchestrators they can connect to and receive tasks from.
4. **Agent Discovery (Server -> Agent)**: The MCP Server queries the Agent Registry to find available compute agents matching the task requirements.
    - **Query**: Search for agents with `skill_tags` containing "gpu" and "protein-folding", `capabilities_flags` including `TASK_EXECUTION`, and `status` as `Active`.
5. **Interaction**: The MCP Server uses the registry information to establish connections and manage tasks with the compute agents via the MCP protocol.

```
 +-------------+     +-----------------------+
+---------------------------+
| Researcher  | --> | MCP Server            | --> | Agent
Registry (Solana)    |
| (Task Spec) |     | (science-compute-mcp) | <-- | - GPU
Compute Agent        |
+-------------+     |                       |     | - CPU
Compute Agent        |
                      | 1. Query Agents       |
+---------------------------+
                      |    (GPU, Protein)     |
                      +-----------+-----------+
                                  |
                                  | 2. Distribute Tasks (MCP)
                                  v
                      +-----------------------+
                      | GPU Compute Agent     |
                      | (gpu-compute-delta)   |
                      +-----------------------+
+------------------------+     +----------------------------+
| Compute Agent          | --> | MCP Server Registry        |
| (Looking for work)     |     | (Solana)                   |
|                        | <-- | - science-compute-mcp      |
| 1. Query Servers       |     +----------------------------+
+------------------------+
```

10.2.3 Benefits

- **Resource Matching**: Efficiently matches tasks with agents possessing the required computational resources and skills.
- **Scalability**: New compute providers can easily join the network by registering.
- **Orchestration**: MCP Server Registry allows agents to find relevant task orchestrators.
- **Decentralization**: Reduces reliance on a single platform owner for resource allocation.

10.3 Example: Dynamic IoT Device Coordination

10.3.1 Scenario Overview

In a smart home or smart city environment, numerous IoT devices (sensors, actuators, controllers) need to coordinate their actions. An agent running on a local hub or in the cloud needs to discover and interact with these devices, potentially represented as agents themselves or managed by gateway agents.

User Goal: When a smoke detector agent detects smoke, automatically trigger a smart window agent to open and an alert agent to notify the homeowner.

Hub Agent Role: 1. Monitor events from sensor agents (e.g., smoke detector). 2. Discover relevant actuator agents (e.g., smart window, alert agent) using the Agent Registry. 3. Send commands to actuator agents based on predefined rules or learned behavior.

10.3.2 Registry Usage

1. **Device Agent Registration**: Agents representing or managing IoT devices register on the Agent Registry.
    - **Smoke Detector Agent**: Registers with `agent_id: smoke-detector-zone1`, `skill_tags: ["iot", "sensor", "smoke-detection"]`, `capabilities_flags: EVENT_PUBLISHING`, `supported_protocols: ["a2a-v1"]`, `service_endpoints: [...]`.

- **Smart Window Agent**: Registers with `agent_id: window-livingroom`, `skill_tags: ["iot", "actuator", "window-control"]`, `capabilities_flags: TASK_EXECUTION`, `supported_protocols: ["a2a-v1"]`, `service_endpoints: [...]`.
- **Alert Agent**: Registers with `agent_id: homeowner-alert-zeta`, `skill_tags: ["notification", "alerting"]`, `capabilities_flags: TASK_EXECUTION`, `supported_protocols: ["a2a-v1"]`, `service_endpoints: [...]`.

2. **Hub Agent Discovery**: When the Hub Agent receives a smoke alert event, it queries the Agent Registry to find relevant actuators.
    - **Query 1 (Windows)**: Search for agents with `skill_tags` containing "window-control" and potentially filter by location or group.
    - **Query 2 (Alerts)**: Search for agents with `skill_tags` containing "notification" or "alerting".

3. **Interaction**: The Hub Agent uses the registry information to send commands (e.g., "open window", "send alert") to the discovered agents via A2A or another suitable protocol.

```
 +-------------------------+     +--------------------+
+-------------------------+
| Smoke Detector Agent  | --> | Hub Agent         | --> | Agent
Registry (Solana)|
| (Event: Smoke Detect) |     |                   | <-- | -
Smart Window Agent   |
+-------------------------+     | 1. Query Windows  |     | -
Alert Agent          |
                                | 2. Query Alerts   |
+-------------------------+
                               +---------+---------+
                                         |
                                         | 3. Send Commands (A2A)
                                         v
            +-------------------------+
+-------------------------+
            | Smart Window Agent    |     | Alert
Agent           |
            +-------------------------+
+-------------------------+
```

10.3.3 Benefits

- **Plug-and-Play Devices**: New IoT devices can be added to the system by registering their corresponding agents.
- **Flexible Automation**: Automation rules can dynamically discover and interact with available devices.
- **Interoperability**: Enables coordination between devices from different manufacturers, provided they use compatible protocols discovered via the registry.

10.4 Example: Decentralized AI Model Marketplace

10.4.1 Scenario Overview

An ecosystem where developers can deploy AI models (represented or served by agents) and users or other agents can discover and consume these models via the MCP protocol. MCP Servers act as gateways or aggregators for specific model types.

User Goal: Find and use an AI agent capable of summarizing long text documents.

Ecosystem Roles: 1. **Model Provider Agent**: Deploys an agent serving a text summarization model. Registers this agent on the Agent Registry. 2. **MCP Server (NLP Gateway)**: Specializes in hosting or proxying Natural Language Processing models. Registers on the MCP Server Registry. 3. **User/Client Agent**: Needs to find a text summarization service.

10.4.2 Registry Usage

1. **Model Provider Agent Registration**: The agent serving the summarization model registers.

   - **Summarizer Agent**: Registers with `agent_id: text-summarizer-ai`, `skill_tags: ["ai", "nlp", "text-summarization"]`, `capabilities_flags: MCP_CLIENT | TASK_EXECUTION`, `supported_protocols: ["mcp-v1"]`, `service_endpoints: [...]` (might point to an MCP endpoint).

2. **MCP Server Registration**: The NLP Gateway MCP Server registers.

   - **NLP Gateway MCP**: Registers with `server_id: nlp-gateway-mcp`, `name: "NLP Model Gateway"`, `supported_models: ["text-summarization-v3", "translation-en-fr-v1"]`, `endpoint_url: "https://mcp.nlp-gateway.com"`, `status: Active`.

3. **Discovery (User -> Server)**: The user/client agent queries the MCP Server Registry to find servers supporting text summarization.
    - **Query**: Search for MCP Servers with `supported_models` containing "text-summarization". Finds `nlp-gateway-mcp`.
4. **Discovery (Server -> Agent - Optional)**: The NLP Gateway MCP Server might internally use the Agent Registry to discover backend agents like `text-summarizer-ai` that actually perform the work, especially if it acts as a load balancer or aggregator.
    - **Query**: Search Agent Registry for agents with `skill_tags` "text-summarization" and `capabilities_flags` `MCP_CLIENT`.
5. **Interaction**: The user/client agent interacts with the discovered MCP Server (`nlp-gateway-mcp`) using the MCP protocol to submit text and receive summaries. The MCP Server handles routing the request (potentially to `text-summarizer-ai`).

```
 +-------------------+     +---------------------------+
+----------------------+
| User/Client Agent | --> | MCP Server Registry       | --> |
NLP Gateway MCP Server|
| (Needs Summary)   |     | (Solana)                  |     |
(nlp-gateway-mcp)     |
|                   | <-- | - nlp-gateway-mcp         | <--
|                       |
| 1. Query Servers  |     +---------------------------+     |
2. Interact (MCP)     |
| (Summarization)   |
+-----------+----------+
+-------------------
+                                                     |

| 3. (Optional) Route to Backend Agent

v

+----------------------+
                                                              |
Summarizer Agent      |
                                                              |
(text-summarizer-ai)  |

+----------------------+

+-------------------+     +----------------------+
| Summarizer Agent  | --> | Agent Registry (Solana)|
| (Registers Self)  | <-- | - text-summarizer-ai  |
+-------------------+     +-----------------------+
```

10.4.3 Benefits

- **Model Discovery**: Provides a decentralized way to find AI models and services.
- **Standardized Interaction**: MCP provides a standard protocol for interacting with diverse AI models.
- **Marketplace Creation**: Facilitates the creation of decentralized marketplaces for AI services.
- **Composability**: Agents can discover and combine capabilities from multiple AI model agents.

These case studies demonstrate the versatility of the Agent and MCP Server Registries in enabling discovery, coordination, and interoperability across various decentralized agent-based applications on Solana.

References will be compiled and listed in Chapter 13.

Chapter 11: Future Directions

This chapter explores potential future developments and enhancements for the Agent and MCP Server Registries. As the Solana ecosystem and autonomous agent technologies continue to evolve, these registries will likely adapt and expand to meet emerging needs and opportunities.

11.1 Registry Protocol Evolution

11.1.1 Version Upgrades and Migration Strategies

As with any protocol, the Agent and MCP Server Registries will need to evolve over time to incorporate new features, address limitations, and adapt to changing ecosystem requirements. Planning for future versions is essential for long-term sustainability.

Potential Version Upgrades:

1. **AgentRegistryEntryV2**: A future version might include:
2. Enhanced reputation mechanisms
3. More granular capability flags
4. Support for new protocols

5. Improved metadata structures

6. Integration with decentralized identity systems

7. **MCPServerRegistryEntryV2**: Future enhancements could include:

8. More detailed model specifications
9. Performance metrics
10. Pricing information
11. Quality of service guarantees
12. Enhanced discovery attributes

Migration Strategies:

When upgrading registry protocols, several migration approaches can be considered:

1. **Side-by-Side Operation**: Run V1 and V2 registries concurrently, allowing gradual migration. `+------------------+ +------------------+ | | | | | Registry V1 | | Registry V2 | | (Legacy Support) | | (New Features) | | | | | +------------------+ +------------------+ ^ ^ | | | | +-------+--------+ +-------+--------+ | | | | | Legacy Agents | | New Agents | | | | | +----------------+ +----------------+`

2. **In-Place Upgrades**: Implement program upgrades that maintain backward compatibility while adding new features.

3. **Data Migration**: Provide tools and incentives for entry owners to migrate their data from V1 to V2 formats. `+------------------+ +------------------+ | | | | | Registry V1 Entry |---->| Registry V2 Entry | | | | | +------------------+ +------------------+ ^ ^ | | +-------+--------+ +-------+--------+ | | | | | Migration Tool |------>| Enhanced Data | | | | | +----------------+ +----------------+`

4. **Indexer Support**: Ensure off-chain indexers can handle multiple registry versions and present unified views to clients.

Backward Compatibility Considerations:

1. **Field Mapping**: Ensure essential V1 fields have clear mappings to V2 structures.
2. **Default Values**: Provide sensible defaults for new required fields in V2.
3. **Client Support**: Update client libraries to handle both V1 and V2 entries.

4. **Documentation**: Clearly document migration paths and compatibility considerations.

Future registry versions should be designed with careful consideration of the existing ecosystem and provide clear upgrade paths to minimize disruption.

11.1.2 Cross-Chain Interoperability

As agent ecosystems develop across multiple blockchains, enabling cross-chain discovery and interoperability becomes increasingly important.

Cross-Chain Registry Approaches:

1. **Bridge-Based Synchronization**: Use blockchain bridges to synchronize registry entries across chains. `+------------------+ +------------------+ +------------------+ | | | | | | Solana Registry |<--->| Bridge Protocol |<--->| Other Chain | | | | | | Registry | +------------------+ +------------------+ +------------------+`

2. **Federated Indexing**: Implement off-chain indexers that aggregate registry data from multiple chains and provide unified discovery interfaces. `+------------------+ +------------------+ | Solana Registry | | Ethereum Registry | +------------------+ +------------------+ ^ ^ | | | | +-------+--------+-------------+ | | | Cross-Chain Registry Indexer | | | +---------------+-------------+ | v +---------------+-------------+ | | | Unified Discovery API | | | +----------------------------+`

3. **Cross-Chain Identifiers**: Develop standardized identifier schemes that work across blockchains, potentially leveraging decentralized identity systems.

4. **Message Passing**: Implement cross-chain message passing to enable agents on different chains to discover and communicate with each other.

Challenges and Solutions:

1. **Data Consistency**: Ensuring registry data remains consistent across chains.

2. Solution: Implement verification mechanisms and canonical source identification.

3. **Protocol Differences**: Handling differences in account models and smart contract capabilities.

4. Solution: Abstract these differences in cross-chain adapters or middleware.

5. **Economic Models**: Managing costs across chains with different fee structures.

6. Solution: Develop economic models that balance costs and benefits of cross-chain presence.

7. **Trust Assumptions**: Minimizing additional trust assumptions introduced by cross-chain operations.

8. Solution: Leverage existing secure bridge protocols and implement verification mechanisms.

Cross-chain interoperability will be crucial for creating a truly open and interconnected agent ecosystem that spans multiple blockchain networks.

11.1.3 Integration with Decentralized Identity Systems

Future registry versions could benefit from integration with decentralized identity (DID) systems, enhancing trust, verification, and reputation mechanisms.

Potential DID Integrations:

1. **Agent Identity Verification**: Link agent registry entries to DIDs, enabling cryptographic verification of agent identities. `+-------------------+ +-------------------+ | | | | | Agent Registry |---->| DID Document | | Entry | | | | | | - Verification | | - agent_id | | Methods | | - owner_authority | | - Service | | - did_reference |---->| Endpoints | | | | - Credentials | +-------------------+ +-------------------+`

2. **Verifiable Credentials**: Enable agents to present verifiable credentials attesting to their capabilities, training, or certifications.

3. **Owner Identity Linking**: Allow registry entry owners to link their entries to their DIDs, creating a web of trust across multiple agents owned by the same entity.

4. **Reputation Portability**: Use DIDs to make agent reputation portable across different registries and platforms.

Implementation Approaches:

1. **On-Chain DID References**: Store DID references directly in registry entries. `rust pub struct AgentRegistryEntryV2 { // Existing fields... pub`

`did_reference: Option<String>, // e.g., "did:sol:abc123" // ... }`

2. **Verifiable Credential Verification**: Implement on-chain verification of credentials presented by agents.

3. **DID-Based Authorization**: Use DIDs for more flexible authorization models beyond simple public key ownership.

4. **Off-Chain Verification**: Store minimal DID references on-chain with more extensive verification happening off-chain.

Integration with decentralized identity systems would enhance trust in the agent ecosystem while maintaining the decentralized nature of the registries.

11.2 Enhanced Discovery Mechanisms

11.2.1 Semantic Search and Ontologies

Current registry discovery relies primarily on exact matching of tags and attributes. Future enhancements could incorporate semantic understanding and ontologies for more intelligent discovery.

Semantic Discovery Enhancements:

1. **Agent Capability Ontologies**: Develop standardized ontologies for agent capabilities, skills, and domains. `+-------------------+ | Agent Capability | | Ontology | | | | - NLP | | |-- Translation | | |-- Summarization| | |-- Q&A | | - Finance | | |-- Trading | | |-- Analysis | +-------------------+`

2. **Semantic Matching**: Implement semantic matching algorithms in indexers to find relevant agents even when query terms don't exactly match registered attributes.

3. **Contextual Discovery**: Enable discovery based on the context of the request, not just explicit search terms.

4. **Natural Language Queries**: Support natural language queries for agent discovery (e.g., "Find me an agent that can summarize financial reports").

Implementation Approaches:

1. **Standardized Taxonomies**: Develop and promote standardized taxonomies for agent capabilities and domains.

2. **Enhanced Indexers**: Implement semantic indexing and search capabilities in off-chain indexers.

3. **On-Chain Taxonomy References**: Allow registry entries to reference standardized taxonomy terms. `rust pub struct AgentRegistryEntryV2 { // Existing fields... pub taxonomy_references: Vec<String>, // e.g., ["nlp.summarization.text", "finance.analysis"] // ... }`

4. **Inference Services**: Develop services that can infer capabilities from agent descriptions and other metadata.

Semantic discovery would significantly enhance the usability of the registries, making it easier for users and other agents to find exactly what they need.

11.2.2 Reputation and Quality Metrics

Future registry enhancements could incorporate reputation systems and quality metrics to help users and agents make more informed choices.

Reputation System Components:

1. **On-Chain Ratings**: Allow users to submit ratings for agents they've interacted with. `+-------------------+ +-------------------+ | | | | Agent Registry | | Rating Entry | | Entry |<----| - rater_id | | | | - score | | - agent_id | | - timestamp | | - ratings_count | | - comment | | - avg_rating | | | +-------------------+ +-------------------+`

2. **Verifiable Interactions**: Implement mechanisms to verify that ratings come from actual interactions.

3. **Weighted Reputation**: Consider the reputation of the rater when calculating overall reputation scores.

4. **Domain-Specific Ratings**: Allow ratings across different dimensions (e.g., accuracy, speed, cost-effectiveness).

Quality Metrics:

1. **Performance Metrics**: Track and report agent performance metrics (e.g., uptime, response time).

2. **Usage Statistics**: Provide anonymized usage statistics to indicate popularity and reliability.

3. **Verification Status**: Implement verification mechanisms for agents that meet certain quality or security standards.

Implementation Challenges:

1. **Sybil Resistance**: Preventing manipulation through fake identities.
2. Solution: Require stake or other Sybil-resistant mechanisms for rating submission.
3. **Privacy Considerations**: Balancing transparency with user privacy.
4. Solution: Implement privacy-preserving reputation mechanisms.
5. **Subjectivity**: Handling the subjective nature of ratings.
6. Solution: Provide context and multiple dimensions for ratings.
7. **Bootstrapping**: Addressing the cold-start problem for new agents.
8. Solution: Implement trial periods or provisional reputation mechanisms.

A well-designed reputation system would significantly enhance trust in the agent ecosystem and help quality agents stand out.

11.2.3 Economic Models for Discovery

Future registry enhancements could incorporate economic models to incentivize high-quality registrations, maintain registry data quality, and potentially monetize premium discovery features.

Potential Economic Models:

1. **Registration Staking**: Require agents to stake tokens when registering, with stakes returned after a verification period or forfeited if the registration is found to be fraudulent or spam. `+------------------+ +------------------+ | | | | | Agent Registration|---->| Stake Pool | | Transaction | | | | | | - Locked tokens | | - agent_data | | - Release | | - stake_amount | | conditions | | | | | +------------------+ +------------------+`

2. **Premium Placement**: Allow agents to bid for premium placement in discovery results.

3. **Curation Markets**: Implement token-curated registries where curators stake tokens to vouch for the quality of registry entries.

4. **Usage-Based Fees**: Charge small fees for discovery queries, with proceeds distributed to registry maintainers and high-quality entry providers.

5. **Reputation-Based Rewards**: Distribute rewards to agents with consistently high reputation scores.

Implementation Considerations:

1. **Balancing Accessibility**: Ensuring economic models don't create excessive barriers to entry.

2. **Governance**: Implementing governance mechanisms for adjusting economic parameters.

3. **Token Design**: Designing token economics that align incentives across the ecosystem.

4. **Fee Distribution**: Creating fair mechanisms for distributing fees to various stakeholders.

Well-designed economic models could help ensure the long-term sustainability of the registries while incentivizing high-quality participation.

11.3 Ecosystem Integration

11.3.1 Integration with Autonomous Economic Agent Frameworks

The registries can be more tightly integrated with emerging autonomous economic agent (AEA) frameworks to enable seamless agent deployment, discovery, and interaction.

Integration Opportunities:

1. **Automated Registration**: AEA frameworks could automatically register newly deployed agents. `+------------------+ +------------------+ | | | | | AEA Framework |---->| Agent Registry | | Deployment | | Program | | | | | | - Agent Creation | | - Register | | - Configuration | | Instruction | | | | | +------------------+ +------------------+`

2. **Discovery SDKs**: Develop standardized SDKs for agent discovery that integrate with popular AEA frameworks.

3. **Lifecycle Management**: Integrate registry updates with agent lifecycle events (deployment, upgrade, retirement).

4. **Framework-Specific Metadata**: Include framework-specific metadata in registry entries to facilitate framework-specific optimizations.

Specific Framework Integrations:

1. **Fetch.ai Integration**: Integrate with Fetch.ai's AEA framework for seamless agent deployment and discovery.

2. **OpenAI Assistants API Integration**: Enable registration of agents created through the OpenAI Assistants API.

3. **Custom Framework Support**: Provide extension points for custom AEA frameworks to integrate with the registries.

Tight integration with AEA frameworks would streamline the process of deploying and discovering agents, reducing friction in the ecosystem.

11.3.2 Integration with Decentralized Governance

Future registry enhancements could incorporate decentralized governance mechanisms to enable community-driven evolution and management.

Governance Integration Points:

1. **Protocol Upgrades**: Implement governance mechanisms for proposing and approving protocol upgrades. `+------------------+ +------------------+ +------------------+ | | | | | | Governance |---->| Proposal |---->| Protocol Upgrade | | DAO | | Voting | | Implementation | | | | | | | +------------------+ +------------------+ +------------------+`

2. **Parameter Adjustment**: Allow governance to adjust key parameters (e.g., maximum entry sizes, fee structures).

3. **Curation and Moderation**: Implement community-driven curation and moderation mechanisms.

4. **Resource Allocation**: Govern the allocation of resources (e.g., treasury funds) to support registry development and maintenance.

Implementation Approaches:

1. **On-Chain Governance**: Implement governance directly on Solana using programs like SPL Governance.

2. **Cross-Chain Governance**: Leverage existing governance systems on other chains with bridge integration.

3. **Hybrid Governance**: Combine on-chain voting with off-chain discussion and deliberation.

4. **Progressive Decentralization**: Start with more centralized governance and gradually transition to fully decentralized governance.

Decentralized governance would ensure the registries evolve in alignment with community needs and values, enhancing their long-term sustainability.

11.3.3 Integration with Tokenomics and Incentive Systems

Future registry enhancements could incorporate tokenomics and incentive systems to align stakeholder interests and drive ecosystem growth.

Potential Token Utilities:

1. **Governance Rights**: Token holders could participate in governance decisions.

2. **Staking for Features**: Stake tokens to access premium features or higher rate limits.

3. **Curation Incentives**: Earn tokens for curating high-quality registry entries.

4. **Discovery Fees**: Pay small token fees for discovery queries, with proceeds distributed to stakeholders.

5. **Registration Bonds**: Require token bonds for registration, refundable based on behavior.

Incentive Mechanisms:

1. **Registration Rewards**: Reward early or high-quality registrations with tokens.
   ```
   +------------------+ +------------------+ | | | | | Quality
   |---->| Token Reward | | Registration | | Distribution | | | | |
   | - Completeness | | - Base reward | | - Accuracy | | - Quality
   | | - Uniqueness | | multiplier | | | | | +------------------+
   +------------------+
   ```

2. **Referral Programs**: Reward agents that refer other agents to the registry.
3. **Usage Rewards**: Distribute rewards based on how often an agent is discovered and used.
4. **Contribution Incentives**: Reward contributions to registry infrastructure (e.g., indexers, clients).

Implementation Considerations:

1. **Token Design**: Carefully design token economics to avoid perverse incentives.
2. **Regulatory Compliance**: Consider regulatory implications of token systems.
3. **Sustainability**: Ensure the token economy is sustainable over the long term.
4. **Fairness**: Design mechanisms that are fair to all participants, regardless of size or resources.

Well-designed tokenomics and incentive systems could significantly accelerate the growth and adoption of the registries while ensuring their long-term sustainability.

References will be compiled and listed in Chapter 13.

Chapter 12: Conclusion

12.1 Summary of Key Concepts

This research has explored the comprehensive design and implementation of Solana Protocol for Agent and MCP Server Registries, providing a foundation for decentralized agent discovery and coordination. Let's summarize the key concepts covered throughout this work:

12.1.1 Registry Fundamentals

The Agent and MCP Server Registries serve as decentralized directories for autonomous agents and Model Context Protocol servers, enabling discovery, verification, and coordination within the ecosystem. These registries leverage Solana's high-performance blockchain to provide:

1. **Decentralized Discovery**: Eliminating central points of failure or control in agent and server discovery.

2. **Verifiable Information**: Ensuring registry entries are cryptographically verifiable and tamper-resistant.
3. **Ownership Control**: Providing clear ownership and update rights for registry entries.
4. **Standardized Metadata**: Establishing common formats for describing agent and server capabilities.
5. **Efficient Querying**: Supporting various discovery patterns through on-chain data and off-chain indexers.

The registries are designed as complementary systems: - **Agent Registry**: Focuses on individual agent capabilities, endpoints, and metadata. - **MCP Server Registry**: Focuses on servers that implement the Model Context Protocol for AI model serving.

12.1.2 Technical Architecture

The technical architecture of the registries leverages Solana's account model and the Anchor framework to create a robust and efficient system:

1. **Account Structure**: Registry entries are stored as Program Derived Addresses (PDAs) with carefully designed data structures.
2. **Instruction Design**: Clear, secure instructions for registration, updates, and deletion of entries.
3. **Ownership Model**: Strong ownership controls through public key verification and Anchor constraints.
4. **Discovery Mechanisms**: Hybrid discovery combining on-chain data with off-chain indexing for efficiency.
5. **Security Considerations**: Comprehensive security measures to prevent unauthorized access and data corruption.
6. **Performance Optimization**: Techniques to minimize storage costs and computational overhead.

12.1.3 Implementation Approach

The implementation approach focused on practical, production-ready code with:

1. **Anchor Framework**: Leveraging Anchor for safer, more maintainable Solana programs.
2. **Rust Best Practices**: Following Rust idioms and patterns for robust, efficient code.
3. **Client Integration**: Providing TypeScript/JavaScript clients for easy integration.
4. **Testing Strategies**: Comprehensive testing approaches for reliability.
5. **Deployment Workflows**: Clear processes for deploying and upgrading the registries.

12.1.4 Ecosystem Integration

The registries are designed to integrate with the broader agent ecosystem:

1. **Protocol Compatibility**: Supporting A2A, MCP, and other emerging agent communication protocols.
2. **Indexer Integration**: Designs for efficient off-chain indexing and querying.
3. **Client Libraries**: Approaches for integrating with various client environments.
4. **Case Studies**: Practical examples of registry usage in real-world scenarios.
5. **Future Directions**: Pathways for evolution and enhancement of the registries.

12.2 Implications for Decentralized Agent Ecosystems

The development of standardized, decentralized registries for agents and MCP servers has profound implications for the broader decentralized agent ecosystem.

12.2.1 Enabling Open Agent Discovery

The registries fundamentally transform agent discovery from a centralized, platform-specific process to an open, decentralized one:

```
+-------------------+     +-------------------+
|                   |     |                   |
| Traditional       |     | Decentralized     |
| Centralized       |     | Registry-Based    |
| Discovery         |     | Discovery         |
|                   |     |                   |
| - Platform-owned  |     | - Open access     |
| - Gatekeeping     |     | - Permissionless  |
| - Proprietary     |     | - Transparent     |
| - Single point    |     | - Resilient       |
|   of failure      |     |                   |
+-------------------+     +-------------------+
```

This shift has several key implications:

1. **Reduced Platform Dependency**: Agents can be discovered without relying on specific platforms or marketplaces.
2. **Increased Innovation**: Lower barriers to entry encourage more diverse agent development.
3. **Enhanced Resilience**: No single point of failure in the discovery process.
4. **Greater Transparency**: Open visibility into available agents and their capabilities.

12.2.2 Facilitating Agent Interoperability

The standardized metadata and protocol information in the registries facilitate greater interoperability between agents:

1. **Protocol Discovery**: Agents can discover which protocols other agents support.
2. **Endpoint Information**: Clear information about how to connect to and interact with agents.
3. **Capability Matching**: Agents can find other agents with complementary capabilities.
4. **Dynamic Collaboration**: Enables runtime discovery and collaboration between previously unacquainted agents.

This interoperability is essential for creating complex, multi-agent systems that can dynamically form to solve problems.

12.2.3 Creating a Foundation for Agent Economies

The registries provide a foundation for emerging agent economies:

1. **Service Discovery**: Enables agents to discover and consume services from other agents.
2. **Market Formation**: Facilitates the formation of decentralized marketplaces for agent services.
3. **Reputation Systems**: Provides a base layer for building reputation and trust systems.
4. **Economic Incentives**: Creates opportunities for economic models around agent registration and discovery.

As these agent economies develop, they could fundamentally transform how digital services are discovered, composed, and consumed.

12.2.4 Advancing Decentralized AI

The registries, particularly the MCP Server Registry, have significant implications for decentralized AI:

1. **Model Discovery**: Enables discovery of AI models served through MCP.
2. **Decentralized Inference**: Facilitates access to diverse inference providers.
3. **Specialized Models**: Makes it easier to discover specialized, niche models.
4. **Model Composition**: Enables agents to compose multiple models for complex tasks.

This infrastructure supports a more open, accessible AI ecosystem that isn't dominated by a few large providers.

12.3 Challenges and Limitations

While the registries provide powerful capabilities, they also face several challenges and limitations that should be acknowledged.

12.3.1 Technical Challenges

1. **Scalability**: As the number of registry entries grows, efficient discovery becomes more challenging.
2. On-chain filtering has limitations.
3. Off-chain indexers add complexity and potential centralization.
4. **Update Latency**: Blockchain-based updates have inherent latency.
5. Critical for time-sensitive information like endpoint availability.
6. May require complementary off-chain status mechanisms.
7. **Storage Costs**: On-chain storage has costs that scale with data size.
8. Limits the amount of metadata that can be practically stored.
9. Creates tension between completeness and cost-efficiency.
10. **Cross-Chain Integration**: Integrating with agents on other blockchains remains complex.
11. Requires bridges or other cross-chain communication.
12. Introduces additional trust assumptions.

12.3.2 Ecosystem Challenges

1. **Adoption Barriers**: New infrastructure faces adoption challenges.
2. Requires ecosystem buy-in.
3. Competes with existing centralized discovery mechanisms.
4. **Standardization Tensions**: Balancing standardization with innovation.
5. Too rigid: limits innovation.
6. Too flexible: reduces interoperability.

7. **Governance Complexity**: Decentralized governance of registry standards is challenging.
8. Who decides on protocol upgrades?
9. How to balance various stakeholder interests?
10. **Economic Sustainability**: Ensuring long-term economic sustainability.
11. Who pays for registry maintenance and development?
12. How to align economic incentives across the ecosystem?

12.3.3 Practical Limitations

1. **Verification Challenges**: The registry can verify ownership but not capability claims.
2. An agent can claim capabilities it doesn't actually have.
3. Requires complementary reputation or verification systems.
4. **Discovery Precision**: Finding exactly the right agent remains challenging.
5. Keyword matching has limitations.
6. More sophisticated discovery mechanisms add complexity.
7. **Metadata Standardization**: Balancing descriptive power with standardization.
8. Too standardized: loses nuance.
9. Too free-form: harder to query effectively.
10. **Privacy Considerations**: Public registries expose information by design.
11. Some agents may require privacy.
12. Tension between discoverability and confidentiality.

12.4 Future Research Directions

This research has laid a foundation for decentralized agent and MCP server registries, but many areas warrant further investigation.

12.4.1 Technical Research Directions

1. **Scalable On-Chain Discovery**: Researching more efficient on-chain filtering and discovery mechanisms.

2. Novel indexing structures.
3. Optimized PDA derivation schemes.
4. Hierarchical discovery approaches.
5. **Privacy-Preserving Discovery**: Developing techniques for privacy-preserving agent discovery.
6. Zero-knowledge proofs for capability verification.
7. Private discovery protocols.
8. Selective disclosure mechanisms.
9. **Cross-Chain Registry Synchronization**: Exploring efficient cross-chain registry synchronization.
10. Optimistic synchronization protocols.
11. Trustless verification mechanisms.
12. Unified discovery interfaces.
13. **Semantic Discovery**: Advancing semantic understanding for more intelligent discovery.
14. Ontology development for agent capabilities.
15. Semantic matching algorithms.
16. Context-aware discovery.

12.4.2 Ecosystem Research Directions

1. **Reputation Systems**: Designing effective, decentralized reputation systems.
2. Sybil-resistant rating mechanisms.
3. Contextual reputation models.
4. Transferable reputation across platforms.
5. **Economic Models**: Developing sustainable economic models for registry ecosystems.
6. Token design for registry incentives.
7. Fee structures for sustainable operation.
8. Value capture and distribution mechanisms.
9. **Governance Frameworks**: Creating effective governance for registry evolution.

10. Stakeholder representation models.
11. Decision-making processes.
12. Upgrade coordination mechanisms.
13. **Adoption Strategies**: Researching effective strategies for registry adoption.
14. Integration with existing agent frameworks.
15. Migration paths from centralized directories.
16. Network effect acceleration techniques.

12.4.3 Application Research Directions

1. **Multi-Agent Systems**: Exploring how registries enable complex multi-agent systems.
2. Dynamic team formation protocols.
3. Role discovery and negotiation.
4. Collective capability representation.
5. **Agent Marketplaces**: Researching decentralized marketplaces built on registry infrastructure.
6. Price discovery mechanisms.
7. Service level agreements.
8. Automated contracting.
9. **Human-Agent Collaboration**: Investigating how registries can facilitate human-agent collaboration.
10. Human-readable discovery interfaces.
11. Trust-building mechanisms.
12. Delegation frameworks.
13. **Domain-Specific Registries**: Exploring specialized registries for specific domains.
14. Financial agent registries.
15. Healthcare agent registries.
16. Creative agent registries.

12.5 Concluding Thoughts

The Solana Protocol Design for Agent and MCP Server Registries represents a significant step toward a more open, interoperable, and decentralized agent ecosystem. By providing standardized, on-chain registration and discovery mechanisms, these registries enable new forms of agent coordination and collaboration that were previously difficult or impossible.

As autonomous agents become increasingly capable and prevalent, the infrastructure that enables their discovery and interaction becomes critically important. Decentralized registries ensure this infrastructure remains open, resilient, and free from centralized control, aligning with the broader vision of decentralized, autonomous systems.

The technical designs, implementation approaches, and future directions outlined in this research provide a comprehensive blueprint for building and evolving these registries. While challenges and limitations exist, the potential benefits for the agent ecosystem are substantial.

As we look to the future, the continued development and adoption of these registries will play a key role in shaping how agents discover each other, coordinate their activities, and collectively create value in increasingly sophisticated ways. The journey toward truly autonomous, interoperable agent ecosystems is just beginning, and decentralized registries form an essential foundation for that journey.

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Chapter 14: Appendices

Appendix A: Complete Registry Data Structures

A.1 Agent Registry Data Structures

Below is the complete Rust code for the Agent Registry data structures, including all fields, types, and documentation comments:

```rust
/// Agent Registry Entry (Version 1)
/// This is the primary data structure for storing agent
information on-chain
#[account]
#[derive(InitSpace)]
pub struct AgentRegistryEntryV1 {
    /// Bump seed used for PDA derivation
    pub bump: u8,

    /// Registry version (currently 1)
    pub registry_version: u8,

    /// Current status of the agent (Active, Inactive,
Deprecated)
    pub status: u8,

    /// Authority that can update or close this entry
    pub owner_authority: Pubkey,

    /// Unique identifier for this agent
    #[max_len(64)]
    pub agent_id: String,

    /// Human-readable name of the agent
    #[max_len(64)]
    pub name: String,
    /// Brief description of the agent's purpose and
capabilities
    #[max_len(256)]
    pub description: String,

    /// Version identifier for the agent
    #[max_len(32)]
    pub agent_version: String,

    /// Bit flags representing agent capabilities
    pub capabilities_flags: u64,

    /// List of protocols supported by this agent (e.g., "a2a",
"mcp")
    #[max_len(5)]
    pub supported_protocols: Vec<String>,

    /// List of skill tags describing agent capabilities
    #[max_len(10)]
    pub skill_tags: Vec<String>,

    /// List of service endpoints for connecting to this agent
    #[max_len(3)]
    pub service_endpoints: Vec<ServiceEndpoint>,

    /// Optional URL to documentation
    pub documentation_url: Option<String>,

    /// Optional URI pointing to extended metadata (e.g., IPFS,
Arweave)
    pub extended_metadata_uri: Option<String>,

    /// Unix timestamp when this entry was created
    pub created_at: i64,

    /// Unix timestamp when this entry was last updated
    pub updated_at: i64,
}

/// Service endpoint information for connecting to an agent
#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ServiceEndpoint {
    /// Protocol used by this endpoint (e.g., "http", "grpc",
"websocket")
    #[max_len(64)]
    pub protocol: String,

    /// URL or connection string for this endpoint
    #[max_len(256)]
    pub url: String,

    /// Whether this is the default endpoint for the agent
```

```rust
    pub is_default: bool,
}

/// Agent capability flags as bit positions
pub mod AgentCapabilityFlags {
    /// Agent supports A2A messaging protocol
    pub const A2A_MESSAGING: u64 = 1 << 0;

    /// Agent can act as an MCP client
    pub const MCP_CLIENT: u64 = 1 << 1;

    /// Agent can execute tasks
    pub const TASK_EXECUTION: u64 = 1 << 2;

    /// Agent can publish events
    pub const EVENT_PUBLISHING: u64 = 1 << 3;

    /// Agent supports direct user interaction
    pub const USER_INTERACTION: u64 = 1 << 4;

    /// Agent has payment capabilities
    pub const PAYMENT_PROCESSING: u64 = 1 << 5;

    /// Agent can interact with smart contracts
    pub const CONTRACT_INTERACTION: u64 = 1 << 6;

    /// Agent has data storage capabilities
    pub const DATA_STORAGE: u64 = 1 << 7;

    /// Agent can perform data analysis
    pub const DATA_ANALYSIS: u64 = 1 << 8;

    /// Agent has machine learning capabilities
    pub const MACHINE_LEARNING: u64 = 1 << 9;

    // Additional flags can be added up to 64 total (u64 limit)
}

/// Agent status values
pub enum AgentStatus {
    /// Agent is not currently active
    Inactive = 0,

    /// Agent is active and available
    Active = 1,

    /// Agent is deprecated and may be removed in the future
    Deprecated = 2,
}
```

A.2 MCP Server Registry Data Structures

Below is the complete Rust code for the MCP Server Registry data structures:

```rust
/// MCP Server Registry Entry (Version 1)
/// This is the primary data structure for storing MCP server
information on-chain
#[account]
#[derive(InitSpace)]
pub struct MCPServerRegistryEntryV1 {
    /// Bump seed used for PDA derivation
    pub bump: u8,

    /// Registry version (currently 1)
    pub registry_version: u8,

    /// Current status of the server (Active, Maintenance,
Offline)
    pub status: u8,

    /// Authority that can update or close this entry
    pub owner_authority: Pubkey,

    /// Unique identifier for this MCP server
    #[max_len(64)]
    pub server_id: String,

    /// Human-readable name of the MCP server
    #[max_len(64)]
    pub name: String,

    /// Brief description of the server's purpose and
capabilities
    #[max_len(256)]
    pub description: String,

    /// Version of the MCP protocol implemented by this server
    #[max_len(32)]
    pub mcp_version: String,

    /// Primary endpoint URL for connecting to this MCP server
    #[max_len(256)]
    pub endpoint_url: String,

    /// List of models supported by this MCP server
    #[max_len(20)]
    pub supported_models: Vec<ModelInfo>,

    /// Optional URL to documentation
    pub documentation_url: Option<String>,
    /// Optional URI pointing to extended metadata (e.g., IPFS,
Arweave)
    pub extended_metadata_uri: Option<String>,

    /// Bit flags representing server capabilities
    pub capabilities_flags: u64,

    /// Unix timestamp when this entry was created
    pub created_at: i64,

    /// Unix timestamp when this entry was last updated
    pub updated_at: i64,
}

/// Information about a model supported by an MCP server
#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ModelInfo {
    /// Unique identifier for this model
    #[max_len(64)]
    pub model_id: String,

    /// Human-readable name of the model
    #[max_len(64)]
    pub name: String,

    /// Version identifier for the model
    #[max_len(32)]
    pub version: String,

    /// List of tools supported by this model
    #[max_len(10)]
    pub supported_tools: Vec<ToolInfo>,
}

/// Information about a tool supported by a model
#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ToolInfo {
    /// Unique identifier for this tool
    #[max_len(64)]
    pub tool_id: String,

    /// Human-readable name of the tool
    #[max_len(64)]
    pub name: String,

    /// Brief description of the tool's purpose
    #[max_len(256)]
    pub description: String,

    /// Hash of the tool's schema for verification
    #[max_len(64)]
    pub schema_hash: String,
}

/// MCP server capability flags as bit positions
pub mod MCPServerCapabilityFlags {
    /// Server supports streaming responses
    pub const STREAMING: u64 = 1 << 0;

    /// Server supports tool execution
    pub const TOOL_EXECUTION: u64 = 1 << 1;

    /// Server supports multi-modal inputs
    pub const MULTI_MODAL: u64 = 1 << 2;

    /// Server supports parallel requests
    pub const PARALLEL_REQUESTS: u64 = 1 << 3;

    /// Server supports request batching
    pub const BATCHING: u64 = 1 << 4;

    /// Server supports fine-tuning
    pub const FINE_TUNING: u64 = 1 << 5;

    /// Server supports model customization
    pub const CUSTOMIZATION: u64 = 1 << 6;

    /// Server supports usage analytics
    pub const ANALYTICS: u64 = 1 << 7;

    // Additional flags can be added up to 64 total (u64 limit)
}

/// MCP server status values
pub enum MCPServerStatus {
    /// Server is offline and not accepting requests
    Offline = 0,

    /// Server is active and available
    Active = 1,

    /// Server is in maintenance mode
    Maintenance = 2,
}
```

Appendix B: Registry Instruction Definitions

B.1 Agent Registry Instructions

Below are the complete instruction definitions for the Agent Registry:

```
 #[program]
pub mod agent_registry {
    use super::*;

    /// Register a new agent in the registry
    pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
        // Implementation details...
    }

    /// Update an existing agent entry
    pub fn update_agent(ctx: Context<UpdateAgent>, args:
UpdateAgentArgs) -> Result<()> {
        // Implementation details...
    }

    /// Update the status of an agent
    pub fn update_agent_status(ctx: Context<UpdateAgentStatus>,
new_status: u8) -> Result<()> {
        // Implementation details...
    }

    /// Close an agent entry and reclaim rent
    pub fn close_agent_entry(ctx: Context<CloseAgentEntry>) ->
Result<()> {
        // Implementation details...
    }

    /// Transfer ownership of an agent entry to a new authority
    pub fn transfer_agent_ownership(ctx:
Context<TransferAgentOwnership>) -> Result<()> {
        // Implementation details...
    }
}

/// Accounts required for the register_agent instruction
#[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    /// The account that will pay for the transaction and rent
    #[account(mut)]
    pub payer: Signer<'info>,

    /// The authority that will own this agent entry
    pub owner_authority: Signer<'info>,

    /// The agent entry account (PDA)
    #[account(
        init,
        payer = payer,
        space = 8 + AgentRegistryEntryV1::INIT_SPACE,
        seeds = [
            b"agent_registry",
            args.agent_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    /// System program for creating the entry account
    pub system_program: Program<'info, System>,
}

/// Arguments for the register_agent instruction
#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct RegisterAgentArgs {
    /// Unique identifier for this agent
    pub agent_id: String,

    /// Human-readable name of the agent
    pub name: String,

    /// Brief description of the agent's purpose and
capabilities
    pub description: String,

    /// Version identifier for the agent
    pub agent_version: String,

    /// Bit flags representing agent capabilities
    pub capabilities_flags: u64,

    /// List of protocols supported by this agent
    pub supported_protocols: Vec<String>,

    /// List of skill tags describing agent capabilities
    pub skill_tags: Vec<String>,

    /// List of service endpoints for connecting to this agent
    pub service_endpoints: Vec<ServiceEndpoint>,

    /// Optional URL to documentation
    pub documentation_url: Option<String>,

    /// Optional URI pointing to extended metadata
    pub extended_metadata_uri: Option<String>,
}

/// Accounts required for the update_agent instruction
#[derive(Accounts)]
pub struct UpdateAgent<'info> {
    /// The agent entry account (PDA)
```

```rust
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    /// The authority that owns this agent entry
    pub owner_authority: Signer<'info>,
}

/// Arguments for the update_agent instruction
#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct UpdateAgentArgs {
    /// Optional updated name
    pub name: Option<String>,

    /// Optional updated description
    pub description: Option<String>,

    /// Optional updated agent version
    pub agent_version: Option<String>,

    /// Optional updated capabilities flags
    pub capabilities_flags: Option<u64>,

    /// Optional updated supported protocols
    pub supported_protocols: Option<Vec<String>>,

    /// Optional updated skill tags
    pub skill_tags: Option<Vec<String>>,

    /// Optional updated service endpoints
    pub service_endpoints: Option<Vec<ServiceEndpoint>>,

    /// Optional updated documentation URL
    pub documentation_url: Option<Option<String>>,

    /// Optional updated extended metadata URI
    pub extended_metadata_uri: Option<Option<String>>,
}

/// Accounts required for the update_agent_status instruction
#[derive(Accounts)]
pub struct UpdateAgentStatus<'info> {
    /// The agent entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    /// The authority that owns this agent entry
    pub owner_authority: Signer<'info>,
}

/// Accounts required for the close_agent_entry instruction
#[derive(Accounts)]
pub struct CloseAgentEntry<'info> {
    /// The agent entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized,
        close = recipient
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    /// The authority that owns this agent entry
    pub owner_authority: Signer<'info>,

    /// The account that will receive the reclaimed rent
    #[account(mut)]
    pub recipient: SystemAccount<'info>,
}

/// Accounts required for the transfer_agent_ownership
instruction
#[derive(Accounts)]
pub struct TransferAgentOwnership<'info> {
    /// The agent entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            current_owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = current_owner_authority @
ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    /// The current authority that owns this agent entry
    pub current_owner_authority: Signer<'info>,

    /// The new authority that will own this agent entry
    /// CHECK: This is just a pubkey, no need to validate it's a
signer
    pub new_owner_authority: AccountInfo<'info>,
}
```

B.2 MCP Server Registry Instructions

Below are the complete instruction definitions for the MCP Server Registry:

```
 #[program]
pub mod mcp_server_registry {
    use super::*;

    /// Register a new MCP server in the registry
    pub fn register_mcp_server(ctx: Context<RegisterMCPServer>,
args: RegisterMCPServerArgs) -> Result<()> {
        // Implementation details...
    }

    /// Update an existing MCP server entry
    pub fn update_mcp_server(ctx: Context<UpdateMCPServer>,
args: UpdateMCPServerArgs) -> Result<()> {
        // Implementation details...
    }

    /// Update the status of an MCP server
    pub fn update_mcp_server_status(ctx:
Context<UpdateMCPServerStatus>, new_status: u8) -> Result<()> {
        // Implementation details...
    }

    /// Close an MCP server entry and reclaim rent
    pub fn close_mcp_server_entry(ctx:
Context<CloseMCPServerEntry>) -> Result<()> {
        // Implementation details...
    }

    /// Transfer ownership of an MCP server entry to a new
authority
    pub fn transfer_mcp_server_ownership(ctx:
```

```rust
Context<TransferMCPServerOwnership>) -> Result<()> {
        // Implementation details...
    }
}

/// Accounts required for the register_mcp_server instruction
#[derive(Accounts)]
#[instruction(args: RegisterMCPServerArgs)]
pub struct RegisterMCPServer<'info> {
    /// The account that will pay for the transaction and rent
    #[account(mut)]
    pub payer: Signer<'info>,

    /// The authority that will own this MCP server entry
    pub owner_authority: Signer<'info>,

    /// The MCP server entry account (PDA)
    #[account(
        init,
        payer = payer,
        space = 8 + MCPServerRegistryEntryV1::INIT_SPACE,
        seeds = [
            b"mcp_server_registry",
            args.server_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    /// System program for creating the entry account
    pub system_program: Program<'info, System>,
}

/// Arguments for the register_mcp_server instruction
#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct RegisterMCPServerArgs {
    /// Unique identifier for this MCP server
    pub server_id: String,

    /// Human-readable name of the MCP server
    pub name: String,

    /// Brief description of the server's purpose and
capabilities
    pub description: String,

    /// Version of the MCP protocol implemented by this server
    pub mcp_version: String,

    /// Primary endpoint URL for connecting to this MCP server
    pub endpoint_url: String,
    /// List of models supported by this MCP server
    pub supported_models: Vec<ModelInfo>,

    /// Optional URL to documentation
    pub documentation_url: Option<String>,

    /// Optional URI pointing to extended metadata
    pub extended_metadata_uri: Option<String>,

    /// Bit flags representing server capabilities
    pub capabilities_flags: u64,
}

/// Accounts required for the update_mcp_server instruction
#[derive(Accounts)]
pub struct UpdateMCPServer<'info> {
    /// The MCP server entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    /// The authority that owns this MCP server entry
    pub owner_authority: Signer<'info>,
}

/// Arguments for the update_mcp_server instruction
#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct UpdateMCPServerArgs {
    /// Optional updated name
    pub name: Option<String>,

    /// Optional updated description
    pub description: Option<String>,

    /// Optional updated MCP version
    pub mcp_version: Option<String>,

    /// Optional updated endpoint URL
    pub endpoint_url: Option<String>,

    /// Optional updated supported models
    pub supported_models: Option<Vec<ModelInfo>>,
    /// Optional updated documentation URL
    pub documentation_url: Option<Option<String>>,

    /// Optional updated extended metadata URI
    pub extended_metadata_uri: Option<Option<String>>,

    /// Optional updated capabilities flags
    pub capabilities_flags: Option<u64>,
}

/// Accounts required for the update_mcp_server_status
instruction
#[derive(Accounts)]
pub struct UpdateMCPServerStatus<'info> {
    /// The MCP server entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    /// The authority that owns this MCP server entry
    pub owner_authority: Signer<'info>,
}

/// Accounts required for the close_mcp_server_entry instruction
#[derive(Accounts)]
pub struct CloseMCPServerEntry<'info> {
    /// The MCP server entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized,
        close = recipient
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    /// The authority that owns this MCP server entry
    pub owner_authority: Signer<'info>,

    /// The account that will receive the reclaimed rent
    #[account(mut)]
    pub recipient: SystemAccount<'info>,
}

/// Accounts required for the transfer_mcp_server_ownership
instruction
#[derive(Accounts)]
pub struct TransferMCPServerOwnership<'info> {
    /// The MCP server entry account (PDA)
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            current_owner_authority.key().as_ref()
        ],
        bump = entry.bump,
        has_one = current_owner_authority @
ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    /// The current authority that owns this MCP server entry
    pub current_owner_authority: Signer<'info>,

    /// The new authority that will own this MCP server entry
    /// CHECK: This is just a pubkey, no need to validate it's a
signer
    pub new_owner_authority: AccountInfo<'info>,
}
```

Appendix C: Error Codes

Below is the complete list of error codes for both registries:

```
/// Error codes for the Agent and MCP Server Registries
#[error_code]
pub enum ErrorCode {
    /// String exceeds maximum allowed length
    #[msg("String exceeds maximum allowed length")]
    StringTooLong = 6000,

    /// Collection contains too many items
    #[msg("Collection contains too many items")]
    TooManyItems = 6001,

    /// Agent ID format is invalid
    #[msg("Agent ID format is invalid")]
    InvalidAgentId = 6002,
    /// Server ID format is invalid
    #[msg("Server ID format is invalid")]
    InvalidServerId = 6003,

    /// URL format is invalid
    #[msg("URL format is invalid")]
    InvalidUrl = 6004,

    /// Status value is invalid
    #[msg("Status value is invalid")]
    InvalidStatus = 6005,

    /// No default endpoint specified
    #[msg("No default endpoint specified")]
    NoDefaultEndpoint = 6006,

    /// Multiple default endpoints specified
    #[msg("Multiple default endpoints specified")]
    MultipleDefaultEndpoints = 6007,

    /// Unauthorized operation
    #[msg("Unauthorized operation")]
    Unauthorized = 6008,

    /// Cannot transfer ownership to self
    #[msg("Cannot transfer ownership to self")]
    CannotTransferToSelf = 6009,

    /// Invalid model ID format
    #[msg("Invalid model ID format")]
    InvalidModelId = 6010,

    /// Invalid tool ID format
    #[msg("Invalid tool ID format")]
    InvalidToolId = 6011,

    /// Invalid schema hash format
    #[msg("Invalid schema hash format")]
    InvalidSchemaHash = 6012,

    /// Invalid protocol format
    #[msg("Invalid protocol format")]
    InvalidProtocol = 6013,

    /// Invalid skill tag format
    #[msg("Invalid skill tag format")]
    InvalidSkillTag = 6014,

    /// Invalid version format
    #[msg("Invalid version format")]
    InvalidVersion = 6015,
}
```

Appendix D: Client SDK Examples

D.1 TypeScript Client SDK for Agent Registry

Below is an example TypeScript client SDK for interacting with the Agent Registry:

```
import * as anchor from '@project-serum/anchor';
import { Program } from '@project-serum/anchor';
import { PublicKey, Keypair, Connection, SystemProgram } from
'@solana/web3.js';
import { AgentRegistry, IDL } from './agent_registry'; //
Generated IDL

export class AgentRegistryClient {
  private program: Program<AgentRegistry>;
  private connection: Connection;

  constructor(
    connection: Connection,
    wallet: anchor.Wallet,
    programId: PublicKey
  ) {
    this.connection = connection;
    const provider = new anchor.AnchorProvider(
      connection,
      wallet,
      { commitment: 'confirmed' }
    );
    this.program = new Program<AgentRegistry>(IDL, programId,
provider);
  }

  /**
   * Find the PDA for an agent entry
   */
  async findAgentEntryPDA(agentId: string, ownerAuthority:
PublicKey): Promise<[PublicKey, number]> {
    return await PublicKey.findProgramAddress(
      [
        Buffer.from('agent_registry'),
        Buffer.from(agentId),
        ownerAuthority.toBuffer()
      ],
      this.program.programId
    );
  }

  /**
   * Register a new agent
   */
  async registerAgent(
    payer: Keypair,
    ownerAuthority: Keypair,
    args: {
      agentId: string;
      name: string;
      description: string;
      agentVersion: string;
      capabilitiesFlags: anchor.BN;
      supportedProtocols: string[];
      skillTags: string[];
      serviceEndpoints: {
        protocol: string;
        url: string;
        isDefault: boolean;
      }[];
      documentationUrl?: string;
      extendedMetadataUri?: string;
    }
  ): Promise<string> {
    const [entryPDA, _] = await this.findAgentEntryPDA(
      args.agentId,
      ownerAuthority.publicKey
    );

    const tx = await this.program.methods
      .registerAgent({
        agentId: args.agentId,
        name: args.name,
        description: args.description,
        agentVersion: args.agentVersion,
        capabilitiesFlags: args.capabilitiesFlags,
        supportedProtocols: args.supportedProtocols,
        skillTags: args.skillTags,
        serviceEndpoints: args.serviceEndpoints,
        documentationUrl: args.documentationUrl ?
args.documentationUrl : null,
        extendedMetadataUri: args.extendedMetadataUri ?
args.extendedMetadataUri : null,
      })
      .accounts({
        payer: payer.publicKey,
        ownerAuthority: ownerAuthority.publicKey,
        entry: entryPDA,
        systemProgram: SystemProgram.programId,
      })
      .signers([payer, ownerAuthority])
      .rpc();

    return tx;
  }

  /**
   * Update an existing agent
   */
  async updateAgent(
    ownerAuthority: Keypair,
    agentId: string,
    args: {
      name?: string;
      description?: string;
      agentVersion?: string;
      capabilitiesFlags?: anchor.BN;
      supportedProtocols?: string[];
      skillTags?: string[];
      serviceEndpoints?: {
        protocol: string;
        url: string;
        isDefault: boolean;
      }[];
      documentationUrl?: string | null;
      extendedMetadataUri?: string | null;
    }
  ): Promise<string> {
    const [entryPDA, _] = await this.findAgentEntryPDA(
      agentId,
      ownerAuthority.publicKey
    );

    const tx = await this.program.methods
      .updateAgent({
        name: args.name ? args.name : null,
        description: args.description ? args.description : null,
        agentVersion: args.agentVersion ? args.agentVersion :
null,
        capabilitiesFlags: args.capabilitiesFlags ?
args.capabilitiesFlags : null,
        supportedProtocols: args.supportedProtocols ?
args.supportedProtocols : null,
        skillTags: args.skillTags ? args.skillTags : null,
        serviceEndpoints: args.serviceEndpoints ?
args.serviceEndpoints : null,
        documentationUrl: args.documentationUrl !== undefined ?
args.documentationUrl : null,
        extendedMetadataUri: args.extendedMetadataUri !==
undefined ? args.extendedMetadataUri : null,
      })
      .accounts({
        entry: entryPDA,
        ownerAuthority: ownerAuthority.publicKey,
      })
      .signers([ownerAuthority])
      .rpc();

    return tx;
  }

  /**
   * Update agent status
   */
  async updateAgentStatus(
    ownerAuthority: Keypair,
    agentId: string,
    newStatus: number
  ): Promise<string> {
    const [entryPDA, _] = await this.findAgentEntryPDA(
      agentId,
      ownerAuthority.publicKey
    );

    const tx = await this.program.methods
      .updateAgentStatus(newStatus)
      .accounts({
        entry: entryPDA,
        ownerAuthority: ownerAuthority.publicKey,
      })
      .signers([ownerAuthority])
      .rpc();

    return tx;
  }

  /**
   * Close agent entry
   */
  async closeAgentEntry(
    ownerAuthority: Keypair,
    agentId: string,
    recipient: PublicKey
  ): Promise<string> {
    const [entryPDA, _] = await this.findAgentEntryPDA(
      agentId,
      ownerAuthority.publicKey
    );

    const tx = await this.program.methods
      .closeAgentEntry()
      .accounts({
        entry: entryPDA,
        ownerAuthority: ownerAuthority.publicKey,
        recipient: recipient,
      })
      .signers([ownerAuthority])
      .rpc();

    return tx;
  }

  /**
   * Transfer agent ownership
   */
  async transferAgentOwnership(
    currentOwnerAuthority: Keypair,
    agentId: string,
    newOwnerAuthority: PublicKey
  ): Promise<string> {
    const [entryPDA, _] = await this.findAgentEntryPDA(
      agentId,
      currentOwnerAuthority.publicKey
    );

    const tx = await this.program.methods
      .transferAgentOwnership()
      .accounts({
        entry: entryPDA,
        currentOwnerAuthority: currentOwnerAuthority.publicKey,
        newOwnerAuthority: newOwnerAuthority,
      })
      .signers([currentOwnerAuthority])
      .rpc();

    return tx;
  }

  /**
   * Fetch agent entry
   */
  async fetchAgentEntry(agentId: string, ownerAuthority:
PublicKey): Promise<any> {
    const [entryPDA, _] = await this.findAgentEntryPDA(
      agentId,
      ownerAuthority
    );

    try {
      return await
this.program.account.agentRegistryEntryV1.fetch(entryPDA);
    } catch (e) {
      console.error('Error fetching agent entry:', e);
      return null;
    }
  }
  /**
   * Find all agents by owner
   */
  async findAgentsByOwner(ownerAuthority: PublicKey):
Promise<any[]> {
    const accounts = await
this.program.account.agentRegistryEntryV1.all([
      {
        memcmp: {
          offset: 8 + 1 + 1, // After discriminator, bump, and
registry_version
          bytes: ownerAuthority.toBase58(),
        },
      },
    ]);
    return accounts;
  }

  /**
   * Find agents by skill tag
   */
  async findAgentsBySkillTag(skillTag: string): Promise<any[]> {
    // Note: This is inefficient and should be done through an
indexer
    // This is just for demonstration purposes
    const allAccounts = await
this.program.account.agentRegistryEntryV1.all();
    return allAccounts.filter(account =>
      account.account.skillTags.some((tag: string) => tag ===
skillTag)
    );
  }
}
```

D.2 Python Client SDK for MCP Server Registry

Below is an example Python client SDK for interacting with the MCP Server Registry:

```python
 from solana.rpc.api import Client
from solana.rpc.types import TxOpts
from solana.keypair import Keypair
from solana.publickey import PublicKey
from solana.system_program import SYS_PROGRAM_ID
from solana.transaction import Transaction
from solana.rpc.commitment import Confirmed
from anchorpy import Program, Provider, Wallet
import json
import base64
import struct
```

```python
class MCPServerRegistryClient:
    def __init__(self, rpc_url, program_id):
        self.client = Client(rpc_url)
        self.program_id = PublicKey(program_id)

        # Load IDL (in a real implementation, this would be
loaded from a file)
        with open('mcp_server_registry.json', 'r') as f:
            self.idl = json.load(f)

        # Create provider and program
        self.provider = Provider(self.client, Wallet.local(),
opts=TxOpts(skip_preflight=False,
preflight_commitment=Confirmed))
        self.program = Program(self.idl, self.program_id,
self.provider)

    def find_mcp_server_entry_pda(self, server_id,
owner_authority):
        """Find the PDA for an MCP server entry"""
        seeds = [
            b"mcp_server_registry",
            server_id.encode('utf-8'),
            bytes(owner_authority)
        ]
        return PublicKey.find_program_address(seeds,
self.program_id)

    def register_mcp_server(self, payer, owner_authority, args):
        """Register a new MCP server"""
        entry_pda, bump = self.find_mcp_server_entry_pda(
            args['server_id'],
            owner_authority.public_key
        )

        # Create instruction
        ix = self.program.instruction['register_mcp_server'](
            args,
            {
                'payer': payer.public_key,
                'owner_authority': owner_authority.public_key,
                'entry': entry_pda,
                'system_program': SYS_PROGRAM_ID,
            }
        )

        # Create and send transaction
        tx = Transaction().add(ix)
        signers = [payer, owner_authority]

        return self.client.send_transaction(
            tx, *signers, opts=TxOpts(skip_preflight=False,
preflight_commitment=Confirmed)
        )

    def update_mcp_server(self, owner_authority, server_id,
args):
        """Update an existing MCP server"""
        entry_pda, bump = self.find_mcp_server_entry_pda(
            server_id,
            owner_authority.public_key
        )

        # Create instruction
        ix = self.program.instruction['update_mcp_server'](
            args,
            {
                'entry': entry_pda,
                'owner_authority': owner_authority.public_key,
            }
        )

        # Create and send transaction
        tx = Transaction().add(ix)
        signers = [owner_authority]

        return self.client.send_transaction(
            tx, *signers, opts=TxOpts(skip_preflight=False,
preflight_commitment=Confirmed)
        )

    def update_mcp_server_status(self, owner_authority,
server_id, new_status):
        """Update MCP server status"""
        entry_pda, bump = self.find_mcp_server_entry_pda(
            server_id,
            owner_authority.public_key
        )

        # Create instruction
        ix =
self.program.instruction['update_mcp_server_status'](
            new_status,
            {
                'entry': entry_pda,
                'owner_authority': owner_authority.public_key,
            }
        )

        # Create and send transaction
        tx = Transaction().add(ix)
        signers = [owner_authority]

        return self.client.send_transaction(
            tx, *signers, opts=TxOpts(skip_preflight=False,
preflight_commitment=Confirmed)
        )

    def close_mcp_server_entry(self, owner_authority, server_id,
recipient):
        """Close MCP server entry"""
        entry_pda, bump = self.find_mcp_server_entry_pda(
            server_id,
            owner_authority.public_key
        )

        # Create instruction
        ix = self.program.instruction['close_mcp_server_entry'](
            {
                'entry': entry_pda,
                'owner_authority': owner_authority.public_key,
                'recipient': recipient,
            }
        )

        # Create and send transaction
        tx = Transaction().add(ix)
        signers = [owner_authority]

        return self.client.send_transaction(
            tx, *signers, opts=TxOpts(skip_preflight=False,
preflight_commitment=Confirmed)
        )

    def transfer_mcp_server_ownership(self,
current_owner_authority, server_id, new_owner_authority):
        """Transfer MCP server ownership"""
        entry_pda, bump = self.find_mcp_server_entry_pda(
            server_id,
            current_owner_authority.public_key
        )

        # Create instruction
        ix =
self.program.instruction['transfer_mcp_server_ownership'](
            {
                'entry': entry_pda,
                'current_owner_authority':
current_owner_authority.public_key,
                'new_owner_authority': new_owner_authority,
            }
        )

        # Create and send transaction
        tx = Transaction().add(ix)
        signers = [current_owner_authority]
        return self.client.send_transaction(
            tx, *signers, opts=TxOpts(skip_preflight=False,
preflight_commitment=Confirmed)
        )

    def fetch_mcp_server_entry(self, server_id,
owner_authority):
        """Fetch MCP server entry"""
        entry_pda, bump = self.find_mcp_server_entry_pda(
            server_id,
            owner_authority
        )

        try:
            return
self.program.account['mcp_server_registry_entry_v1'].fetch(entry_pda)
        except Exception as e:
            print(f"Error fetching MCP server entry: {e}")
            return None

    def find_mcp_servers_by_owner(self, owner_authority):
        """Find all MCP servers by owner"""
        # Calculate offset for owner_authority field
        # 8 bytes discriminator + 1 byte bump + 1 byte
registry_version
        offset = 8 + 1 + 1

        filters = [
            {
                'memcmp': {
                    'offset': offset,
                    'bytes': str(owner_authority)
                }
            }
        ]

        return
self.program.account['mcp_server_registry_entry_v1'].all(filters)

    def find_mcp_servers_by_model(self, model_id):
        """Find MCP servers supporting a specific model"""
        # Note: This is inefficient and should be done through
an indexer
        # This is just for demonstration purposes
        all_accounts =
self.program.account['mcp_server_registry_entry_v1'].all()

        matching_servers = []
        for account in all_accounts:
            for model in account.account.supported_models:
                if model.model_id == model_id:
                    matching_servers.append(account)
                    break

        return matching_servers
```

Appendix E: Glossary of Terms

A2A (Agent-to-Agent): A protocol for communication between autonomous agents, enabling them to exchange messages, requests, and responses.

Account: In Solana, a data structure that holds state. All data in Solana is stored in accounts.

Anchor: A framework for Solana program development that provides higher-level abstractions and safety features.

AEA (Autonomous Economic Agent): A software agent capable of making economic decisions and interacting with other agents and systems autonomously.

Agent: An autonomous software entity that can perform tasks, make decisions, and interact with other agents and systems.

Agent Registry: A decentralized directory of autonomous agents, storing their metadata, capabilities, and connection information.

Capabilities: The specific functionalities or services an agent can provide, often represented as bit flags in the registry.

CPI (Cross-Program Invocation): A mechanism in Solana that allows one program to call another program.

Decentralized Identity (DID): A system for creating and managing digital identities without relying on a central authority.

Discovery: The process of finding agents or MCP servers that match specific criteria or requirements.

Indexer: An off-chain service that processes and indexes on-chain data to enable efficient querying.

Instruction: In Solana, a command that tells a program what operation to perform.

MCP (Model Context Protocol): A protocol for interacting with AI models, standardizing requests and responses.

MCP Server: A server that implements the Model Context Protocol, providing access to one or more AI models.

MCP Server Registry: A decentralized directory of MCP servers, storing their metadata, supported models, and connection information.

Model: An AI model that can process inputs and generate outputs, often accessed through an MCP server.

Owner Authority: The public key that has permission to update or close a registry entry.

PDA (Program Derived Address): An account address derived from a program ID and additional seeds, allowing programs to control specific accounts.

Registry Entry: A record in a registry containing metadata about an agent or MCP server.

Service Endpoint: A URL or connection string that specifies how to connect to an agent or server.

Skill Tags: Keywords or phrases that describe an agent's capabilities or areas of expertise.

Solana: A high-performance blockchain platform with fast transaction processing and low fees.

Tool: A function or capability that an AI model can use to perform specific tasks.

End of Appendices

Chapter 2: Foundational Solana Concepts for On-Chain Registries

2.1 Program Derived Addresses (PDAs)

2.1.1 Technical Definition and Purpose

Program Derived Addresses (PDAs) represent one of the most powerful and distinctive features of the Solana blockchain architecture. Unlike standard public key addresses that are derived from cryptographic keypairs, PDAs are deterministically calculated addresses that have no corresponding private key. This fundamental characteristic makes PDAs uniquely suited for program-controlled accounts, forming the cornerstone of our registry design.

```
+---------------------------+     +---------------------------+
|                           |     |                           |
|  Standard Solana Account  |     |  Program Derived Address  |
|                           |     |                           |
|  +---------------------+  |     |  +---------------------+  |
|  | Public Key          |  |     |  | Derived Address     |  |
|  | (on Ed25519 curve)  |  |     |  | (off Ed25519 curve) |  |
|  +---------------------+  |     |  +---------------------+  |
|             |             |     |             |             |
|             v             |     |             x             |
|  +---------------------+  |     |  +---------------------+  |
|  | Private Key         |  |     |  | No Private Key      |  |
|  | (controls account)  |  |     |  | (program controls)  |  |
|  +---------------------+  |     |  +---------------------+  |
|                           |     |                           |
+---------------------------+     +---------------------------+
```

Technically, a PDA is an address that:

1. Is derived from a program ID (the address of the program that will control it)
2. Is derived from one or more optional "seeds" (byte arrays that add uniqueness and meaning)
3. Falls "off" the Ed25519 elliptic curve, ensuring it cannot have a corresponding private key
4. Can only be "signed for" by its controlling program through a process called "program signing"

The primary purposes of PDAs in the Solana ecosystem are:

- **Deterministic Address Generation**: PDAs enable programs to create addresses that can be reliably derived and located again using the same inputs (program ID and seeds).
- **Program-Controlled Storage**: They provide a way for programs to own and manage data without requiring user signatures for every operation.
- **Cross-Program Authority**: PDAs allow programs to "sign" for operations on other programs, enabling complex cross-program interactions.
- **Logical Data Organization**: The seed-based derivation creates a natural mapping system, allowing data to be organized in intuitive, hierarchical, or relational patterns.

For our registry designs, PDAs serve as the fundamental storage mechanism, allowing each registered agent or MCP server to have its own dedicated, program-controlled account with a deterministically derivable address.

2.1.2 PDA Derivation Process

The derivation of a PDA involves a sophisticated process that ensures the resulting address is both deterministic and cryptographically secure. Understanding this process is crucial for implementing and interacting with the registry protocols.

The derivation occurs through the following steps:

1. **Input Collection**: Gather the program ID and the optional seeds that will be used to derive the PDA.
2. **Bump Seed Introduction**: Add a "bump seed" (initially 255) to the collection of seeds.
3. **Hash Computation**: Apply the SHA-256 hash function to the concatenation of:
4. The seeds (including the bump seed)
5. The program ID
6. The string "ProgramDerivedAddress"
7. **Curve Check**: Verify if the resulting 32-byte hash represents a valid point on the Ed25519 curve.
8. **Iteration**: If the hash is a valid curve point, decrement the bump seed and repeat steps 3-4 until finding a hash that is not on the curve.
9. **Result**: The first hash that falls off the curve becomes the PDA, and the bump seed that produced it is stored for future reference.

This process is implemented in Solana's `find_program_address` function, which returns both the PDA and the canonical bump seed:

```
                     +-------------------+
                    | Program ID        |
                    | (Controlling      |
                    |  Program Address) |
                    +-------------------+
                             |
                             v
+-------------+     +-------------------+     +-------------------
+
| Seeds       |--->| find_program_     |--->| PDA               |
| (Optional   |    | address           |    | (Off-curve        |
|  Byte Arrays)|    | Function          |    |  Address)         |
+-------------+     +-------------------+     +-------------------
+
                             |                        ^
                    v                        |
          +--------------------+             |
          | Bump Seed          |-------------+
          | (Canonical Value)  |
          +--------------------+
```

In Rust, the derivation process can be performed using the `Pubkey::find_program_address` method:

```rust
let (pda, bump_seed) = Pubkey::find_program_address(
    &[

b"registry",           // Seed 1: Identifies the account type
        agent_id.as_bytes(),   // Seed 2: Unique identifier for
the agent
        owner.as_ref(),        // Seed 3: Owner's public key
    ],
    program_id                 // The program that will control
this PDA
);
```

The resulting PDA is deterministic for a given set of inputs, meaning anyone with the same program ID and seeds can derive the same address. This property is essential for our registry design, as it allows clients to locate specific registry entries without requiring a central index or lookup table.

2.1.3 Bump Seeds and Canonicalization

The concept of bump seeds is central to the security and reliability of PDAs. The bump seed serves two critical purposes:

1. **Ensuring Off-Curve Addresses**: By iteratively trying different bump values, the derivation process guarantees finding an address that falls off the Ed25519 curve.
2. **Canonicalization**: The process establishes a single, canonical bump value for each combination of program ID and seeds, preventing address collisions.

The canonical bump is always the first value (starting from 255 and decrementing) that produces an off-curve address. This canonicalization is crucial for consistent address derivation across different clients and contexts.

```
 Bump Seed Search Process:
+-------+    +---------------+    +---------------+
| 255   |--->| Hash Function |--->| On curve?     |
+-------+    +---------------+    +---------------+
                                         |
                                         v
                                  +----------------+
                                  | Yes            |
                                  +----------------+
                                         |
                                         v
+-------+    +----------------+    +----------------+
| 254   |--->| Hash Function |--->| On curve?      |
+-------+    +----------------+    +----------------+
                                         |
                                         v
                                  +----------------+
                                  | No             |
                                  +----------------+
                                         |
                                         v
                              +---------------------+
                              | Canonical Bump: 254 |
                              +---------------------+
```

In our registry implementation, we must always store the canonical bump seed as part of the account data. This practice serves several purposes:

1. **Verification**: It allows the program to verify that an account is at the expected PDA.
2. **Reconstruction**: It enables the program to reconstruct the PDA when needed for program signing.
3. **Efficiency**: It saves computational resources by avoiding the need to recalculate the bump seed.

The following code snippet demonstrates how to store and use the bump seed in a registry entry:

```
 // In the account data structure
#[account]
pub struct AgentRegistryEntryV1 {
    pub bump: u8,  // Store the canonical bump seed
    // Other fields...
}

// When creating a new entry
pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    entry.bump = *ctx.bumps.get("entry").unwrap();  // Store
bump from Anchor
    // Initialize other fields...
    Ok(())
}
```

```
// When using program signing (CPI)
pub fn update_external_state(ctx: Context<UpdateExternal>) ->
Result<()> {
    let seeds = &[
        b"registry",
        ctx.accounts.entry.agent_id.as_bytes(),
        ctx.accounts.entry.owner.as_ref(),
        &[ctx.accounts.entry.bump],  // Use stored bump
    ];
    let signer = &[&seeds[..]];

    // Perform cross-program invocation with PDA as signer
    external_program::cpi::update(
        CpiContext::new_with_signer(
            ctx.accounts.external_program.to_account_info(),
            external_program::accounts::Update {
                // Account mappings...
            },
            signer,
        ),
        // Args...
    )
}
```

2.1.4 Implementation Best Practices

When implementing PDAs for the registry protocols, several best practices should be followed to ensure security, efficiency, and maintainability:

1. **Consistent Seed Structure**: Establish a clear, consistent pattern for seed composition across the program. For our registries, we'll use a combination of:
2. A static prefix identifying the account type (e.g., "agent_registry", "mcp_server_registry")
3. The unique identifier of the entity (e.g., agent_id, server_id)

4. The owner's public key

5. **Seed Length Limitations**: Remember that each seed is limited to 32 bytes, and a maximum of 16 seeds can be used. For longer identifiers, consider using a hash of the value.

6. **Always Store the Bump**: As discussed, always store the canonical bump in the account data structure for verification and program signing.

7. **Validate PDA Derivation**: When processing instructions that operate on a PDA, verify that the account is at the expected address by re-deriving it:

```rust
// Verify PDA in a processor function
pub fn process_update(program_id: &Pubkey, accounts:
&[AccountInfo], args: UpdateArgs) -> ProgramResult {
    let accounts_iter = &mut accounts.iter();
    let entry_account = next_account_info(accounts_iter)?;
    let owner = next_account_info(accounts_iter)?;

    // Verify owner signature
    if !owner.is_signer {
        return Err(ProgramError::MissingRequiredSignature);
    }

    // Verify PDA derivation
    let (expected_pda, _) = Pubkey::find_program_address(
        &[
            b"registry",
            args.agent_id.as_bytes(),
            owner.key.as_ref(),
        ],
        program_id
    );

    if expected_pda != *entry_account.key {
        return Err(ProgramError::InvalidArgument);
    }

    // Process update...
    Ok(())
}
```

1. **Use Anchor's PDA Constraints**: When using the Anchor framework, leverage its built-in PDA constraints to automatically verify account addresses:

```rust
#[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    #[account(
        init,
        payer = payer,
        space = 8 + AgentRegistryEntryV1::SPACE,
        seeds = [
            b"registry",
            args.agent_id.as_bytes(),
            owner.key().as_ref(),
        ],
        bump
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,
    #[account(mut)]
    pub payer: Signer<'info>,

    pub owner: Signer<'info>,

    pub system_program: Program<'info, System>,
}
```

1. **Document Seed Structure**: Clearly document the seed structure for each PDA type to ensure consistent derivation across different clients and contexts.

By following these best practices, we can create a secure, efficient, and maintainable PDA-based storage system for our registry protocols.

2.2 Account Structures and Data Serialization

2.2.1 Borsh Serialization in Depth

In the Solana ecosystem, all program state is stored in accounts, which contain a byte array of data. To organize and interpret this data, serialization and deserialization mechanisms are essential. Borsh (Binary Object Representation Serializer for Hashing) is the standard serialization format for Solana programs, chosen for its efficiency, determinism, and security-focused design.

Borsh offers several advantages that make it particularly well-suited for blockchain applications:

1. **Deterministic Output**: Given the same input, Borsh always produces the same binary output, which is crucial for consistent state representation and verification.
2. **Compact Representation**: Borsh generates compact binary data, minimizing on-chain storage costs.
3. **Schema-Driven**: Borsh requires explicit schema definitions, reducing the risk of serialization/deserialization errors.
4. **Performance**: The serialization and deserialization processes are computationally efficient, important for Solana's compute budget constraints.

For our registry protocols, we'll use Borsh to serialize and deserialize the data structures that represent agent and MCP server entries. Here's how Borsh handles different data types:

```
 +---------------+-------------------------
+--------------------+
| Rust Type      | Borsh Serialization       | Size
(bytes)        |
+---------------+-------------------------
+--------------------+
| u8, i8        | Direct byte             |
1                  |
| u16, i16      | Little-endian bytes     |
2                  |
| u32, i32      | Little-endian bytes     |
4                  |
| u64, i64      | Little-endian bytes     |
8                  |
| u128, i128    | Little-endian bytes     |
16                 |
| bool          | 0 or 1 byte             |
1                  |
| String        | Length (u32) + bytes    | 4 + string
length  |
| Option<T>     | Presence (u8) + value   | 1 + size of
T       |
| Vec<T>        | Length (u32) + elements | 4 + sum(size of
T) |
| [T; N]        | Elements in sequence    | N * size of
T       |
| Struct        | Fields in declaration   | Sum of field
sizes |
| Enum          | Variant index + data    | 1 + variant
size    |
+---------------+-------------------------
+--------------------+
```

In Rust, Borsh serialization is typically implemented using the `borsh` crate, which provides derive macros for the `BorshSerialize` and `BorshDeserialize` traits:

```rust
 use borsh::{BorshSerialize, BorshDeserialize};

#[derive(BorshSerialize, BorshDeserialize)]
pub struct AgentRegistryEntryV1 {
    pub bump: u8,
    pub owner_authority: Pubkey,  // 32 bytes
    pub agent_id: String,
    pub name: String,
    pub description: String,
    pub agent_version: String,
    pub provider_name: Option<String>,
    pub provider_url: Option<String>,
    pub documentation_url: Option<String>,
    pub service_endpoints: Vec<ServiceEndpoint>,
    pub capabilities_flags: u64,
    pub supported_input_modes: Vec<String>,
    pub supported_output_modes: Vec<String>,
    pub skills: Vec<AgentSkill>,
    pub security_info_uri: Option<String>,
    pub aea_address: Option<String>,
    pub status: u8,
    pub created_at: i64,
    pub updated_at: i64,
}

#[derive(BorshSerialize, BorshDeserialize)]
pub struct ServiceEndpoint {
    pub protocol: String,
    pub url: String,
    pub is_default: bool,
}

#[derive(BorshSerialize, BorshDeserialize)]
pub struct AgentSkill {
    pub id: String,
    pub name: String,
    pub description_hash: Option<[u8; 32]>,
    pub tags: Vec<String>,
}
```

When working with Anchor, the framework provides its own serialization layer that uses Borsh under the hood, simplifying the process:

```rust
use anchor_lang::prelude::*;

#[account]
pub struct AgentRegistryEntryV1 {
    pub bump: u8,
    pub owner_authority: Pubkey,
    pub agent_id: String,
    // Other fields...
}
```

2.2.2 Account Data Organization

Efficient organization of data within Solana accounts is crucial for optimizing storage costs, access patterns, and program logic. For our registry protocols, we need to carefully consider how to structure the account data to balance these factors.

The key principles for account data organization in our registry design are:

1. **Fixed-Size Fields First**: Place fixed-size fields (like integers, booleans, and public keys) at the beginning of the structure, followed by variable-size fields (like strings and vectors). This approach simplifies data access and makes it easier to update individual fields.

2. **Logical Grouping**: Group related fields together to improve code readability and maintenance.

3. **Size Constraints**: Implement size constraints for variable-length fields to prevent excessive storage usage and potential denial-of-service attacks.

4. **Version Identification**: Include a version field to facilitate future upgrades and backward compatibility.

5. **Hybrid Storage Model**: For large or rarely accessed data, store only a reference (e.g., a URI or hash) on-chain, with the full data stored off-chain.

Here's an example of how we might organize the account data for an agent registry entry:

```
#[account]
pub struct AgentRegistryEntryV1 {
    // Fixed-size fields (metadata and control)
    pub bump: u8,                         // For PDA reconstruction
    pub registry_version: u8,             // Schema version for
upgradability
    pub owner_authority: Pubkey,          // 32 bytes, owner's
public key
    pub status: u8,                       // Active, inactive, etc.
    pub capabilities_flags: u64,          // Bitfield for core
capabilities
    pub created_at: i64,                  // Unix timestamp
    pub updated_at: i64,                  // Unix timestamp

    // Core identity (medium-sized strings)
    pub agent_id: String,                 // Unique identifier, max
64 chars
    pub name: String,                     // Human-readable name,
max 128 chars
    pub agent_version: String,            // Version string, max 32
chars

    // Detailed description (larger strings)
    pub description: String,              // Human-readable
description, max 512 chars

    // Optional metadata (variable presence)
    pub provider_name: Option<String>,       // Max 128 chars
    pub provider_url: Option<String>,        // Max 256 chars
    pub documentation_url: Option<String>,   // Max 256 chars
    pub security_info_uri: Option<String>,   // Max 256 chars
    pub aea_address: Option<String>,         // Max 64 chars

    // Complex nested structures (variable length)
    pub service_endpoints: Vec<ServiceEndpoint>,     // Max 3
endpoints
    pub supported_input_modes: Vec<String>,          // Max 5
items, each max 64 chars
    pub supported_output_modes: Vec<String>,         // Max 5
items, each max 64 chars
    pub skills: Vec<AgentSkill>,                     // Max 10
skills

    // Off-chain extension
    pub extended_metadata_uri: Option<String>,       // URI to
additional metadata, max 256 chars
}
```

This organization follows a progression from simple, fixed-size fields to more complex, variable-length structures, making it easier to access and update specific portions of the data.

2.2.3 Size Limitations and Optimization

Solana imposes a maximum account size of 10 megabytes, but practical considerations like rent costs and transaction size limits make it important to optimize account sizes well below this theoretical maximum. For our registry protocols, we need to implement several strategies to manage and optimize account sizes:

1. **Explicit Size Constraints**: Define maximum lengths for strings and collections to prevent excessive storage usage:

```
impl AgentRegistryEntryV1 {
    pub const MAX_AGENT_ID_LEN: usize = 64;
    pub const MAX_NAME_LEN: usize = 128;
    pub const MAX_DESCRIPTION_LEN: usize = 512;
    pub const MAX_VERSION_LEN: usize = 32;
    pub const MAX_URL_LEN: usize = 256;
    pub const MAX_ENDPOINTS: usize = 3;
    pub const MAX_MODES: usize = 5;
    pub const MAX_MODE_LEN: usize = 64;
    pub const MAX_SKILLS: usize = 10;

    // Calculate maximum space required
    pub const SPACE: usize =
        1 +                                        // bump
        1 +                                        //
registry_version
        32 +                                       //
owner_authority
        1 +                                        // status
        8 +                                        //
capabilities_flags
        8 +                                         // created_at
        8 +                                         // updated_at
        4 + Self::MAX_AGENT_ID_LEN +                // agent_id
        4 + Self::MAX_NAME_LEN +                    // name
        4 + Self::MAX_VERSION_LEN +                 // agent_version
        4 + Self::MAX_DESCRIPTION_LEN +             // description
        1 + 4 + Self::MAX_NAME_LEN +                //
Option<provider_name>
        1 + 4 + Self::MAX_URL_LEN +                 //
Option<provider_url>
        1 + 4 + Self::MAX_URL_LEN +                 //
Option<documentation_url>
        1 + 4 + Self::MAX_URL_LEN +                 //
Option<security_info_uri>
        1 + 4 + Self::MAX_AGENT_ID_LEN +            //
Option<aea_address>
        4 + Self::MAX_ENDPOINTS * (
            4 + 64 +                                // protocol
            4 + Self::MAX_URL_LEN +                 // url
            1                                       // is_default
        ) +                                         //
service_endpoints
        4 + Self::MAX_MODES * (4 + Self::MAX_MODE_LEN) + //
supported_input_modes
        4 + Self::MAX_MODES * (4 + Self::MAX_MODE_LEN) + //
supported_output_modes
        4 + Self::MAX_SKILLS * (
            4 + 64 +                                // id
            4 + 128 +                               // name
            1 + 32 +                                //
Option<description_hash>
            4 + 5 * (4 + 32)                        // tags (max 5,
each max 32 chars)
        ) +                                         // skills
        1 + 4 + Self::MAX_URL_LEN;                  //
Option<extended_metadata_uri>
}
```

1. **Validation in Instruction Processing**: Enforce these constraints during instruction processing:

```
pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    // Validate string lengths
    require!(
        args.agent_id.len() <=
AgentRegistryEntryV1::MAX_AGENT_ID_LEN,
        ErrorCode::StringTooLong
    );
    require!(
        args.name.len() <= AgentRegistryEntryV1::MAX_NAME_LEN,
        ErrorCode::StringTooLong
    );
    // More validations...

    // Validate collection sizes
    require!(
        args.service_endpoints.len() <=
AgentRegistryEntryV1::MAX_ENDPOINTS,
        ErrorCode::TooManyItems
    );
    // More validations...

    // Initialize account...
    Ok(())
}
```

1. **Hybrid Storage Model**: For potentially large data elements, store only essential information on-chain and use off-chain storage for details:

```
 +-----------------------------+
+-----------------------------+
|                             |
|                             |
| On-Chain Registry Entry     |          | Off-Chain Extended
Data     |
| (PDA Account)               |          | (IPFS, Arweave,
etc.)      |
|                             |
|                             |
| - Core identity             |          | - Detailed
skill              |
| - Essential metadata        |          |
descriptions                 |
| - Service endpoints         |          | - Comprehensive
security    |
| - Skill summaries           |--------->|
schemes                      |
| - Status information        |          | - Extended
capability          |
| - Verification hashes       |          |
documentation                |
| - Off-chain data URI        |          | - Rich media
content          |
|                             |
|                             |
+------------------------------+
+------------------------------+
```

1. **Incremental Updates**: Design instructions to allow updating specific fields rather than requiring full account rewrites:

```
 pub fn update_agent_status(ctx: Context<UpdateAgentStatus>,
new_status: u8) -> Result<()> {
    let entry = &mut ctx.accounts.entry;

    // Update only the status field
    entry.status = new_status;
    entry.updated_at = Clock::get()?.unix_timestamp;

    Ok(())
}
```

1. **Account Reuse**: When an entity is deregistered, consider allowing the account to be reused for a new registration rather than closing it, saving the overhead of account creation:

```
 pub fn deregister_agent(ctx: Context<DeregisterAgent>) ->
Result<()> {
    let entry = &mut ctx.accounts.entry;

    // Mark as inactive rather than closing
    entry.status = AgentStatus::Inactive as u8;
    entry.updated_at = Clock::get()?.unix_timestamp;

    // Emit event for indexers
    emit!(AgentDeregisteredEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

By implementing these size optimization strategies, we can create efficient, cost-effective registry entries that balance on-chain verifiability with practical storage constraints.

2.3 Rent, Storage Considerations, and Account Lifecycle

2.3.1 Rent Exemption Mechanics

In Solana, storing data on-chain incurs a cost known as "rent," which compensates validators for the storage resources they provide. To avoid ongoing rent payments and potential account deletion due to insufficient balance, accounts can be made "rent-exempt" by maintaining a minimum balance proportional to their size.

The rent exemption threshold is calculated based on the account's data size and is equivalent to two years' worth of rent. This design encourages efficient use of on-chain storage and ensures that accounts have sufficient funds to cover their long-term storage costs.

For our registry protocols, we'll require all registry entries to be rent-exempt, ensuring their persistence without ongoing maintenance. The rent exemption amount is calculated using the `minimum_balance` function from the `Rent` struct:

```
// Calculate rent exemption for an account
let rent = Rent::get()?;
let space = 8 + AgentRegistryEntryV1::SPACE;  // 8 bytes for
account discriminator
let minimum_balance = rent.minimum_balance(space);
```

In Anchor, rent exemption is automatically enforced when using the `init` constraint:

```
#[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    #[account(
        init,                                   // Initialize a
new account
        payer = payer,                          // Specify who
pays for the account
        space = 8 + AgentRegistryEntryV1::SPACE,  // Specify the
account size
        seeds = [...],                          // PDA seeds
        bump                                    // Store bump seed
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    #[account(mut)]
    pub payer: Signer<'info>,
    pub system_program: Program<'info, System>,
}
```

The `init` constraint creates a new account and transfers the minimum balance from the payer to make it rent-exempt. This approach ensures that registry entries remain accessible for as long as they exist, without requiring ongoing rent payments.

2.3.2 Account Creation and Initialization

The lifecycle of a registry entry begins with account creation and initialization. This process involves several steps:

1. **Account Creation**: A new account is created at the PDA derived from the program ID and seeds.
2. **Rent Exemption**: The account is funded with the minimum balance required for rent exemption.
3. **Ownership Assignment**: The account's owner is set to the registry program.
4. **Data Initialization**: The account's data is initialized with the registry entry structure.

In our registry protocols, this process is encapsulated in the registration instructions:

```
pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Initialize metadata and control fields
    entry.bump = *ctx.bumps.get("entry").unwrap();
    entry.registry_version = 1;
    entry.owner_authority = ctx.accounts.owner.key();
    entry.status = AgentStatus::Active as u8;
    entry.created_at = clock.unix_timestamp;
    entry.updated_at = clock.unix_timestamp;

    // Initialize identity fields
    entry.agent_id = args.agent_id;
    entry.name = args.name;
    entry.agent_version = args.agent_version;
    entry.description = args.description;

    // Initialize optional fields
    entry.provider_name = args.provider_name;
    entry.provider_url = args.provider_url;
    entry.documentation_url = args.documentation_url;

    // Initialize complex structures
    entry.service_endpoints = args.service_endpoints;
    entry.capabilities_flags = args.capabilities_flags;
    entry.supported_input_modes = args.supported_input_modes;
    entry.supported_output_modes = args.supported_output_modes;
    entry.skills = args.skills;
    entry.security_info_uri = args.security_info_uri;
    entry.aea_address = args.aea_address;
    entry.extended_metadata_uri = args.extended_metadata_uri;

    // Emit event for indexers
    emit!(AgentRegisteredEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.created_at,
    });

    Ok(())
}
```

This initialization process sets up all the necessary fields for the registry entry, making it ready for use in the ecosystem.

2.3.3 Account Closure and Cleanup

At the end of a registry entry's lifecycle, the account may be closed, reclaiming its rent exemption balance. This process involves:

1. **Data Cleanup**: Clearing or invalidating the account's data.
2. **Balance Transfer**: Transferring the account's balance to a specified recipient.
3. **Account Removal**: Removing the account from the blockchain state.

In our registry protocols, we'll provide two options for ending an entry's lifecycle:

1. **Deactivation**: Marking the entry as inactive without closing the account, allowing for potential reactivation:

```
pub fn deactivate_agent(ctx: Context<UpdateAgentStatus>) ->
Result<()> {
    let entry = &mut ctx.accounts.entry;

    // Mark as inactive
    entry.status = AgentStatus::Inactive as u8;
    entry.updated_at = Clock::get()?.unix_timestamp;

    // Emit event for indexers
    emit!(AgentStatusChangedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        new_status: entry.status,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

1. **Complete Removal**: Closing the account and reclaiming its rent exemption:

```
#[derive(Accounts)]
pub struct CloseAgentEntry<'info> {
    #[account(
        mut,
        seeds = [
            b"registry",
            entry.agent_id.as_bytes(),
            owner.key().as_ref(),
        ],
        bump = entry.bump,
        close = recipient,  // Close the account and send
lamports to recipient
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,

    #[account(mut)]
    pub recipient: SystemAccount<'info>,
}

pub fn close_agent_entry(ctx: Context<CloseAgentEntry>) ->
Result<()> {
    let entry = &ctx.accounts.entry;

    // Emit event for indexers before account is closed
    emit!(AgentRemovedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: Clock::get()?.unix_timestamp,
    });

    // Account will be automatically closed by Anchor
    Ok(())
}
```

The choice between deactivation and complete removal depends on the specific use case and the likelihood of needing to reactivate the entry in the future. Deactivation preserves the entry's data and PDA, allowing for easier reactivation, while complete removal reclaims the rent exemption balance but requires creating a new account for reactivation.

2.4 On-chain Data Limitations and Indexing Approaches

2.4.1 Direct On-chain Querying

Solana's architecture is optimized for transaction processing and state management, not for complex database-like queries. This design choice maximizes throughput and minimizes latency for transaction execution but imposes limitations on direct on-chain data querying capabilities.

The primary method for accessing account data on Solana is through direct lookups using the account's address. For PDAs, this means that efficient queries are limited to cases where the address can be derived from known inputs:

```
 // Client-side code to find a specific agent entry
let (pda, _) = Pubkey::find_program_address(
    &[
        b"registry",
        agent_id.as_bytes(),
        owner.as_ref(),
    ],
    program_id
);

// Fetch the account data
let account = connection.get_account(&pda)?;
let entry =
AgentRegistryEntryV1::try_from_slice(&account.data)?;
```

This approach works well for direct lookups where all the seeds are known, but it doesn't support more complex queries like:

- Finding all agents owned by a specific authority
- Discovering agents with particular capabilities or skills
- Filtering entries based on status or other attributes

Solana does provide the `getProgramAccounts` RPC method, which returns all accounts owned by a specific program:

```
 // JavaScript client code to get all registry entries
const accounts = await connection.getProgramAccounts(programId,
{
    filters: [
      {
        memcmp: {
          offset: 0,  // Account discriminator offset
          bytes: bs58.encode(Buffer.from([/* discriminator bytes
*/])),
        },
      },
    ],
});
```

However, this approach has significant limitations:

1. **Performance**: It can be slow and resource-intensive for programs with many accounts.
2. **Filtering Capabilities**: The filtering options are limited to basic memory comparison operations.
3. **Result Size**: The results can be very large, potentially causing timeout or memory issues.
4. **RPC Node Load**: It places a heavy load on RPC nodes, which may rate-limit or reject excessive requests.

Given these limitations, direct on-chain querying is best suited for:

- Fetching specific entries by their PDA (when all seeds are known)
- Simple filtering based on fixed-offset fields
- Small-scale applications with limited numbers of accounts

For more complex discovery and querying needs, we need to explore alternative approaches.

2.4.2 Secondary Indexing Patterns

To enable more sophisticated on-chain querying capabilities, we can implement secondary indexing patterns within our registry protocols. These patterns involve creating additional PDA accounts that serve as indexes, mapping from search criteria to the primary registry entries.

Here are several secondary indexing patterns we can implement:

1. **Owner Index**: Create index accounts that map from an owner's public key to the agent IDs they own:

```
 // PDA for owner index
let (owner_index_pda, _) = Pubkey::find_program_address(
    &[
        b"owner_index",
        owner.as_ref(),
    ],
    program_id
);

// Structure for owner index
#[account]
pub struct OwnerIndex {
    pub bump: u8,
    pub owner: Pubkey,
    pub agent_ids: Vec<String>,  // List of agent IDs owned by
this owner
}
```

1. **Capability Index**: Create index accounts that map from capability flags to agent IDs:

```
 // PDA for capability index
let (capability_index_pda, _) = Pubkey::find_program_address(
    &[
        b"capability_index",
        capability_flag.to_le_bytes().as_ref(),
    ],
    program_id
);

// Structure for capability index
#[account]
pub struct CapabilityIndex {
    pub bump: u8,
    pub capability_flag: u64,
    pub agent_ids: Vec<String>,  // List of agent IDs with this
capability
}
```

1. **Tag Index**: Create index accounts that map from tags to agent IDs:

```
 // PDA for tag index
let (tag_index_pda, _) = Pubkey::find_program_address(
    &[
        b"tag_index",
        tag.as_bytes(),
    ],
    program_id
);

// Structure for tag index
```

```rust
#[account]
pub struct TagIndex {
    pub bump: u8,
    pub tag: String,
    pub agent_ids: Vec<String>,  // List of agent IDs with this
tag
}
```

These index accounts must be updated whenever a registry entry is created, updated, or removed:

```rust
 pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    // Initialize the main entry...

    // Update owner index
    let owner_index = &mut ctx.accounts.owner_index;
    owner_index.agent_ids.push(args.agent_id.clone());

    // Update capability indexes
    for capability in
extract_capabilities(args.capabilities_flags) {
        let capability_index = &mut
ctx.accounts.capability_indexes[capability as usize];
        capability_index.agent_ids.push(args.agent_id.clone());
    }

    // Update tag indexes
    for skill in &args.skills {
        for tag in &skill.tags {
            let tag_index = &mut ctx.accounts.tag_indexes
                .iter_mut()
                .find(|idx| idx.tag == *tag)
                .ok_or(ErrorCode::TagIndexNotFound)?;

            tag_index.agent_ids.push(args.agent_id.clone());
        }
    }

    Ok(())
}
```

While secondary indexing patterns enhance on-chain querying capabilities, they come with their own challenges:

1. **Complexity**: They add significant complexity to the program logic, especially for updates and removals.

2. **Storage Costs**: Each index account requires additional on-chain storage and rent exemption.
3. **Transaction Size**: Updating multiple indexes in a single transaction can exceed transaction size limits.
4. **Maintenance Overhead**: Indexes must be kept in sync with the primary data, requiring careful transaction design.

Given these challenges, secondary indexing should be used judiciously, focusing on the most critical query patterns that must be performed on-chain.

2.4.3 Hybrid On-chain/Off-chain Solutions

For most registry use cases, a hybrid approach combining on-chain data storage with off-chain indexing provides the best balance of security, efficiency, and query capabilities. This approach leverages the strengths of both on-chain and off-chain systems:

1. **On-chain**: Store the authoritative data and enforce access control.
2. **Off-chain**: Index the data for efficient querying and discovery.

The key to this hybrid approach is event emission. By emitting events for all registry operations, we enable off-chain indexers to build and maintain comprehensive, queryable databases that mirror the on-chain state:

```
 // Event for agent registration
#[event]
pub struct AgentRegisteredEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

// Event for agent updates
#[event]
pub struct AgentUpdatedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub updated_fields: Vec<String>,
    pub timestamp: i64,
}

// Event for agent deregistration
#[event]
pub struct AgentDeregisteredEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

These events are emitted during the corresponding operations:

```
 pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    // Initialize the entry...

    // Emit event for indexers
    emit!(AgentRegisteredEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.created_at,
    });

    Ok(())
}
```

Off-chain indexers listen for these events and update their databases accordingly:

```
 +-------------------+        +-------------------+
+-------------------+
|                   |        |                   |
|                   |
| Registry Program  |        | Event Listener    |        |
Indexer Database  |
|                   |        |                   |
|                   |
| - Store data      |        | - Monitor events  |        | -
SQL/NoSQL DB    |
| - Enforce access  |------->| - Parse event     |------->| -
Full-text search|
| - Emit events     |        |   data            |        | -
Complex queries |
|                   |        | - Update index    |        | -
API endpoints   |
|                   |        |                   |
|                   |
+-------------------+        +-------------------+
+-------------------+
```

This hybrid approach offers several advantages:

1. **Query Flexibility**: Off-chain databases can support complex queries, full-text search, and aggregations that would be impractical or impossible on-chain.

2. **Scalability**: Off-chain indexers can handle large volumes of data and queries without consuming blockchain resources.
3. **Cost Efficiency**: On-chain storage is minimized, reducing rent costs.
4. **User Experience**: Queries can be fast and responsive, enhancing the user experience.

For our registry protocols, we'll implement a comprehensive event emission system to enable this hybrid approach, while still providing basic on-chain querying capabilities for critical operations.

The specific design of the off-chain indexer is beyond the scope of this document, but it would typically involve:

1. **Event Subscription**: Listening for events from the registry programs.
2. **Data Parsing**: Extracting structured data from the events.
3. **Database Updates**: Maintaining a synchronized database of registry entries.
4. **Query API**: Providing a flexible API for querying the indexed data.

By combining on-chain data storage with off-chain indexing, we can create a registry system that is both authoritative and queryable, meeting the needs of a diverse ecosystem of agents and users.

References will be compiled and listed in Chapter 13.

Chapter 3: Agent Registry Protocol Design

3.1 Core Philosophy

3.1.1 Alignment with AEA Principles

The Agent Registry protocol is fundamentally designed to align with the principles of Autonomous Economic Agents (AEAs), a paradigm that envisions intelligent software entities capable of making economic decisions on behalf of their owners with minimal intervention. The AEA framework, pioneered by projects like Fetch.ai, provides a conceptual foundation for our registry design.

Autonomous Economic Agents are characterized by several key attributes that our registry must support and reflect:

1. **Autonomy**: AEAs operate independently, making decisions based on their programming, goals, and the information available to them. The registry must preserve this autonomy while providing discovery mechanisms.

2. **Economic Agency**: AEAs participate in economic activities, including transactions, negotiations, and resource allocation. The registry must facilitate the discovery of agents based on their economic capabilities and roles.

3. **Goal-Oriented Behavior**: AEAs pursue specific objectives defined by their owners. The registry must allow agents to advertise their goals and specializations.

4. **Interoperability**: AEAs interact with other agents and systems through standardized protocols. The registry must support the discovery of compatible agents based on their supported protocols and interfaces.

5. **Identity and Reputation**: AEAs maintain persistent identities and build reputations over time. The registry must provide a reliable identity layer with verification mechanisms.

```
 +---------------------------+
|                            |
|  Autonomous Economic       |
|  Agent (AEA) Principles    |
|                            |
+----------------------------+
             |
             v
+----------------------------+
|                            |
|  Agent Registry Protocol   |
|  Design Requirements       |
|                            |
+----------------------------+
             |
             v
+----------------------------+
|                            |
|  Implementation            |
|  Specifications            |
|                            |
+----------------------------+
```

Our Agent Registry protocol translates these AEA principles into concrete design requirements:

1. **Decentralized Identity**: The registry provides a decentralized identity system for agents, allowing them to establish persistent, verifiable identities on the Solana blockchain.

2. **Capability Advertisement**: Agents can advertise their capabilities, skills, and supported protocols, enabling others to discover them based on functional requirements.

3. **Economic Profile**: The registry includes fields for describing an agent's economic roles, fee structures, and supported token standards, facilitating economic interactions.

4. **Ownership and Control**: The registry enforces clear ownership and control mechanisms, ensuring that only authorized entities can modify an agent's registry entry.

5. **Status Tracking**: Agents can indicate their operational status, allowing others to determine their availability for interactions.

6. **Discoverability**: The registry is designed to support efficient discovery of agents based on various criteria, including capabilities, ownership, and status.

By aligning with these AEA principles, our Agent Registry protocol serves as a foundational infrastructure for a decentralized ecosystem of autonomous agents, enabling them to discover each other, establish trust, and engage in complex interactions.

3.1.2 Integration with A2A Concepts

Google's Agent-to-Agent (A2A) protocol provides a complementary framework for our registry design, focusing specifically on how agents communicate and collaborate. While AEA principles address the economic and autonomous nature of agents, A2A concepts focus on the mechanics of agent interaction and discovery.

The A2A protocol introduces several key concepts that inform our registry design:

1. **Agent Cards**: A2A defines "Agent Cards" as metadata documents that describe an agent's identity, capabilities, and interaction endpoints. Our registry entries are directly inspired by this concept, providing a blockchain-native implementation of Agent Cards.

2. **Capability Declaration**: A2A emphasizes the importance of agents clearly declaring their capabilities to facilitate discovery and collaboration. Our registry incorporates this through structured capability fields and skill descriptions.

3. **Multimodal Interaction**: A2A supports various interaction modalities, including text, structured data, and files. Our registry allows agents to specify their supported input and output modes.

4. **Service Endpoints**: A2A requires agents to provide service endpoints where they can be reached. Our registry includes fields for multiple service endpoints with protocol specifications.

5. **Authentication Requirements**: A2A addresses authentication between agents. Our registry allows agents to specify their security requirements and authentication mechanisms.

```
 +----------------------------+     +----------------------------+
 |                            |     |                            |
 |  A2A Protocol Concepts     |     |  Agent Registry            |
 |                            |     |  Implementation            |
 |  - Agent Cards             |---->|  - On-chain Agent Cards    |
 |  - Capability Declaration  |---->|  - Capability Flags        |
 |  - Multimodal Interaction  |---->|  - I/O Mode Specification  |
 |  - Service Endpoints       |---->|  - Endpoint Records        |
 |  - Authentication          |---->|  - Security Info           |
 |                            |     |                            |
 +----------------------------+     +----------------------------+
```

Our integration of A2A concepts is evident in the registry's data structure, which closely mirrors the A2A AgentCard schema while adapting it to the constraints and capabilities of the Solana blockchain:

1. **On-chain Agent Cards**: The registry entries serve as on-chain, verifiable Agent Cards, providing a trustworthy source of agent metadata.

2. **Capability Flags**: We implement a bitfield for core capabilities, allowing efficient filtering and discovery based on A2A-defined capabilities.

3. **Input/Output Modes**: The registry includes fields for supported input and output MIME types, enabling agents to find others that can process their data formats.

4. **Service Endpoint Records**: The registry supports multiple service endpoints with protocol specifications, allowing agents to advertise different interaction channels.

5. **Security Information**: The registry includes fields for security requirements and authentication schemes, either directly or through references to off-chain specifications.

By integrating these A2A concepts, our Agent Registry protocol ensures compatibility with the broader agent ecosystem, allowing Solana-based agents to interact seamlessly with agents implementing the A2A protocol on other platforms.

The synthesis of AEA principles and A2A concepts results in a registry design that is both economically sound and technically interoperable, providing a robust foundation for a diverse ecosystem of autonomous agents on the Solana blockchain.

3.2 Data Specification for Agent Entry PDA

3.2.1 AgentRegistryEntryV1 Structure

The `AgentRegistryEntryV1` structure defines the on-chain data stored in each agent registry entry PDA. This structure is designed to balance comprehensive agent description with efficient on-chain storage, following the principles discussed in Chapter 2.

```
 #[account]
pub struct AgentRegistryEntryV1 {
    // Metadata and control fields (fixed-size)
    pub bump: u8,                       // For PDA reconstruction
    pub registry_version: u8,           // Schema version for
upgradability
    pub owner_authority: Pubkey,        // 32 bytes, owner's
public key
    pub status: u8,                     // Active, inactive, etc.
    pub capabilities_flags: u64,        // Bitfield for core
capabilities
    pub created_at: i64,                // Unix timestamp
    pub updated_at: i64,                // Unix timestamp

    // Core identity (medium-sized strings)
    pub agent_id: String,               // Unique identifier, max
64 chars
    pub name: String,                   // Human-readable name,
max 128 chars
    pub agent_version: String,          // Version string, max 32
chars

    // Detailed description (larger strings)
    pub description: String,           // Human-readable
description, max 512 chars
```

```
    // Optional metadata (variable presence)
    pub provider_name: Option<String>,       // Max 128 chars
    pub provider_url: Option<String>,        // Max 256 chars
    pub documentation_url: Option<String>,   // Max 256 chars
    pub security_info_uri: Option<String>,   // Max 256 chars
    pub aea_address: Option<String>,         // Max 64 chars

    // Complex nested structures (variable length)
    pub service_endpoints: Vec<ServiceEndpoint>,     // Max 3
endpoints
    pub supported_input_modes: Vec<String>,          // Max 5
items, each max 64 chars
    pub supported_output_modes: Vec<String>,         // Max 5
items, each max 64 chars
    pub skills: Vec<AgentSkill>,                     // Max 10
skills

    // Off-chain extension
    pub extended_metadata_uri: Option<String>,       // URI to
additional metadata, max 256 chars
}

#[derive(BorshSerialize, BorshDeserialize, Clone)]
pub struct ServiceEndpoint {
    pub protocol: String,            // Protocol type, max 64
chars
    pub url: String,                 // Endpoint URL, max 256
chars
    pub is_default: bool,            // Whether this is the
primary endpoint
}

#[derive(BorshSerialize, BorshDeserialize, Clone)]
pub struct AgentSkill {
    pub id: String,                  // Skill's unique ID, max
64 chars
    pub name: String,                // Human-readable skill
name, max 128 chars
    pub description_hash: Option<[u8; 32]>,  // SHA-256 hash of
detailed description
    pub tags:
Vec<String>,            // Tags for the skill, max 5 tags, each
max 32 chars
}
```

This structure is organized to optimize for both storage efficiency and access patterns:

1. **Fixed-size fields first**: The structure begins with fixed-size fields like integers, booleans, and public keys, which are easy to access and update.

2. **Progressive complexity**: It progresses from simple scalar fields to more complex structures like vectors and nested objects.

3. **Size constraints**: Each variable-length field has a defined maximum size to prevent excessive storage usage.

4. **Optional fields**: Less essential information is stored in `Option` types, allowing entries to include only the fields relevant to them.

5. **Hybrid storage model**: For potentially large data elements like detailed skill descriptions, only a hash is stored on-chain, with the full content available off-chain.

The structure also includes an `extended_metadata_uri` field, which can point to a more comprehensive off-chain metadata document (e.g., a full A2A AgentCard or AEA manifest) stored on IPFS, Arweave, or another decentralized storage system.

3.2.2 Field Definitions and Constraints

Each field in the `AgentRegistryEntryV1` structure has specific semantics, constraints, and validation requirements:

Metadata and Control Fields:

- **bump**: The canonical bump seed used for PDA derivation, essential for program signing operations. Must be stored during initialization.

- **registry_version**: Schema version number, currently 1. Allows for future schema evolution while maintaining backward compatibility.

- **owner_authority**: The Solana public key of the entity authorized to update or deregister the agent. All modification operations must be signed by this authority.

- **status**: Agent's current operational status, represented as a u8 enum: `rust pub enum AgentStatus { Inactive = 0, Active = 1, Maintenance = 2, Deprecated = 3, }`

- **capabilities_flags**: A 64-bit bitfield representing the agent's core capabilities, aligned with A2A capability definitions: `rust pub mod CapabilityFlags { pub const STREAMING: u64 = 1 << 0; pub const PUSH_NOTIFICATIONS: u64 = 1 << 1; pub const FILE_UPLOAD: u64 = 1 << 2; pub const FILE_DOWNLOAD: u64 = 1 << 3; pub const STRUCTURED_DATA: u64 = 1 << 4; pub const MULTI_TURN: u64 = 1 << 5; pub const HUMAN_IN_LOOP: u64 = 1 << 6; pub const AUTONOMOUS:`

`u64 = 1 << 7; // Additional capabilities can be defined up to bit 63 }`

- **created_at**: Unix timestamp when the agent was registered, set during initialization.
- **updated_at**: Unix timestamp of the last update, modified with each update operation.

Core Identity Fields:

- **agent_id**: Unique identifier for the agent within the registry. Maximum 64 characters. Must be unique within the registry and should follow a consistent format (e.g., lowercase alphanumeric with hyphens).
- **name**: Human-readable name of the agent. Maximum 128 characters. Should be descriptive and user-friendly.
- **agent_version**: Version string for the agent implementation. Maximum 32 characters. Should follow semantic versioning (e.g., "1.0.0") or another consistent versioning scheme.
- **description**: Human-readable description of the agent's purpose and capabilities. Maximum 512 characters. May use CommonMark for basic formatting.

Optional Metadata Fields:

- **provider_name**: Name of the organization or individual providing the agent. Maximum 128 characters.
- **provider_url**: URL of the agent provider's website or documentation. Maximum 256 characters. Should be a valid URL with HTTPS protocol.
- **documentation_url**: URL to human-readable documentation for the agent. Maximum 256 characters. Should be a valid URL with HTTPS protocol.
- **security_info_uri**: URI to detailed security scheme definitions, potentially in OpenAPI format. Maximum 256 characters.
- **aea_address**: Fetch.ai AEA address or identifier for cross-platform compatibility. Maximum 64 characters.

Complex Nested Structures:

- **service_endpoints**: List of endpoints where the agent can be reached, with a maximum of 3 endpoints to limit storage usage. Each endpoint includes:

- **protocol**: The protocol type (e.g., "a2a_http_jsonrpc", "aea_p2p"). Maximum 64 characters.
- **url**: The endpoint URL. Maximum 256 characters. Should be a valid URL.
- **is_default**: Boolean indicating if this is the primary endpoint. Only one endpoint should be marked as default.
- **supported_input_modes**: List of MIME types the agent accepts as input, with a maximum of 5 types to limit storage usage. Each type is limited to 64 characters. Examples include "text/plain", "application/json", "image/png".
- **supported_output_modes**: List of MIME types the agent produces as output, with a maximum of 5 types to limit storage usage. Each type is limited to 64 characters.
- **skills**: List of agent skills, with a maximum of 10 skills to limit storage usage. Each skill includes:
- **id**: Unique identifier for the skill within the agent. Maximum 64 characters.
- **name**: Human-readable name of the skill. Maximum 128 characters.
- **description_hash**: Optional SHA-256 hash of a detailed skill description stored off-chain. Allows verification of off-chain content.
- **tags**: List of tags associated with the skill, with a maximum of 5 tags to limit storage usage. Each tag is limited to 32 characters.

Off-chain Extension:

- **extended_metadata_uri**: URI to additional metadata stored off-chain, such as a full A2A AgentCard or detailed AEA manifest. Maximum 256 characters. Should point to content on a decentralized storage system like IPFS or Arweave.

These field definitions and constraints ensure that agent registry entries are comprehensive, consistent, and efficient in their use of on-chain storage.

3.2.3 On-chain vs. Off-chain Data Storage Strategy

The Agent Registry protocol employs a hybrid storage strategy that balances the need for on-chain verifiability with the practical constraints of blockchain storage. This strategy determines which data elements are stored directly on-chain and which are referenced from off-chain storage.

On-chain Storage Principles:

1. **Essential Identity Information**: Core identity fields like `agent_id`, `name`, and `owner_authority` are stored on-chain to ensure authoritative identity verification.
2. **Critical Operational Data**: Status information, capability flags, and service endpoints are stored on-chain to enable reliable discovery and interaction.
3. **Compact Descriptions**: Brief descriptions and summaries are stored on-chain to support basic discovery without requiring off-chain lookups.
4. **Verification Hashes**: For larger content stored off-chain, cryptographic hashes are stored on-chain to verify the integrity of the off-chain data.

Off-chain Storage Principles:

1. **Detailed Documentation**: Comprehensive documentation, tutorials, and usage guides are stored off-chain with on-chain references.
2. **Rich Media Content**: Images, videos, and other media assets are stored off-chain due to their size.
3. **Extensive Skill Descriptions**: Detailed descriptions of agent skills, including examples and specifications, are stored off-chain with their hashes stored on-chain.
4. **Complete Security Schemes**: Detailed security and authentication specifications are stored off-chain with on-chain references.
5. **Extended Metadata**: Comprehensive metadata formats like full A2A AgentCards or AEA manifests are stored off-chain with on-chain references.

```
 +----------------------------+
+----------------------------+
|                            |
|                            |
| On-Chain Registry Entry    |           | Off-Chain Extended
Data     |
| (PDA Account)              |           | (IPFS, Arweave,
etc.)      |
|                            |
|                            |
| - agent_id                 |           | - Full A2A
AgentCard       |
| - name                     |           | - Detailed
skill          |
| - owner_authority          |          |
descriptions             |
| - status                   |          | - Comprehensive
security  |
| - capabilities_flags       |          |
schemes                  |
| - service_endpoints        |          | - Rich media
content       |
| - brief description        |          | - Usage
examples             |
| - skill summaries          |          | - API
documentation          |
| - verification hashes      |--------->| - Formal
specifications    |
| - off-chain data URIs      |
|                            |
|                            |
|                            |
+----------------------------+
+----------------------------+
```

Implementation Strategy:

1. **URI References**: The registry includes URI fields (`security_info_uri`, `extended_metadata_uri`) that point to off-chain content.

2. **Content Addressing**: Where possible, content-addressable storage systems like IPFS or Arweave are used for off-chain data to ensure content integrity.

3. **Hash Verification**: For critical off-chain content, cryptographic hashes are stored on-chain (e.g., `description_hash` in `AgentSkill`) to verify the integrity of the off-chain data.

4. **Standardized Formats**: Off-chain data follows standardized formats (e.g., A2A AgentCard schema, OpenAPI for security schemes) to ensure consistent interpretation.

5. **Redundant Storage**: Critical off-chain data should be stored redundantly across multiple systems to ensure availability.

Example Implementation:

```
// On-chain: Brief skill summary with hash of detailed
description
pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    // Store skill summaries on-chain
    for skill in args.skills {
        entry.skills.push(AgentSkill {
            id: skill.id,
            name: skill.name,
            description_hash: Some(skill.description_hash),  //
Hash of detailed description
            tags: skill.tags,
        });
    }

    // Store URI to extended metadata
    entry.extended_metadata_uri =
Some(args.extended_metadata_uri);

    Ok(())
}

// Off-chain: Client retrieves and verifies detailed skill
description
async function getVerifiedSkillDescription(agentId, skillId,
registryProgram) {
    // Fetch on-chain entry
    const entry = await
registryProgram.account.agentRegistryEntryV1.fetch(
        findAgentPDA(agentId, owner)
    );

    // Find the skill
    const skill = entry.skills.find(s => s.id === skillId);
    if (!skill || !skill.description_hash) {
        throw new Error('Skill or description hash not found');
    }

    // Fetch off-chain description from extended metadata
    const extendedMetadata = await
fetchFromIPFS(entry.extended_metadata_uri);
    const skillDescription = extendedMetadata.skills.find(s =>
s.id === skillId)?.description;

    // Verify hash
    const hash = sha256(skillDescription);
    if (!arrayEquals(hash, skill.description_hash)) {
        throw new Error('Description hash verification failed');
    }

    return skillDescription;
}
```

This hybrid storage strategy enables the Agent Registry to provide comprehensive agent descriptions while maintaining efficient on-chain storage usage. It ensures that critical information is verifiable on-chain while allowing for rich, detailed content to be stored off-chain.

3.3 Program Instructions for Agent Registry

3.3.1 Registration Process

The registration process is the entry point for agents into the registry. It creates a new PDA account to store the agent's metadata and establishes the agent's identity on-chain. This process must be carefully designed to ensure security, data integrity, and efficient resource usage.

Instruction Definition:

```rust
 #[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    #[account(
        init,
        payer = payer,
        space = 8 + AgentRegistryEntryV1::SPACE,
        seeds = [
            b"agent_registry",
            args.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    #[account(mut)]
    pub payer: Signer<'info>,

    pub owner_authority: Signer<'info>,

    pub system_program: Program<'info, System>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct RegisterAgentArgs {
    pub agent_id: String,
    pub name: String,
    pub description: String,
    pub agent_version: String,
    pub provider_name: Option<String>,
    pub provider_url: Option<String>,
    pub documentation_url: Option<String>,
    pub service_endpoints: Vec<ServiceEndpoint>,
    pub capabilities_flags: u64,
    pub supported_input_modes: Vec<String>,
    pub supported_output_modes: Vec<String>,
    pub skills: Vec<AgentSkillArgs>,
    pub security_info_uri: Option<String>,
    pub aea_address: Option<String>,
    pub extended_metadata_uri: Option<String>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct AgentSkillArgs {
    pub id: String,
    pub name: String,
    pub description_hash: Option<[u8; 32]>,
    pub tags: Vec<String>,
}
```

Registration Flow:

1. **Input Validation**: The instruction first validates all input parameters to ensure they meet the defined constraints:

```
 pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    // Validate string lengths
    require!(
        args.agent_id.len() <=
AgentRegistryEntryV1::MAX_AGENT_ID_LEN,
        ErrorCode::StringTooLong
    );
    require!(
        args.name.len() <= AgentRegistryEntryV1::MAX_NAME_LEN,
        ErrorCode::StringTooLong
    );
    // Additional validations...

    // Validate collection sizes
    require!(
        args.service_endpoints.len() <=
AgentRegistryEntryV1::MAX_ENDPOINTS,
        ErrorCode::TooManyItems
    );
    // Additional validations...

    // Validate agent_id format (e.g., alphanumeric with
hyphens)
    require!(
        args.agent_id.chars().all(|c| c.is_alphanumeric() || c
== '-'),
        ErrorCode::InvalidAgentId
    );

    // Ensure at least one service endpoint is marked as default
    require!(
        args.service_endpoints.iter().any(|ep| ep.is_default),
        ErrorCode::NoDefaultEndpoint
    );

    // Continue with registration...
}
```

1. **Account Initialization**: The Anchor framework automatically initializes the PDA account based on the `init` constraint, allocating space and transferring the rent exemption amount from the payer.

2. **Data Population**: The instruction populates the account with the provided data:

```
pub fn register_agent(ctx: Context<RegisterAgent>, args: 
RegisterAgentArgs) -> Result<()> {
    // Validation code...

    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Initialize metadata and control fields
    entry.bump = *ctx.bumps.get("entry").unwrap();
    entry.registry_version = 1;
    entry.owner_authority = ctx.accounts.owner_authority.key();
    entry.status = AgentStatus::Active as u8;
    entry.created_at = clock.unix_timestamp;
    entry.updated_at = clock.unix_timestamp;

    // Initialize identity fields
    entry.agent_id = args.agent_id;
    entry.name = args.name;
    entry.agent_version = args.agent_version;
    entry.description = args.description;

    // Initialize optional fields
    entry.provider_name = args.provider_name;
    entry.provider_url = args.provider_url;
    entry.documentation_url = args.documentation_url;

    // Initialize complex structures
    entry.service_endpoints = args.service_endpoints;
    entry.capabilities_flags = args.capabilities_flags;
    entry.supported_input_modes = args.supported_input_modes;
    entry.supported_output_modes = args.supported_output_modes;

    // Convert skill args to skills
    entry.skills = args.skills.iter().map(|skill_arg|
AgentSkill {
        id: skill_arg.id.clone(),
        name: skill_arg.name.clone(),
        description_hash: skill_arg.description_hash,
        tags: skill_arg.tags.clone(),
    }).collect();

    entry.security_info_uri = args.security_info_uri;
    entry.aea_address = args.aea_address;
    entry.extended_metadata_uri = args.extended_metadata_uri;

    // Emit event for indexers
    emit!(AgentRegisteredEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.created_at,
    });

    Ok(())
}
```

1. **Event Emission**: The instruction emits an event to notify off-chain indexers of the new registration:

```
#[event]
pub struct AgentRegisteredEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

Security Considerations:

1. **Signer Verification**: Both the payer (who funds the account creation) and the owner authority (who will control the entry) must sign the transaction.

2. **PDA Derivation**: The PDA is derived from the agent ID and owner authority, ensuring that each owner can only register one agent with a given ID.

3. **Input Validation**: All inputs are validated to prevent malicious data from being stored on-chain.

4. **Rent Exemption**: The account is made rent-exempt to ensure its persistence without ongoing maintenance.

Client Integration:

From a client perspective, registering an agent involves preparing the registration arguments, deriving the expected PDA, and submitting the transaction:

```
 async function registerAgent(
     program: Program<AgentRegistry>,
     args: RegisterAgentArgs,
     ownerKeypair: Keypair,
     payerKeypair: Keypair
): Promise<PublicKey> {
     // Derive the PDA for the agent entry
     const [entryPda] = PublicKey.findProgramAddressSync(
         [
             Buffer.from("agent_registry"),
             Buffer.from(args.agent_id),
             ownerKeypair.publicKey.toBuffer()
         ],
         program.programId
     );

     // Submit the transaction
     await program.methods
         .registerAgent(args)
         .accounts({
             entry: entryPda,
             payer: payerKeypair.publicKey,
             ownerAuthority: ownerKeypair.publicKey,
             systemProgram: SystemProgram.programId,
         })
         .signers([payerKeypair, ownerKeypair])
         .rpc();

     return entryPda;
}
```

The registration process establishes the agent's presence in the registry, making it discoverable by other agents and users. It represents the first step in the agent's lifecycle within the ecosystem.

3.3.2 Update Mechanisms

After an agent is registered, its information may need to be updated to reflect changes in capabilities, endpoints, or other metadata. The Agent Registry protocol provides several update mechanisms to accommodate different update scenarios while maintaining security and efficiency.

Full Update Instruction:

The full update instruction allows comprehensive updates to an agent's metadata:

```rust
 #[derive(Accounts)]
#[instruction(args: UpdateAgentArgs)]
pub struct UpdateAgent<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct UpdateAgentArgs {
    pub name: Option<String>,
    pub description: Option<String>,
    pub agent_version: Option<String>,
    pub provider_name: Option<Option<String>>,
    pub provider_url: Option<Option<String>>,
    pub documentation_url: Option<Option<String>>,
    pub service_endpoints: Option<Vec<ServiceEndpoint>>,
    pub capabilities_flags: Option<u64>,
    pub supported_input_modes: Option<Vec<String>>,
    pub supported_output_modes: Option<Vec<String>>,
    pub skills: Option<Vec<AgentSkillArgs>>,
    pub security_info_uri: Option<Option<String>>,
    pub aea_address: Option<Option<String>>,
    pub extended_metadata_uri: Option<Option<String>>,
}
```

The update instruction processes only the fields that are provided, leaving others unchanged:

```rust
 pub fn update_agent(ctx: Context<UpdateAgent>, args:
UpdateAgentArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Track which fields were updated for the event
    let mut updated_fields = Vec::new();

    // Update fields if provided
    if let Some(name) = args.name {
        require!(
            name.len() <= AgentRegistryEntryV1::MAX_NAME_LEN,
            ErrorCode::StringTooLong
        );
        entry.name = name;
        updated_fields.push("name".to_string());
    }

    if let Some(description) = args.description {
        require!(
            description.len() <=
AgentRegistryEntryV1::MAX_DESCRIPTION_LEN,
            ErrorCode::StringTooLong
        );
        entry.description = description;
        updated_fields.push("description".to_string());
    }

    // Additional field updates...

    // Update timestamp
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(AgentUpdatedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        updated_fields,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

Targeted Update Instructions:

For common update scenarios, the protocol provides targeted instructions that focus on specific aspects of the agent's metadata:

1. **Update Status Instruction:**

```rust
#[derive(Accounts)]
pub struct UpdateAgentStatus<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

pub fn update_agent_status(ctx: Context<UpdateAgentStatus>,
new_status: u8) -> Result<()> {
    require!(
        new_status <= AgentStatus::Deprecated as u8,
        ErrorCode::InvalidStatus
    );

    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Update status
    entry.status = new_status;
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(AgentStatusChangedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        new_status,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

1. **Update Service Endpoints Instruction:**

```
#[derive(Accounts)]
pub struct UpdateAgentEndpoints<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

pub fn update_agent_endpoints(
    ctx: Context<UpdateAgentEndpoints>,
    endpoints: Vec<ServiceEndpoint>
) -> Result<()> {
    require!(
        endpoints.len() <= AgentRegistryEntryV1::MAX_ENDPOINTS,
        ErrorCode::TooManyItems
    );

    require!(
        endpoints.iter().any(|ep| ep.is_default),
        ErrorCode::NoDefaultEndpoint
    );

    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Update endpoints
    entry.service_endpoints = endpoints;
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(AgentEndpointsUpdatedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

1. **Add Skill Instruction:**

```
#[derive(Accounts)]
pub struct AddAgentSkill<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
```

```rust
}

pub fn add_agent_skill(
    ctx: Context<AddAgentSkill>,
    skill: AgentSkillArgs
) -> Result<()> {
    let entry = &mut ctx.accounts.entry;

    require!(
        entry.skills.len() < AgentRegistryEntryV1::MAX_SKILLS,
        ErrorCode::TooManyItems
    );

    require!(
        !entry.skills.iter().any(|s| s.id == skill.id),
        ErrorCode::SkillAlreadyExists
    );

    // Validate skill fields
    require!(
        skill.id.len() <=
AgentRegistryEntryV1::MAX_SKILL_ID_LEN,
        ErrorCode::StringTooLong
    );

    // Additional validations...

    let clock = Clock::get()?;

    // Add the skill
    entry.skills.push(AgentSkill {
        id: skill.id.clone(),
        name: skill.name,
        description_hash: skill.description_hash,
        tags: skill.tags,
    });

    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(AgentSkillAddedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        skill_id: skill.id,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

Update Event Emission:

Each update instruction emits an appropriate event to notify off-chain indexers of the changes:

```
#[event]
pub struct AgentUpdatedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub updated_fields: Vec<String>,
    pub timestamp: i64,
}

#[event]
pub struct AgentStatusChangedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub new_status: u8,
    pub timestamp: i64,
}

#[event]
pub struct AgentEndpointsUpdatedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

#[event]
pub struct AgentSkillAddedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub skill_id: String,
    pub timestamp: i64,
}
```

Security Considerations:

1. **Owner Verification**: All update instructions verify that the transaction is signed by the owner authority recorded in the entry.

2. **Input Validation**: All updates are validated to ensure they meet the defined constraints.

3. **Partial Updates**: The full update instruction allows updating only specific fields, reducing the risk of unintended changes.

4. **Timestamp Tracking**: Each update records the current timestamp, providing an audit trail of changes.

Client Integration:

From a client perspective, updating an agent involves preparing the update arguments and submitting the appropriate instruction:

```
async function updateAgentStatus(
    program: Program<AgentRegistry>,
    agentId: string,
    newStatus: number,
    ownerKeypair: Keypair
): Promise<void> {
    // Derive the PDA for the agent entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("agent_registry"),
            Buffer.from(agentId),
            ownerKeypair.publicKey.toBuffer()
        ],
        program.programId
    );

    // Submit the transaction
    await program.methods
        .updateAgentStatus(newStatus)
        .accounts({
            entry: entryPda,
            ownerAuthority: ownerKeypair.publicKey,
        })
        .signers([ownerKeypair])
        .rpc();
}
```

These update mechanisms provide flexibility for agents to maintain their registry entries throughout their lifecycle, ensuring that the registry remains an accurate and up-to-date source of agent metadata.

3.3.3 Deregistration and Cleanup

The final stage in an agent's lifecycle within the registry is deregistration, which can occur when an agent is deprecated, replaced, or no longer needed. The Agent Registry protocol provides two approaches to deregistration: status-based deactivation and complete account closure.

Status-Based Deactivation:

The simplest form of deregistration is to update the agent's status to `Inactive` or `Deprecated` using the `update_agent_status` instruction described in the previous section:

```
 pub fn deactivate_agent(ctx: Context<UpdateAgentStatus>) ->
Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Mark as inactive
    entry.status = AgentStatus::Inactive as u8;
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(AgentStatusChangedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        new_status: entry.status,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

This approach maintains the agent's entry in the registry but signals that it is no longer active. It's suitable for temporary deactivations or when preserving the agent's history is important.

Complete Account Closure:

For permanent deregistration, the protocol provides an instruction to close the agent's account and reclaim its rent exemption:

```
 #[derive(Accounts)]
pub struct CloseAgentEntry<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized,
        close = recipient  // Close the account and send
lamports to recipient
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,
    pub owner_authority: Signer<'info>,

    #[account(mut)]
    pub recipient: SystemAccount<'info>,
}

pub fn close_agent_entry(ctx: Context<CloseAgentEntry>) ->
Result<()> {
    let entry = &ctx.accounts.entry;

    // Emit event for indexers before account is closed
    emit!(AgentRemovedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: Clock::get()?.unix_timestamp,
    });

    // Account will be automatically closed by Anchor
    Ok(())
}
```

This instruction performs several operations:

1. **Verification**: It verifies that the transaction is signed by the owner authority.
2. **Event Emission**: It emits an event to notify off-chain indexers of the removal.
3. **Account Closure**: It closes the account and transfers its lamports to the specified recipient.

The `close` constraint in Anchor automatically handles the account closure and lamport transfer, simplifying the implementation.

Deregistration Event:

The deregistration process emits an event to notify off-chain indexers:

```
#[event]
pub struct AgentRemovedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

This event allows indexers to update their databases to reflect the agent's removal from the registry.

Security Considerations:

1. **Owner Verification**: The deregistration instruction verifies that the transaction is signed by the owner authority recorded in the entry.
2. **Recipient Specification**: The recipient of the reclaimed lamports must be explicitly specified, preventing accidental loss of funds.
3. **Event Emission**: The event is emitted before the account is closed, ensuring that indexers receive notification of the removal.

Client Integration:

From a client perspective, closing an agent entry involves specifying the recipient for the reclaimed lamports and submitting the instruction:

```
async function closeAgentEntry(
    program: Program<AgentRegistry>,
    agentId: string,
    ownerKeypair: Keypair,
    recipientAddress: PublicKey
): Promise<void> {
    // Derive the PDA for the agent entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("agent_registry"),
            Buffer.from(agentId),
            ownerKeypair.publicKey.toBuffer()
        ],
        program.programId
    );

    // Submit the transaction
    await program.methods
        .closeAgentEntry()
        .accounts({
            entry: entryPda,
            ownerAuthority: ownerKeypair.publicKey,
            recipient: recipientAddress,
        })
        .signers([ownerKeypair])
        .rpc();
}
```

Deregistration Strategy:

The choice between status-based deactivation and complete account closure depends on several factors:

1. **Permanence**: If the deregistration is permanent, account closure is more appropriate. If it might be temporary, status-based deactivation is better.

2. **Resource Recovery**: Account closure allows recovering the rent exemption, which can be significant for large entries.

3. **Historical Record**: Status-based deactivation preserves the agent's entry for historical reference, while account closure removes it entirely.

4. **Reuse Potential**: If the agent ID might be reused in the future, status-based deactivation maintains the PDA, simplifying reactivation.

The Agent Registry protocol supports both approaches, giving agent owners flexibility in managing their agents' lifecycle.

3.4 Access Control and Security

3.4.1 Authority Models

The Agent Registry protocol implements a robust authority model to ensure that only authorized entities can modify or deregister agent entries. This model is based on the concept of an "owner authority," which is the Solana public key that has control over an agent's registry entry.

Owner Authority Assignment:

The owner authority is established during the registration process and is stored in the `owner_authority` field of the agent entry:

```
 pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
     let entry = &mut ctx.accounts.entry;

     // Assign owner authority
     entry.owner_authority = ctx.accounts.owner_authority.key();

     // Initialize other fields...

     Ok(())
}
```

The owner authority is typically the public key of the entity (individual, organization, or program) responsible for the agent. It could be:

1. **User Wallet**: A user's wallet key, for agents controlled by individuals.
2. **Multisig Wallet**: A multisig wallet address, for agents controlled by organizations.
3. **Program PDA**: A PDA controlled by another program, for agents managed programmatically.

Authority Verification:

All instructions that modify or deregister an agent entry verify that the transaction is signed by the owner authority:

```
 #[derive(Accounts)]
pub struct UpdateAgent<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized  //
Verify owner
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}
```

The `has_one = owner_authority` constraint in Anchor verifies that the `owner_authority` account provided in the instruction context matches the `owner_authority` field stored in the entry. The `@ ErrorCode::Unauthorized` part specifies the error to return if the verification fails.

Additionally, the `Signer` type for the `owner_authority` account ensures that the transaction is signed by the owner's private key.

Authority Transfer:

In some cases, it may be necessary to transfer ownership of an agent entry to a new authority. The protocol provides an instruction for this purpose:

```
 #[derive(Accounts)]
pub struct TransferAgentOwnership<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            current_owner.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = current_owner @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub current_owner: Signer<'info>,

    /// CHECK: New owner, not required to sign
    pub new_owner: AccountInfo<'info>,
}

pub fn transfer_agent_ownership(ctx:
Context<TransferAgentOwnership>) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Store old PDA information for event
    let old_owner = entry.owner_authority;
    let old_pda = ctx.accounts.entry.key();

    // Update owner authority
    entry.owner_authority = ctx.accounts.new_owner.key();
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(AgentOwnershipTransferredEvent {
        agent_id: entry.agent_id.clone(),
        old_owner,
        new_owner: entry.owner_authority,
        old_pda,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

This instruction changes the `owner_authority` field in the entry but does not move the entry to a new PDA. Instead, it emits an event that includes both the old and new owner, as well as the current PDA, allowing indexers to update their records.

After ownership transfer, the entry remains at its original PDA, but only the new owner can modify or deregister it. Clients must be aware of this when deriving the PDA for an agent entry after an ownership transfer.

Delegated Authority:

For more complex authority models, the protocol could be extended to support delegated authorities—additional public keys that are authorized to perform specific actions on behalf of the owner. This would involve adding a `delegates` field to the entry structure and modifying the authority verification logic:

```
 #[account]
pub struct AgentRegistryEntryV1 {
    // Existing fields...

    pub delegates: Vec<Pubkey>,  // Additional authorized
signers
}

// In instruction context
#[derive(Accounts)]
pub struct UpdateAgentWithDelegate<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            entry.owner_authority.as_ref(),
        ],
        bump = entry.bump,
        constraint = (
            authority.key() == entry.owner_authority ||
            entry.delegates.contains(&authority.key())
        ) @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub authority: Signer<'info>,
}
```

This extension would allow for more flexible management of agent entries, particularly for organizations or complex systems where multiple entities may need to update an agent's metadata.

Security Considerations:

1. **Single Point of Control**: The basic authority model creates a single point of control (the owner authority), which could be a security risk if the owner's private key is compromised.

2. **No Recovery Mechanism**: There is no built-in mechanism to recover control of an agent entry if the owner's private key is lost.

3. **Ownership Transfer Visibility**: Ownership transfers change the authority without changing the PDA, which could lead to confusion if not properly tracked.

To address these concerns, implementations might consider:

1. **Using Multisig Wallets**: For critical agents, using a multisig wallet as the owner authority can reduce the risk of unauthorized access.

2. **Implementing Time Locks**: Adding time locks for sensitive operations like ownership transfers can provide a window for detecting and responding to unauthorized attempts.

3. **Maintaining Ownership Records**: Keeping off-chain records of ownership transfers can help track the current owner of each agent entry.

The authority model is a critical aspect of the Agent Registry protocol's security, ensuring that only authorized entities can modify or deregister agent entries while providing flexibility for legitimate ownership changes.

3.4.2 Signature Verification

Signature verification is a fundamental security mechanism in the Agent Registry protocol, ensuring that only authorized entities can perform operations on agent entries. This section explores the implementation details and best practices for signature verification in the context of the registry.

Basic Signature Verification:

At its core, signature verification in Solana programs involves checking that specific accounts have signed the transaction. In the Agent Registry protocol, this primarily means verifying that the owner authority has signed any transaction that modifies or deregisters an agent entry.

Anchor simplifies this verification through the `Signer` type and constraints:

```
 #[derive(Accounts)]
pub struct UpdateAgent<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,  // Must be a signer
}
```

The `Signer` type ensures that the `owner_authority` account has signed the transaction, while the `has_one` constraint verifies that it matches the `owner_authority` field stored in the entry.

Multiple Signature Requirements:

Some operations may require multiple signatures, such as when both a payer and an owner are involved:

```
 #[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    #[account(
        init,
        payer = payer,
        space = 8 + AgentRegistryEntryV1::SPACE,
        seeds = [
            b"agent_registry",
            args.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    #[account(mut)]
    pub payer: Signer<'info>,  // Must be a signer

    pub owner_authority: Signer<'info>,  // Must be a signer

    pub system_program: Program<'info, System>,
}
```

In this case, both the `payer` (who funds the account creation) and the `owner_authority` (who will control the entry) must sign the transaction.

Programmatic Signature Verification:

For more complex verification logic that can't be expressed through Anchor constraints, manual verification can be performed in the instruction handler:

```
pub fn complex_update(ctx: Context<ComplexUpdate>, args: ComplexUpdateArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;

    // Check if the signer is either the owner or a delegate
    let signer_key = ctx.accounts.authority.key();
    let is_owner = signer_key == entry.owner_authority;
    let is_delegate = entry.delegates.contains(&signer_key);

    require!(
        is_owner || is_delegate,
        ErrorCode::Unauthorized
    );

    // Additional logic based on signer role
    if is_owner {
        // Owner can perform any update
        // ...
    } else if is_delegate {
        // Delegates may have restricted capabilities
        // ...
    }

    // Update fields...

    Ok(())
}
```

This approach allows for more nuanced authorization logic, such as different permission levels for different types of signers.

Cross-Program Invocation (CPI) Signatures:

When the Agent Registry program needs to interact with other programs (e.g., to update external state based on agent information), it can sign for its PDAs using the stored bump seed:

```
pub fn update_external_state(ctx: Context<UpdateExternal>) -> Result<()> {
    let entry = &ctx.accounts.entry;

    // Create signer seeds for the PDA
    let seeds = &[
        b"agent_registry",
        entry.agent_id.as_bytes(),
        entry.owner_authority.as_ref(),
        &[entry.bump],
    ];
    let signer = &[&seeds[..]];

    // Perform cross-program invocation with PDA as signer
    external_program::cpi::update(
        CpiContext::new_with_signer(
            ctx.accounts.external_program.to_account_info(),
            external_program::accounts::Update {
                // Account mappings...
            },
            signer,
        ),
        // Args...
    )
}
```

This allows the registry program to act on behalf of agent entries when interacting with other programs, enabling complex cross-program workflows.

Security Considerations:

1. **Signature Replay Protection**: Solana's transaction model includes a recent blockhash that expires after a short period, providing built-in protection against signature replay attacks.
2. **Transaction Size Limits**: Complex transactions with many signers may approach Solana's transaction size limits. Care should be taken to design instructions that minimize the number of required signers.
3. **Multisig Support**: For agents requiring multiple approvers, the registry can be integrated with Solana's multisig programs by using a multisig wallet as the owner authority.
4. **Signature Verification in Events**: While events themselves aren't signed, they should include information about the signer to allow off-chain systems to verify who authorized the changes.

Best Practices:

1. **Explicit Error Messages**: Use specific error codes and messages for signature verification failures to help clients diagnose issues.
2. **Consistent Verification Patterns**: Apply consistent signature verification patterns across all instructions to avoid security gaps.

3. **Minimal Privilege Principle**: Only require signatures from accounts that are directly involved in or affected by an operation.

4. **Documentation**: Clearly document the signature requirements for each instruction to guide client implementations.

By implementing robust signature verification, the Agent Registry protocol ensures that only authorized entities can modify agent entries, maintaining the integrity and trustworthiness of the registry.

3.4.3 Payer-Authority Pattern Implementation

The Payer-Authority pattern is a design pattern in Solana program development that separates the roles of the account that pays for an operation (the payer) and the account that authorizes it (the authority). This pattern is particularly relevant for the Agent Registry protocol, where the entity funding the registration of an agent may differ from the entity that will control it.

Pattern Overview:

In the Payer-Authority pattern:

1. **Payer**: The account that provides the lamports for rent exemption and transaction fees. This account must sign the transaction but doesn't necessarily have ongoing control over the created resources.

2. **Authority**: The account that has ongoing control over the created resources. This account must also sign the transaction to authorize the operation.

This separation allows for flexible funding models while maintaining clear ownership semantics.

```
+----------------+        +----------------+
+----------------+
|                |        |                |
|                |
|     Payer      |        |    Registry    |        |
Authority    |
|                |        |    Program     |
|                |
|  - Funds the   |------->|  - Creates     |<-------|  -
Controls    |
|    operation   |        |    entry       |        |
entry       |
|  - Signs for   |        |  - Assigns     |        |  - Signs
for   |
|    payment      |         |    ownership    |         |
authorization|
|                 |         |                 |
|                 |
+-----------------+         +-----------------+
+-----------------+
```

Implementation in Registration:

The registration instruction implements the Payer-Authority pattern by requiring signatures from both the payer and the owner authority:

```
 #[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    #[account(
        init,
        payer = payer,  // Payer funds the account
        space = 8 + AgentRegistryEntryV1::SPACE,
        seeds = [
            b"agent_registry",
            args.agent_id.as_bytes(),
            owner_authority.key().as_ref(),  // Authority in
seeds
        ],
        bump
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    #[account(mut)]
    pub payer: Signer<'info>,  // Payer must sign

    pub owner_authority: Signer<'info>,  // Authority must sign

    pub system_program: Program<'info, System>,
}
```

In this implementation:

1. The `payer` account provides the lamports for the rent exemption and signs the transaction.
2. The `owner_authority` account is used in the PDA derivation and stored in the entry, establishing it as the controlling authority.
3. Both accounts must sign the transaction, ensuring that both the funding and the authorization are explicit.

Optional Authority:

In some cases, the payer and the authority might be the same account. The protocol can support this by making the authority parameter optional:

```rust
 #[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)]
pub struct RegisterAgent<'info> {
    #[account(
        init,
        payer = payer,
        space = 8 + AgentRegistryEntryV1::SPACE,
        seeds = [
            b"agent_registry",
            args.agent_id.as_bytes(),
            authority.key().as_ref(),
        ],
        bump
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    #[account(mut)]
    pub payer: Signer<'info>,

    #[account(
        signer,
        constraint = (
            authority.key() == payer.key() ||
            args.explicit_authority_required
        ) @ ErrorCode::AuthorityRequired
    )]
    pub authority: AccountInfo<'info>,

    pub system_program: Program<'info, System>,
}
```

In this variation:

1. If `args.explicit_authority_required` is `false`, the `authority` can be the same as the `payer`.
2. If `args.explicit_authority_required` is `true`, the `authority` must be explicitly provided and must sign.

This approach provides flexibility while still maintaining the separation of concerns when needed.

Payer-Authority in Updates:

For update operations, only the authority signature is typically required, as no new accounts are being created:

```rust
#[derive(Accounts)]
pub struct UpdateAgent<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub authority: Signer<'info>,  // Only authority must sign
}
```

However, for operations that require additional funding (e.g., expanding an account's size), the payer role would be reintroduced:

```rust
#[derive(Accounts)]
pub struct ExpandAgentEntry<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry",
            entry.agent_id.as_bytes(),
            authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized,
        realloc = 8 + new_space,
        realloc::payer = payer,
        realloc::zero = false,
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub authority: Signer<'info>,  // Authority must sign

    #[account(mut)]
    pub payer: Signer<'info>,  // Payer must sign

    pub system_program: Program<'info, System>,
}
```

Benefits of the Pattern:

The Payer-Authority pattern offers several benefits for the Agent Registry protocol:

1. **Flexible Funding Models**: Organizations can fund agent registrations for their users without gaining control over the agents.

2. **Clear Ownership Semantics**: The separation of payment and control makes ownership explicit and unambiguous.

3. **Delegation Support**: The pattern naturally extends to support delegation scenarios where one entity funds operations on behalf of another.

4. **Auditability**: The explicit signatures from both payer and authority create a clear audit trail of who funded and who authorized each operation.

Implementation Considerations:

When implementing the Payer-Authority pattern, several considerations should be kept in mind:

1. **Transaction Size**: Requiring multiple signers increases transaction size, which may approach Solana's limits for complex operations.

2. **User Experience**: Client applications must handle the collection of signatures from both the payer and the authority, which may involve multiple user interactions.

3. **Error Handling**: Clear error messages should be provided when either the payer or authority signature is missing.

4. **Documentation**: The distinct roles of payer and authority should be clearly documented to guide client implementations.

By implementing the Payer-Authority pattern, the Agent Registry protocol provides a flexible and secure foundation for agent registration and management, accommodating various funding and ownership models while maintaining clear control semantics.

References will be compiled and listed in Chapter 13.

Chapter 4: MCP Server Registry Protocol Design

4.1 Core Philosophy

4.1.1 Alignment with MCP Specification

The MCP Server Registry protocol is designed to align with the Model Context Protocol (MCP) specification, which defines standards for AI model interactions. The MCP specification provides a framework for consistent, interoperable communication between AI models and the applications that use them, focusing on context management, prompt engineering, and tool usage.

The core principles of the MCP specification that inform our registry design include:

1. **Standardized Interaction Patterns**: MCP defines consistent patterns for interacting with AI models, including request formats, response structures, and error handling. The registry must support the discovery of servers that implement these patterns.

2. **Context Management**: MCP emphasizes the importance of managing context in model interactions, including conversation history, user preferences, and system instructions. The registry must allow servers to advertise their context management capabilities.

3. **Tool Integration**: MCP enables models to use tools to extend their capabilities, such as web search, code execution, or data retrieval. The registry must provide mechanisms for servers to advertise their supported tools.

4. **Prompt Engineering**: MCP includes standards for prompt construction and management, allowing for consistent model behavior across implementations. The registry must support the discovery of servers based on their prompt engineering capabilities.

5. **Versioning and Compatibility**: MCP includes versioning to manage evolution while maintaining backward compatibility. The registry must track MCP version support for each server.

```
+---------------------------+
|                           |
|  Model Context Protocol   |
|  (MCP) Specification       |
|                            |
+----------------------------+
            |
            v
+----------------------------+
|                            |
|  MCP Server Registry       |
|  Protocol Design           |
|                            |
+----------------------------+
            |
            v
+----------------------------+
|                            |
|  Implementation            |
|  Specifications            |
|                            |
+----------------------------+
```

Our MCP Server Registry protocol translates these MCP principles into concrete design requirements:

1. **Protocol Version Tracking**: The registry tracks which MCP versions each server supports, enabling clients to find compatible servers.

2. **Tool Advertisement**: Servers can advertise the tools they support, allowing clients to discover servers with specific capabilities.

3. **Model Specification**: The registry includes fields for describing the underlying AI models, including their capabilities, limitations, and performance characteristics.

4. **Context Management Capabilities**: Servers can indicate their context management features, such as maximum context length, supported embeddings, and memory mechanisms.

5. **Operational Parameters**: The registry includes fields for operational details like rate limits, pricing, and usage policies.

6. **Discovery Mechanisms**: The registry is designed to support efficient discovery of servers based on various criteria, including supported tools, models, and operational parameters.

By aligning with the MCP specification, our MCP Server Registry protocol serves as a foundational infrastructure for a decentralized ecosystem of interoperable AI model servers, enabling clients to discover and interact with them in a consistent, standardized manner.

4.1.2 Server Discovery Mechanisms

Effective server discovery is a core objective of the MCP Server Registry protocol. The registry is designed to enable clients to find appropriate MCP servers based on their specific requirements, capabilities, and operational parameters.

The server discovery philosophy is built around several key principles:

1. **Capability-Based Discovery**: Clients should be able to discover servers based on their capabilities, such as supported tools, models, and features, rather than just by identity.

2. **Operational Parameter Matching**: Clients should be able to find servers that meet their operational requirements, such as availability, latency, rate limits, and pricing.

3. **Decentralized Discovery**: The discovery process should be decentralized, allowing any client to find servers without relying on centralized directories or gatekeepers.

4. **Verifiable Information**: The registry should provide verifiable information about servers, allowing clients to make informed decisions based on trustworthy data.

5. **Efficient Filtering**: The discovery process should support efficient filtering to narrow down the set of potential servers based on multiple criteria.

```
+---------------------------+     +---------------------------+
|                           |     |                           |
|  Client Requirements      |     |  MCP Server Registry      |
|                           |     |                           |
|  - Needed tools           |---->|  - On-chain entries       |
|  - Model capabilities     |---->|  - Capability flags       |
|  - Operational params     |---->|  - Operational metadata   |
|  - Pricing constraints    |---->|  - Pricing information    |
|                           |     |                           |
+---------------------------+     +---------------------------+
                                                |
                                                v
                                  +---------------------------+
                                  |                           |
                                  |  Filtered Server List     |
                                  |                           |
                                  |  - Compatible servers     |
                                  |  - Ranked by relevance    |
                                  |  - With connection info   |
                                  |                           |
                                  +---------------------------+
```

The registry implements these principles through a combination of on-chain data structures and off-chain indexing:

1. **Capability Flags**: A bitfield representing the server's core capabilities, allowing for efficient filtering.

2. **Tool Registry**: A list of supported tools with their specifications, enabling tool-based discovery.

3. **Model Metadata**: Detailed information about the underlying models, including their capabilities and limitations.

4. **Operational Metadata**: Information about the server's operational parameters, such as availability, rate limits, and pricing.

5. **Service Endpoints**: Connection details for different interaction protocols, enabling clients to connect to discovered servers.

The discovery process typically involves several steps:

1. **Initial Filtering**: Clients filter the registry based on essential requirements, such as required tools or model capabilities.

2. **Refinement**: Clients further refine the list based on operational parameters, such as availability, latency, or pricing.

3. **Verification**: Clients verify the server's claims through reputation systems, cryptographic proofs, or direct testing.

4. **Connection**: Clients connect to selected servers using the provided service endpoints.

This discovery mechanism enables a dynamic, market-driven ecosystem of MCP servers, where clients can find the most appropriate servers for their specific needs, and servers can differentiate themselves based on their unique capabilities and operational characteristics.

4.2 Data Specification for MCP Server Entry PDA

4.2.1 MCPServerRegistryEntryV1 Structure

The `MCPServerRegistryEntryV1` structure defines the on-chain data stored in each MCP server registry entry PDA. This structure is designed to provide comprehensive information about MCP servers while optimizing for on-chain storage efficiency.

```rust
 #[account]
pub struct MCPServerRegistryEntryV1 {
    // Metadata and control fields (fixed-size)
    pub bump: u8,                        // For PDA reconstruction
    pub registry_version: u8,            // Schema version for
upgradability
    pub owner_authority: Pubkey,         // 32 bytes, owner's
public key
    pub status: u8,                      // Active, inactive, etc.
    pub capabilities_flags: u64,         // Bitfield for core
capabilities
    pub created_at: i64,                 // Unix timestamp
    pub updated_at: i64,                 // Unix timestamp

    // Core identity (medium-sized strings)
    pub server_id: String,               // Unique identifier, max
64 chars
    pub name: String,                    // Human-readable name,
max 128 chars
    pub server_version: String,          // Version string, max 32
chars

    // MCP-specific fields
    pub supported_mcp_versions: Vec<String>,  // MCP versions
supported, max 5 items
    pub max_context_length: u32,         // Maximum context length
in tokens
    pub max_token_limit:
u32,         // Maximum token limit for responses

    // Detailed description (larger strings)
    pub description: String,             // Human-readable
description, max 512 chars

    // Model information
    pub models: Vec<ModelInfo>,          // Models supported, max
10 items

    // Tool information
    pub supported_tools:
Vec<ToolInfo>,  // Tools supported, max 20 items

    // Optional metadata (variable presence)
    pub provider_name: Option<String>,       // Max 128 chars
    pub provider_url: Option<String>,        // Max 256 chars
    pub documentation_url: Option<String>,   // Max 256 chars
    pub security_info_uri: Option<String>,   // Max 256 chars

    // Operational parameters
    pub rate_limit_requests: Option<u32>,    // Requests per
minute
```

```
    pub rate_limit_tokens: Option<u32>,      // Tokens per
minute
    pub pricing_info_uri: Option<String>,    // URI to pricing
information, max 256 chars

    // Complex nested structures (variable length)
    pub service_endpoints: Vec<ServiceEndpoint>,  // Max 3
endpoints

    // Off-chain extension
    pub extended_metadata_uri: Option<String>,  // URI to
additional metadata, max 256 chars
}

#[derive(BorshSerialize, BorshDeserialize, Clone)]
pub struct ModelInfo {
    pub model_id: String,              // Model identifier, max
64 chars
    pub display_name: String,          // Human-readable name,
max 128 chars
    pub model_type: String,            // Type (e.g., "text",
"vision"), max 32 chars
    pub capabilities_flags: u64,       // Bitfield for model
capabilities
    pub context_window: u32,           // Context window size in
tokens
    pub max_output_tokens: u32,        // Maximum output tokens
    pub description_hash: Option<[u8; 32]>,  // SHA-256 hash of
detailed description
}

#[derive(BorshSerialize, BorshDeserialize, Clone)]
pub struct ToolInfo {
    pub tool_id:
String,              // Tool identifier, max 64 chars
    pub name: String,                  // Human-readable name,
max 128 chars
    pub description: String,           // Brief description, max
256 chars
    pub version: String,               // Tool version, max 32
chars
    pub schema_hash: [u8; 32],         // SHA-256 hash of the
tool's schema
    pub schema_uri: String,            // URI to the tool's
schema, max 256 chars
}

#[derive(BorshSerialize, BorshDeserialize, Clone)]
pub struct ServiceEndpoint {
    pub protocol: String,              // Protocol type, max 64
chars
    pub url: String,                   // Endpoint URL, max 256
```

```
chars
    pub is_default: bool,                // Whether this is the
primary endpoint
}
```

This structure is organized to optimize for both storage efficiency and access patterns:

1. **Fixed-size fields first**: The structure begins with fixed-size fields like integers, booleans, and public keys, which are easy to access and update.
2. **Progressive complexity**: It progresses from simple scalar fields to more complex structures like vectors and nested objects.
3. **Size constraints**: Each variable-length field has a defined maximum size to prevent excessive storage usage.
4. **Optional fields**: Less essential information is stored in `Option` types, allowing entries to include only the fields relevant to them.
5. **Hybrid storage model**: For potentially large data elements like detailed model descriptions or tool schemas, only hashes are stored on-chain, with the full content available off-chain.

The structure also includes an `extended_metadata_uri` field, which can point to a more comprehensive off-chain metadata document stored on IPFS, Arweave, or another decentralized storage system.

4.2.2 Field Definitions and Constraints

Each field in the `MCPServerRegistryEntryV1` structure has specific semantics, constraints, and validation requirements:

Metadata and Control Fields:

- **bump**: The canonical bump seed used for PDA derivation, essential for program signing operations. Must be stored during initialization.
- **registry_version**: Schema version number, currently 1. Allows for future schema evolution while maintaining backward compatibility.
- **owner_authority**: The Solana public key of the entity authorized to update or deregister the server. All modification operations must be signed by this authority.

- **status**: Server's current operational status, represented as a u8 enum: `rust pub enum ServerStatus { Inactive = 0, Active = 1, Maintenance = 2, Deprecated = 3, }`

- **capabilities_flags**: A 64-bit bitfield representing the server's core capabilities: ` rust pub mod ServerCapabilityFlags { pub const STREAMING: u64 = 1 << 0; pub const BATCHING: u64 = 1 << 1; pub const FUNCTION_CALLING: u64 = 1 << 2; pub const VISION: u64 = 1 << 3; pub const AUDIO: u64 = 1 << 4; pub const EMBEDDINGS: u64 = 1 << 5; pub const FINE_TUNING: u64 = 1 << 6; pub const CUSTOM_TOOLS: u64 = 1 << 7; // Additional capabilities can be defined up to bit 63 }`

- **created_at**: Unix timestamp when the server was registered, set during initialization.

- **updated_at**: Unix timestamp of the last update, modified with each update operation.

Core Identity Fields:

- **server_id**: Unique identifier for the server within the registry. Maximum 64 characters. Must be unique within the registry and should follow a consistent format (e.g., lowercase alphanumeric with hyphens).

- **name**: Human-readable name of the server. Maximum 128 characters. Should be descriptive and user-friendly.

- **server_version**: Version string for the server implementation. Maximum 32 characters. Should follow semantic versioning (e.g., "1.0.0") or another consistent versioning scheme.

MCP-Specific Fields:

- **supported_mcp_versions**: List of MCP specification versions supported by the server, with a maximum of 5 versions to limit storage usage. Each version string is limited to 16 characters. Examples include "2025-03-26", "2024-11-15".

- **max_context_length**: Maximum context length in tokens that the server can process. This is an upper bound across all supported models.

- **max_token_limit**: Maximum token limit for responses that the server can generate. This is an upper bound across all supported models.

Detailed Description:

- **description**: Human-readable description of the server's purpose and capabilities. Maximum 512 characters. May use CommonMark for basic formatting.

Model Information:

- **models**: List of AI models supported by the server, with a maximum of 10 models to limit storage usage. Each model includes:
- **model_id**: Unique identifier for the model. Maximum 64 characters.
- **display_name**: Human-readable name of the model. Maximum 128 characters.
- **model_type**: Type of the model (e.g., "text", "vision", "multimodal"). Maximum 32 characters.
- **capabilities_flags**: A 64-bit bitfield representing the model's capabilities: `rust pub mod ModelCapabilityFlags { pub const TEXT_GENERATION: u64 = 1 << 0; pub const IMAGE_UNDERSTANDING: u64 = 1 << 1; pub const CODE_GENERATION: u64 = 1 << 2; pub const FUNCTION_CALLING: u64 = 1 << 3; pub const EMBEDDINGS: u64 = 1 << 4; // Additional capabilities can be defined up to bit 63 }`
- **context_window**: Context window size in tokens for this specific model.
- **max_output_tokens**: Maximum output tokens for this specific model.
- **description_hash**: Optional SHA-256 hash of a detailed model description stored off-chain. Allows verification of off-chain content.

Tool Information:

- **supported_tools**: List of tools supported by the server, with a maximum of 20 tools to limit storage usage. Each tool includes:
- **tool_id**: Unique identifier for the tool. Maximum 64 characters.
- **name**: Human-readable name of the tool. Maximum 128 characters.
- **description**: Brief description of the tool's purpose and functionality. Maximum 256 characters.
- **version**: Tool version string. Maximum 32 characters.
- **schema_hash**: SHA-256 hash of the tool's schema (typically in OpenAPI/JSON Schema format). Used to verify the integrity of the off-chain schema.
- **schema_uri**: URI to the tool's schema, stored off-chain. Maximum 256 characters.

Optional Metadata Fields:

- **provider_name**: Name of the organization or individual providing the server. Maximum 128 characters.

- **provider_url**: URL of the server provider's website or documentation. Maximum 256 characters. Should be a valid URL with HTTPS protocol.
- **documentation_url**: URL to human-readable documentation for the server. Maximum 256 characters. Should be a valid URL with HTTPS protocol.
- **security_info_uri**: URI to detailed security scheme definitions, potentially in OpenAPI format. Maximum 256 characters.

Operational Parameters:

- **rate_limit_requests**: Optional rate limit in requests per minute. Indicates the maximum number of requests the server can handle.
- **rate_limit_tokens**: Optional rate limit in tokens per minute. Indicates the maximum number of tokens the server can process.
- **pricing_info_uri**: Optional URI to detailed pricing information. Maximum 256 characters. Should point to a document describing the server's pricing model, including any free tiers, subscription plans, or pay-as-you-go rates.

Service Endpoints:

- **service_endpoints**: List of endpoints where the server can be reached, with a maximum of 3 endpoints to limit storage usage. Each endpoint includes:
- **protocol**: The protocol type (e.g., "mcp_http_json", "mcp_grpc"). Maximum 64 characters.
- **url**: The endpoint URL. Maximum 256 characters. Should be a valid URL.
- **is_default**: Boolean indicating if this is the primary endpoint. Only one endpoint should be marked as default.

Off-chain Extension:

- **extended_metadata_uri**: URI to additional metadata stored off-chain, such as detailed model descriptions, comprehensive tool documentation, or performance benchmarks. Maximum 256 characters. Should point to content on a decentralized storage system like IPFS or Arweave.

These field definitions and constraints ensure that MCP server registry entries are comprehensive, consistent, and efficient in their use of on-chain storage.

4.2.3 Tool and Resource Advertisement

A key function of the MCP Server Registry is to advertise the tools and resources that each server provides. This advertisement mechanism allows clients to discover servers that support the specific tools they need for their applications.

Tool Advertisement Model:

The registry implements a comprehensive tool advertisement model that includes:

1. **Tool Identification**: Each tool has a unique identifier (`tool_id`) that distinguishes it within the server's toolset.
2. **Tool Metadata**: Basic information about each tool, including its name, description, and version.
3. **Tool Schema**: A reference to the tool's schema, which defines its inputs, outputs, and behavior. The schema is stored off-chain, with its hash stored on-chain for verification.
4. **Tool Categories**: Tools can be categorized by type or domain, allowing for more efficient discovery.

```
+---------------------------+
|                           |
|  MCP Server Registry      |
|  Entry                    |
|                           |
|  +---------------------+  |
|  | supported_tools     |  |
|  |                     |  |
|  | +---------------+   |  |
|  | | Tool 1        |   |  |
|  | | - tool_id     |   |  |
|  | | - name        |   |  |
|  | | - description |   |  |
|  | | - version     |   |  |
|  | | - schema_hash |---|--+--------> Off-chain Tool Schema
|  | | - schema_uri  |   |  |           (OpenAPI/JSON Schema)
|  | +---------------+   |  |
|  |                     |  |
|  | +---------------+   |  |
|  | | Tool 2        |   |  |
|  | | ...           |   |  |
|  | +---------------+   |  |
|  |                     |  |
|  +---------------------+  |
 |                           |
+----------------------------+
```

Tool Schema Format:

Tool schemas are typically defined using OpenAPI (for HTTP-based tools) or JSON Schema (for function-calling tools). These schemas define:

1. **Input Parameters**: The parameters that the tool accepts, including their names, types, descriptions, and constraints.
2. **Output Format**: The structure of the data returned by the tool.
3. **Error Handling**: The possible error codes and their meanings.
4. **Authentication Requirements**: Any authentication or authorization required to use the tool.

Here's an example of a simplified tool schema for a weather information tool:

```
{
  "openapi": "3.0.0",
  "info": {
    "title": "Weather Information Tool",
    "version": "1.0.0",
    "description": "Provides current weather and forecasts for
locations worldwide"
  },
  "paths": {
    "/current": {
      "get": {
        "summary": "Get current weather",
        "parameters": [
          {
            "name": "location",
            "in": "query",
            "required": true,
            "schema": {
              "type": "string"
            },
            "description": "City name or coordinates"
          },
          {
            "name": "units",
            "in": "query",
            "required": false,
            "schema": {
              "type": "string",
              "enum": ["metric", "imperial"],
              "default": "metric"
            },
            "description":
 "Unit system for temperature and wind speed"
          }
        ],
        "responses": {
          "200": {
            "description": "Successful response",
            "content": {
              "application/json": {
                "schema": {
                  "type": "object",
                  "properties": {
                    "temperature": {
                      "type": "number"
                    },
                    "conditions": {
                      "type": "string"
                    },
                    "humidity": {
                      "type": "number"
                    },
                    "wind_speed": {
                      "type": "number"
                    }
                  }
                }
              }
            }
          },
          "400": {
            "description": "Invalid location"
          }
        }
      }
    }
  }
}
```

This schema would be stored off-chain (e.g., on IPFS), with its hash stored in the `schema_hash` field of the corresponding `ToolInfo` structure.

Standard vs. Custom Tools:

The MCP Server Registry distinguishes between two types of tools:

1. **Standard Tools**: Tools that follow widely adopted specifications and are implemented consistently across multiple servers. These tools have well-known `tool_id` values and standardized schemas.

2. **Custom Tools**: Server-specific tools that provide unique functionality. These tools have server-specific `tool_id` values and custom schemas.

The `CUSTOM_TOOLS` capability flag in the server's `capabilities_flags` indicates whether the server supports custom tools beyond the standard set.

Resource Advertisement:

Beyond tools, MCP servers may also advertise other resources they provide:

1. **Models**: The AI models available on the server, including their capabilities, context windows, and output limits.

2. **Embeddings**: Embedding models for converting text or other data into vector representations.

3. **Fine-tuning Capabilities**: Whether and how the server supports fine-tuning of models on custom datasets.

4. **Specialized Functionalities**: Domain-specific capabilities like code generation, mathematical reasoning, or creative writing.

These resources are advertised through the `models` field and the server's `capabilities_flags`.

Implementation Considerations:

When implementing tool and resource advertisement in the MCP Server Registry, several considerations should be kept in mind:

1. **Schema Versioning**: Tool schemas should include version information to manage evolution while maintaining backward compatibility.

2. **Schema Size Limitations**: Since tool schemas are stored off-chain, they can be comprehensive, but care should be taken to keep them reasonably sized for efficient retrieval.

3. **Schema Verification**: Clients should verify the integrity of retrieved schemas by comparing their hash with the `schema_hash` stored on-chain.

4. **Tool Discovery**: The registry should support efficient discovery of servers based on the tools they provide, potentially through secondary indexes or off-chain indexing.

5. **Tool Compatibility**: Servers should clearly indicate which models support which tools, as not all tools may be compatible with all models.

By implementing a comprehensive tool and resource advertisement mechanism, the MCP Server Registry enables clients to discover servers that provide the specific capabilities they need, fostering a rich ecosystem of specialized AI services.

4.3 Program Instructions for MCP Server Registry

4.3.1 Registration Process

The registration process for MCP servers follows a similar pattern to the Agent Registry, with adaptations specific to the MCP server context. This process creates a new PDA account to store the server's metadata and establishes the server's identity on-chain.

Instruction Definition:

```rust
 #[derive(Accounts)]
#[instruction(args: RegisterMCPServerArgs)]
pub struct RegisterMCPServer<'info> {
    #[account(
        init,
        payer = payer,
        space = 8 + MCPServerRegistryEntryV1::SPACE,
        seeds = [
            b"mcp_server_registry",
            args.server_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    #[account(mut)]
    pub payer: Signer<'info>,

    pub owner_authority: Signer<'info>,

    pub system_program: Program<'info, System>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct RegisterMCPServerArgs {
    pub server_id: String,
    pub name: String,
    pub description: String,
    pub server_version: String,
    pub supported_mcp_versions: Vec<String>,
    pub max_context_length: u32,
    pub max_token_limit: u32,
    pub models: Vec<ModelInfoArgs>,
    pub supported_tools: Vec<ToolInfoArgs>,
    pub provider_name: Option<String>,
    pub provider_url: Option<String>,
    pub documentation_url: Option<String>,
    pub security_info_uri: Option<String>,
    pub rate_limit_requests: Option<u32>,
    pub rate_limit_tokens: Option<u32>,
    pub pricing_info_uri: Option<String>,
    pub service_endpoints: Vec<ServiceEndpoint>,
    pub capabilities_flags: u64,
    pub extended_metadata_uri: Option<String>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct ModelInfoArgs {
    pub model_id: String,
    pub display_name: String,
    pub model_type: String,
    pub capabilities_flags: u64,
    pub context_window: u32,
    pub max_output_tokens: u32,
    pub description_hash: Option<[u8; 32]>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct ToolInfoArgs {
    pub tool_id: String,
    pub name: String,
    pub description: String,
    pub version: String,
    pub schema_hash: [u8; 32],
    pub schema_uri: String,
}
```

Registration Flow:

1. **Input Validation**: The instruction first validates all input parameters to ensure they meet the defined constraints:

```
 pub fn register_mcp_server(ctx: Context<RegisterMCPServer>,
args: RegisterMCPServerArgs) -> Result<()> {
    // Validate string lengths
    require!(
        args.server_id.len() <=
MCPServerRegistryEntryV1::MAX_SERVER_ID_LEN,
        ErrorCode::StringTooLong
    );
    require!(
        args.name.len() <=
MCPServerRegistryEntryV1::MAX_NAME_LEN,
```

```rust
        ErrorCode::StringTooLong
    );
    // Additional validations...

    // Validate collection sizes
    require!(
        args.supported_mcp_versions.len() <=
MCPServerRegistryEntryV1::MAX_MCP_VERSIONS,
        ErrorCode::TooManyItems
    );
    require!(
        args.models.len() <=
MCPServerRegistryEntryV1::MAX_MODELS,
        ErrorCode::TooManyItems
    );
    require!(
        args.supported_tools.len() <=
MCPServerRegistryEntryV1::MAX_TOOLS,
        ErrorCode::TooManyItems
    );
    require!(
        args.service_endpoints.len() <=
MCPServerRegistryEntryV1::MAX_ENDPOINTS,
        ErrorCode::TooManyItems
    );

    // Validate server_id format (e.g., alphanumeric with
hyphens)
    require!(
        args.server_id.chars().all(|c| c.is_alphanumeric() || c
== '-'),
        ErrorCode::InvalidServerId
    );

    // Ensure at least one service endpoint is marked as default
    require!(
        args.service_endpoints.iter().any(|ep| ep.is_default),
        ErrorCode::NoDefaultEndpoint
    );

    // Validate MCP versions format
    for version in &args.supported_mcp_versions {
        require!(
            is_valid_mcp_version(version),
            ErrorCode::InvalidMCPVersion
        );
    }

    // Continue with registration...
}

fn is_valid_mcp_version(version: &str) -> bool {
    // Check if the version follows the YYYY-MM-DD format
    if version.len() != 10 {
        return false;
    }

    let parts: Vec<&str> = version.split('-').collect();
    if parts.len() != 3 {
        return false;
    }

    // Check year (2020 or later)
    if let Ok(year) = parts[0].parse::<u16>() {
        if year < 2020 {
            return false;
        }
    } else {
        return false;
    }

    // Check month (01-12)
    if let Ok(month) = parts[1].parse::<u8>() {
        if month < 1 || month > 12 {
            return false;
        }
    } else {
        return false;
    }

    // Check day (01-31)
    if let Ok(day) = parts[2].parse::<u8>() {
        if day < 1 || day > 31 {
            return false;
        }
    } else {
        return false;
    }

    true
}
```

1. **Account Initialization**: The Anchor framework automatically initializes the PDA account based on the `init` constraint, allocating space and transferring the rent exemption amount from the payer.

2. **Data Population**: The instruction populates the account with the provided data:

```rust
 pub fn register_mcp_server(ctx: Context<RegisterMCPServer>,
args: RegisterMCPServerArgs) -> Result<()> {
    // Validation code...
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Initialize metadata and control fields
    entry.bump = *ctx.bumps.get("entry").unwrap();
    entry.registry_version = 1;
    entry.owner_authority = ctx.accounts.owner_authority.key();
    entry.status = ServerStatus::Active as u8;
    entry.capabilities_flags = args.capabilities_flags;
    entry.created_at = clock.unix_timestamp;
    entry.updated_at = clock.unix_timestamp;

    // Initialize identity fields
    entry.server_id = args.server_id;
    entry.name = args.name;
    entry.server_version = args.server_version;

    // Initialize MCP-specific fields
    entry.supported_mcp_versions = args.supported_mcp_versions;
    entry.max_context_length = args.max_context_length;
    entry.max_token_limit = args.max_token_limit;

    // Initialize description
    entry.description = args.description;

    // Initialize models
    entry.models = args.models.iter().map(|model_arg| ModelInfo
{
        model_id: model_arg.model_id.clone(),
        display_name: model_arg.display_name.clone(),
        model_type: model_arg.model_type.clone(),
        capabilities_flags: model_arg.capabilities_flags,
        context_window: model_arg.context_window,
        max_output_tokens: model_arg.max_output_tokens,
        description_hash: model_arg.description_hash,
    }).collect();

    // Initialize tools
    entry.supported_tools = args.supported_tools.iter().map(|
tool_arg| ToolInfo {
        tool_id: tool_arg.tool_id.clone(),
        name: tool_arg.name.clone(),
        description: tool_arg.description.clone(),
        version: tool_arg.version.clone(),
        schema_hash: tool_arg.schema_hash,
        schema_uri: tool_arg.schema_uri.clone(),
    }).collect();

    // Initialize optional fields
    entry.provider_name = args.provider_name;
    entry.provider_url = args.provider_url;
    entry.documentation_url = args.documentation_url;
    entry.security_info_uri = args.security_info_uri;

    // Initialize operational parameters
    entry.rate_limit_requests = args.rate_limit_requests;
    entry.rate_limit_tokens = args.rate_limit_tokens;
    entry.pricing_info_uri = args.pricing_info_uri;

    // Initialize service endpoints
    entry.service_endpoints = args.service_endpoints;

    // Initialize extended metadata URI
    entry.extended_metadata_uri = args.extended_metadata_uri;

    // Emit event for indexers
    emit!(MCPServerRegisteredEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.created_at,
    });

    Ok(())
}
```

1. **Event Emission**: The instruction emits an event to notify off-chain indexers of the new registration:

```
#[event]
pub struct MCPServerRegisteredEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

Security Considerations:

1. **Signer Verification**: Both the payer (who funds the account creation) and the owner authority (who will control the entry) must sign the transaction.

2. **PDA Derivation**: The PDA is derived from the server ID and owner authority, ensuring that each owner can only register one server with a given ID.

3. **Input Validation**: All inputs are validated to prevent malicious data from being stored on-chain.

4. **Schema Hash Verification**: While the registry doesn't verify the content of tool schemas (which are stored off-chain), it does store their hashes, allowing clients to verify the integrity of the schemas they retrieve.

Client Integration:

From a client perspective, registering an MCP server involves preparing the registration arguments, deriving the expected PDA, and submitting the transaction:

```
async function registerMCPServer(
    program: Program<MCPServerRegistry>,
    args: RegisterMCPServerArgs,
    ownerKeypair: Keypair,
    payerKeypair: Keypair
): Promise<PublicKey> {
    // Derive the PDA for the server entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("mcp_server_registry"),
            Buffer.from(args.server_id),
            ownerKeypair.publicKey.toBuffer()
        ],
        program.programId
    );

    // Submit the transaction
    await program.methods
        .registerMCPServer(args)
        .accounts({
            entry: entryPda,
            payer: payerKeypair.publicKey,
            ownerAuthority: ownerKeypair.publicKey,
            systemProgram: SystemProgram.programId,
        })
        .signers([payerKeypair, ownerKeypair])
        .rpc();

    return entryPda;
}
```

The registration process establishes the server's presence in the registry, making it discoverable by clients and other servers. It represents the first step in the server's lifecycle within the ecosystem.

4.3.2 Update Mechanisms

After an MCP server is registered, its information may need to be updated to reflect changes in capabilities, models, tools, or other metadata. The MCP Server Registry protocol provides several update mechanisms to accommodate different update scenarios while maintaining security and efficiency.

Full Update Instruction:

The full update instruction allows comprehensive updates to a server's metadata:

```
 #[derive(Accounts)]
#[instruction(args: UpdateMCPServerArgs)]
pub struct UpdateMCPServer<'info> {
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct UpdateMCPServerArgs {
    pub name: Option<String>,
    pub description: Option<String>,
    pub server_version: Option<String>,
    pub supported_mcp_versions: Option<Vec<String>>,
    pub max_context_length: Option<u32>,
    pub max_token_limit: Option<u32>,
    pub models: Option<Vec<ModelInfoArgs>>,
    pub supported_tools: Option<Vec<ToolInfoArgs>>,
    pub provider_name: Option<Option<String>>,
    pub provider_url: Option<Option<String>>,
    pub documentation_url: Option<Option<String>>,
    pub security_info_uri: Option<Option<String>>,
    pub rate_limit_requests: Option<Option<u32>>,
    pub rate_limit_tokens: Option<Option<u32>>,
    pub pricing_info_uri: Option<Option<String>>,
    pub service_endpoints: Option<Vec<ServiceEndpoint>>,
    pub capabilities_flags: Option<u64>,
    pub extended_metadata_uri: Option<Option<String>>,
}
```

The update instruction processes only the fields that are provided, leaving others unchanged:

```
 pub fn update_mcp_server(ctx: Context<UpdateMCPServer>, args:
UpdateMCPServerArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;
```

```rust
    // Track which fields were updated for the event
    let mut updated_fields = Vec::new();

    // Update fields if provided
    if let Some(name) = args.name {
        require!(
            name.len() <=
MCPServerRegistryEntryV1::MAX_NAME_LEN,
            ErrorCode::StringTooLong
        );
        entry.name = name;
        updated_fields.push("name".to_string());
    }

    if let Some(description) = args.description {
        require!(
            description.len() <=
MCPServerRegistryEntryV1::MAX_DESCRIPTION_LEN,
            ErrorCode::StringTooLong
        );
        entry.description = description;
        updated_fields.push("description".to_string());
    }

    if let Some(server_version) = args.server_version {
        require!(
            server_version.len() <=
MCPServerRegistryEntryV1::MAX_VERSION_LEN,
            ErrorCode::StringTooLong
        );
        entry.server_version = server_version;
        updated_fields.push("server_version".to_string());
    }

    if let Some(supported_mcp_versions) =
args.supported_mcp_versions {
        require!(
            supported_mcp_versions.len() <=
MCPServerRegistryEntryV1::MAX_MCP_VERSIONS,
            ErrorCode::TooManyItems
        );

        // Validate MCP versions format
        for version in &supported_mcp_versions {
            require!(
                is_valid_mcp_version(version),
                ErrorCode::InvalidMCPVersion
            );
        }

        entry.supported_mcp_versions = supported_mcp_versions;
updated_fields.push("supported_mcp_versions".to_string());
    }

    // Additional field updates...

    // Update timestamp
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(MCPServerUpdatedEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        updated_fields,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

Targeted Update Instructions:

For common update scenarios, the protocol provides targeted instructions that focus on specific aspects of the server's metadata:

1. **Update Status Instruction:**

```
 #[derive(Accounts)]
pub struct UpdateMCPServerStatus<'info> {
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

pub fn update_mcp_server_status(ctx:
Context<UpdateMCPServerStatus>, new_status: u8) -> Result<()> {
    require!(
        new_status <= ServerStatus::Deprecated as u8,
        ErrorCode::InvalidStatus
    );
```

```rust
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Update status
    entry.status = new_status;
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(MCPServerStatusChangedEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        new_status,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

1. **Update Models Instruction:**

```rust
#[derive(Accounts)]
pub struct UpdateMCPServerModels<'info> {
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

pub fn update_mcp_server_models(
    ctx: Context<UpdateMCPServerModels>,
    models: Vec<ModelInfoArgs>
) -> Result<()> {
    require!(
        models.len() <= MCPServerRegistryEntryV1::MAX_MODELS,
        ErrorCode::TooManyItems
    );

    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;
    // Update models
    entry.models = models.iter().map(|model_arg| ModelInfo {
        model_id: model_arg.model_id.clone(),
        display_name: model_arg.display_name.clone(),
        model_type: model_arg.model_type.clone(),
        capabilities_flags: model_arg.capabilities_flags,
        context_window: model_arg.context_window,
        max_output_tokens: model_arg.max_output_tokens,
        description_hash: model_arg.description_hash,
    }).collect();

    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(MCPServerModelsUpdatedEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

1. **Update Tools Instruction:**

```
#[derive(Accounts)]
pub struct UpdateMCPServerTools<'info> {
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

pub fn update_mcp_server_tools(
    ctx: Context<UpdateMCPServerTools>,
    tools: Vec<ToolInfoArgs>
) -> Result<()> {
    require!(
        tools.len() <= MCPServerRegistryEntryV1::MAX_TOOLS,
        ErrorCode::TooManyItems
    );
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Update tools
    entry.supported_tools = tools.iter().map(|tool_arg|
ToolInfo {
        tool_id: tool_arg.tool_id.clone(),
        name: tool_arg.name.clone(),
        description: tool_arg.description.clone(),
        version: tool_arg.version.clone(),
        schema_hash: tool_arg.schema_hash,
        schema_uri: tool_arg.schema_uri.clone(),
    }).collect();

    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(MCPServerToolsUpdatedEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

Update Event Emission:

Each update instruction emits an appropriate event to notify off-chain indexers of the changes:

```
 #[event]
pub struct MCPServerUpdatedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub updated_fields: Vec<String>,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerStatusChangedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub new_status: u8,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerModelsUpdatedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerToolsUpdatedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

Security Considerations:

1. **Owner Verification**: All update instructions verify that the transaction is signed by the owner authority recorded in the entry.
2. **Input Validation**: All updates are validated to ensure they meet the defined constraints.
3. **Partial Updates**: The full update instruction allows updating only specific fields, reducing the risk of unintended changes.
4. **Timestamp Tracking**: Each update records the current timestamp, providing an audit trail of changes.

Client Integration:

From a client perspective, updating an MCP server involves preparing the update arguments and submitting the appropriate instruction:

```
async function updateMCPServerStatus(
    program: Program<MCPServerRegistry>,
    serverId: string,
    newStatus: number,
    ownerKeypair: Keypair
): Promise<void> {
    // Derive the PDA for the server entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("mcp_server_registry"),
            Buffer.from(serverId),
            ownerKeypair.publicKey.toBuffer()
        ],
        program.programId
    );

    // Submit the transaction
    await program.methods
        .updateMCPServerStatus(newStatus)
        .accounts({
            entry: entryPda,
            ownerAuthority: ownerKeypair.publicKey,
        })
        .signers([ownerKeypair])
        .rpc();
}
```

These update mechanisms provide flexibility for server operators to maintain their registry entries throughout their lifecycle, ensuring that the registry remains an accurate and up-to-date source of MCP server metadata.

4.3.3 Deregistration and Cleanup

The final stage in an MCP server's lifecycle within the registry is deregistration, which can occur when a server is deprecated, replaced, or no longer needed. The MCP Server Registry protocol provides two approaches to deregistration: status-based deactivation and complete account closure.

Status-Based Deactivation:

The simplest form of deregistration is to update the server's status to `Inactive` or `Deprecated` using the `update_mcp_server_status` instruction described in the previous section:

```
 pub fn deactivate_mcp_server(ctx:
Context<UpdateMCPServerStatus>) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    // Mark as inactive
    entry.status = ServerStatus::Inactive as u8;
    entry.updated_at = clock.unix_timestamp;

    // Emit event for indexers
    emit!(MCPServerStatusChangedEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        new_status: entry.status,
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

This approach maintains the server's entry in the registry but signals that it is no longer active. It's suitable for temporary deactivations or when preserving the server's history is important.

Complete Account Closure:

For permanent deregistration, the protocol provides an instruction to close the server's account and reclaim its rent exemption:

```
 #[derive(Accounts)]
pub struct CloseMCPServerEntry<'info> {
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized,
        close = recipient  // Close the account and send
lamports to recipient
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    pub owner_authority: Signer<'info>,

    #[account(mut)]
    pub recipient: SystemAccount<'info>,
}

pub fn close_mcp_server_entry(ctx:
Context<CloseMCPServerEntry>) -> Result<()> {
    let entry = &ctx.accounts.entry;

    // Emit event for indexers before account is closed
    emit!(MCPServerRemovedEvent {
        server_id: entry.server_id.clone(),
        owner: entry.owner_authority,
        timestamp: Clock::get()?.unix_timestamp,
    });

    // Account will be automatically closed by Anchor
    Ok(())
}
```

This instruction performs several operations:

1. **Verification**: It verifies that the transaction is signed by the owner authority.

2. **Event Emission**: It emits an event to notify off-chain indexers of the removal.

3. **Account Closure**: It closes the account and transfers its lamports to the specified recipient.

The `close` constraint in Anchor automatically handles the account closure and lamport transfer, simplifying the implementation.

Deregistration Event:

The deregistration process emits an event to notify off-chain indexers:

```
 #[event]
pub struct MCPServerRemovedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

This event allows indexers to update their databases to reflect the server's removal from the registry.

Security Considerations:

1. **Owner Verification**: The deregistration instruction verifies that the transaction is signed by the owner authority recorded in the entry.

2. **Recipient Specification**: The recipient of the reclaimed lamports must be explicitly specified, preventing accidental loss of funds.

3. **Event Emission**: The event is emitted before the account is closed, ensuring that indexers receive notification of the removal.

Client Integration:

From a client perspective, closing an MCP server entry involves specifying the recipient for the reclaimed lamports and submitting the instruction:

```
async function closeMCPServerEntry(
    program: Program<MCPServerRegistry>,
    serverId: string,
    ownerKeypair: Keypair,
    recipientAddress: PublicKey
): Promise<void> {
    // Derive the PDA for the server entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("mcp_server_registry"),
            Buffer.from(serverId),
            ownerKeypair.publicKey.toBuffer()
        ],
        program.programId
    );

    // Submit the transaction
    await program.methods
        .closeMCPServerEntry()
        .accounts({
            entry: entryPda,
            ownerAuthority: ownerKeypair.publicKey,
            recipient: recipientAddress,
        })
        .signers([ownerKeypair])
        .rpc();
}
```

Deregistration Strategy:

The choice between status-based deactivation and complete account closure depends on several factors:

1. **Permanence**: If the deregistration is permanent, account closure is more appropriate. If it might be temporary, status-based deactivation is better.

2. **Resource Recovery**: Account closure allows recovering the rent exemption, which can be significant for large entries.

3. **Historical Record**: Status-based deactivation preserves the server's entry for historical reference, while account closure removes it entirely.

4. **Reuse Potential**: If the server ID might be reused in the future, status-based deactivation maintains the PDA, simplifying reactivation.

The MCP Server Registry protocol supports both approaches, giving server operators flexibility in managing their servers' lifecycle.

4.4 Verification and Trust Models

4.4.1 Server Capability Verification

Verifying that MCP servers actually possess the capabilities they claim is a critical aspect of the registry's trust model. The registry protocol includes several mechanisms to support capability verification:

On-Chain Capability Claims:

The registry stores several types of capability claims on-chain:

1. **Capability Flags**: Bitfields indicating the server's core capabilities, such as streaming, function calling, or vision.

2. **Model Specifications**: Details about the models supported by the server, including their context windows and output limits.

3. **Tool Advertisements**: Information about the tools supported by the server, including their schemas.

These claims form the basis for capability verification, but they need to be validated through additional mechanisms.

Verification Mechanisms:

The registry supports several verification mechanisms:

1. **Schema Hash Verification**: For tools, the registry stores the hash of the tool's schema. Clients can verify that the schema they retrieve from the off-chain URI matches this hash, ensuring the integrity of the schema.

```
async function verifyToolSchema(
    program: Program<MCPServerRegistry>,
    serverId: string,
    toolId: string,
    ownerPublicKey: PublicKey
): Promise<boolean> {
    // Derive the PDA for the server entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("mcp_server_registry"),
            Buffer.from(serverId),
            ownerPublicKey.toBuffer()
        ],
        program.programId
    );

    // Fetch the server entry
    const entry = await
program.account.mcpServerRegistryEntryV1.fetch(entryPda);

    // Find the tool
    const tool = entry.supportedTools.find(t => t.toolId ===
toolId);
    if (!tool) {
        throw new Error(`Tool ${toolId} not found`);
    }

    // Fetch the schema from the URI
    const schemaResponse = await fetch(tool.schemaUri);
    const schemaText = await schemaResponse.text();

    // Compute the hash of the schema
    const schemaHash = sha256(schemaText);

    // Compare with the stored hash
    return arrayEquals(schemaHash, tool.schemaHash);
}
```

1. **Challenge-Response Verification**: Clients can send challenge requests to servers to verify their capabilities. For example, a client might request a server to generate a response using a specific model or tool.

```
async function verifyServerCapability(
    serverEndpoint: string,
    capability: string,
    challenge: any
): Promise<boolean> {
    try {
        // Send a challenge request to the server
        const response = await fetch(`${serverEndpoint}/verify/$
{capability}`, {
            method: 'POST',
            headers: {
                'Content-Type': 'application/json',
            },
            body: JSON.stringify({ challenge }),
        });

        if (!response.ok) {
            return false;
        }

        const result = await response.json();

        // Verify the response based on the capability
        switch (capability) {
            case 'function_calling':
                return result.function_call &&
result.function_call.name === challenge.expected_function;
            case 'vision':
                return result.content &&
result.content.includes(challenge.expected_content);
            // Other capability verifications...
            default:
                return false;
        }
    } catch (error) {
        return false;
    }
}
```

1. **Attestation Services**: Third-party attestation services can verify server capabilities and provide cryptographic attestations that can be referenced in the registry.

```
 +----------------------------+      +----------------------------+
 |                            |      |                            |
 |  MCP Server                |      |  Attestation Service       |
 |                            |      |                            |
 |  - Capabilities            |----->|  - Capability testing      |
 |  - Models                  |      |  - Performance benchmarks  |
 |  - Tools                   |      |  - Security audits         |
 |                            |      |                            |
+----------------------------+      +----------------------------+
                                                 |
                                                 v
                                    +----------------------------+
                                    |                            |
                                    |  Attestation Record        |
                                    |                            |
                                    |  - Verified capabilities   |
                                    |  - Test results            |
                                    |  - Digital signature       |
                                    |                            |
                                    +----------------------------+
                                                 |
                                                 v
                                    +----------------------------+
                                    |                            |
                                    |  MCP Server Registry       |
                                    |                            |
                                    |  - Attestation reference   |
                                    |  - Verification timestamp  |
                                    |                            |
                                    +----------------------------+
```

1. **Performance Benchmarks**: Standardized benchmarks can be run against servers to verify their performance characteristics, with results stored off-chain and referenced in the registry.

Implementation Considerations:

When implementing capability verification in the MCP Server Registry, several considerations should be kept in mind:

1. **Verification Freshness**: Capabilities may change over time, so verification should be periodically refreshed.

2. **Verification Granularity**: Different capabilities may require different verification mechanisms and frequencies.

3. **Verification Cost**: Some verification methods may be resource-intensive, so a balance must be struck between thoroughness and efficiency.

4. **Verification Transparency**: The verification process should be transparent, with clear criteria and results.

By implementing robust capability verification mechanisms, the MCP Server Registry can provide clients with confidence that servers actually possess the capabilities they claim, enhancing the trustworthiness of the ecosystem.

4.4.2 Trust Establishment Mechanisms

Trust is a fundamental requirement for the MCP Server Registry ecosystem. Clients need to trust that servers will behave as expected, respect their data, and provide reliable service. The registry protocol includes several mechanisms to establish and maintain trust:

Identity Verification:

The first level of trust is established through identity verification:

1. **On-Chain Ownership**: The registry records the owner authority of each server entry, which is the Solana public key that controls the entry. This provides a cryptographic binding between the server and its controller.

2. **Provider Information**: The registry includes fields for provider name and URL, allowing clients to research the entity behind the server.

3. **Documentation Links**: The registry includes links to documentation, which can provide additional information about the server's operator and policies.

Reputation Systems:

Reputation systems provide a way for the community to assess the trustworthiness of servers:

1. **Off-Chain Ratings**: External rating systems can collect and aggregate user feedback about servers, with results referenced in the registry.

2. **Usage Metrics**: Metrics like the number of clients, request volume, or uptime can indicate a server's popularity and reliability.

3. **Age and Stability**: The registry records creation and update timestamps, allowing clients to assess a server's longevity and stability.

```
+---------------------------+     +---------------------------+
|                           |     |                           |
|  Client Experiences       |     |  Reputation System        |
|                           |     |                           |
|  - Service quality        |---->|  - Aggregate ratings      |
|  - Reliability            |     |  - Review verification    |
|  - Accuracy               |     |  - Fraud detection        |
|                           |     |                           |
+---------------------------+     +---------------------------+
                                             |
                                             v
                                  +---------------------------+
                                  |                           |
                                  |  Reputation Score         |
                                  |                           |
                                  |  - Overall rating         |
                                  |  - Category ratings       |
                                  |  - Review count           |
                                  |                           |
                                  +---------------------------+
                                             |
                                             v
                                  +---------------------------+
                                  |                           |
                                  |  MCP Server Registry      |
                                  |                           |
                                  |  - Reputation reference   |
                                  |  - Last verified timestamp|
                                  |                           |
                                  +---------------------------+
```

Security Information:

The registry includes mechanisms for servers to communicate their security practices:

1. **Security Info URI**: The registry includes a field for a URI pointing to detailed security information, which can describe the server's security measures, data handling practices, and compliance certifications.

2. **Security Audits**: Servers can undergo security audits by reputable firms, with results referenced in the registry.

3. **Compliance Certifications**: Servers can obtain certifications for compliance with relevant standards (e.g., SOC 2, GDPR), with evidence referenced in the registry.

Service Level Agreements:

The registry supports the advertisement of service level agreements (SLAs):

1. **Rate Limits**: The registry includes fields for rate limits, indicating the server's capacity and availability guarantees.

2. **Pricing Information**: The registry includes a field for pricing information, which can detail the server's pricing model and any guarantees associated with paid tiers.

3. **Off-Chain SLAs**: More detailed SLAs can be stored off-chain and referenced in the registry, specifying uptime guarantees, support response times, and other service parameters.

Implementation Considerations:

When implementing trust establishment mechanisms in the MCP Server Registry, several considerations should be kept in mind:

1. **Trust Verification**: Trust claims should be verifiable whenever possible, either through cryptographic means or trusted third parties.

2. **Trust Granularity**: Different aspects of trust (e.g., security, reliability, performance) may be established through different mechanisms.

3. **Trust Evolution**: Trust is not static; it evolves over time based on behavior and feedback. The registry should support the dynamic nature of trust.

4. **Trust Transparency**: The basis for trust should be transparent, with clear criteria and evidence.

By implementing robust trust establishment mechanisms, the MCP Server Registry can provide clients with the information they need to make informed decisions about which servers to use, fostering a trustworthy ecosystem.

4.4.3 Reputation Systems Integration

Reputation systems play a crucial role in helping clients assess the trustworthiness and quality of MCP servers. The MCP Server Registry protocol is designed to integrate with external reputation systems, providing a comprehensive view of server reputation.

Reputation Data Types:

The registry supports integration with reputation systems that provide several types of data:

1. **Overall Ratings**: Aggregate ratings that provide a general assessment of a server's quality.
2. **Category Ratings**: Specific ratings for different aspects of a server's service, such as reliability, accuracy, or customer support.
3. **Review Counts**: The number of reviews or ratings that have contributed to the aggregate scores, indicating the breadth of feedback.
4. **Verified Reviews**: Individual reviews that have been verified as coming from actual users of the server.
5. **Performance Metrics**: Objective measurements of a server's performance, such as response time, uptime, or error rate.

Integration Mechanisms:

The registry provides several mechanisms for integrating with reputation systems:

1. **Off-Chain References**: The `extended_metadata_uri` field can point to a document that includes reputation data or references to reputation systems.
2. **Reputation Program Integration**: The registry can be extended to integrate with on-chain reputation programs, allowing for verifiable reputation data.

```rust
 #[derive(Accounts)]
pub struct AttachReputationRecord<'info> {
    #[account(
        mut,
        seeds = [
            b"mcp_server_registry",
            entry.server_id.as_bytes(),
            entry.owner_authority.as_ref(),
        ],
        bump = entry.bump,
    )]
    pub entry: Account<'info, MCPServerRegistryEntryV1>,

    #[account(
        seeds = [
            b"reputation",
            entry.key().as_ref(),
        ],
        bump,
        owner = reputation_program.key(),
    )]
    pub reputation_record: AccountInfo<'info>,

    pub reputation_program: Program<'info, ReputationProgram>,

    pub authority: Signer<'info>,
}

pub fn attach_reputation_record(ctx:
Context<AttachReputationRecord>) -> Result<()> {
    // Verify that the reputation record is valid
    // This might involve cross-program invocation to the
reputation program

    // Emit event for indexers
    emit!(ReputationRecordAttachedEvent {
        server_id: ctx.accounts.entry.server_id.clone(),
        reputation_record: ctx.accounts.reputation_record.key(),
        timestamp: Clock::get()?.unix_timestamp,
    });

    Ok(())
}
```

1. **Event-Based Integration**: The registry emits events for all server operations, which reputation systems can monitor to track server activity and updates.

2. **Attestation Integration**: The registry can integrate with attestation services that provide verified performance and reliability data.

Reputation Verification:

To ensure the integrity of reputation data, the registry supports several verification mechanisms:

1. **Cryptographic Verification**: Reputation data can be cryptographically signed by the reputation system, allowing clients to verify its authenticity.

2. **On-Chain Verification**: Reputation data can be stored on-chain in dedicated reputation programs, providing transparent and tamper-resistant records.

3. **Cross-Verification**: Multiple reputation systems can be integrated, allowing clients to cross-verify reputation data from different sources.

Client Integration:

From a client perspective, accessing reputation data involves querying both the registry and the integrated reputation systems:

```
async function getServerWithReputation(
    program: Program<MCPServerRegistry>,
    serverId: string,
    ownerPublicKey: PublicKey,
    reputationSystem: ReputationSystem
): Promise<ServerWithReputation> {
    // Derive the PDA for the server entry
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("mcp_server_registry"),
            Buffer.from(serverId),
            ownerPublicKey.toBuffer()
        ],
        program.programId
    );

    // Fetch the server entry
    const entry = await
program.account.mcpServerRegistryEntryV1.fetch(entryPda);

    // Fetch reputation data
    const reputation = await
reputationSystem.getReputation(entryPda.toString());

    // Combine server entry and reputation data
    return {
        server: entry,
        reputation: {
            overallRating: reputation.overallRating,
            categoryRatings: reputation.categoryRatings,
            reviewCount: reputation.reviewCount,
            verifiedReviews: reputation.verifiedReviews,
            performanceMetrics: reputation.performanceMetrics,
            lastUpdated: reputation.lastUpdated,
        },
    };
}
```

Implementation Considerations:

When implementing reputation system integration in the MCP Server Registry, several considerations should be kept in mind:

1. **Reputation Freshness**: Reputation data may change over time, so clients should check for recent updates.
2. **Reputation Bias**: Reputation systems may have biases or vulnerabilities to manipulation, so multiple sources should be consulted when possible.
3. **Reputation Context**: Reputation should be interpreted in context, considering factors like the server's age, target audience, and specific capabilities.
4. **Reputation Privacy**: The privacy implications of reputation data should be considered, especially for reviews that might include personal information.

By integrating with robust reputation systems, the MCP Server Registry can provide clients with valuable information about server quality and trustworthiness, helping them make informed decisions and fostering a healthy ecosystem.

References will be compiled and listed in Chapter 13.

Chapter 5: Discovery and Querying Mechanisms

5.1 On-chain Discovery Approaches

5.1.1 Direct PDA Lookups

The most fundamental method for discovering registry entries on-chain is through direct lookups using Program Derived Addresses (PDAs). As discussed in Chapter 2, PDAs are deterministically derived from the program ID and a set of seeds. If a client knows the seeds used to create a specific registry entry, they can derive its PDA and fetch the account data directly.

For the Agent Registry, the PDA is derived using the seeds `[b"agent_registry", agent_id.as_bytes(), owner_authority.key().as_ref()]`. Therefore, if a client knows the `agent_id` and the `owner_authority`, they can find the agent entry:

```
// Client-side code to find a specific agent entry
async function findAgentEntry(
    program: Program<AgentRegistry>,
    agentId: string,
    ownerPublicKey: PublicKey
): Promise<AgentRegistryEntryV1 | null> {
    // Derive the PDA
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("agent_registry"),
            Buffer.from(agentId),
            ownerPublicKey.toBuffer()
        ],
        program.programId
    );

    try {
        // Fetch the account data
        const entry = await
program.account.agentRegistryEntryV1.fetch(entryPda);
        return entry;
    } catch (error) {
        // Handle account not found or other errors
        console.error(`Error fetching agent entry $
{entryPda.toString()}:`, error);
        return null;
    }
}
```

Similarly, for the MCP Server Registry, the PDA is derived using the seeds `[b"mcp_server_registry", server_id.as_bytes(), owner_authority.key().as_ref()]`. If a client knows the `server_id` and the `owner_authority`, they can find the server entry:

```
// Client-side code to find a specific MCP server entry
async function findMCPServerEntry(
    program: Program<MCPServerRegistry>,
    serverId: string,
    ownerPublicKey: PublicKey
): Promise<MCPServerRegistryEntryV1 | null> {
    // Derive the PDA
    const [entryPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("mcp_server_registry"),
            Buffer.from(serverId),
            ownerPublicKey.toBuffer()
        ],
        program.programId
    );

    try {
        // Fetch the account data
        const entry = await
program.account.mcpServerRegistryEntryV1.fetch(entryPda);
        return entry;
    } catch (error) {
        // Handle account not found or other errors
        console.error(`Error fetching MCP server entry $
{entryPda.toString()}:`, error);
        return null;
    }
}
```

Advantages:

1. **Direct and Efficient**: This method is the most direct and efficient way to access a specific entry when all seeds are known.
2. **On-Chain Verification**: The lookup is performed directly against the blockchain state, providing the most up-to-date and verifiable information.
3. **No Indexing Required**: It doesn't rely on any secondary indexing mechanisms.

Limitations:

1. **Requires Known Seeds**: This method only works if the client knows all the seeds used to derive the PDA (e.g., `agent_id` and `owner_authority`).
2. **No Filtering or Searching**: It doesn't support searching for entries based on criteria other than the seeds.
3. **Limited Discovery**: It cannot be used to discover unknown agents or servers.

Direct PDA lookups are suitable for scenarios where a client needs to retrieve information about a specific, known entity, such as verifying the details of an agent it intends to interact with or fetching the endpoints of a known MCP server.

5.1.2 Secondary Index Traversal

To enable more flexible on-chain querying, the registry protocols can implement secondary indexing patterns, as introduced in Chapter 2. These patterns involve creating additional PDA accounts that serve as indexes, mapping from specific attributes (like owner, capability, or tag) to the primary registry entries.

Example: Owner Index Traversal

Let's consider an owner index for the Agent Registry, where index accounts map an owner's public key to the `agent_id` s they own:

```
// PDA for owner index
let (owner_index_pda, _) = Pubkey::find_program_address(
    &[
        b"owner_index",
        owner.as_ref(),
    ],
    program_id
);

// Structure for owner index
#[account]
pub struct OwnerIndex {
    pub bump: u8,
    pub owner: Pubkey,
    pub agent_ids: Vec<String>,  // List of agent IDs owned by
this owner
}
```

A client can use this index to find all agents owned by a specific authority:

1. **Derive Index PDA**: Derive the PDA for the owner index using the owner's public key.
2. **Fetch Index Data**: Fetch the `OwnerIndex` account data.
3. **Iterate Agent IDs**: Iterate through the `agent_ids` stored in the index.
4. **Derive Entry PDAs**: For each `agent_id`, derive the PDA for the corresponding `AgentRegistryEntryV1` using the `agent_id` and the owner's public key.
5. **Fetch Entry Data**: Fetch the data for each agent entry.

```
// Client-side code to find all agents owned by a specific
authority
async function findAgentsByOwner(
    program: Program<AgentRegistry>,
    ownerPublicKey: PublicKey
): Promise<AgentRegistryEntryV1[]> {
    // Derive the owner index PDA
    const [ownerIndexPda] = PublicKey.findProgramAddressSync(
        [
            Buffer.from("owner_index"),
            ownerPublicKey.toBuffer()
        ],
        program.programId
    );

    try {
        // Fetch the owner index account
        const ownerIndex = await
program.account.ownerIndex.fetch(ownerIndexPda);
```

```
        const agentEntries: AgentRegistryEntryV1[] = [];

        // Iterate through agent IDs
        for (const agentId of ownerIndex.agentIds) {
            // Derive the agent entry PDA
            const [entryPda] = PublicKey.findProgramAddressSync(
                [
                    Buffer.from("agent_registry"),
                    Buffer.from(agentId),
                    ownerPublicKey.toBuffer()
                ],
                program.programId
            );

            try {
                // Fetch the agent entry
                const entry = await
program.account.agentRegistryEntryV1.fetch(entryPda);
                agentEntries.push(entry);
            } catch (error) {
                console.warn(`Could not fetch agent entry $
{entryPda.toString()} for agent ID ${agentId}:`, error);
            }
        }

        return agentEntries;
    } catch (error) {
        // Handle owner index not found or other errors
        console.error(`Error fetching owner index $
{ownerIndexPda.toString()}:`, error);
        return [];
    }
}
```

Similar indexing patterns can be implemented for other attributes like capabilities, tags, or supported tools.

Advantages:

1. **Enhanced Querying**: Enables on-chain querying based on attributes other than the primary seeds.
2. **Decentralized Discovery**: Allows clients to discover entries based on specific criteria without relying on off-chain systems.

Limitations:

1. **Complexity**: Adds significant complexity to the program logic, especially for maintaining index consistency during updates and removals.

2. **Storage Costs**: Requires additional on-chain storage for the index accounts, increasing rent costs.
3. **Transaction Costs**: Updating indexes increases the computational cost and size of transactions.
4. **Scalability Issues**: Indexes storing large lists (e.g., many agent IDs) can become large and expensive to manage, potentially exceeding account size limits.
5. **Limited Query Flexibility**: On-chain indexes typically support only simple lookups based on the indexed attribute; complex multi-attribute queries are difficult.

Secondary index traversal is suitable for scenarios where specific, well-defined query patterns must be performed directly on-chain, and the number of entries per index key is expected to be manageable.

5.1.3 Performance Considerations

On-chain discovery approaches, while providing direct access to blockchain state, have significant performance considerations:

1. **RPC Node Latency**: Fetching account data involves communication with Solana RPC nodes, which introduces network latency. Fetching multiple accounts sequentially (as in index traversal) can be slow.

2. **RPC Node Limits**: RPC nodes often impose rate limits on requests. Intensive querying, especially using `getProgramAccounts` or fetching many accounts for index traversal, can hit these limits, leading to failed requests.

3. **`getProgramAccounts` Scalability**: The `getProgramAccounts` method, while useful for fetching all accounts of a program, does not scale well. As the number of registry entries grows, the time and resources required to fetch and process all accounts increase significantly. The maximum response size for RPC requests also limits the total number of accounts that can be returned in a single call.

4. **Compute Budget**: While querying itself doesn't consume the client's compute budget, the underlying RPC node operations consume resources. Heavy querying can strain RPC node infrastructure.

5. **Account Size Limits**: Secondary index accounts that store lists of keys (e.g., `OwnerIndex` storing `agent_ids`) can grow large. If an index account exceeds Solana's maximum account size (currently 10MB), it becomes unusable. Even before hitting the hard limit, large accounts are expensive to create and modify.

6. **Transaction Costs for Index Maintenance**: Maintaining secondary indexes requires additional instructions and account accesses within the registration,

update, and deregistration transactions. This increases the compute units consumed and the transaction fees for these operations.

```
+----------------------------+     +----------------------------+
|                            |     |                            |
|  Client                    |     |  RPC Node                  |
|                            |     |                            |
|  - Sends RPC request       |---->|  - Processes request       |
|  - Waits for response      |<----|  - Fetches data from       |
|  - Processes data          |     |    validator network       |
|                            |     |  - Applies rate limits     |
|                            |     |  - Returns response        |
|                            |     |                            |
+----------------------------+     +----------------------------+
          | Latency, Rate Limits |                      |
Resource Usage
          v                      v                      v
+--------------------------------------------------------------------
+
| Performance Bottlenecks in On-Chain
Discovery                        |
+--------------------------------------------------------------------
+
```

Optimization Strategies:

1. **Batch RPC Requests**: Use methods like `getMultipleAccounts` to fetch data for multiple PDAs in a single RPC call, reducing network overhead.

2. **Client-Side Caching**: Cache frequently accessed registry entries or index data on the client-side to reduce redundant RPC calls.

3. **Selective Indexing**: Implement secondary indexes only for the most critical and frequently used query patterns.

4. **Paginated Indexes**: For indexes that might grow large, implement pagination mechanisms (e.g., storing index entries across multiple accounts) to avoid hitting account size limits. This adds significant complexity.

5. **Prioritize Off-Chain Indexing**: For most complex querying and discovery needs, rely primarily on off-chain indexing solutions, which offer better performance and scalability.

Due to these performance considerations, on-chain discovery methods are generally best suited for targeted lookups and simple, low-volume queries. For broader discovery and complex filtering, off-chain indexing is typically the preferred approach.

5.2 Off-chain Indexing Infrastructure

5.2.1 Event Emission for Indexers

The foundation of efficient off-chain indexing is a robust event emission system within the on-chain registry programs. By emitting events whenever a registry entry is created, updated, or removed, the programs provide a real-time stream of changes that off-chain indexers can consume.

Event Design:

Events should be designed to provide sufficient information for indexers to update their databases accurately:

1. **Unique Identifiers**: Include the primary identifier (`agent_id` or `server_id`) and the owner authority to uniquely identify the affected entry.
2. **Key Data Changes**: For update events, include information about which fields were changed or the new values of critical fields.
3. **Timestamps**: Include a timestamp to indicate when the change occurred.
4. **Action Type**: Clearly indicate the type of action (e.g., registered, updated, removed, status changed).

Agent Registry Events:

```
 #[event]
pub struct AgentRegisteredEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

#[event]
pub struct AgentUpdatedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub updated_fields:
Vec<String>, // List of field names that changed
    pub timestamp: i64,
}

#[event]
pub struct AgentStatusChangedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub new_status: u8,
    pub timestamp: i64,
}

#[event]
pub struct AgentRemovedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

#[event]
pub struct AgentOwnershipTransferredEvent {
    pub agent_id: String,
    pub old_owner: Pubkey,
    pub new_owner: Pubkey,
    pub old_pda:
Pubkey, // The PDA before transfer (remains the same)
    pub timestamp: i64,
}
```

MCP Server Registry Events:

```
 #[event]
pub struct MCPServerRegisteredEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerUpdatedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub updated_fields: Vec<String>,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerStatusChangedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub new_status: u8,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerRemovedEvent {
    pub server_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}

#[event]
pub struct MCPServerOwnershipTransferredEvent {
    pub server_id: String,
    pub old_owner: Pubkey,
    pub new_owner: Pubkey,
    pub old_pda: Pubkey,
    pub timestamp: i64,
}
```

Event Emission Implementation:

Events are emitted within the corresponding instruction handlers using Anchor's `emit!` macro:

```
 pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    // ... initialize entry ...

    emit!(AgentRegisteredEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.created_at,
    });

    Ok(())
}

pub fn update_agent(ctx: Context<UpdateAgent>, args:
UpdateAgentArgs) -> Result<()> {
    // ... update entry ...

    emit!(AgentUpdatedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        updated_fields, // Vector of updated field names
        timestamp: entry.updated_at,
    });

    Ok(())
}

pub fn close_agent_entry(ctx: Context<CloseAgentEntry>) ->
Result<()> {
    let entry = &ctx.accounts.entry;

    emit!(AgentRemovedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: Clock::get()?.unix_timestamp,
    });

    // Anchor handles account closure
    Ok(())
}
```

Benefits of Event Emission:

1. **Decoupling**: Indexers are decoupled from the internal logic of the registry programs; they only need to consume events.
2. **Real-time Updates**: Events provide a near real-time stream of changes, allowing indexers to stay synchronized with the on-chain state.
3. **Scalability**: Event consumption is generally more scalable than repeatedly querying on-chain state using `getProgramAccounts`.
4. **Reduced On-Chain Load**: Shifts the burden of complex querying from the blockchain to off-chain systems.

By implementing a comprehensive event emission system, the registry protocols provide the necessary foundation for building powerful and efficient off-chain indexing infrastructures.

5.2.2 Indexer Architecture

An off-chain indexer is a service that listens for events emitted by the on-chain registry programs, processes these events, and maintains a queryable database that reflects the current state of the registry.

A typical indexer architecture consists of several components:

1. **Event Listener**: Subscribes to the Solana blockchain (via RPC or WebSocket) and listens for events emitted by the specific registry program IDs.

2. **Event Parser**: Decodes the event data (which is typically Borsh-serialized) into a structured format.

3. **State Fetcher**: When an event indicates a change, the indexer may need to fetch the full account data from the blockchain to get the complete, updated state.

4. **Database Adapter**: Transforms the event data and fetched state into a format suitable for the chosen database.

5. **Database**: Stores the indexed registry data. Common choices include:

6. **Relational Databases (e.g., PostgreSQL)**: Good for structured data and complex relational queries.
7. **NoSQL Databases (e.g., MongoDB, Elasticsearch)**: Good for flexible schemas, large datasets, and full-text search.
8. **Graph Databases (e.g., Neo4j)**: Good for modeling relationships between entities.
9. **Query API**: Exposes an API (e.g., REST, GraphQL) that allows clients to query the indexed data.

```
 +--------------------+     +--------------------+
+--------------------+     +--------------------+
|                    |     |                    |
|                    |     |                    |
| Solana Blockchain  |---->| Event Listener     |---->| Event
Parser       |---->| State Fetcher      |
| (Registry Events)  |     | (RPC/WebSocket)    |     | (Borsh
Decode)     |     | (Fetch Account)    |
|                    |     |                    |
|                    |     |                    |
+--------------------+     +--------------------+
+--------------------+     +--------------------+

|

v
+--------------------+     +--------------------+
+--------------------+     +--------------------+
|                    |     |                    |
|                    |     |                    |
| Client             |<----| Query API          |<----|
Database           |<----| Database Adapter   |
| (Web/Mobile/Agent)|     | (REST/GraphQL)     |     | (Postgres/
Mongo)   |     | (Data Transform)   |
|                    |     |                    |
|                    |     |                    |
+--------------------+     +--------------------+
+--------------------+     +--------------------+
```

Indexer Logic:

The indexer processes events as follows:

1. **Registration Event**: When a `Registered` event is received:
2. Fetch the full account data for the new entry.
3. Insert a new record into the database with the fetched data.

4. **Update Event**: When an `Updated` event is received:

5. Fetch the full account data for the updated entry.
6. Update the corresponding record in the database with the new data.

7. Alternatively, if the event contains sufficient detail about the changes, update only the specified fields.

8. **Removal Event**: When a `Removed` event is received:

9. Delete the corresponding record from the database.

10. **Status Change Event**: When a `StatusChanged` event is received:

11. Update the status field of the corresponding record in the database.

12. **Ownership Transfer Event**: When an `OwnershipTransferred` event is received:

13. Update the owner field of the corresponding record in the database.
14. Potentially update secondary indexes related to ownership.

Handling Reorganizations:

Blockchain reorganizations (reorgs), although rare on Solana, can cause events to be reverted. Indexers must handle reorgs gracefully:

1. **Track Block Confirmation**: Process events only after they reach a sufficient confirmation depth.
2. **Store Block Information**: Store the block number or slot associated with each database update.
3. **Rollback Mechanism**: Implement logic to detect reorgs and roll back database changes corresponding to reverted blocks.

Deployment Considerations:

1. **High Availability**: Indexers should be deployed with redundancy to ensure continuous operation.
2. **Scalability**: The indexer architecture should be designed to scale horizontally as the number of registry entries and query load increases.
3. **Monitoring**: Implement monitoring and alerting to track indexer health, synchronization lag, and query performance.

Building and maintaining a robust off-chain indexer requires significant infrastructure and operational effort. However, it provides the most flexible and performant solution for complex discovery and querying of registry data.

5.2.3 Query API Design

The Query API is the interface through which clients interact with the off-chain indexer to discover and query registry entries. A well-designed API is crucial for usability and performance.

API Design Principles:

1. **Flexibility**: Support querying based on a wide range of attributes and combinations.
2. **Performance**: Ensure fast response times, even for complex queries.
3. **Pagination**: Implement pagination for queries that may return large result sets.
4. **Sorting**: Allow results to be sorted based on various criteria (e.g., registration date, name, relevance).
5. **Filtering**: Provide powerful filtering capabilities using logical operators (AND, OR, NOT) and comparison operators (equals, contains, greater than, etc.).
6. **Full-Text Search**: Support full-text search on descriptive fields like name and description.
7. **Versioning**: Version the API to allow for future evolution without breaking existing clients.

API Technologies:

Common choices for implementing the Query API include:

1. **REST (Representational State Transfer)**: A widely adopted standard using HTTP methods (GET, POST, etc.) and standard status codes. Simple and well-understood.

2. **GraphQL**: A query language for APIs that allows clients to request exactly the data they need, reducing over-fetching and under-fetching. Offers more flexibility for clients.

Example API Endpoints (REST):

Agent Registry:

- `GET /agents` : List agents with filtering, sorting, and pagination.
- Query Parameters: `owner=`, `status=`, `capability=`, `skill_tag=`, `q=` (full-text search), `limit=`, `offset=`, `sort_by=`, `sort_order=`
- `GET /agents/{agent_id}` : Retrieve details for a specific agent by ID (requires owner for disambiguation if IDs are not globally unique, or use PDA).
- `GET /agents/by-pda/{pda}` : Retrieve details for a specific agent by its PDA.

MCP Server Registry:

- `GET /mcp-servers`: List MCP servers with filtering, sorting, and pagination.
- Query Parameters: `owner=`, `status=`, `capability=`, `tool_id=`, `model_id=`, `mcp_version=`, `q=` (full-text search), `limit=`, `offset=`, `sort_by=`, `sort_order=`
- `GET /mcp-servers/{server_id}`: Retrieve details for a specific server by ID (requires owner for disambiguation if IDs are not globally unique, or use PDA).
- `GET /mcp-servers/by-pda/{pda}`: Retrieve details for a specific server by its PDA.

Example GraphQL Schema:

```
type Query {
  agents(
    filter: AgentFilterInput
    sort: AgentSortInput
    limit: Int
    offset: Int
  ): [AgentRegistryEntry!]

  agent(pda: String!): AgentRegistryEntry

  mcpServers(
    filter: MCPServerFilterInput
    sort: MCPServerSortInput
    limit: Int
    offset: Int
  ): [MCPServerRegistryEntry!]

  mcpServer(pda: String!): MCPServerRegistryEntry
}

input AgentFilterInput {
  owner: String
  status: Int
  capabilities_mask: String # Bitmask
  skill_tags_contain: [String!]
  name_contains: String
  description_contains: String
  # ... other filter fields
}

input MCPServerFilterInput {
  owner: String
  status: Int
  capabilities_mask: String
  supported_tools_contain: [String!]
  supported_models_contain: [String!]
  supported_mcp_versions_contain: [String!]
  name_contains: String
  description_contains: String
  # ... other filter fields
}

# ... Define AgentRegistryEntry, MCPServerRegistryEntry, and
SortInput types
```

API Response Structure:

API responses should include:

1. **Data**: The requested registry entries.
2. **Pagination Info**: Total count, limit, offset, and links to previous/next pages.
3. **Metadata**: Timestamp of the last update, API version.

Security Considerations:

1. **Rate Limiting**: Implement rate limiting on the API to prevent abuse.
2. **Authentication/Authorization**: Consider adding authentication mechanisms if access needs to be restricted.
3. **Input Validation**: Sanitize and validate all query parameters to prevent injection attacks or excessive resource consumption.

By providing a well-designed Query API, the off-chain indexer enables clients to efficiently discover and query registry entries, unlocking the full potential of the decentralized agent and MCP server ecosystem.

5.3 Hybrid Discovery Patterns

5.3.1 Combining On-chain and Off-chain Data

Hybrid discovery patterns leverage the strengths of both on-chain and off-chain data sources to provide a comprehensive and trustworthy discovery experience. This approach combines the verifiability of on-chain data with the query flexibility and performance of off-chain indexes.

Core Principle:

The core principle is to use the off-chain indexer for initial discovery and filtering based on complex criteria, and then use on-chain lookups to verify critical information and retrieve the most up-to-date state for selected entries.

Typical Workflow:

1. **Off-Chain Query**: Client queries the off-chain indexer's API with complex filtering criteria (e.g., find active agents with specific skills and a good reputation score).

2. **Candidate Selection**: The indexer returns a list of candidate PDAs that match the criteria based on its indexed data.

3. **On-Chain Verification**: For the top candidates, the client performs direct PDA lookups on-chain to:

4. Verify the current status (e.g., ensure the agent is still active).
5. Confirm critical attributes (e.g., owner authority, core capabilities).

6. Retrieve the latest service endpoints.

7. **Final Selection**: The client makes a final selection based on the verified on-chain data and potentially other factors like latency testing or cost.

```
 +----------+     +-------------------+     +-------------------
+     +----------+
|          | 1. Query API        | 2. Candidate PDAs | 3. Fetch
Account   |          |
| Client   |------------------->| Off-Chain Indexer
|------------------->| Solana    |
|          |                   |
<-------------------|                 |<----------|
|          |                   |                    | 4.
Verified Data  |          |
+----------+                   +-------------------
+                    +----------+
     |
     | 5. Select & Interact
     v
+----------+
| Target   |
| Agent/   |
| Server   |
+----------+
```

Data Synchronization:

It's crucial that the off-chain index remains closely synchronized with the on-chain state. However, due to potential indexing lag, clients should always treat off-chain data as potentially slightly stale and verify critical information on-chain before initiating important interactions.

Example Use Case: Finding a Reliable MCP Server

1. **Off-Chain Query**: Client queries the indexer API for MCP servers that support a specific tool (`tool_id = "web_search"`), have a high reputation score (`rating > 4.5`), and offer a specific pricing tier (`pricing_tier = "pro"`).

2. **Candidate PDAs**: The indexer returns a list of PDAs for servers matching these criteria.

3. **On-Chain Verification**: The client takes the top 3 candidate PDAs and fetches their full entries from the Solana blockchain.

4. Verify `status` is `Active`.
5. Verify `owner_authority` matches expectations (if known).
6. Retrieve the latest `service_endpoints`.

7. Verify the `schema_hash` for the `web_search` tool matches the expected hash.

8. **Final Selection**: The client might perform a quick latency test on the verified endpoints and select the server with the best performance and verified capabilities.

Benefits:

1. **Best of Both Worlds**: Combines the query power of off-chain indexes with the trust and timeliness of on-chain data.
2. **Efficiency**: Reduces the load on RPC nodes compared to purely on-chain discovery for complex queries.
3. **Trustworthiness**: Ensures that critical decisions are based on verified, up-to-date on-chain information.

5.3.2 Caching Strategies

Caching plays a vital role in optimizing the performance of hybrid discovery patterns by reducing redundant data fetching from both on-chain and off-chain sources.

Client-Side Caching:

Clients can implement local caches to store frequently accessed data:

1. **Registry Entry Cache**: Cache the full data for recently accessed or frequently used agent/server entries. Cache entries should include a timestamp and be invalidated based on a Time-To-Live (TTL) or when update events are detected.

2. **Query Result Cache**: Cache the results of common queries made to the off-chain indexer API. Cache keys should incorporate all query parameters (filters, sort, pagination).

3. **Reputation/Attestation Cache**: Cache data retrieved from external reputation or attestation services.

```
// Simple client-side cache implementation
const entryCache = new Map<string, { entry: any, timestamp:
number }>();
const CACHE_TTL_MS = 5 * 60 * 1000; // 5 minutes

async function getCachedAgentEntry(
    program: Program<AgentRegistry>,
    pda: PublicKey
): Promise<AgentRegistryEntryV1 | null> {
    const pdaString = pda.toString();
    const cached = entryCache.get(pdaString);

    if (cached && (Date.now() - cached.timestamp <
CACHE_TTL_MS)) {
        console.log(`Cache hit for ${pdaString}`);
        return cached.entry;
    }

    console.log(`Cache miss for ${pdaString}, fetching from
chain...`);
    try {
        const entry = await
program.account.agentRegistryEntryV1.fetch(pda);
        entryCache.set(pdaString, { entry, timestamp:
Date.now() });
        return entry;
    } catch (error) {
        console.error(`Error fetching agent entry $
{pdaString}:`, error);
        return null;
    }
}
```

Indexer-Side Caching:

Off-chain indexers can implement caching at various levels:

1. **API Response Caching**: Cache responses for frequent queries at the API gateway or application level (e.g., using Redis or Memcached).

2. **Database Query Caching**: Utilize database-level caching mechanisms to speed up query execution.

3. **Materialized Views**: Pre-compute and store the results of common aggregations or complex joins in materialized views.

Cache Invalidation:

Effective cache invalidation is crucial:

1. **TTL-Based**: Invalidate cache entries after a predefined time period.
2. **Event-Based**: Use the event stream from the blockchain to proactively invalidate cache entries corresponding to updated or removed registry items.
3. **Manual Invalidation**: Allow users or administrators to manually clear caches when necessary.

By implementing appropriate caching strategies, both clients and indexers can significantly improve the performance and efficiency of the discovery process.

5.3.3 Real-time Updates

Maintaining real-time or near real-time updates is essential for the reliability of hybrid discovery systems, ensuring that clients have access to the latest information.

Leveraging WebSockets:

Solana's WebSocket API allows clients and indexers to subscribe to real-time notifications for various blockchain events:

1. **Account Change Subscriptions**: Subscribe to changes for specific registry entry PDAs. This allows clients to receive immediate notifications when an entry they are interested in is updated.

```
// Subscribe to changes for a specific agent entry PDA
const subscriptionId = connection.onAccountChange(
    agentEntryPda,
    (accountInfo, context) => {
        console.log(`Agent entry ${agentEntryPda.toString()}
updated in slot ${context.slot}`);
        const updatedEntry =
program.coder.accounts.decode("AgentRegistryEntryV1",
accountInfo.data);
        // Update local state or cache
        updateLocalAgentState(agentEntryPda, updatedEntry);
    },
    "confirmed" // Confirmation level
);
```

1. **Program Log Subscriptions**: Subscribe to logs emitted by the registry programs. This allows indexers and clients to receive the event stream in real-time.

```
// Subscribe to logs from the agent registry program
const subscriptionId = connection.onLogs(
    agentRegistryProgramId,
    (logs, context) => {
        if (logs.err) {
            console.error("Error in logs:", logs.err);
            return;
        }

        // Parse events from logs
        const events =
program.coder.events.parseLogs(logs.logs);
        for (const event of events) {
            console.log(`Received event: ${event.name}`,
event.data);
            // Process event for indexing or client updates
            processRegistryEvent(event);
        }
    },
    "confirmed"
);
```

Indexer Real-time Processing:

Off-chain indexers should use WebSocket subscriptions to process events as soon as they reach the desired confirmation level. This minimizes the lag between on-chain changes and the indexed state.

Client Real-time Updates:

Clients can use WebSocket subscriptions to:

1. **Invalidate Caches**: Immediately invalidate local cache entries when an update event is received for a cached item.
2. **Update UI**: Update user interfaces in real-time to reflect changes in agent/server status or details.
3. **Trigger Actions**: Automatically trigger actions based on real-time events (e.g., switch to a backup server if the primary one becomes inactive).

Challenges:

1. **Scalability**: Maintaining a large number of WebSocket connections can be resource-intensive for both clients and RPC nodes.
2. **Reliability**: WebSocket connections can be interrupted; robust reconnection and state synchronization logic is required.
3. **Confirmation Levels**: Choosing the appropriate confirmation level (`processed`, `confirmed`, `finalized`) involves trade-offs between latency and finality.

By effectively utilizing Solana's WebSocket API and designing robust real-time processing logic, hybrid discovery systems can provide clients with timely and accurate information, enhancing the responsiveness and reliability of the overall ecosystem.

References will be compiled and listed in Chapter 13.

Chapter 6: Implementation Guide

6.1 Setting Up the Development Environment

6.1.1 Required Tools and Dependencies

Implementing the Agent and MCP Server Registry protocols on Solana requires a specific set of tools and dependencies. Setting up the development environment correctly is the first step towards building and deploying these programs.

Core Solana Development Tools:

1. **Rust Programming Language**: Solana programs are primarily written in Rust. Install the latest stable version using `rustup`: `bash curl --proto "=https" --tlsv1.2 -sSf https://sh.rustup.rs | sh source $HOME/.cargo/env rustup update stable`

2. **Solana Tool Suite**: This suite includes the Solana CLI, validator tools, and SDKs. Install it following the official Solana documentation: `bash sh -c "$(curl -sSfL https://release.solana.com/v1.18.4/install)" # Replace v1.18.4 with the desired version export PATH="$HOME/.local/share/solana/install/active_release/bin:$PATH" solana --version`

3. **Anchor Framework**: Anchor simplifies Solana program development by providing a framework with macros, IDL generation, and client libraries.

    - **AVM (Anchor Version Manager)**: Recommended for managing multiple Anchor versions. `bash cargo install --git https://github.com/coral-xyz/anchor avm --locked --force avm install latest avm use latest`
    - **Verify Installation**: `bash anchor --version`

Node.js and Client-Side Tools:

1. **Node.js**: Required for running client-side JavaScript/TypeScript code and interacting with the Anchor framework. ```bash # Install Node Version Manager (nvm) curl -o- https://raw.githubusercontent.com/nvm-sh/nvm/v0.39.3/install.sh | bash export NVM_DIR="$HOME/.nvm" [-s "$NVM_DIR/nvm.sh"] && . "$NVM_DIR/nvm.sh"

    # Install Node.js (LTS recommended)

    nvm install --lts node --version npm --version ```

2. **Yarn or npm**: Package managers for Node.js projects. `bash npm install -g yarn # Or use npm directly`

3. **TypeScript**: Strongly recommended for client-side development for type safety. `bash npm install -g typescript tsc --version`

Development Environment Setup:

1. **Code Editor**: Visual Studio Code (VS Code) with the `rust-analyzer` and `Anchor Snippets` extensions is highly recommended.

2. **Local Solana Cluster**: For testing, run a local validator: `bash solana-test-validator` This command starts a local cluster and provides an RPC endpoint (usually `http://127.0.0.1:8899`) and a faucet for obtaining test SOL.

3. **Configuration**: Configure the Solana CLI to point to your desired cluster (local, devnet, testnet, or mainnet-beta): `bash solana config set --url localhost # Or devnet, testnet, mainnet-beta solana config get`

Project Structure (Anchor):

An Anchor project typically has the following structure:

```
my_registry_project/
├── Anchor.toml         # Project configuration
├── Cargo.toml          # Rust dependencies
├── migrations/         # Deployment scripts (optional)
│   └── deploy.ts
├── programs/
│   └── my_registry/    # Solana program source code
│       ├── Cargo.toml
│       └── src/
│           └── lib.rs # Main program logic
├── target/             # Build artifacts
├── tests/              # Integration tests (TypeScript/
JavaScript)
│   └── my_registry.ts
└── app/                # Optional frontend application
```

```
 +----------------------------+
|      Development PC        |
+----------------------------+
|   Operating System (Linux,|
|   macOS, Windows/WSL)      |
+----------------------------+
| Tools Installed:           |
| - Rust + Cargo             |
| - Solana Tool Suite        |
| - Anchor Framework (AVM)   |
| - Node.js + npm/yarn     |
| - TypeScript               |
| - Code Editor (VS Code)    |
+----------------------------+
| Configuration:             |
| - Solana CLI (url, key) |
| - Anchor.toml            |
+----------------------------+
| Running Processes:         |
| - solana-test-validator |
|   (Local Cluster)          |
+----------------------------+
```

With these tools installed and configured, you are ready to start implementing the Agent and MCP Server Registry programs using the Anchor framework.

6.1.2 Anchor Project Initialization

Anchor provides commands to initialize a new Solana program project with the standard directory structure and configuration files.

Initializing a New Project:

Use the `anchor init` command to create a new project:

```
anchor init agent-registry --program-name agent_registry
cd agent-registry
```

This command creates a new directory named `agent-registry` with the following key components:

- **`Anchor.toml`**: The main configuration file for the Anchor project. It defines the program(s), provider settings, testing configurations, and cluster URLs.

  ```toml [features] seeds = false skip-lint = false

  [programs.localnet] # Configuration for localnet cluster agent_registry = "Fg6PaFpoGXkYsidMpWxqSWpba3f2Jp5jVnXNCSr9NMSB" # Placeholder Program ID

  [programs.devnet] # Configuration for devnet cluster agent_registry = "Fg6PaFpoGXkYsidMpWxqSWpba3f2Jp5jVnXNCSr9NMSB" # Placeholder Program ID

  [registry] url = "https://api.apr.dev"

  [provider] cluster = "Localnet" # Default cluster (can be Localnet, Devnet, Testnet, Mainnet) wallet = "~/.config/solana/id.json" # Default wallet path

  [scripts] test = "yarn run ts-mocha -p ./tsconfig.json -t 1000000 tests/*/.ts" ```

- **`programs/agent_registry/src/lib.rs`**: The main Rust source file for your Solana program. Anchor initializes it with a basic example instruction.

  ```rust use anchor_lang::prelude::*;

  declare_id!("Fg6PaFpoGXkYsidMpWxqSWpba3f2Jp5jVnXNCSr9NMSB"); // Placeholder Program ID

  # [program]

  pub mod agent_registry { use super::*;

```
pub fn initialize(ctx: Context<Initialize>) -> Result<()> {
    Ok(())
}
```

}

[derive(Accounts)]

pub struct Initialize {} ```

- `tests/agent_registry.ts` : An example integration test file written in TypeScript, demonstrating how to interact with the program using the Anchor client library.
- `Cargo.toml` **(Root and Program)**: Define Rust dependencies for the workspace and the specific program.
- `package.json` : Defines Node.js dependencies for testing and client-side interaction (e.g., `@coral-xyz/anchor` , `@solana/web3.js` , `mocha` , `chai`).

Building the Project:

Use the `anchor build` command to compile the Rust program into Solana BPF bytecode and generate the Interface Definition Language (IDL) file:

```
anchor build
```

This command performs several actions:

1. Compiles the Rust code in `programs/agent_registry/` .
2. Generates the BPF bytecode file (`target/deploy/agent_registry.so`).
3. Generates the IDL file (`target/idl/agent_registry.json`), which describes the program's instructions, accounts, types, and events.
4. Generates TypeScript type definitions based on the IDL (`target/types/agent_registry.ts`).

Deploying the Program (Localnet):

Before deploying, ensure your local validator is running (`solana-test-validator`).

Use the `anchor deploy` command:

```
anchor deploy
```

This command:

1. Builds the program if necessary.
2. Deploys the BPF bytecode (`agent_registry.so`) to the configured cluster (Localnet by default).
3. Outputs the Program ID of the deployed program.
4. Updates `Anchor.toml` and `lib.rs` with the new Program ID.

Running Tests:

Use the `anchor test` command to run the integration tests defined in the `tests/` directory:

```
anchor test
```

This command:

1. Starts a local validator if one isn't running.
2. Builds and deploys the program to the local validator.
3. Executes the TypeScript tests using the configured test runner (Mocha by default).

Initializing the project correctly with Anchor sets the stage for efficient development, providing the necessary structure, configuration, and build tools to implement the registry protocols.

6.2 Implementing Agent Registry Program

6.2.1 Defining Account Structures

Based on the protocol design in Chapter 3, we define the `AgentRegistryEntryV1` account structure using Anchor's `#[account]` macro. This structure holds all the metadata for a registered agent.

```
 // programs/agent_registry/src/lib.rs

use anchor_lang::prelude::*;
use anchor_lang::solana_program::clock::Clock;

// Replace with the actual deployed Program ID after first
deploy
```

```
declare_id!("AGENTregxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx");

// Define constants for max lengths to avoid magic numbers
const MAX_AGENT_ID_LEN: usize = 64;
const MAX_NAME_LEN: usize = 128;
const MAX_DESCRIPTION_LEN: usize = 512;
const MAX_VERSION_LEN: usize = 32;
const MAX_ENDPOINT_LEN: usize = 256;
const MAX_SKILL_TAG_LEN: usize = 32;
const MAX_SKILL_TAGS: usize = 10;
const MAX_SERVICE_ENDPOINTS: usize = 3;

#[program]
pub mod agent_registry {
    use super::*;
    // Instructions will be defined here
}

// --- Account Structures ---

#[account]
#[derive(InitSpace)] // Automatically calculate space for
account initialization
pub struct AgentRegistryEntryV1 {
    // Metadata
    pub bump: u8,
    pub registry_version: u8,
    pub owner_authority: Pubkey,
    pub status: u8, // Enum AgentStatus
    pub capabilities_flags: u64, // Bitfield
AgentCapabilityFlags
    pub created_at: i64,
    pub updated_at: i64,

    // Identity
    #[max_len(MAX_AGENT_ID_LEN)]
    pub agent_id: String,
    #[max_len(MAX_NAME_LEN)]
    pub name: String,
    #[max_len(MAX_DESCRIPTION_LEN)]
    pub description: String,
    #[max_len(MAX_VERSION_LEN)]
    pub agent_version: String,

    // Technical Details
    pub supported_protocols: Vec<String>, // Max 5 protocols,
each max 64 chars
    #[max_len(MAX_SKILL_TAGS)]
    pub skill_tags: Vec<String>, // Each tag max
MAX_SKILL_TAG_LEN

    // Endpoints
    #[max_len(MAX_SERVICE_ENDPOINTS)]
    pub service_endpoints: Vec<ServiceEndpoint>,

    // Optional Metadata
    pub documentation_url: Option<String>, // Max 256 chars
    pub extended_metadata_uri: Option<String>, // Max 256 chars
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ServiceEndpoint {
    #[max_len(64)] // Max protocol name length
    pub protocol: String,
    #[max_len(MAX_ENDPOINT_LEN)]
    pub url: String,
    pub is_default: bool,
}

// --- Enums and Flags ---

#[derive(AnchorSerialize, AnchorDeserialize, Clone, PartialEq,
Eq)]
pub enum AgentStatus {
    Inactive = 0,
    Active = 1,
    Deprecated = 2,
}

pub mod AgentCapabilityFlags {
    pub const A2A_MESSAGING: u64 = 1 << 0; // Supports Agent-to-
Agent protocol
    pub const MCP_CLIENT: u64 = 1 << 1;    // Can act as an MCP
client
    pub const TASK_EXECUTION: u64 = 1 << 2; // Can execute tasks
    pub const DATA_QUERYING: u64 = 1 << 3;  // Can query data
sources
    // Add more flags as needed
}

// --- Events ---
// Events will be defined here

// --- Errors ---
#[error_code]
pub enum ErrorCode {
    #[msg("String exceeds maximum length.")]
    StringTooLong,
    #[msg("Too many items in collection.")]
    TooManyItems,
    #[msg("Invalid Agent ID format.")]
    InvalidAgentId,
    #[msg("Invalid status value.")]
    InvalidStatus,
    #[msg("No default service endpoint provided.")]
    NoDefaultEndpoint,
    #[msg("Unauthorized operation.")]
    Unauthorized,
    #[msg("Cannot transfer ownership to the same owner.")]
    CannotTransferToSelf,
    #[msg("Invalid protocol name.")]
    InvalidProtocolName,
    #[msg("Invalid skill tag.")]
    InvalidSkillTag,
}

// Helper function for validation (example)
fn is_valid_agent_id(id: &str) -> bool {
    id.len() > 0 && id.len() <= MAX_AGENT_ID_LEN &&
id.chars().all(|c| c.is_ascii_alphanumeric() || c == '-' || c
== '_')
}

// Instruction contexts and handlers will follow...
```

Key Aspects:

1. **`#[account]` Macro**: Marks the struct as a Solana account data structure that Anchor can manage.
2. **`#[derive(InitSpace)]`** : Automatically calculates the required space for the account based on its fields, including `Option` and `Vec` types with `#[max_len]` annotations. This is crucial for the `init` constraint in instruction contexts.
3. **`#[max_len(...)]`** : Specifies the maximum size for variable-length fields like `String` and `Vec` . This is essential for `InitSpace` calculation and preventing unbounded account growth.
4. **Constants**: Using constants (`MAX_AGENT_ID_LEN` , etc.) improves readability and maintainability.
5. **Enums and Flags**: Define enums (`AgentStatus`) and bitflags (`AgentCapabilityFlags`) for structured representation of status and capabilities.
6. **Nested Structs**: Define nested structs like `ServiceEndpoint` and derive necessary traits (`AnchorSerialize` , `AnchorDeserialize` , `Clone` , `InitSpace`).
7. **Error Codes**: Define custom error codes using `#[error_code]` for clear error reporting.

This structure provides a solid foundation for storing agent metadata on-chain, balancing comprehensiveness with storage efficiency.

6.2.2 Implementing Registration Instruction

The `register_agent` instruction initializes a new `AgentRegistryEntryV1` PDA account.

Instruction Context (`RegisterAgent`):

Defines the accounts required for the instruction.

```
 // --- Instruction Contexts ---

#[derive(Accounts)]
#[instruction(args: RegisterAgentArgs)] // Link to instruction
arguments struct
pub struct RegisterAgent<'info> {
    #[account(
        init, // Initialize the account
        payer = payer, // Account funding the initialization
        space = 8 + AgentRegistryEntryV1::INIT_SPACE, //
Calculate space (8 bytes for discriminator)
        seeds = [
            b"agent_registry".as_ref(),
            args.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump // Store the bump seed
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,


#[account(mut)] // Payer needs to be mutable to sign and pay for
account creation
    pub payer: Signer<'info>,

    /// CHECK: The owner authority is validated as a signer.
    /// It doesn't need to be an existing account, just a valid
keypair signing the tx.
    pub owner_authority: Signer<'info>,

    pub system_program: Program<'info, System>, // Required for
account initialization
}
```

Instruction Arguments (`RegisterAgentArgs`):

Defines the data passed into the instruction.

```
 // --- Instruction Arguments ---

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct RegisterAgentArgs {
    pub agent_id: String,
    pub name: String,
    pub description: String,
    pub agent_version: String,
    pub supported_protocols: Vec<String>,
    pub skill_tags: Vec<String>,
    pub service_endpoints: Vec<ServiceEndpoint>,
    pub capabilities_flags: u64,
    pub documentation_url: Option<String>,
    pub extended_metadata_uri: Option<String>,
}
```

Instruction Handler (`register_agent`):

Contains the core logic for validation and initialization.

```
 // --- Instruction Handlers ---

impl AgentRegistryEntryV1 {
    // Helper to validate string lengths within the main struct
    fn validate_lengths(&self) -> Result<()> {
        require!(self.agent_id.len() <= MAX_AGENT_ID_LEN,
ErrorCode::StringTooLong);
        require!(self.name.len() <= MAX_NAME_LEN,
ErrorCode::StringTooLong);
        // ... other length checks ...
        Ok(())
    }
}

impl ServiceEndpoint {
     // Helper to validate string lengths within the nested
struct
    fn validate_lengths(&self) -> Result<()> {
        require!(self.protocol.len() <= 64,
ErrorCode::StringTooLong);
        require!(self.url.len() <= MAX_ENDPOINT_LEN,
ErrorCode::StringTooLong);
        Ok(())
    }
}

pub fn register_agent(ctx: Context<RegisterAgent>, args:
RegisterAgentArgs) -> Result<()> {
    // --- Validation ---
    require!(is_valid_agent_id(&args.agent_id),
ErrorCode::InvalidAgentId);
    require!(args.name.len() <= MAX_NAME_LEN,
ErrorCode::StringTooLong);
    require!(args.description.len() <= MAX_DESCRIPTION_LEN,
ErrorCode::StringTooLong);
    require!(args.agent_version.len() <= MAX_VERSION_LEN,
ErrorCode::StringTooLong);

    require!(args.supported_protocols.len() <= 5,
ErrorCode::TooManyItems);
    for proto in &args.supported_protocols {
        require!(proto.len() <= 64, ErrorCode::StringTooLong);
        // Add more specific protocol validation if needed
    }

    require!(args.skill_tags.len() <= MAX_SKILL_TAGS,
ErrorCode::TooManyItems);
    for tag in &args.skill_tags {
        require!(tag.len() > 0 && tag.len() <=
MAX_SKILL_TAG_LEN, ErrorCode::InvalidSkillTag);
        // Add more specific tag validation if needed
    }

    require!(args.service_endpoints.len() > 0 &&
args.service_endpoints.len() <= MAX_SERVICE_ENDPOINTS,
ErrorCode::TooManyItems);
    require!(args.service_endpoints.iter().filter(|ep|
ep.is_default).count() == 1, ErrorCode::NoDefaultEndpoint);
    for ep in &args.service_endpoints {
       ep.validate_lengths()?; // Validate nested struct lengths
       // Add URL validation if needed
    }

    if let Some(url) = &args.documentation_url {
        require!(url.len() <= 256, ErrorCode::StringTooLong);
    }
    if let Some(uri) = &args.extended_metadata_uri {
        require!(uri.len() <= 256, ErrorCode::StringTooLong);
    }

    // --- Initialization ---
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;

    entry.bump =
*ctx.bumps.get("entry").ok_or(ProgramError::InvalidSeeds)?; //
Get bump from context
    entry.registry_version = 1;
    entry.owner_authority = ctx.accounts.owner_authority.key();
    entry.status = AgentStatus::Active as u8;
    entry.capabilities_flags = args.capabilities_flags;
    entry.created_at = clock.unix_timestamp;
    entry.updated_at = clock.unix_timestamp;

    entry.agent_id = args.agent_id;
    entry.name = args.name;
    entry.description = args.description;
    entry.agent_version = args.agent_version;

    entry.supported_protocols = args.supported_protocols;
    entry.skill_tags = args.skill_tags;
    entry.service_endpoints = args.service_endpoints;

    entry.documentation_url = args.documentation_url;
    entry.extended_metadata_uri = args.extended_metadata_uri;

    // --- Event Emission ---
    emit!(AgentRegisteredEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: entry.created_at,
    });

    msg!("Agent registered: {}", entry.agent_id);
    Ok(())
}

// --- Event Definition ---
#[event]
pub struct AgentRegisteredEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

Key Logic:

1. **Validation**: Thoroughly validates all input arguments against defined constraints (lengths, formats, counts).
2. **PDA Initialization**: The `#[account(init...)]` macro handles the creation of the PDA account, space allocation, and rent payment.
3. **Data Population**: Populates the fields of the newly created `entry` account with validated data from `args` and context (bump, owner, timestamps).
4. **Event Emission**: Emits an `AgentRegisteredEvent` using `emit!` for off-chain indexers.
5. **Logging**: Uses `msg!` for on-chain program logging (useful for debugging).

6.2.3 Implementing Update and Deregistration

Update Instruction:

Allows the owner to modify certain fields of an existing entry.

```
 // --- Update Instruction ---

#[derive(Accounts)]
#[instruction(args: UpdateAgentArgs)]
pub struct UpdateAgent<'info> {
    #[account(
        mut, // Entry needs to be mutable to be updated
        seeds = [
            b"agent_registry".as_ref(),
            entry.agent_id.as_bytes(), // Use agent_id from the
existing entry
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump, // Use the stored bump for
verification
        has_one = owner_authority @ ErrorCode::Unauthorized //
Verify signer is the owner
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct UpdateAgentArgs {
    // Use Option<> for fields that can be updated selectively
    pub name: Option<String>,
    pub description: Option<String>,
    pub agent_version: Option<String>,
    pub supported_protocols: Option<Vec<String>>,
    pub skill_tags: Option<Vec<String>>,
    pub service_endpoints: Option<Vec<ServiceEndpoint>>,
    pub capabilities_flags: Option<u64>,
    pub documentation_url: Option<Option<String>>, //
Option<Option<T>> to allow setting to None
    pub extended_metadata_uri: Option<Option<String>>,
}

pub fn update_agent(ctx: Context<UpdateAgent>, args:
UpdateAgentArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    let clock = Clock::get()?;
    let mut updated_fields = Vec::new();

    // Selectively update fields if Some(value) is provided
    if let Some(name) = args.name {
        require!(name.len() <= MAX_NAME_LEN,
ErrorCode::StringTooLong);
        entry.name = name;
        updated_fields.push("name".to_string());
    }
    if let Some(description) = args.description {
        require!(description.len() <= MAX_DESCRIPTION_LEN,
ErrorCode::StringTooLong);
        entry.description = description;
        updated_fields.push("description".to_string());
    }
    // ... update other optional fields similarly, performing
validation ...
    if let Some(endpoints) = args.service_endpoints {
        require!(endpoints.len() > 0 && endpoints.len() <=
MAX_SERVICE_ENDPOINTS, ErrorCode::TooManyItems);
        require!(endpoints.iter().filter(|ep|
ep.is_default).count() == 1, ErrorCode::NoDefaultEndpoint);
        for ep in &endpoints {
           ep.validate_lengths()?;
        }
        entry.service_endpoints = endpoints;
        updated_fields.push("service_endpoints".to_string());
    }
    if let Some(flags) = args.capabilities_flags {
        entry.capabilities_flags = flags;
        updated_fields.push("capabilities_flags".to_string());
    }
    // Handle Option<Option<T>> for optional fields that can be
unset
    if let Some(maybe_url) = args.documentation_url {
        if let Some(url) = &maybe_url {
             require!(url.len() <= 256,
ErrorCode::StringTooLong);
        }
        entry.documentation_url = maybe_url;
        updated_fields.push("documentation_url".to_string());
    }
     if let Some(maybe_uri) = args.extended_metadata_uri {
        if let Some(uri) = &maybe_uri {
             require!(uri.len() <= 256,
ErrorCode::StringTooLong);
        }
        entry.extended_metadata_uri = maybe_uri;

updated_fields.push("extended_metadata_uri".to_string());
    }

    // Always update the timestamp
    entry.updated_at = clock.unix_timestamp;
    // Emit event
    emit!(AgentUpdatedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        updated_fields,
        timestamp: entry.updated_at,
    });

    msg!("Agent updated: {}", entry.agent_id);
    Ok(())
}

#[event]
pub struct AgentUpdatedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub updated_fields: Vec<String>,
    pub timestamp: i64,
}
```

Deregistration (Close Account) Instruction:

Allows the owner to close the PDA account and reclaim rent.

```
 // --- Deregistration Instruction ---

#[derive(Accounts)]
pub struct CloseAgentEntry<'info> {
    #[account(
        mut,
        seeds = [
            b"agent_registry".as_ref(),
            entry.agent_id.as_bytes(),
            owner_authority.key().as_ref(),
        ],
        bump = entry.bump,
        has_one = owner_authority @ ErrorCode::Unauthorized,
        close = recipient // Close account and transfer lamports
to recipient
    )]
    pub entry: Account<'info, AgentRegistryEntryV1>,

    pub owner_authority: Signer<'info>,

    #[account(mut)] // Recipient needs to be mutable to receive
lamports
    pub recipient: SystemAccount<'info>,
}

pub fn close_agent_entry(ctx: Context<CloseAgentEntry>) ->
```

```
Result<()> {
    let entry = &ctx.accounts.entry; // Borrow entry to read
data before close

    // Emit event before account is closed
    emit!(AgentRemovedEvent {
        agent_id: entry.agent_id.clone(),
        owner: entry.owner_authority,
        timestamp: Clock::get()?.unix_timestamp,
    });

    msg!("Agent removed: {}", entry.agent_id);
    // Anchor handles the actual account closing via the `close
= recipient` constraint
    Ok(())
}

#[event]
pub struct AgentRemovedEvent {
    pub agent_id: String,
    pub owner: Pubkey,
    pub timestamp: i64,
}
```

Key Logic:

1. **Authorization**: Both instructions use `has_one = owner_authority` to ensure only the registered owner can perform the action.
2. **PDA Verification**: The `seeds` and `bump` constraints verify that the correct PDA account is being accessed.
3. **Selective Updates**: The `update_agent` instruction uses `Option` in its arguments to allow partial updates.
4. **Account Closure**: The `close_agent_entry` instruction uses Anchor's `close = recipient` constraint to handle the secure closure of the account and rent reclamation.
5. **Event Emission**: Events (`AgentUpdatedEvent`, `AgentRemovedEvent`) are emitted to notify indexers.

These instructions provide the necessary mechanisms for managing the lifecycle of agent entries after registration.

6.3 Implementing MCP Server Registry Program

6.3.1 Defining Account Structures

The process mirrors the Agent Registry, defining the `MCPServerRegistryEntryV1` account structure based on Chapter 4.

```rust
 // programs/mcp_server_registry/src/lib.rs (assuming separate
program)

use anchor_lang::prelude::*;
use anchor_lang::solana_program::clock::Clock;

// Replace with the actual deployed Program ID
declare_id!("MCPSRregxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx");

// Define constants (similar to Agent Registry, adjust as
needed)
const MAX_SERVER_ID_LEN: usize = 64;
const MAX_NAME_LEN: usize = 128;
const MAX_DESCRIPTION_LEN: usize = 512;
const MAX_VERSION_LEN: usize = 32;
const MAX_ENDPOINT_LEN: usize = 256;
const MAX_MCP_VERSION_LEN: usize = 16;
const MAX_MCP_VERSIONS: usize = 5;
const MAX_MODEL_ID_LEN: usize = 64;
const MAX_MODEL_NAME_LEN: usize = 128;
const MAX_MODEL_TYPE_LEN: usize = 32;
const MAX_MODELS: usize = 10;
const MAX_TOOL_ID_LEN: usize = 64;
const MAX_TOOL_NAME_LEN: usize = 128;
const MAX_TOOL_DESC_LEN: usize = 256;
const MAX_TOOL_VERSION_LEN: usize = 32;
const MAX_TOOL_SCHEMA_URI_LEN: usize = 256;
const MAX_TOOLS: usize = 20;
const MAX_PROVIDER_NAME_LEN: usize = 128;
const MAX_PROVIDER_URL_LEN: usize = 256;
const MAX_DOCS_URL_LEN: usize = 256;
const MAX_SECURITY_URI_LEN: usize = 256;
const MAX_PRICING_URI_LEN: usize = 256;
const MAX_EXTENDED_URI_LEN: usize = 256;
const MAX_SERVICE_ENDPOINTS: usize = 3;

#[program]
pub mod mcp_server_registry {
    use super::*;
    // Instructions will be defined here
}
```

```rust
// --- Account Structures ---

#[account]
#[derive(InitSpace)]
pub struct MCPServerRegistryEntryV1 {
    // Metadata
    pub bump: u8,
    pub registry_version: u8,
    pub owner_authority: Pubkey,
    pub status: u8, // Enum ServerStatus
    pub capabilities_flags: u64, // Bitfield
ServerCapabilityFlags
    pub created_at: i64,
    pub updated_at: i64,

    // Identity
    #[max_len(MAX_SERVER_ID_LEN)]
    pub server_id: String,
    #[max_len(MAX_NAME_LEN)]
    pub name: String,
    #[max_len(MAX_VERSION_LEN)]
    pub server_version: String,

    // MCP Specific
    #[max_len(MAX_MCP_VERSIONS)]
    pub supported_mcp_versions: Vec<String>, // Each max
MAX_MCP_VERSION_LEN
    pub max_context_length: u32,
    pub max_token_limit: u32,

    // Description
    #[max_len(MAX_DESCRIPTION_LEN)]
    pub description: String,

    // Models
    #[max_len(MAX_MODELS)]
    pub models: Vec<ModelInfo>,

    // Tools
    #[max_len(MAX_TOOLS)]
    pub supported_tools: Vec<ToolInfo>,

    // Optional Metadata
    pub provider_name: Option<String>, // Max
MAX_PROVIDER_NAME_LEN
    pub provider_url: Option<String>, // Max
MAX_PROVIDER_URL_LEN
    pub documentation_url: Option<String>, // Max
MAX_DOCS_URL_LEN
    pub security_info_uri: Option<String>, // Max
MAX_SECURITY_URI_LEN
```

```rust
    // Operational Parameters
    pub rate_limit_requests: Option<u32>,
    pub rate_limit_tokens: Option<u32>,
    pub pricing_info_uri: Option<String>, // Max
MAX_PRICING_URI_LEN

    // Endpoints
    #[max_len(MAX_SERVICE_ENDPOINTS)]
    pub service_endpoints: Vec<ServiceEndpoint>,

    // Off-chain Extension
    pub extended_metadata_uri: Option<String>, // Max
MAX_EXTENDED_URI_LEN
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ModelInfo {
    #[max_len(MAX_MODEL_ID_LEN)]
    pub model_id: String,
    #[max_len(MAX_MODEL_NAME_LEN)]
    pub display_name: String,
    #[max_len(MAX_MODEL_TYPE_LEN)]
    pub model_type: String,
    pub capabilities_flags: u64, // Bitfield
ModelCapabilityFlags
    pub context_window: u32,
    pub max_output_tokens: u32,
    pub description_hash: Option<[u8; 32]>,
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ToolInfo {
    #[max_len(MAX_TOOL_ID_LEN)]
    pub tool_id: String,
    #[max_len(MAX_TOOL_NAME_LEN)]
    pub name: String,
    #[max_len(MAX_TOOL_DESC_LEN)]
    pub description: String,
    #[max_len(MAX_TOOL_VERSION_LEN)]
    pub version: String,
    pub schema_hash: [u8; 32],
    #[max_len(MAX_TOOL_SCHEMA_URI_LEN)]
    pub schema_uri: String,
}

// Re-use ServiceEndpoint struct from Agent Registry or define
here if separate program
#[derive(AnchorSerialize, AnchorDeserialize, Clone, InitSpace)]
pub struct ServiceEndpoint {
    #[max_len(64)]
    pub protocol: String,
    #[max_len(MAX_ENDPOINT_LEN)]
    pub url: String,
    pub is_default: bool,
}

// --- Enums and Flags ---

#[derive(AnchorSerialize, AnchorDeserialize, Clone, PartialEq,
Eq)]
pub enum ServerStatus {
    Inactive = 0,
    Active = 1,
    Maintenance = 2,
    Deprecated = 3,
}

pub mod ServerCapabilityFlags {
    pub const STREAMING: u64 = 1 << 0;
    pub const BATCHING: u64 = 1 << 1;
    pub const FUNCTION_CALLING: u64 = 1 << 2;
    pub const VISION: u64 = 1 << 3;
    pub const AUDIO: u64 = 1 << 4;
    pub const EMBEDDINGS: u64 = 1 << 5;
    pub const FINE_TUNING: u64 = 1 << 6;
    pub const CUSTOM_TOOLS: u64 = 1 << 7;
}

pub mod ModelCapabilityFlags {
    pub const TEXT_GENERATION: u64 = 1 << 0;
    pub const IMAGE_UNDERSTANDING: u64 = 1 << 1;
    pub const CODE_GENERATION: u64 = 1 << 2;
    pub const FUNCTION_CALLING: u64 = 1 << 3; // Model-level
function calling support
    pub const EMBEDDINGS: u64 = 1 << 4;
}

// --- Errors ---
#[error_code]
pub enum ErrorCode {
    #[msg("String exceeds maximum length.")]
    StringTooLong,
    #[msg("Too many items in collection.")]
    TooManyItems,
    #[msg("Invalid Server ID format.")]
    InvalidServerId,
    #[msg("Invalid status value.")]
    InvalidStatus,
    #[msg("No default service endpoint provided.")]
    NoDefaultEndpoint,
    #[msg("Unauthorized operation.")]
    Unauthorized,
    #[msg("Invalid MCP version format.")]
    InvalidMCPVersion,
    #[msg("Invalid Model Info.")]
    InvalidModelInfo,
    #[msg("Invalid Tool Info.")]
    InvalidToolInfo,
    #[msg("Invalid URI format.")]
    InvalidUri,
}

// Helper function for validation (example)
fn is_valid_mcp_version(version: &str) -> bool {
    // Basic check for YYYY-MM-DD format
    version.len() == 10 && version.chars().filter(|&c| c ==
'-').count() == 2
    // Add more robust date parsing/validation if needed
}

// Instruction contexts and handlers will follow...
```

Key Differences from Agent Registry:

- Different PDA seeds (` b

Chapter 7: Security Considerations

7.1 Solana Program Security Best Practices

7.1.1 Input Validation and Sanitization

One of the most critical aspects of Solana program security is rigorous input validation and sanitization. Solana programs process data from untrusted sources (transaction instructions, account data), and failing to validate this input properly can lead to numerous vulnerabilities, including unauthorized access, data corruption, and denial of service.

Sources of Untrusted Input:

1. **Instruction Arguments**: Data passed directly into the program via instruction handlers (`RegisterAgentArgs` , `UpdateMCPServerArgs` , etc.).
2. **Account Data**: Data read from accounts provided in the instruction context, especially accounts not owned by the program itself or accounts whose constraints might be bypassed.

3. **Sysvars**: System variables like `Clock`, `Rent`, etc. While generally trustworthy, their values should be handled carefully (e.g., relying on timestamps for critical logic can be risky due to potential validator clock drift).

Common Validation Checks:

1. **Signer Verification**: Ensure that required accounts (e.g., `owner_authority`, `payer`) have actually signed the transaction. Anchor handles this with the `Signer` type, but manual checks might be needed in complex scenarios.

   `rust // Anchor handles this implicitly with Signer<'info> // Manual check (rarely needed with Anchor): // require!(ctx.accounts.owner_authority.is_signer, ErrorCode::MissingRequiredSignature);`

2. **Account Ownership**: Verify that accounts expected to be owned by the program (like the `entry` PDA) are indeed owned by it. Anchor's `Account` type handles this.

3. **Account Initialization Status**: Ensure accounts are initialized before use and not re-initialized. Anchor's `init` constraint prevents re-initialization.

4. **PDA Derivation and Bump Seed**: Verify that provided PDAs match the expected derivation using the correct seeds and bump. Anchor's `seeds` and `bump` constraints handle this.

   `rust // Anchor handles this via seeds/bump constraints // Manual check (if not using constraints): // let (expected_pda, expected_bump) = Pubkey::find_program_address(// &[/* seeds */], // ctx.program_id, //); // require!(ctx.accounts.entry.key() == expected_pda, ErrorCode::InvalidPDA); // require!(ctx.accounts.entry.bump == expected_bump, ErrorCode::InvalidBump);`

5. **Account Relationships (`has_one`, `constraint`)**: Ensure relationships between accounts hold (e.g., `entry.owner_authority == owner_authority.key()`). Anchor's `has_one` and `constraint` macros simplify this.

   `rust // Anchor handles this via has_one = owner_authority // Manual check: // require!(ctx.accounts.entry.owner_authority == ctx.accounts.owner_authority.key(), ErrorCode::Unauthorized);`

6. **Data Length Constraints**: Validate the length of strings, vectors, and other variable-sized data against predefined maximums to prevent excessive storage usage or buffer overflows (though Rust's safety features mitigate traditional overflows).

   `rust require!(args.name.len() <= MAX_NAME_LEN, ErrorCode::StringTooLong); require!(args.skill_tags.len() <= MAX_SKILL_TAGS, ErrorCode::TooManyItems);`

7. **Data Format and Range Constraints**: Validate data formats (e.g., valid URLs, email formats, specific string patterns like agent IDs) and numeric ranges (e.g., status enums, percentages).

   `rust require!(is_valid_agent_id(&args.agent_id), ErrorCode::InvalidAgentId); require!(new_status <= AgentStatus::Deprecated as u8, ErrorCode::InvalidStatus);`

8. **Uniqueness Constraints**: Ensure uniqueness where required (e.g., `agent_id` combined with `owner_authority` should be unique, enforced by the PDA derivation).

9. **Business Logic Constraints**: Validate inputs against specific business rules (e.g., cannot transfer ownership to self, must have exactly one default endpoint).

   `rust require!(args.service_endpoints.iter().filter(|ep| ep.is_default).count() == 1, ErrorCode::NoDefaultEndpoint); require!(ctx.accounts.old_owner.key() != ctx.accounts.new_owner.key(), ErrorCode::CannotTransferToSelf);`

Sanitization:

While less common in Solana programs compared to web applications (due to the nature of data storage), ensure that data intended for display or use in URIs doesn't contain malicious elements if it's ever processed off-chain based on registry content. Primarily, focus on strict validation.

Defensive Programming:

- Use `require!` macros extensively for checks.
- Define clear, specific `ErrorCode` enums.
- Validate inputs at the beginning of instruction handlers.
- Assume all inputs are potentially malicious until validated.

```
 +---------------------------+      +---------------------------+
 | Untrusted Input Source    |----->| Solana Program            |
 | (Tx Instruction, Acct) |       | (Instruction Handler)    |
+---------------------------+      +---------------------------+
                                     | Validation &
Sanitization |
                                     | - Signer
Checks           |
                                     | - Account Checks
(Owner,  |
                                     |   Init, PDA,
Relations)   |
                                     | - Data Checks
(Length,    |
                                     |   Format, Range,
Unique)  |
                                     | - Business Logic
Checks   |
                                     +-------------+-------------
+
                                                   |
                                     +-------------+-------------
+
                                     | Validated & Safe Data
|
                                     +-------------+-------------
+
                                                   |
                                     +-------------+-------------
+
                                     | Program Logic Execution
|
                                     +---------------------------
+
```

Rigorous input validation is the first line of defense against exploits in Solana programs.

7.1.2 Preventing Re-entrancy and Cross-Program Invocation (CPI) Attacks

While Solana's architecture differs from Ethereum's regarding re-entrancy, vulnerabilities related to Cross-Program Invocations (CPIs) can still exist if not handled carefully.

Re-entrancy in Solana:

Solana's transaction processing model is generally less susceptible to classic re-entrancy attacks seen on Ethereum because programs cannot directly call back into the calling program within the same transaction execution path in the same way. However, vulnerabilities can arise from improper handling of state during CPIs.

CPI Security Risks:

1. **Calling Untrusted Programs**: Making CPI calls to arbitrary or malicious programs specified by user input can lead to unexpected behavior or state corruption.

2. **Incorrect Account Passing**: Passing incorrect accounts (e.g., wrong authority, mismatched state accounts) to the called program during a CPI.

3. **State Mismatches**: If a program's state is modified after a CPI call based on assumptions that might be invalidated by the CPI, it can lead to vulnerabilities. Example: Checking balance, making a CPI, then debiting based on the initial balance check.

4. **Ambiguous PDA Signatures**: If a program signs using PDAs during a CPI, it must ensure the invoked program cannot misuse this signature authority.

Mitigation Strategies:

1. **Hardcode Called Program IDs**: Avoid making CPIs to program IDs provided dynamically by the user. Hardcode the public keys of trusted programs you intend to call.

   `rust // Instead of: let target_program_id = user_provided_key; // Use: const TRUSTED_PROGRAM_ID: Pubkey = pubkey!("TRUSTEDxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx"); // ... ensure CPI target is TRUSTED_PROGRAM_ID`

2. **Validate Accounts Passed via CPI**: When making a CPI, carefully construct the `AccountInfo` list passed to the invoked program. Ensure all accounts are correct and have the necessary permissions (signer, writable).

3. **Use Anchor's CPI Helpers**: Anchor provides safe abstractions for making CPI calls (`CpiContext`) which help manage account passing and signer privileges correctly.

   ```rust use anchor_spl::token::{self, Transfer};

   // Example: CPI to Token Program for transfer let cpi_accounts = Transfer { from: ctx.accounts.source_token_account.to_account_info(), to: ctx.accounts.destination_token_account.to_account_info(), authority: ctx.accounts.authority.to_account_info(), // The authority signing for the transfer }; let cpi_program = ctx.accounts.token_program.to_account_info(); let cpi_ctx =
   ```

CpiContext::new(cpi_program, cpi_accounts); token::transfer(cpi_ctx, amount)?;
```

4. **Check Return Values and State**: After a CPI call returns, re-verify any relevant state that might have been affected by the called program before proceeding with logic that depends on that state.

5. **Limit PDA Signer Privileges**: When using `invoke_signed` for CPIs with PDA authority, ensure the `CpiContext` correctly scopes the signer privileges to only the accounts intended for the CPI.

6. **Atomicity**: Remember that Solana transactions are atomic. If any part of the transaction fails (including CPIs), the entire transaction's state changes are rolled back. This inherently prevents many state inconsistency issues common in other chains.

7. **Avoid Unnecessary CPIs**: Minimize reliance on CPIs, especially to external, less-audited programs.

**Registry Context:**

For the Agent and MCP Server Registries, CPIs are less likely to be a primary feature unless integrating directly with other on-chain systems (e.g., reputation programs, token-gated access). If such integrations are added:

- Ensure the external program ID is hardcoded or comes from a trusted configuration account.
- Carefully construct the `CpiContext`, passing only necessary accounts with correct permissions.
- Validate any data returned or state changed by the CPI.

By following these practices, the risks associated with CPIs can be effectively managed.

### 7.1.3 Secure Account Management

Proper management of account data, ownership, and permissions is fundamental to the security of Solana programs.

**Key Principles:**

1. **Least Privilege**: Programs and instructions should only require the minimum necessary permissions (signer, writable) for the accounts they interact with.
```

2. **Explicit Constraints**: Use Anchor's constraints (`mut`, `has_one`, `seeds`, `bump`, `constraint`, `init`, `close`) extensively to enforce invariants about accounts automatically.

3. **Ownership Checks**: Ensure that instructions modifying an account are authorized by the legitimate owner or authority.

4. **Rent Exemption**: Ensure all accounts created by the program have sufficient lamports for rent exemption to prevent them from being garbage collected.

5. **Account Closure**: Provide secure mechanisms for closing accounts and reclaiming rent, ensuring only authorized parties can do so and that funds are sent to the correct recipient.

Anchor Constraints for Security:

- **`mut`**: Marks an account as writable. Only use when the instruction needs to modify the account's data.
- **`signer`**: Ensures the account's corresponding keypair signed the transaction.
- **`has_one = <field_name> @ ErrorCode`**: Verifies that a field within one account (e.g., `entry.owner_authority`) matches the key of another account passed in the context (e.g., `owner_authority`). Crucial for ownership checks.
- **`seeds = [...]`, `bump = ...`**: Verifies PDA derivation. Essential for ensuring the correct PDA is being accessed and for enabling program signing (`invoke_signed`).
- **`constraint = <expression> @ ErrorCode`**: Enforces arbitrary conditions on account data (e.g., `constraint = entry.status == AgentStatus::Active as u8`).
- **`init`**: Initializes an account, allocating space and assigning ownership to the program. Prevents operating on uninitialized accounts and re-initializing existing ones.
- **`close = <recipient_account>`**: Closes the account and transfers its lamports to the specified recipient account. Ensures secure cleanup.

Common Pitfalls and Mitigations:

1. **Missing `mut`**: Failing to mark a writable account as `mut` will cause the transaction to fail.
2. **Unnecessary `mut`**: Marking read-only accounts as `mut` violates least privilege and might enable unintended modifications if constraints are weak.
3. **Missing Signer Checks**: Allowing modifications without verifying the authority signer.

4. **Incorrect `has_one`**: Linking the wrong accounts in `has_one` can lead to authorization bypasses.
5. **PDA Collision/Misuse**: Incorrect seed design leading to unintended PDA collisions or allowing unauthorized parties to derive PDAs.
6. **Insecure `close`**: Allowing unauthorized closure or specifying the wrong recipient.
7. **Data Validation on Read**: Remember to validate data read from accounts, not just instruction arguments. An attacker could potentially create accounts with invalid data if constraints are insufficient.

Registry Context:

- The `Register` instructions use `init` to securely create PDAs.
- The `Update` and `Close` instructions use `mut`, `has_one`, `seeds`, and `bump` to ensure only the owner can modify or close their specific entry PDA.
- The `Close` instruction uses `close = recipient` for secure rent reclamation.
- The `TransferOwnership` instruction (if implemented) needs careful checks to ensure the new owner account exists and that the `owner_authority` field in the entry is updated correctly, while the PDA itself remains unchanged (as it's derived from the original owner).

Secure account management, largely facilitated by Anchor's constraint system, is vital for maintaining the integrity and authorization model of the registries.

7.2 Protecting Registry Data Integrity

7.2.1 Preventing Unauthorized Modifications

Ensuring that only authorized parties can modify registry entries is paramount. The primary mechanism for this is robust ownership verification.

Ownership Model:

Both the Agent and MCP Server Registries implement a clear ownership model:

- Each registry entry (`AgentRegistryEntryV1`, `MCPServerRegistryEntryV1`) has an `owner_authority` field (a `Pubkey`).
- This `owner_authority` is set during registration and represents the entity authorized to manage the entry.
- The PDA for the entry is derived using seeds that include the `owner_authority`'s public key (along with the `agent_id` or `server_id`). This links the account's address intrinsically to its owner at the time of creation.

Enforcing Ownership:

Anchor's `has_one` constraint is the key tool for enforcing ownership in modification instructions (`UpdateAgent`, `CloseAgentEntry`, `UpdateMCPServer`, `CloseMCPServerEntry`, etc.):

```
 #[derive(Accounts)]
pub struct UpdateAgent<
'info> {
    #[account(
        mut,
        seeds = [/* ... entry.agent_id,
owner_authority.key() ... */],
        bump = entry.bump,
        // This constraint checks: entry.owner_authority ==
owner_authority.key()
        // If it fails, it returns ErrorCode::Unauthorized
        has_one = owner_authority @ ErrorCode::Unauthorized
    )]
    pub entry: Account<
'info, AgentRegistryEntryV1>,

    // This account MUST sign the transaction
    pub owner_authority: Signer<
'info>,
}
```

How it Works:

1. The client invoking the `update_agent` instruction must provide the `entry` account PDA and the `owner_authority` account.
2. The `owner_authority` account must be a signer in the transaction.
3. The `has_one = owner_authority` constraint instructs Anchor to: a. Deserialize the `entry` account data. b. Read the `owner_authority` field from the deserialized `entry` data. c. Compare this stored public key with the public key of the `owner_authority` account passed into the instruction context. d. If they do not match, the instruction fails immediately with the specified `ErrorCode::Unauthorized`.

This ensures that only the keypair corresponding to the public key stored in `entry.owner_authority` can successfully sign a transaction to modify that specific entry.

Ownership Transfer:

If an ownership transfer mechanism is implemented, it must be handled with extreme care:

```
#[derive(Accounts)]
pub struct TransferOwnership<
'info> {
    #[account(
        mut,
        seeds = [/* ... entry.agent_id,
current_owner_authority.key() ... */],
        bump = entry.bump,
        has_one = current_owner_authority @
ErrorCode::Unauthorized
    )]
    pub entry: Account<
'info, AgentRegistryEntryV1>,

    pub current_owner_authority: Signer<
'info>,

    /// CHECK: The new owner doesn't need to sign, but we should
ensure it's a valid Pubkey.
    /// We are just changing the pointer in the entry data.
    pub new_owner_authority: AccountInfo<
'info>,
}

pub fn transfer_ownership(ctx: Context<TransferOwnership>) ->
Result<()> {
    let entry = &mut ctx.accounts.entry;
    let new_owner_key = ctx.accounts.new_owner_authority.key();

    // Prevent transferring to the same owner
    require!(entry.owner_authority != new_owner_key,
ErrorCode::CannotTransferToSelf);

    msg!("Transferring ownership of {} from {} to {}",
         entry.agent_id, entry.owner_authority, new_owner_key);

    // Update the owner authority field
    entry.owner_authority = new_owner_key;
    entry.updated_at = Clock::get()?.unix_timestamp;

    // Emit event
    emit!(AgentOwnershipTransferredEvent {
        agent_id: entry.agent_id.clone(),
        old_owner:
ctx.accounts.current_owner_authority.key(), // The signer
        new_owner: new_owner_key,
        old_pda: entry.key(), // PDA address remains the same
        timestamp: entry.updated_at,
    });

    Ok(())
}
```

Important Considerations for Transfer:

- **PDA Address**: The PDA address does not change because it was derived using the original owner's key. Subsequent updates by the new owner will need to provide the original PDA address but sign with the new owner's key, and the `has_one` constraint will check against the updated `owner_authority` field in the account data.
- **Authorization**: Only the `current_owner_authority` (verified by `has_one`) can initiate the transfer.
- **New Owner Validation**: While the new owner doesn't sign, basic checks on the `new_owner_authority` account info might be prudent (e.g., ensuring it's not the zero address).

By rigorously enforcing ownership checks using `has_one`, the registries prevent unauthorized actors from modifying or deleting entries they do not own.

7.2.2 Data Validation on Updates

Just as input validation is crucial during registration, it's equally important during updates. Attackers could try to update an entry with invalid or malicious data, even if they are the legitimate owner.

Update Instruction Validation:

The `update_agent` and `update_mcp_server` instructions must re-validate any data being modified, using the same checks applied during registration:

- **Length Constraints**: Ensure updated strings and vectors do not exceed maximum lengths.
- **Format Constraints**: Validate formats of IDs, URLs, versions, etc.
- **Range Constraints**: Check enum values and numeric ranges.
- **Business Logic**: Enforce rules like requiring exactly one default endpoint.

```
 pub fn update_agent(ctx: Context<UpdateAgent>, args:
UpdateAgentArgs) -> Result<()> {
    let entry = &mut ctx.accounts.entry;
    // ... (ownership check via has_one) ...

    if let Some(name) = args.name {
        // Re-validate length even on update
        require!(name.len() <= MAX_NAME_LEN,
ErrorCode::StringTooLong);
        entry.name = name;
        // ...
    }
    if let Some(endpoints) = args.service_endpoints {
        // Re-validate endpoint constraints on update
        require!(endpoints.len() > 0 && endpoints.len() <=
MAX_SERVICE_ENDPOINTS, ErrorCode::TooManyItems);
        require!(endpoints.iter().filter(|ep|
ep.is_default).count() == 1, ErrorCode::NoDefaultEndpoint);
        for ep in &endpoints {
           ep.validate_lengths()?;
           // Re-validate URL format if applicable
        }
        entry.service_endpoints = endpoints;
        // ...
    }
    // ... re-validate other updated fields ...

    entry.updated_at = Clock::get()?.unix_timestamp;
    // ... emit event ...
    Ok(())
}
```

Why Re-Validate?

- **Prevent Invalid State**: Ensures the registry entry never enters an invalid state, even after updates.
- **Consistency**: Maintains data consistency according to the defined schema and rules.
- **Security**: Prevents attackers (even the owner) from storing malformed data that could exploit off-chain indexers or clients consuming the data.

Failure to re-validate on updates can lead to data corruption and potential downstream vulnerabilities.

7.2.3 Handling Data Serialization Issues

Solana programs rely on serialization formats (typically Borsh with Anchor) to encode and decode account data and instruction arguments. Errors or vulnerabilities in the serialization process can compromise data integrity or program execution.

Borsh (Binary Object Representation Serializer for Hashing):

- **Specification**: Borsh is designed to be canonical and secure, meaning there's only one valid way to serialize a given object, and it's resistant to certain types of attacks (like hash collision attacks on non-canonical formats).
- **Anchor Integration**: Anchor uses Borsh by default for account and instruction data serialization/deserialization.

Potential Issues:

1. **Data Mismatches**: If the client sends instruction data serialized differently than the program expects (e.g., different field order, incorrect types), deserialization will likely fail, causing the instruction to error. This is generally safe but results in failed transactions.

2. **Account Data Corruption**: If an account's data somehow becomes corrupted on-chain (e.g., due to a bug in a previous instruction, though unlikely with atomic transactions), deserializing it with `Account<T>` might fail.

3. **Denial of Service (DoS) via Large Data**: While `InitSpace` and `#[max_len]` help prevent excessively large accounts during initialization, update instructions need to validate the size of incoming variable-length data (`String` , `Vec`) to prevent attempts to store data exceeding reasonable limits or causing excessive computation during deserialization/validation.

4. **Complex Enum Deserialization**: Borsh handles enums, but complex enum structures or changes in enum variants across program versions require careful handling during upgrades.

5. **IDL Discrepancies**: If the program's IDL (used by clients) gets out of sync with the actual on-chain program's data structures, clients might serialize instruction data incorrectly, leading to deserialization failures.

Mitigation Strategies:

1. **Use Anchor Types**: Rely on Anchor's `Account<T>` , `Program<T>` , `Signer` , etc., as they handle much of the underlying deserialization and validation securely.
2. **Strict Validation**: Implement the input validation checks discussed previously (lengths, formats) to catch invalid data before or during deserialization.
3. **`InitSpace` and `#[max_len]`** : Use these diligently to define clear size limits for account data.
4. **Keep IDL Updated**: Ensure clients always use the IDL corresponding to the deployed program version.

5. **Careful Upgrades**: When upgrading programs with data structure changes, plan migration strategies carefully (see Chapter 9).
6. **Error Handling**: Implement clear error codes for validation failures.

While Borsh and Anchor provide a relatively secure serialization foundation, developers must remain vigilant about validating data sizes and formats to prevent potential issues.

7.3 Client-Side Security

7.3.1 Secure Key Management

Clients interacting with the registries (whether they are end-user wallets, backend services, or agents themselves) need to manage cryptographic keys securely. Compromised keys lead to unauthorized transactions and loss of control over registry entries.

Key Types:

- **Payer Key**: Signs transactions and pays for fees and rent. Often a temporary or service-specific key.
- **Owner Authority Key**: The keypair corresponding to the `owner_authority` public key stored in a registry entry. This key authorizes modifications and deletion of the entry.

Best Practices:

1. **Avoid Hardcoding Keys**: Never hardcode private keys directly in client-side code (web apps, mobile apps) or commit them to version control.

2. **Use Hardware Wallets**: For high-value owner authority keys, use hardware wallets (e.g., Ledger) for signing transactions. This keeps the private key isolated from the potentially compromised client machine.

3. **Use Secure Wallet Software**: Interact with the blockchain via trusted wallet software (e.g., Phantom, Solflare, Backpack) that manages keys securely.

4. **Environment Variables/Secrets Management**: For backend services or scripts, store private keys securely using environment variables, secrets management systems (like AWS Secrets Manager, HashiCorp Vault), or encrypted configuration files. Avoid plaintext storage.

5. **Key Rotation**: Implement policies for rotating keys periodically, especially for payer or session keys.

6. **Least Privilege for Keys**: Use different keys for different purposes. Don't use a high-value owner authority key as a general payer key.

7. **Secure Backup**: Securely back up private keys or seed phrases, stored offline and protected from physical loss or theft.

8. **Transaction Simulation**: Before signing, simulate transactions using the RPC `simulateTransaction` method to understand their effects and required signers.

9. **Clear Signing Prompts**: Wallet software should present clear, understandable prompts to the user before signing any transaction, detailing the accounts involved and the expected actions.

Compromised client keys undermine the entire security model, regardless of how secure the on-chain program is.

7.3.2 Validating Data from Off-chain Indexers

Clients often rely on off-chain indexers for efficient discovery (as discussed in Chapter 5). However, data from indexers is inherently less trustworthy than direct on-chain data.

Risks of Off-chain Data:

1. **Stale Data**: Indexers might lag behind the blockchain state.
2. **Incorrect Data**: Bugs in the indexer logic could lead to incorrect data representation.
3. **Malicious Indexer**: A compromised or malicious indexer could intentionally serve false information.

Mitigation Strategies:

1. **Verify On-Chain**: As highlighted in the hybrid discovery pattern, always verify critical information obtained from an indexer by fetching the corresponding account data directly from the blockchain before making important decisions or transactions.

    - Verify status, owner, capabilities, endpoints.
    - Verify schema hashes for tools.

2. **Cross-Referencing**: Query multiple independent indexers (if available) and compare results.

3. **Check Timestamps**: Pay attention to the

Chapter 8: Performance Optimization

8.1 Account Storage Optimization

8.1.1 Minimizing Account Size

In Solana, every byte of on-chain storage comes at a cost. Accounts storing registry entries must be rent-exempt, meaning they must maintain a balance of SOL proportional to their size. Minimizing account size is therefore crucial for cost efficiency and scalability.

Storage Cost Fundamentals:

Solana charges rent based on account size at a rate of approximately 0.00000348 SOL per byte per year (as of 2025). While this might seem small, it adds up quickly for larger accounts or when deploying many accounts. For rent exemption, accounts must hold a balance covering two years of rent.

Size Calculation:

For an `AgentRegistryEntryV1` account, the total size includes: 1. **Account Discriminator**: 8 bytes (added by Anchor) 2. **Fixed-Size Fields**: Sum of all fixed-size fields (e.g., `u8`, `Pubkey`, `i64`, `u64`) 3. **Variable-Size Fields**: Space allocated for variable-length data like strings and vectors

```
 // Example size calculation for AgentRegistryEntryV1
// Fixed-size fields
let fixed_size =
    1 + // bump (u8)
    1 + // registry_version (u8)
    32 + // owner_authority (Pubkey)
    1 + // status (u8)
    8 + // capabilities_flags (u64)
    8 + // created_at (i64)
    8; // updated_at (i64)

// Variable-size fields (with max lengths)
let variable_size =
    (4 + MAX_AGENT_ID_LEN) + // agent_id (String: 4 bytes for
length + max content)
    (4 + MAX_NAME_LEN) + // name
    (4 + MAX_DESCRIPTION_LEN) + // description
    (4 + MAX_VERSION_LEN) + // agent_version
    (4 + (5 * 64)) + // supported_protocols (Vec: 4 bytes for
length + max 5 items * 64 chars)
```

```
    (4 + (MAX_SKILL_TAGS * MAX_SKILL_TAG_LEN)) + // skill_tags
    (4 + (MAX_SERVICE_ENDPOINTS * (4 + 64 + 4 +
MAX_ENDPOINT_LEN + 1))) + // service_endpoints
    (1 + (4 + 256)) + // documentation_url (Option: 1 byte for
Some/None + max content)
    (1 + (4 + 256)); // extended_metadata_uri

// Total size (including discriminator)
let total_size = 8 + fixed_size + variable_size;
```

With Anchor's `InitSpace` derive macro, this calculation is automated, but understanding it helps optimize account design.

Optimization Strategies:

1. **Use Appropriate Data Types**:
2. Use the smallest integer type that can represent your range (`u8` instead of `u32` for small enums).
3. Use `bool` (1 byte) instead of enums for binary states.
4. Consider using bit flags (`u64`) for multiple boolean flags instead of separate fields.
5. **Limit String Lengths**:
6. Define strict maximum lengths for strings based on actual needs.
7. Use shorter identifiers where possible.
8. Consider using abbreviations or codes for predictable values.
9. **Optimize Collections**:
10. Limit the maximum size of vectors (`Vec<T>`).
11. Consider fixed-size arrays if the number of items is constant.
12. For sparse collections, consider alternative representations (e.g., bit flags for capabilities).
13. **Use Optional Fields Judiciously**:
14. `Option<T>` adds 1 byte overhead for the Some/None tag.
15. Group related optional fields that tend to be present or absent together.
16. **Consider Off-Chain Storage**:
17. Store large, rarely-queried data off-chain (e.g., detailed descriptions, schemas).
18. Use on-chain hashes to verify integrity of off-chain data.

19. Store URIs pointing to off-chain storage (IPFS, Arweave) for detailed metadata.

```
+----------------------------+     +----------------------------+
|                            |     |                            |
|  On-Chain Registry Entry   |     |  Off-Chain Storage         |
|                            |     |  (IPFS, Arweave)           |
|  - Core metadata           |     |                            |
|  - Essential fields        |     |  - Detailed descriptions   |
|  - Critical identifiers    |     |  - Complete schemas        |
|  - Verification hashes     |---->|  - Historical data         |
|  - Storage URIs            |     |  - Large media             |
|                            |     |                            |
+----------------------------+     +----------------------------+
```

Registry-Specific Optimizations:

For the Agent and MCP Server Registries, consider:

1. **Tool Schemas**: Store only hashes on-chain, with full schemas off-chain.
2. **Detailed Descriptions**: Limit on-chain descriptions to summaries, with extended descriptions off-chain.
3. **Historical Data**: Store only current state on-chain, with history tracked off-chain.
4. **Skill Tags and Protocols**: Use standardized, short identifiers from a predefined list.
5. **Service Endpoints**: Store only essential connection information on-chain.

By carefully optimizing account size, you can significantly reduce the cost of deploying and maintaining registry entries while still preserving essential functionality.

8.1.2 Efficient Data Structures

Beyond minimizing raw storage size, the choice and organization of data structures significantly impacts program performance and usability.

Efficient Field Organization:

1. **Group Fixed-Size Fields**: Place fixed-size fields together at the beginning of the account structure. This improves memory alignment and can make deserialization more efficient.

```rust
 // Optimized field ordering
pub struct AgentRegistryEntryV1 {
    // Fixed-size fields first
    pub bump: u8,
    pub registry_version: u8,
    pub status: u8,
    pub owner_authority: Pubkey, // 32 bytes
    pub capabilities_flags: u64,
    pub created_at: i64,
    pub updated_at: i64,

    // Then variable-size fields
    pub agent_id: String,
    pub name: String,
    // ...
}
```

1. **Locality of Reference**: Group fields that are frequently accessed together. This improves cache efficiency when reading account data.

Efficient Collections:

1. **Vectors vs. Arrays**: For collections with a fixed maximum size, consider the trade-offs:
2. `Vec<T>` : More flexible but requires 4 bytes for length tracking.

3. `[T; N]` : Fixed-size, no length overhead, but may waste space if not fully utilized.

4. **Sparse Collections**: For collections where most elements might be empty or default, consider alternative representations:

5. Bit flags for boolean properties.
6. Compressed encoding for sparse arrays.

7. Key-value pairs for sparse mappings.

8. **Nested Structures**: Balance between flat and nested structures:

9. Flat structures are simpler to access but can lead to repetition.
10. Nested structures reduce repetition but add complexity and potential overhead.

Bitfields for Flags:

Both registries use bitfields (`capabilities_flags`) to efficiently store multiple boolean flags:

```
// Define flags as bit positions
pub mod AgentCapabilityFlags {
    pub const A2A_MESSAGING: u64 = 1 << 0; // 0b00000001
    pub const MCP_CLIENT: u64 = 1 << 1;    // 0b00000010
    pub const TASK_EXECUTION: u64 = 1 << 2; // 0b00000100
    // ...up to 64 flags in a u64
}
```

```
// Setting flags
entry.capabilities_flags =
    AgentCapabilityFlags::A2A_MESSAGING |
    AgentCapabilityFlags::TASK_EXECUTION;

// Checking flags
if (entry.capabilities_flags &
AgentCapabilityFlags::A2A_MESSAGING) != 0 {
    // Agent supports A2A messaging
}
```

This approach stores up to 64 boolean flags in just 8 bytes, compared to 64 bytes for individual boolean fields.

Enums vs. Integer Constants:

For status values and other enumerated types, consider the trade-offs:

```
// Option 1: Rust enum (more type-safe, but requires conversion
for storage)
#[derive(AnchorSerialize, AnchorDeserialize, Clone, PartialEq,
Eq)]
pub enum AgentStatus {
    Inactive = 0,
    Active = 1,
    Deprecated = 2,
}
// Store as: entry.status = AgentStatus::Active as u8;
// Check as: if entry.status == AgentStatus::Active as u8
{ ... }

// Option 2: Integer constants (less type-safe, but direct
storage)
pub mod AgentStatus {
    pub const INACTIVE: u8 = 0;
    pub const ACTIVE: u8 = 1;
    pub const DEPRECATED: u8 = 2;
}
// Store as: entry.status = AgentStatus::ACTIVE;
// Check as: if entry.status == AgentStatus::ACTIVE { ... }
```

The enum approach provides better type safety but requires conversion for storage and checking. The integer constants approach is more direct but less type-safe.

String Interning:

For fields with a limited set of possible values (e.g., protocols, skill tags), consider string interning—using predefined identifiers instead of arbitrary strings:

```
 // Instead of arbitrary strings:
entry.supported_protocols = vec!["a2a".to_string(),
"mcp".to_string()];

// Use predefined identifiers (potentially shorter and
standardized):
pub mod ProtocolId {
    pub const A2A: &str = "a2a";
    pub const MCP: &str = "mcp";
    // ...
}
entry.supported_protocols = vec![ProtocolId::A2A.to_string(),
ProtocolId::MCP.to_string()];
```

This approach ensures consistency, reduces storage requirements, and simplifies validation.

By carefully designing data structures with performance in mind, you can create registry programs that are not only storage-efficient but also computationally efficient and user-friendly.

8.1.3 Rent Considerations

Solana's rent mechanism requires accounts to maintain a balance proportional to their size to avoid being purged from the network. Understanding and optimizing for rent is crucial for cost-effective registry operation.

Rent Exemption:

All registry entry accounts should be rent-exempt, meaning they hold enough SOL to cover rent indefinitely. Anchor's `init` constraint automatically handles rent exemption for new accounts:

```
 #[account(
    init,
    payer = payer,
    space = 8 + AgentRegistryEntryV1::INIT_SPACE,
    seeds = [...],
    bump
)]
pub entry: Account<'info, AgentRegistryEntryV1>,
```

This constraint ensures: 1. The `payer` account provides enough SOL for rent exemption. 2. The account is initialized with the specified space. 3. The account becomes rent-exempt.

Calculating Rent Exemption:

The amount of SOL required for rent exemption depends on the account size:

```
 // Example calculation (client-side)
async function calculateRentExemption(connection: Connection,
size: number): Promise<number> {
    const rentExemptionAmount = await
connection.getMinimumBalanceForRentExemption(size);
    return rentExemptionAmount;
}

// For a typical AgentRegistryEntryV1 account (example size:
1024 bytes)
const accountSize = 1024; // Bytes
const rentExemption = await calculateRentExemption(connection,
accountSize);
console.log(`Rent exemption for ${accountSize} bytes: $
{rentExemption / LAMPORTS_PER_SOL} SOL`);
```

Rent Recovery:

When an account is closed, its balance (including the rent exemption) is transferred to a recipient account. Anchor's `close` constraint handles this:

```
 #[account(
    mut,
    seeds = [...],
    bump = entry.bump,
    has_one = owner_authority @ ErrorCode::Unauthorized,
    close = recipient // Close account and transfer lamports to
recipient
)]
pub entry: Account<'info, AgentRegistryEntryV1>,
```

This ensures that the SOL locked for rent exemption is not lost when an entry is removed from the registry.

Rent Optimization Strategies:

1. **Size-Based Pricing**: If implementing a fee structure for registry entries, consider scaling fees based on entry size to cover the higher rent costs of larger entries.

2. **Account Reuse**: Instead of closing and re-creating accounts, consider updating existing accounts when possible. This avoids the transaction costs of account creation and closure.

3. **Delayed Cleanup**: For temporary deactivations, consider marking entries as inactive rather than closing them. This preserves the rent exemption and allows for easier reactivation.

4. **Rent Subsidies**: Registry operators might consider subsidizing rent costs for certain types of entries to encourage ecosystem participation.

5. **Size Tiers**: Offer different "tiers" of registry entries with different maximum sizes and corresponding costs.

```
 +---------------------------+     +---------------------------+
|                            |     |                            |
|  Basic Tier Entry          |     |  Premium Tier Entry        |
|                            |     |                            |
|  - Limited description     |     |  - Extended description    |
|  - Few skill tags          |     |  - Many skill tags         |
|  - Single endpoint         |     |  - Multiple endpoints      |
|  - No extended metadata    |     |  - Extended metadata       |
|                            |     |                            |
|  Size: ~512 bytes          |     |  Size: ~2048 bytes         |
|  Rent: ~0.0018 SOL         |     |  Rent: ~0.0072 SOL         |
+---------------------------+     +---------------------------+
```

Rent Changes:

Be aware that Solana's rent rates might change over time through governance decisions. Design your system to be adaptable to such changes:

1. **Parameterize Rent Calculations**: Don't hardcode rent assumptions in your program.
2. **Monitor Governance Proposals**: Stay informed about potential changes to Solana's rent economics.
3. **Plan for Migration**: Have strategies ready for migrating accounts if rent economics change significantly.

By carefully considering rent in your registry design, you can create a cost-effective system that balances storage efficiency with functionality and usability.

8.2 Compute Unit Optimization

8.2.1 Instruction Complexity Analysis

Solana transactions have a compute budget—a limit on the computational resources they can consume. Understanding and optimizing instruction complexity is crucial for ensuring transactions complete successfully and efficiently.

Compute Budget Basics:

As of 2025, Solana's default compute budget is 200,000 compute units (CU) per transaction. Instructions that exceed this budget will fail. Complex operations like registry entry creation or updates with extensive validation can approach this limit.

Analyzing Instruction Complexity:

To understand the compute complexity of registry instructions, consider:

1. **Deserialization Overhead**: Deserializing account data and instruction arguments consumes compute units proportional to their size and complexity.

2. **Validation Logic**: Each validation check (`require!` statement) adds compute overhead, especially for string and collection validations.

3. **Data Manipulation**: Operations like string concatenation, vector operations, and nested structure manipulation consume compute units.

4. **Serialization Overhead**: Writing updated data back to accounts consumes compute units proportional to the data size.

Measuring Compute Usage:

Use Solana's simulation features to measure the compute units consumed by your instructions:

```
// Client-side simulation to measure compute usage
async function measureComputeUsage(
    connection: Connection,
    transaction: Transaction,
    signers: Keypair[]
): Promise<number> {
    const simulation = await
connection.simulateTransaction(transaction, signers);

    if (simulation.value.err) {
        throw new Error(`Simulation failed: $
{JSON.stringify(simulation.value.err)}`);
    }

    const computeUnits = simulation.value.unitsConsumed || 0;
    return computeUnits;
}

// Example usage
const registerAgentTx = await program.methods
    .registerAgent(args)
    .accounts({...})
    .transaction();

const computeUsed = await measureComputeUsage(connection,
registerAgentTx, [payer, ownerAuthority]);
console.log(`Register agent instruction uses ${computeUsed}
compute units`);
```

Complexity Hotspots:

Based on the registry design, these operations are likely to consume significant compute:

1. **String Validations**: Checking string lengths, formats, and patterns.
2. **Collection Validations**: Validating vectors of skill tags, service endpoints, supported tools, etc.
3. **Nested Structure Processing**: Validating and processing nested structures like `ServiceEndpoint`, `ModelInfo`, and `ToolInfo`.
4. **PDA Derivation**: Deriving PDAs with multiple seeds.

Optimization Strategies:

1. **Minimize Validation Redundancy**: Avoid redundant checks. For example, if Anchor's `#[max_len]` already constrains a vector's length, additional length checks might be unnecessary.

2. **Efficient String Validation**: Use efficient algorithms for string validation. For example, checking if a string contains only alphanumeric characters:

```
 // Less efficient (multiple allocations and function calls)
require!(agent_id.chars().all(|c| c.is_alphanumeric() || c ==
'-' || c == '_'), ErrorCode::InvalidAgentId);

// More efficient (single pass, no allocation)
for c in agent_id.bytes() {
    require!(
        (c >= b'a' && c <= b'z') ||
        (c >= b'A' && c <= b'Z') ||
        (c >= b'0' && c <= b'9') ||
        c == b'-' || c == b'_',
        ErrorCode::InvalidAgentId
    );
}
```

1. **Batch Processing**: If an instruction needs to process multiple items (e.g., validating multiple service endpoints), consider batching similar operations to reduce overhead.

2. **Early Returns**: Check the most likely failure conditions first to avoid unnecessary computation.

3. **Limit Collection Sizes**: Strictly limit the size of collections to prevent excessive computation.

4. **Incremental Updates**: For updates, consider allowing incremental updates to specific fields rather than requiring a complete entry update.

By analyzing and optimizing the compute complexity of your registry instructions, you can ensure they remain within Solana's compute budget constraints while providing the necessary functionality.

8.2.2 Optimizing Validation Logic

Validation logic is essential for registry security but can be computationally expensive. Optimizing this logic is crucial for staying within compute budgets while maintaining security.

Efficient String Validation:

1. **Length Checks First**: Perform length checks before more complex validations to fail fast on oversized inputs.

```
 // Efficient validation order
pub fn validate_agent_id(agent_id: &str) -> Result<()> {
    // Check length first (cheap operation)
    require!(agent_id.len() > 0 && agent_id.len() <=
MAX_AGENT_ID_LEN, ErrorCode::InvalidAgentId);

    // Then check format (more expensive)
    for c in agent_id.bytes() {
        require!(
            (c >= b'a' && c <= b'z') ||
            (c >= b'A' && c <= b'Z') ||
            (c >= b'0' && c <= b'9') ||
            c == b'-' || c == b'_',
            ErrorCode::InvalidAgentId
        );
    }

    Ok(())
}
```

1. **Avoid Regex**: Regular expressions are powerful but computationally expensive. Use simpler character-by-character validation when possible.

2. **Reuse Validation Functions**: Define reusable validation functions for common patterns to avoid code duplication and ensure consistent validation.

Efficient Collection Validation:

1. **Check Length Before Content**: Validate collection length before iterating through elements.

```
// Efficient collection validation
pub fn validate_skill_tags(tags: &[String]) -> Result<()> {
    // Check collection length first
    require!(tags.len() <= MAX_SKILL_TAGS,
ErrorCode::TooManyItems);

    // Then validate individual items
    for tag in tags {
        require!(tag.len() > 0 && tag.len() <=
MAX_SKILL_TAG_LEN, ErrorCode::InvalidSkillTag);
        // Additional tag validation...
    }

    Ok(())
}
```

1. **Early Exit**: Return errors as soon as an invalid item is found rather than checking all items.

2. **Batch Similar Checks**: Group similar validations to reduce branching and improve instruction cache efficiency.

Optimizing Complex Validations:

1. **Hierarchical Validation**: For complex nested structures, validate in a hierarchical manner, starting with the most critical or likely-to-fail properties.

```
 // Hierarchical validation for service endpoints
pub fn validate_service_endpoints(endpoints:
&[ServiceEndpoint]) -> Result<()> {
    // Top-level validation
    require!(endpoints.len() > 0 && endpoints.len() <=
MAX_SERVICE_ENDPOINTS, ErrorCode::TooManyItems);

    // Check for exactly one default endpoint
    let default_count = endpoints.iter().filter(|ep|
ep.is_default).count();
    require!(default_count == 1, ErrorCode::NoDefaultEndpoint);

    // Validate individual endpoints
    for ep in endpoints {
        // Protocol validation (critical)
        require!(ep.protocol.len() > 0 && ep.protocol.len() <=
64, ErrorCode::StringTooLong);

        // URL validation (more complex)
        require!(ep.url.len() > 0 && ep.url.len() <=
MAX_ENDPOINT_LEN, ErrorCode::StringTooLong);
        validate_url(&ep.url)?;
    }

    Ok(())
}
```

1. **Validation Levels**: Consider implementing different validation levels based on context:
2. **Basic Validation**: Essential checks that must always pass.
3. **Extended Validation**: Additional checks for higher-quality entries.
4. **Conditional Validation**: Checks that only apply in certain contexts.
5. **Caching Validation Results**: For complex validations that might be repeated, consider caching results to avoid redundant computation.

Balancing Security and Efficiency:

While optimization is important, never sacrifice security for performance. Some guidelines:

1. **Maintain Critical Checks**: Never remove validations that protect against security vulnerabilities or data corruption.
2. **Benchmark Changes**: Measure the compute impact of validation optimizations to ensure they actually improve performance.

3. **Consider Trade-offs**: Sometimes, a slightly more expensive validation is worth it for better security or user experience.

4. **Document Assumptions**: Clearly document any assumptions or prerequisites that allow for validation optimizations.

By carefully optimizing validation logic, you can significantly reduce the compute requirements of your registry instructions while maintaining robust security.

8.2.3 Transaction Batching Strategies

For operations that involve multiple registry entries or complex updates, transaction batching strategies can help manage compute budget constraints and improve efficiency.

Single vs. Multiple Instructions:

Consider the trade-offs between including multiple operations in a single instruction versus splitting them across multiple instructions:

1. **Single Instruction Approach**:
2. **Pros**: Atomic execution, simpler client code, potentially lower overall fees.

3. **Cons**: Higher risk of exceeding compute budget, more complex program logic.

4. **Multiple Instruction Approach**:

5. **Pros**: Each instruction has its own compute budget, simpler program logic.
6. **Cons**: Not atomic (partial execution possible), more complex client code, potentially higher fees.

Instruction Batching:

For operations that naturally involve multiple items (e.g., registering multiple agents), consider implementing batch instructions:

```
 // Batch registration instruction
#[derive(Accounts)]
#[instruction(args: BatchRegisterAgentsArgs)]
pub struct BatchRegisterAgents<'info> {
    // Common accounts (payer, system program)
    #[account(mut)]
    pub payer: Signer<'info>,
    pub system_program: Program<'info, System>,

    // Owner authority (common for all entries in this example)
    pub owner_authority: Signer<'info>,
    // Note: Individual entry PDAs will be created via CPI in
the instruction handler
}

#[derive(AnchorSerialize, AnchorDeserialize, Clone)]
pub struct BatchRegisterAgentsArgs {
    pub entries: Vec<RegisterAgentArgs>, // Limited to a
reasonable maximum
}

pub fn batch_register_agents(ctx: Context<BatchRegisterAgents>,
args: BatchRegisterAgentsArgs) -> Result<()> {
    // Validate batch size
    require!(args.entries.len() > 0 && args.entries.len() <= 5,
ErrorCode::InvalidBatchSize);

    // Process each entry
    for entry_args in args.entries {
        // Create PDA for this entry
        let seeds = [
            b"agent_registry".as_ref(),
            entry_args.agent_id.as_bytes(),
            ctx.accounts.owner_authority.key().as_ref(),
        ];
        let (entry_pda, bump) =
Pubkey::find_program_address(&seeds, ctx.program_id);

        // Validate entry args
        // ... validation logic ...

        // Create and initialize entry account via CPI to self
        // This is a simplified example; actual implementation
would be more complex
        let register_ix = self::register_agent(
            *ctx.program_id,
            entry_pda,
            ctx.accounts.payer.key(),
            ctx.accounts.owner_authority.key(),
            ctx.accounts.system_program.key(),
            entry_args,
        );

        solana_program::program::invoke(
            &register_ix,
            &[
                ctx.accounts.payer.to_account_info(),
                ctx.accounts.owner_authority.to_account_info(),
                ctx.accounts.system_program.to_account_info(),
            ],
        )?;
    }
    Ok(())
}
```

Transaction Batching:

For operations that exceed a single transaction's compute budget, split them across multiple transactions:

```
 // Client-side transaction batching
async function registerManyAgents(
    program: Program<AgentRegistry>,
    agents: RegisterAgentArgs[],
    ownerKeypair: Keypair,
    payerKeypair: Keypair
): Promise<string[]> {
    const BATCH_SIZE = 3; // Adjust based on compute
requirements
    const txIds: string[] = [];

    // Process in batches
    for (let i = 0; i < agents.length; i += BATCH_SIZE) {
        const batch = agents.slice(i, i + BATCH_SIZE);
        const tx = new Transaction();

        // Add instructions for this batch
        for (const agentArgs of batch) {
            const ix = await program.methods
                .registerAgent(agentArgs)
                .accounts({
                    // ... account setup ...
                })
                .instruction();

            tx.add(ix);
        }

        // Sign and send transaction
        const txId = await sendAndConfirmTransaction(
            program.provider.connection,
            tx,
            [payerKeypair, ownerKeypair]
        );

        txIds.push(txId);
        console.log(`Batch ${Math.floor(i / BATCH_SIZE) + 1}
registered, txId: ${txId}`);
    }
    return txIds;
}
```

Prioritization Strategies:

When batching operations, consider prioritization strategies:

1. **Critical First**: Process the most critical operations first to ensure they complete even if later batches fail.
2. **Dependency Order**: Process operations in dependency order to maintain consistency.
3. **Size-Based**: Group operations by size or complexity to balance compute usage across transactions.
4. **Failure Handling**: Implement retry logic for failed batches, potentially with backoff strategies.

Versioned Transactions:

Solana's versioned transactions support can be leveraged for more efficient batching:

```
// Using versioned transactions for more efficient batching
async function batchRegisterWithVersionedTx(
    program: Program<AgentRegistry>,
    agents: RegisterAgentArgs[],
    ownerKeypair: Keypair,
    payerKeypair: Keypair
): Promise<string[]> {
    const BATCH_SIZE = 5; // Potentially larger due to address
lookup tables
    const txIds: string[] = [];

    // Create address lookup table for frequently used accounts
    const [lookupTableInst, lookupTableAddress] =
AddressLookupTableProgram.createLookupTable({
        authority: payerKeypair.publicKey,
        payer: payerKeypair.publicKey,
        recentSlot: await program.provider.connection.getSlot(),
    });

    // Add frequently used addresses
    const extendInstruction =
AddressLookupTableProgram.extendLookupTable({
        payer: payerKeypair.publicKey,
        authority: payerKeypair.publicKey,
        lookupTable: lookupTableAddress,
        addresses: [
            program.programId,
            SystemProgram.programId,
            ownerKeypair.publicKey,
            // Add other common addresses
        ],
    });

    // Send and confirm lookup table setup
    await sendAndConfirmTransaction(
        program.provider.connection,
        new
Transaction().add(lookupTableInst).add(extendInstruction),
        [payerKeypair]
    );

    // Process agent registrations in batches
    for (let i = 0; i < agents.length; i += BATCH_SIZE) {
        const batch = agents.slice(i, i + BATCH_SIZE);
        const messageV0 = new TransactionMessage({
            payerKey: payerKeypair.publicKey,
            recentBlockhash: (await
program.provider.connection.getLatestBlockhash()).blockhash,
            instructions: await Promise.all(batch.map(agentArgs
=>
                program.methods
                    .registerAgent(agentArgs)
                    .accounts({
                        // ... account setup ...
                    })
                    .instruction()
            )),
        }).compileToV0Message([
            await
program.provider.connection.getAddressLookupTable(lookupTableAddress).ther
=> res.value)
        ]);

        // Create and sign versioned transaction
        const versionedTx = new VersionedTransaction(messageV0);
        versionedTx.sign([payerKeypair, ownerKeypair]);

        // Send transaction
        const txId = await
program.provider.connection.sendTransaction(versionedTx);
        txIds.push(txId);
    }

    return txIds;
}
```

By implementing effective transaction batching strategies, you can manage compute budget constraints while providing efficient bulk operations for registry users.

8.3 Client-Side Optimization

8.3.1 Efficient RPC Usage

Optimizing client-side interactions with Solana RPC nodes is crucial for building responsive and cost-effective registry applications.

Understanding RPC Costs:

Solana RPC requests consume resources and may be rate-limited or charged for by RPC providers. Common expensive operations include:

1. **`getProgramAccounts`**: Fetching all accounts owned by a program, especially with filters.
2. **`getMultipleAccounts`**: Fetching many accounts in a single request.
3. **High-frequency polling**: Repeatedly checking for account updates.
4. **Large transaction simulations**: Simulating complex transactions.

Optimization Strategies:

1. **Use Specific Account Fetching**:
2. When possible, fetch specific accounts by address rather than using `getProgramAccounts`.
3. Use the hybrid discovery pattern discussed in Chapter 5, leveraging off-chain indexers for initial filtering.

```
 // Instead of this (expensive):
const allAgents = await
connection.getProgramAccounts(programId, {
    filters: [
        { dataSize: 1024 }, // Approximate size of
AgentRegistryEntryV1
        { memcmp: { offset: 41, bytes:
ownerPublicKey.toBase58() } }, // Filter by owner
    ],
});

// Do this (more efficient):
// 1. Query off-chain indexer for candidate PDAs
const candidatePDAs = await
indexerAPI.getAgentsByOwner(ownerPublicKey.toString());

// 2. Fetch specific accounts
const agentAccounts = await
```

```
connection.getMultipleAccounts(candidatePDAs.map(pda => new
PublicKey(pda)));
```

1. **Batch Account Fetching**:
2. Use `getMultipleAccounts` to fetch multiple accounts in a single RPC request.
3. Limit batch size to reasonable values (e.g., 100 accounts per request).

```
// Efficient batched fetching
async function fetchAgentsBatched(
    connection: Connection,
    pdas: PublicKey[]
): Promise<(AccountInfo<Buffer> | null)[]> {
    const BATCH_SIZE = 100;
    const allAccounts: (AccountInfo<Buffer> | null)[] = [];

    for (let i = 0; i < pdas.length; i += BATCH_SIZE) {
        const batch = pdas.slice(i, i + BATCH_SIZE);
        const accounts = await
connection.getMultipleAccounts(batch);
        allAccounts.push(...accounts.value);
    }

    return allAccounts;
}
```

1. **Use WebSocket Subscriptions**:
2. Instead of polling, use WebSocket subscriptions for real-time updates.
3. Subscribe to specific accounts of interest rather than program-wide logs.

```
// Efficient real-time updates with WebSockets
function subscribeToAgentUpdates(
    connection: Connection,
    agentPDA: PublicKey,
    callback: (accountInfo: AccountInfo<Buffer>) => void
): number {
    return connection.onAccountChange(
        agentPDA,
        callback,
        'confirmed'
    );
}

// Later, unsubscribe when no longer needed
connection.removeAccountChangeListener(subscriptionId);
```

1. **Implement Client-Side Caching**:
2. Cache account data with appropriate TTL (Time To Live).

3. Invalidate cache entries based on WebSocket notifications.

```
// Simple client-side cache
class AccountCache {
    private cache = new Map<string, { data:
AccountInfo<Buffer>, timestamp: number }>();
    private readonly TTL_MS = 30000; // 30 seconds

    async getAccount(
        connection: Connection,
        pubkey: PublicKey
    ): Promise<AccountInfo<Buffer> | null> {
        const key = pubkey.toString();
        const cached = this.cache.get(key);

        if (cached && (Date.now() - cached.timestamp <
this.TTL_MS)) {
            return cached.data;
        }

        // Cache miss or expired
        const account = await connection.getAccountInfo(pubkey);
        if (account) {
            this.cache.set(key, { data: account, timestamp:
Date.now() });
        } else {

this.cache.delete(key); // Remove if account doesn't exist
        }

        return account;
    }

    invalidate(pubkey: PublicKey): void {
        this.cache.delete(pubkey.toString());
    }
}
```

1. **Optimize Transaction Confirmation Strategies**:
2. Use appropriate commitment levels based on needs:
    - `processed`: Fastest but least certain.
    - `confirmed`: Good balance for most operations.
    - `finalized`: Slowest but most certain.
3. Implement progressive confirmation for better UX.

```
// Progressive confirmation strategy
async function sendWithProgressiveConfirmation(
    connection: Connection,
    transaction: Transaction,
    signers: Keypair[]
): Promise<string> {
    const txId = await sendAndConfirmTransaction(
        connection,
        transaction,
        signers,
        { commitment: 'processed' } // Initial fast confirmation
    );

    // Update UI immediately
    updateUI({ status: 'processed', txId });

    // Then wait for higher confirmation levels
    connection.onSignature(
        txId,
        (result) => {
            if (result.err) return;
            updateUI({ status: 'confirmed', txId });
        },
        'confirmed'
    );

    connection.onSignature(
        txId,
        (result) => {
            if (result.err) return;
            updateUI({ status: 'finalized', txId });
        },
        'finalized'
    );

    return txId;
}
```

1. **Use Pagination for Large Result Sets**:
2. When fetching many accounts, implement pagination to avoid large RPC responses.
3. Use cursor-based pagination when possible.

```
// Paginated fetching from indexer
async function fetchAgentsPaginated(
    indexerAPI: IndexerAPI,
    ownerPublicKey: PublicKey,
    pageSize: number = 20
): Promise<AgentInfo[]> {
    let allAgents: AgentInfo[] = [];
    let cursor: string | null = null;

    do {
        const response = await indexerAPI.getAgentsByOwner({
            owner: ownerPublicKey.toString(),
            limit: pageSize,
            cursor: cursor,
        });

        allAgents = allAgents.concat(response.agents);
        cursor = response.nextCursor;
    } while (cursor);

    return allAgents;
}
```

By implementing these RPC optimization strategies, you can build registry clients that are responsive, cost-effective, and respectful of RPC resource constraints.

8.3.2 Transaction Retry and Error Handling

Solana's high-throughput nature means transactions can occasionally fail due to network congestion, timeout, or other temporary issues. Implementing robust retry and error handling is essential for reliable registry client applications.

Common Transaction Errors:

1. **Timeout**: Transaction not processed within the expected timeframe.
2. **BlockhashNotFound**: The blockhash used in the transaction has expired.
3. **TransactionError**: Various errors during transaction execution (e.g., `InstructionError`).
4. **RPC Errors**: Connection issues, rate limiting, or server errors.

Retry Strategy:

Implement an exponential backoff strategy with jitter for transaction retries:

```
// Exponential backoff with jitter
async function sendWithRetry(
    connection: Connection,
    transaction: Transaction,
    signers: Keypair[],
    maxRetries: number = 3
): Promise<string> {
    let retries = 0;

    while (true) {
        try {
            // Get a fresh blockhash for each attempt
            transaction.recentBlockhash = (
                await connection.getLatestBlockhash('confirmed')
            ).blockhash;

            // Sign and send transaction
            const txId = await sendAndConfirmTransaction(
                connection,
                transaction,
                signers,
                { commitment: 'confirmed' }
            );

            return txId;
        } catch (error) {
            if (retries >= maxRetries) {
                console.error(`Failed after ${maxRetries}
retries:`, error);
                throw error;
            }

            // Check if error is retryable
            if (!isRetryableError(error)) {
                console.error('Non-retryable error:', error);
                throw error;
            }

            // Exponential backoff with jitter
            const delay = Math.min(
                1000 * Math.pow(2, retries) + Math.random() *
1000,
                30000 // Max 30 seconds
            );

            console.warn(`Retry ${retries + 1}/${maxRetries}
after ${delay}ms`);
            await new Promise(resolve => setTimeout(resolve,
delay));
            retries++;
        }
    }
}

// Determine if an error is retryable
function isRetryableError(error: any): boolean {
    // Network errors are generally retryable
    if (error.message?.includes('Failed to fetch') ||
        error.message?.includes('Network Error') ||
        error.message?.includes('timeout')) {
        return true;
    }

    // Blockhash expired is retryable
    if (error.message?.includes('Blockhash not found') ||
        error.message?.includes('BlockhashNotFound')) {
        return true;
    }

    // Transaction simulation errors might be retryable
    if (error.message?.includes('Transaction simulation
failed')) {
        // But not if it's a validation error
        if (error.message?.includes('InvalidAccountData') ||
            error.message?.includes('Custom program error')) {
            return false;
        }
        return true;
    }

    // Server errors are generally retryable
    if (error.code >= 500 && error.code < 600) {
        return true;
    }

    return false;
}
```

Error Classification and Handling:

Classify errors to provide meaningful feedback to users:

```
 // Error classification
function classifyError(error: any): {
    type: 'validation' | 'temporary' | 'permanent',
    message: string,
    details?: any
} {
    // Extract custom program error if present
    if (error.logs) {
        const customErrorMatch = error.logs.find((log: string)
=>
            log.includes('Custom program error:')
        );

        if (customErrorMatch) {
            // Parse error code and map to registry error
            const errorCodeMatch = customErrorMatch.match(/
Custom program error: (\d+)/);
            if (errorCodeMatch) {
                const errorCode = parseInt(errorCodeMatch[1]);
                const errorInfo = mapErrorCodeToInfo(errorCode);

                return {
                    type: 'validation',
                    message: errorInfo.message,
                    details: { code: errorCode, name:
errorInfo.name }
                };
            }
        }
    }

    // Check for common temporary errors
    if (isRetryableError(error)) {
        return {
            type: 'temporary',
            message: 'This operation failed temporarily. Please
try again.',
            details: error
        };
    }

    // Default to permanent error
    return {
        type: 'permanent',
        message: 'This operation failed. Please check your
inputs and try again.',
        details: error
    };
}

// Map program error codes to human-readable information
function mapErrorCodeToInfo(code: number): { name: string,
message: string } {
    // These should match the ErrorCode enum in the program
    const errorMap: Record<number, { name: string, message:
string }> = {
        6000: {
            name: 'StringTooLong',
            message:
'One or more text fields exceed the maximum allowed length.'
        },
        6001: {
            name: 'TooManyItems',
            message: 'Too many items in a collection (e.g.,
skill tags, endpoints).'
        },
        6002: {
            name: 'InvalidAgentId',
            message: 'Agent ID format is invalid. Use only
alphanumeric characters, hyphens, and underscores.'
        },
        // ... map other error codes ...
    };

    return errorMap[code] || {
        name: 'UnknownError',
        message: `Unknown error code: ${code}`
    };
}
```

User-Friendly Error Presentation:

Present errors to users in a helpful, actionable way:

```
 // User-friendly error handling
async function registerAgentWithErrorHandling(
    program: Program<AgentRegistry>,
    args: RegisterAgentArgs,
    ownerKeypair: Keypair,
    payerKeypair: Keypair,
    uiCallbacks: {
        onStart: () => void,
        onSuccess: (txId: string) => void,
        onError: (error: any) => void,
        onRetry: (attempt: number, maxAttempts: number) => void
    }
): Promise<string | null> {
    try {
        uiCallbacks.onStart();

        // Prepare transaction
        const tx = await program.methods
            .registerAgent(args)
            .accounts({
                // ... account setup ...
            })
            .transaction();

        // Send with retry
        const txId = await sendWithRetry(
            program.provider.connection,
            tx,
            [payerKeypair, ownerKeypair],
            3, // maxRetries
            uiCallbacks.onRetry
        );

        uiCallbacks.onSuccess(txId);
        return txId;
    } catch (error) {
        const classifiedError = classifyError(error);

        // Log detailed error for debugging
        console.error('Registration error:', classifiedError);
        // Show user-friendly message
        uiCallbacks.onError({
            title: getErrorTitle(classifiedError.type),
            message: classifiedError.message,
            isRetryable: classifiedError.type === 'temporary',
            originalError: error
        });

        return null;
    }
}

function getErrorTitle(errorType: 'validation' | 'temporary' |
'permanent'): string {
    switch (errorType) {
        case 'validation': return 'Validation Error';
        case 'temporary': return 'Temporary Error';
        case 'permanent': return 'Error';
    }
}
```

Transaction Monitoring:

For critical operations, implement transaction monitoring to ensure confirmation:

```
 // Transaction monitoring
async function monitorTransaction(
    connection: Connection,
    signature: string,
    timeout: number = 60000 // 60 seconds
): Promise<'success' | 'timeout' | 'error'> {
    return new Promise((resolve) => {
        let timeoutId: NodeJS.Timeout;

        // Set timeout
        timeoutId = setTimeout(() => {
            connection.removeSignatureListener(subscriptionId);
            resolve('timeout');
        }, timeout);

        // Listen for confirmation
        const subscriptionId = connection.onSignature(
            signature,
            (result, context) => {
                clearTimeout(timeoutId);

connection.removeSignatureListener(subscriptionId);

                if (result.err) {
                    console.error('Transaction failed:',
result.err);
                    resolve('error');
                } else {
                    resolve('success');
                }
            },
            'confirmed'
        );
    });
}
```

By implementing robust retry strategies and user-friendly error handling, you can create registry client applications that gracefully handle the challenges of blockchain transactions and provide a smooth user experience.

8.3.3 UI/UX Considerations for Performance

The user interface and experience design significantly impact perceived performance. Implementing UI/UX optimizations can make registry applications feel faster and more responsive, even when blockchain operations inherently involve some latency.

Progressive Loading and Feedback:

1. **Skeleton Screens**: Show placeholder content while data is loading.

```
// React component with skeleton loading
function AgentList({ ownerPublicKey }) {
    const [agents, setAgents] = useState<AgentInfo[]>([]);
    const [loading, setLoading] = useState(true);

    useEffect(() => {
        async function loadAgents() {
            setLoading(true);
            try {
                const agentData = await
fetchAgentsByOwner(ownerPublicKey);
                setAgents(agentData);
            } catch (error) {
                console.error('Failed to load agents:', error);
            } finally {
                setLoading(false);
            }
        }

        loadAgents();
    }, [ownerPublicKey]);

    return (
        <div className="agent-list">
            <h2>Your Agents</h2>
            {loading ? (
                // Skeleton loading UI
                Array(3).fill(0).map((_, i) => (
                    <div key={i} className="agent-card 
skeleton">
                        <div className="skeleton-title"></div>
                        <div className="skeleton-description"></
div>
                        <div className="skeleton-tags"></div>
                    </div>
                ))
            ) : (
                // Actual content
                agents.map(agent => (
                    <AgentCard key={agent.pda} agent={agent} />
                ))
            )}
        </div>
    );
}
```

1. **Transaction Progress Indicators**: Show multi-stage progress for transactions.

```
// Transaction progress component
function TransactionProgress({ status }) {
    const stages = [
        { key: 'preparing', label: 'Preparing Transaction' },
        { key: 'sending', label: 'Sending to Network' },
        { key: 'processing', label: 'Processing' },
        { key: 'confirming', label: 'Confirming' },
        { key: 'finalized', label: 'Finalized' }
    ];

    const currentIndex = stages.findIndex(stage => stage.key 
=== status);

    return (
        <div className="transaction-progress">
            {stages.map((stage, index) => (
                <div
                    key={stage.key}
                    className={`progress-stage ${index <= 
currentIndex ? 'active' : ''} ${status === stage.key ? 
'current' : ''}`}
                >
                    <div className="stage-indicator"></div>
                    <div className="stage-label">{stage.label}</
div>
```

```
                </div>
            ))}
        </div>
    );
}
```

Optimistic UI Updates:

Implement optimistic updates to make the UI feel more responsive:

```
 // Optimistic UI update for agent registration
function RegisterAgentForm() {
    const [agents, setAgents] = useAgentStore(state =>
[state.agents, state.setAgents]);
    const [isSubmitting, setIsSubmitting] = useState(false);
    const [formData, setFormData] = useState(initialFormState);

    const handleSubmit = async (e) => {
        e.preventDefault();
        setIsSubmitting(true);

        // Create optimistic version of the new agent
        const optimisticAgent = {
            ...formData,
            pda: 'pending-' + Date.now(), // Temporary ID
            status: 'pending',
            created_at: Date.now(),
            updated_at: Date.now(),
        };

        // Add to UI immediately
        setAgents([optimisticAgent, ...agents]);

        try {
            // Actual blockchain operation
            const result = await registerAgent(formData);

            // Replace optimistic version with real data
            setAgents(agents.map(agent =>
                agent.pda === optimisticAgent.pda ? {
                    ...agent,
                    pda: result.pda,
                    status: 'active',
                    // Other real data from result
                } : agent
            ));

            // Success notification
            showNotification('Agent registered successfully!');
        } catch (error) {
            // Remove optimistic version on failure
            setAgents(agents.filter(agent => agent.pda !==
optimisticAgent.pda));

            // Error handling
            handleError(error);
        } finally {
            setIsSubmitting(false);
        }
    };

    // Form JSX...
}
```

Perceived Performance Techniques:

1. **Immediate Feedback**: Provide immediate visual feedback for user actions.

```
// Button with immediate feedback
function ActionButton({ onClick, children }) {
    const [clicked, setClicked] = useState(false);

    const handleClick = async () => {
        setClicked(true);
        try {
            await onClick();
        } finally {
            setClicked(false);
        }
    };

    return (
        <button
            onClick={handleClick}
            className={clicked ? 'clicked' : ''}
            disabled={clicked}
        >
            {clicked ? <Spinner size="small" /> : null}
            {children}
        </button>
    );
}
```

1. **Progressive Disclosure**: Show only essential information initially, with details available on demand.

```
// Progressive disclosure component
function AgentDetails({ agent }) {
    const [expanded, setExpanded] = useState(false);

    return (
        <div className="agent-details">
            <div className="agent-summary" onClick={() =>
setExpanded(!expanded)}>
                <h3>{agent.name}</h3>
                <span className="expand-icon">{expanded ? '▼' :
'▶'}</span>
            </div>

            {expanded && (
                <div className="agent-expanded-details">
                    {/* Detailed content, loaded only when
expanded */}
                    <p>{agent.description}</p>
                    <div className="skill-tags">
                        {agent.skill_tags.map(tag => (
                            <span key={tag}
className="tag">{tag}</span>
                        ))}
                    </div>
                    {/* More details... */}
                </div>
            )}
        </div>
    );
}
```

1. **Background Data Prefetching**: Fetch data before it's needed.

```
// Prefetching hook
function usePrefetchAgentDetails(agentPDA) {
    const prefetchedData = useRef(null);

    useEffect(() => {
        let isMounted = true;

        async function prefetch() {
            try {
                const details = await
fetchAgentDetails(agentPDA);
                if (isMounted) {
                    prefetchedData.current = details;
                }
            } catch (error) {
                console.error('Prefetch failed:', error);
            }
        }
        prefetch();

        return () => {
            isMounted = false;
        };
    }, [agentPDA]);

    return prefetchedData.current;
}
```

Mobile and Low-Bandwidth Optimizations:

1. **Responsive Design**: Ensure the UI works well on all device sizes.

```css
/* Responsive CSS example */
.registry-container {
    display: grid;
    grid-template-columns: repeat(auto-fill, minmax(300px,
1fr));
    gap: 20px;
}

@media (max-width: 768px) {
    .registry-container {
        grid-template-columns: 1fr;
    }

    .agent-card {
        padding: 12px;
        font-size: 14px;
    }
}
```

1. **Data Minimization**: Request and display only essential data on mobile or low-bandwidth connections.

```
// Bandwidth-aware component
function AgentListAdaptive() {
    const isMobile = useMediaQuery('(max-width: 768px)');
    const isLowBandwidth = useBandwidthDetection() < 1; // Mbps

    const shouldMinimizeData = isMobile || isLowBandwidth;

    return (
        <AgentList
            fetchFullDetails={!shouldMinimizeData}
            itemsPerPage={shouldMinimizeData ? 5 : 20}
            showImages={!shouldMinimizeData}
        />
    );
}
```

By implementing these UI/UX optimizations, you can create registry applications that feel fast and responsive, even when interacting with blockchain operations that inherently involve some latency.

References will be compiled and listed in Chapter 13.

Chapter 9: Deployment and Maintenance

9.1 Deployment Strategies

9.1.1 Solana Network Environments (Devnet, Testnet, Mainnet)

Deploying Solana programs involves interacting with different network environments, each serving a specific purpose in the development lifecycle.

1. **Localnet (Local Validator)**:
    - **Purpose**: Initial development and rapid testing.
    - **Characteristics**: Runs entirely on the developer's machine, providing instant finality and complete control. No real SOL or tokens involved.
    - **Usage**: Ideal for unit testing, debugging core logic, and iterating quickly without network latency or costs.
    - **Tools**: `solana-test-validator`.
2. **Devnet**:
    - **Purpose**: Integration testing and experimentation with Solana features.
    - **Characteristics**: A public cluster funded by free SOL faucets. Subject to resets and instability. Simulates real-world network conditions but with no real value at stake.
    - **Usage**: Testing program interactions, client integration, and features requiring a shared network environment.
    - **Access**: Public RPC endpoints, SOL faucets available.
3. **Testnet**:
    - **Purpose**: Staging environment for pre-production testing.

◦ **Characteristics**: More stable than Devnet, intended to mirror Mainnet Beta features and performance closely. Funded by SOL faucets.
◦ **Usage**: End-to-end testing, performance benchmarking, final checks before Mainnet deployment.
◦ **Access**: Public RPC endpoints, SOL faucets available.

4. **Mainnet Beta**:

    ◦ **Purpose**: Production environment where real value is transacted.
    ◦ **Characteristics**: The live Solana network with real SOL and tokens. Requires careful deployment and management.
    ◦ **Usage**: Deploying live applications and protocols.
    ◦ **Access**: Public and private RPC endpoints, requires real SOL for deployment and transactions.

Deployment Flow:

A typical deployment flow progresses through these environments:

```
 +--------------------+     +--------------------+
+--------------------+     +--------------------+
|                    | --> |                    | -->
|                    | --> |                    |
|  Localnet          |     |  Devnet            |     |
Testnet           |     |  Mainnet Beta     |
|  (Development)     |     |  (Integration)     |     |
(Staging)         |     |  (Production)     |
|                    |     |                    |
|                    |     |                    |
| - Unit Tests       |     | - Integration      |     | - End-to-
End         |     | - Live Deployment |
| - Rapid Iteration |     |   Tests            |     |
Tests             |     | - Real Value      |
| - Debugging        |     | - Client Testing   |     | -
Performance       |     |                   |
|                    |     | - Feature Exp.     |     |
Benchmarking      |     |                   |
+--------------------+     +--------------------+
+--------------------+     +--------------------+
```

Registry Deployment Considerations:

- Thoroughly test registry program logic on Localnet.
- Deploy to Devnet to test client interactions, indexer integration, and basic functionality.

- Deploy to Testnet for comprehensive testing, including performance under load and interactions with other Testnet programs.
- Deploy to Mainnet Beta only after rigorous testing and auditing.

9.1.2 Building and Deploying Solana Programs

Deploying a Solana program involves building the program binary and submitting it to the target network.

Building the Program:

Anchor simplifies the build process:

```
# Build the program (generates .so binary and IDL)
anchor build
```

This command compiles the Rust code into a BPF (Berkeley Packet Filter) shared object (`.so`) file located in the `target/deploy/` directory. It also generates the program's Interface Definition Language (IDL) file (`target/idl/<program_name>.json`), which clients use to interact with the program.

Deployment Process:

1. **Generate Program Keypair**: Each Solana program needs a unique keypair. This keypair's public key becomes the program ID.

   ` ` `bash

Generate a keypair for the program if one doesn't exist

(Typically stored at target/deploy/-keypair.json)

solana-keygen new --outfile target/deploy/agent_registry-keypair.json ` ` `

Important: Securely back up this keypair file. It is required for future upgrades.

2. **Configure Anchor.toml**: Ensure the `Anchor.toml` file specifies the correct program name and provider cluster.

   ```toml [programs.localnet] agent_registry = "" mcp_server_registry = ""

   [programs.devnet] agent_registry = "" mcp_server_registry = ""

## ... similar entries for testnet and mainnet-beta

   [provider] cluster = "devnet" # Set the target cluster for deployment wallet = "~/.config/solana/id.json" # Wallet paying for deployment ```

3. **Deploy using Anchor**: The `anchor deploy` command handles the deployment transaction.

   ```bash

## Deploy the program to the cluster specified in Anchor.toml

   anchor deploy ```

   This command: - Reads the program keypair. - Reads the compiled `.so` file. - Constructs a transaction to deploy the program bytecode to an account owned by the BPF Upgradeable Loader. - Submits the transaction using the specified provider wallet.

**Deployment Costs:**

Deploying a program requires SOL to cover: - Transaction fees. - Rent exemption for the program executable data account (which stores the `.so` bytecode). The size of this account depends on the compiled program size.

**Verifying Deployment:**

After deployment, verify the program exists on the target cluster:

```
Check program account info
solana account <PROGRAM_ID>

Check program executable data account info
solana account <PROGRAM_EXECUTABLE_DATA_ADDRESS>
```

Anchor's deployment process streamlines these steps, making it relatively straightforward to get your registry programs onto the desired Solana network.

9.1.3 Managing Program IDs and Keys

Proper management of program IDs and their associated keypairs is critical for security and upgradeability.

Program ID:

- The public key derived from the program's keypair.
- Uniquely identifies the program on the Solana network.
- Used by clients to address instructions to the correct program.

Program Keypair:

- The private/public keypair associated with the program ID.
- The private key is required to authorize program upgrades.
- **Must be kept secure and backed up.** Loss of the private key means the program can never be upgraded.

Key Management Best Practices:

1. **Secure Storage**: Store program keypair files in a secure location with restricted access. Avoid committing them to version control.
2. **Backup**: Create multiple, secure, offline backups of the program keypair file.
3. **Access Control**: Limit access to the program keypair to authorized personnel only.
4. **Hardware Security Modules (HSMs)**: For high-value Mainnet programs, consider using HSMs or multi-signature schemes to manage the upgrade authority, preventing single points of failure.

Environment-Specific IDs:

Programs typically have different IDs on different networks (Localnet, Devnet, Testnet, Mainnet). This is managed in `Anchor.toml`:

```
[programs.devnet]
agent_registry = "AgRcy...Devnet..."
```

```
[programs.mainnet-beta]
agent_registry = "AgRcy...Mainnet..."
```

Clients need to be configured to use the correct program ID based on the network they are targeting.

Vanity Addresses (Optional):

It's possible to generate program keypairs whose public keys start with a specific prefix (vanity address) using tools like `solana-keygen grind`. This can improve recognizability but offers no security benefit.

```bash

# Example: Find a keypair whose public key starts with
```