Coding Contest Platform Backend

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Requirements Gathering

Functional Requirements

Core Contest Management: - Create and manage coding contests with configurable duration and rules - Support multiple contest formats: ACM ICPC, CodeChef, Codeforces, AtCoder styles - Problem statement creation with rich text, images, and mathematical formulas - Test case management with input/output validation and custom judging - Multi-language support for submissions (C++, Java, Python, JavaScript, etc.)

Submission Processing: - Real-time code submission with syntax highlighting and validation - Secure code execution in isolated environments with resource limits - Comprehensive test case evaluation with detailed feedback - Plagiarism detection and similarity analysis - Version control for multiple submission attempts

Ranking and Leaderboards: - Real-time leaderboard updates during contests - Multiple scoring systems: time penalty, partial scoring, IOI style - Historical ranking data and performance analytics - Team and individual participant support - Rating systems with ELO-based calculations

User Experience Features: - Practice mode with extensive problem archives - Editorial and solution discussions post-contest - Virtual contests and replay functionality - Social features: following, friend challenges, forums - Detailed submission history and performance statistics

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Non-Functional Requirements

Performance Requirements: - Support 100,000 concurrent users during major contests - Handle 10,000 submissions per minute during peak periods - Code execution completion within 5 seconds for 95% of submissions - Leaderboard updates within 30 seconds of submission evaluation - System availability: 99.9% uptime during contests

Scalability Requirements: - Horizontally scalable evaluation infrastructure - Auto-scaling based on contest size and submission volume - Global deployment for low-latency access worldwide - Support for contests with 50,000+ participants - Linear performance scaling with added compute resources

Security Requirements: - Complete code execution isolation to prevent system compromise - Contest data protection against unauthorized access - Plagiarism detection with advanced similarity algorithms - DDoS protection and rate limiting for submission endpoints - Secure handling of sensitive contest data and user information

Reliability Requirements: - Zero data loss for submissions and contest results - Eventual consistency acceptable for leaderboards (< 30 seconds) - Strong consistency for final contest rankings - Disaster recovery with cross-region backup capabilities - Graceful degradation during infrastructure failures

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Traffic Estimation & Capacity Planning

Contest Participation Analysis

User Base Projections: - 1 million registered users across all skill levels - 100,000 monthly active contestants - 10,000 concurrent users during major contests - Average 5-10 contests per month with varying sizes

Contest Distribution: - Major contests (10,000+ participants): 2 per month - Regular contests (1,000-5,000 participants): 8 per month - Practice contests and virtual contests: Daily - Educational contests and tutorials: Weekly

Geographic Distribution: - Asia-Pacific: 45% of participants - Europe: 25% of participants - North America: 20% of participants - Other regions: 10% of participants

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Submission Volume Calculations

Submission Patterns: - Average 20 submissions per participant per contest - Peak submission rate: 10,000 submissions per minute - Average submission size: 2 KB (source code) - Test case execution time: 1-5 seconds per submission

Daily Operations: - Contest submissions: 500,000 per day - Practice submissions: 1,000,000 per day - Total daily evaluations: 1.5 million submissions - Peak hourly load: 150,000 submissions during major contests

Resource Requirements: - Compute: 1,000 CPU cores for code execution during peaks - Storage: 10 TB for submissions, test cases, and contest data - Network: 1 Gbps sustained bandwidth for global access - Memory: 500 GB for caching and real-time processing

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Real-time Evaluation Load

Evaluation Metrics: - Average evaluation time: 3 seconds per submission - Concurrent evaluations during peak: 3,000 parallel executions - Test case complexity: 1-100 test cases per problem - Memory limit per execution: 256 MB - 1 GB - Time limit per execution: 1-10 seconds

Infrastructure Scaling: - Base capacity: 500 concurrent evaluations - Auto-scaling up to: 5,000 concurrent evaluations - EC2 instance types: M5.2xlarge for balanced compute - Container orchestration: Kubernetes for execution management - Queue management: SQS/Kafka for submission processing

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Database Schema Design

Contest Management Schema

Contests Table: - Contest ID (Primary Key): Unique contest identifier - Contest Name: Display name and title - Start Time: Contest beginning timestamp - Duration: Contest length in minutes - Contest Type: ACM, IOI, CodeChef format - Visibility: Public, private, invite-only - Registration Status: Open, closed, invite-based

Problems Table: - Problem ID (Primary Key): Unique problem identifier - Contest ID (Foreign Key): Associated contest - Problem Title: Display name for the problem - Problem Statement: Rich text with formatting - Time Limit: Execution time constraint per test case - Memory Limit: Memory usage constraint - Difficulty Rating: Problem complexity score

Test Cases Table: - Test Case ID (Primary Key): Unique test case identifier - Problem ID (Foreign Key): Associated problem - Input Data: Test case input (potentially large) - Expected Output: Correct answer for validation - Test Case Type: Sample, hidden, stress test - Points: Scoring weight for this test case

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Submission Processing Schema

Submissions Table: - Submission ID (Primary Key): Unique submission identifier - User ID (Foreign Key): Submitting user - Problem ID (Foreign Key): Target problem - Contest ID (Foreign Key): Associated contest - Source Code: User's solution code - Language: Programming language used - Submission Time: When code was submitted - Status: Pending, Running, Accepted, Wrong Answer, TLE, etc.

Evaluation Results: - Evaluation ID (Primary Key): Unique evaluation run - Submission ID (Foreign Key): Associated submission - Test Case ID (Foreign Key): Specific test case - Execution Time: Actual runtime in milliseconds - Memory Used: Peak memory consumption - Exit Code: Program termination status - Output: Program output for comparison - Verdict: Correct, Wrong, TLE, MLE, RE, etc.

Execution Environments: - Environment ID: Unique execution sandbox identifier - Language Configuration: Compiler/interpreter settings - Resource Limits: CPU, memory, time constraints - Security Settings: Sandbox configuration - Judge Version: Evaluation system version

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Leaderboard and Ranking Schema

Contest Standings: - Standing ID (Primary Key): Unique ranking entry - Contest ID (Foreign Key): Associated contest - User ID (Foreign Key): Participant - Total Score: Accumulated points - Penalty Time: Time-based penalty calculation - Problems Solved: Count of accepted submissions - Rank: Current position in contest - Last Update: Timestamp of last ranking calculation

Problem Statistics: - Problem ID (Composite Key): Target problem - Contest ID (Composite Key): Associated contest - Total Submissions: Count of all attempts - Accepted Submissions: Count of correct solutions - Acceptance Rate: Percentage of successful submissions - Average Time: Mean solving time for accepted solutions - First Solver: User who solved first - First Solve Time: Timestamp of first correct submission

User Ratings: - User ID (Primary Key): User identifier - Current Rating: Latest skill rating - Peak Rating: Highest achieved rating - Contest Participation: Number of contests attended - Problems Solved: Total problems solved across all contests - Rating History: Time-series rating changes - Performance Trend: Recent performance analysis

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System API Design

Contest Management APIs

Contest Lifecycle Management: - Create, update, and delete contests with full configuration - Register participants with eligibility validation - Start and end contests with automatic timing - Handle contest extensions and modifications - Generate contest analytics and reports

Problem Management: - Create and edit problem statements with rich formatting - Upload and validate test cases with correctness verification - Set resource limits and judging criteria - Version control for problem updates - Batch problem import/export functionality

User Registration and Authentication: - User registration with email verification - Authentication with OAuth integration - Role management: admin, problem setter, participant - Team creation and management for team contests - Access control for private contests and practice sessions

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Submission Processing APIs

Code Submission Management: - Submit source code with language detection - Pre-submission validation and syntax checking - File upload support for large submissions - Submission history and version tracking - Bulk submission upload for testing

Real-time Feedback: - Live submission status updates via WebSocket - Detailed compilation and execution error messages - Test case results with partial feedback (when allowed) - Performance metrics: execution time and memory usage - Queue position and estimated evaluation time

Administrative Controls: - Rejudge submissions with updated test cases - Manual evaluation override for special cases - Submission analysis and plagiarism detection - Batch operations for contest administration - Detailed execution logs for debugging

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Evaluation and Judging APIs

Test Case Execution: - Secure code compilation in isolated environments - Multi-language support with consistent judging - Resource monitoring and limit enforcement - Custom judges for special problem types - Parallel execution for faster evaluation

Scoring and Ranking: - Real-time score calculation with configurable systems - Leaderboard generation with tie-breaking rules - Historical ranking data and performance trends - Rating calculation using established algorithms - Contest statistics and analytics generation

Quality Assurance: - Test case validation and correctness verification - Performance regression testing for judge updates - A/B testing for new evaluation features - Error analysis and judge system monitoring - Automated testing of judge infrastructure

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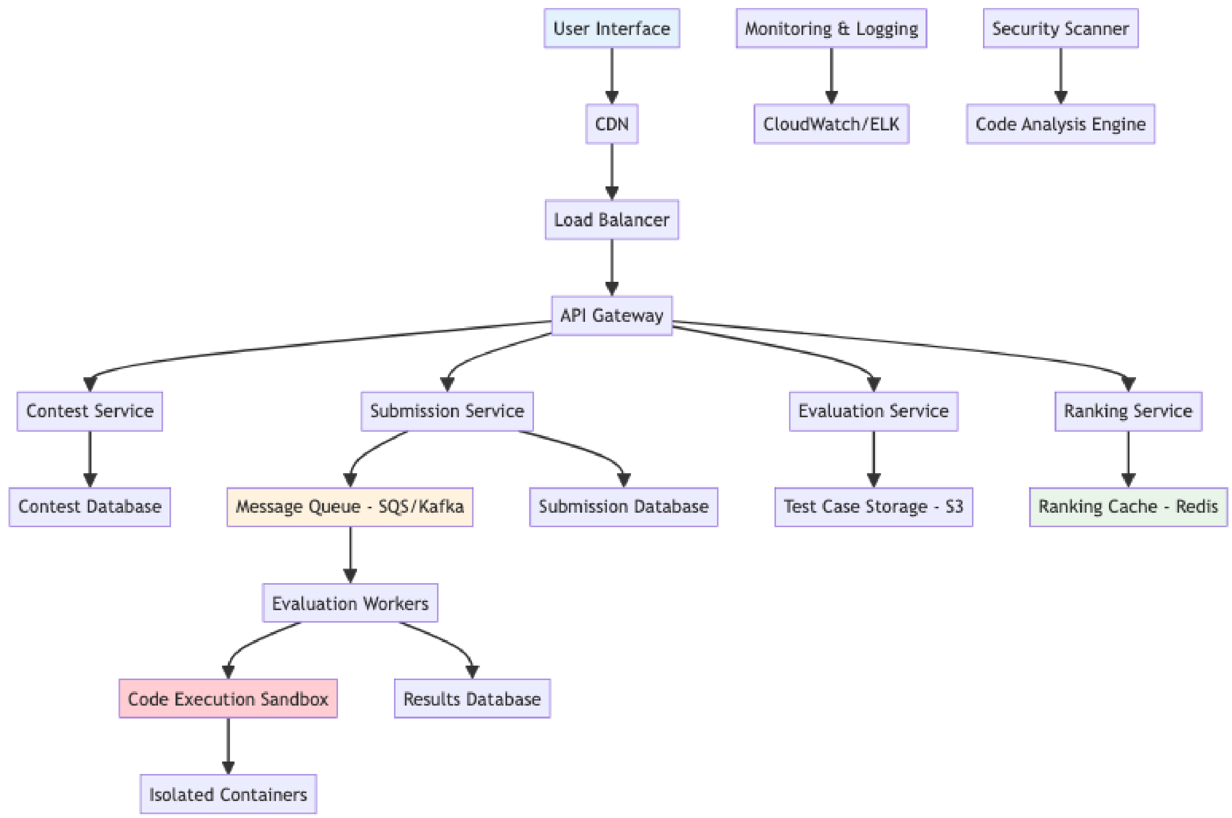
High-Level Design (HLD)

System Architecture Overview

Distributed Contest Platform Architecture:



Core Components: - **Contest Service**: Contest lifecycle management and configuration - **Submission Service**: Code submission handling and preprocessing - **Evaluation Service**: Test case execution and result processing - **Ranking Service**: Real-time leaderboard and rating calculations - **Code Execution Sandbox**: Secure, isolated code execution environment - **Message Queue**: Asynchronous submission processing and load distribution

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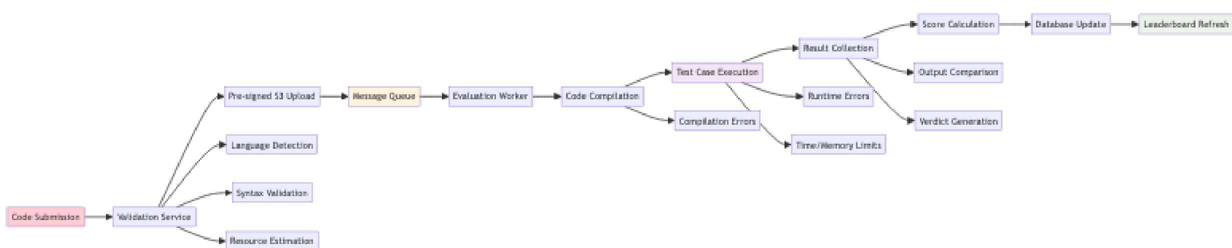
Submission Processing Flow

Complete Submission-to-Result Pipeline:



Async Processing Benefits: - **Scalability**: Handle submission spikes without blocking user interface - **Reliability**: Queue persistence ensures no submission loss - **Performance**: Parallel processing of multiple submissions - **Resource Management**: Dynamic scaling based on queue depth

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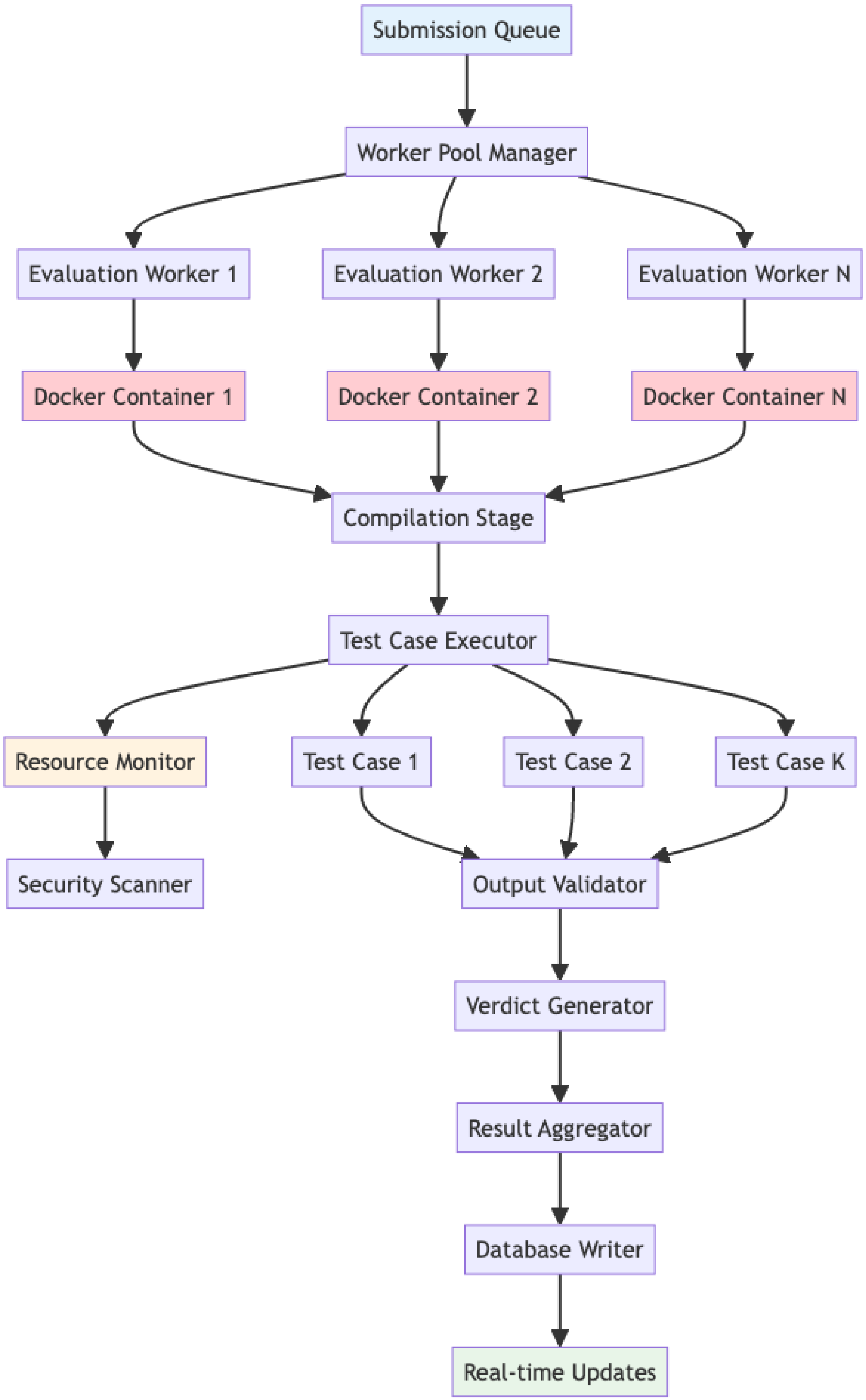
Real-time Evaluation Pipeline

Secure Code Execution Architecture:


Submission Queue
Worker Pool Manager
Evaluation Worker 1
Evaluation Worker 2
Evaluation Worker N
Docker Container 1
Docker Container 2
Docker Container N
Compilation Stage
Test Case Executor
Resource Monitor
Test Case 1
Test Case 2
Test Case K
Security Scanner
Output Validator
Verdict Generator
Result Aggregator
Database Writer
Real-time Updates

Security Layers: - **Container Isolation**: Each submission runs in isolated Docker container - **Resource Limits**: CPU, memory, and time constraints enforced - **Network Isolation**: No external network access during execution - **File System Protection**: Read-only environment with limited write access

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Low-Level Design (LLD)

Code Execution Engine

Sandboxed Execution Environment: - **Container Management**: Docker-based isolation with custom resource controls - **Language Support**: Multi-compiler environment with version management - **Security Hardening**: Seccomp profiles, AppArmor, and capability restrictions - **Resource Monitoring**: Real-time tracking of CPU, memory, and I/O usage

Execution Pipeline: - **Pre-execution Validation**: Source code analysis and security scanning - **Compilation Phase**: Language-specific compilation with error capture - **Test Case Iteration**: Sequential or parallel test case execution - **Output Collection**: Capture stdout, stderr, and execution metadata - **Cleanup**: Container destruction and resource deallocation

Performance Optimization: - **Container Pooling**: Pre-warmed containers for faster execution startup - **Compilation Caching**: Cache compiled binaries for identical submissions - **Parallel Testing**: Concurrent test case execution when possible - **Resource Recycling**: Efficient container reuse and cleanup

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Queue Management System

Message Queue Architecture: - **Priority Queues**: Different priority levels for contest vs practice submissions - **Dead Letter Queues**: Handle failed submissions with retry mechanisms - **Queue Partitioning**: Distribute load across multiple worker pools - **Backpressure Handling**: Graceful degradation during overload conditions

Worker Pool Management: - **Dynamic Scaling**: Auto-scaling workers based on queue depth - **Health Monitoring**: Worker health checks and automatic replacement - **Load Distribution**: Intelligent work assignment based on worker capacity - **Failure Recovery**: Automatic restart and submission requeue on worker failure

Quality of Service: - **SLA Guarantees**: Different processing guarantees for different submission types - **Rate Limiting**: Per-user and global submission rate controls - **Fair Scheduling**: Prevent single user from monopolizing evaluation resources - **Emergency Modes**: Special handling during contest critical periods

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Leaderboard Generation Service

Real-time Ranking Calculation: - **Incremental Updates**: Efficient recalculation on new submission results - **Ranking Algorithms**: Support for different contest scoring systems - **Tie-breaking Logic**: Consistent and fair tie resolution - **Historical Tracking**: Maintain ranking changes over time

Caching Strategy: - **Multi-level Caching**: Memory, Redis, and database-level caching - **Cache Invalidation**: Smart invalidation on ranking changes - **Pre-computation**: Background calculation of expensive ranking operations - **Geographic Caching**: Regional caches for global contest access

Data Consistency: - **Eventually Consistent**: Accept brief delays for performance - **Conflict Resolution**: Handle concurrent ranking updates - **Audit Trail**: Maintain history for ranking verification - **Rollback Capability**: Revert rankings on error detection

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Core Algorithms

1. Secure Code Execution Algorithm

Multi-layer Security Enforcement: - Initialize isolated execution environment with strict resource limits - Perform static code analysis to detect potentially malicious patterns - Compile code in restricted environment with timeout controls - Execute against test cases with real-time resource monitoring - Terminate execution on resource limit violations or security threats - Collect results while maintaining sandbox integrity

Resource Management: - **Memory Limiting**: Enforce heap and stack size restrictions - **CPU Throttling**: Limit CPU usage and prevent infinite loops - **I/O Controls**: Restrict file system access and network connectivity - **Time Limits**: Hard and soft timeout enforcement - **Process Management**: Control child process creation and execution

Security Scanning: - **Pattern Detection**: Identify suspicious system calls and operations - **Behavioral Analysis**: Monitor runtime behavior for anomalies - **Sandbreak Prevention**: Detect and prevent container escape attempts - **Code Injection**: Scan for code injection and shell access attempts

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2. Real-time Ranking Algorithm

Incremental Ranking Updates: - Maintain sorted leaderboard data structure in memory - Process new submission results and calculate score changes - Perform efficient rank updates using binary search and heap operations - Handle tie-breaking with secondary criteria (time, penalty) - Propagate ranking changes to cached and persistent storage - Notify users of significant ranking changes

Multi-criteria Scoring: - **ACM Style**: Time penalty with problem-solving count - **IOI Style**: Partial scoring with weighted test case results - **CodeChef Style**: Combination of accuracy and speed - **Custom Scoring**: Configurable scoring algorithms per contest

Performance Optimization: - **Lazy Updates**: Batch ranking updates for efficiency - **Approximate Rankings**: Use sampling for very large contests - **Materialized Views**: Pre-computed rankings for common queries - **Delta Compression**: Store only ranking changes for history

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3. Test Case Validation Algorithm

Correctness Verification: - Parse expected output format and validate structure - Perform exact string matching with whitespace normalization - Support custom comparators for floating-point and special formats - Handle multiple correct answers with validator functions - Provide detailed feedback on test case failures - Generate test case statistics and coverage metrics

Output Comparison: - **Exact Match**: Byte-by-byte comparison for precise outputs - **Whitespace Tolerant**: Normalize spaces and line endings - **Floating Point**: Epsilon-based comparison for numerical results - **Custom Validators**: Problem-specific validation logic - **Interactive Problems**: Support for interactive input/output protocols

Error Categorization: - **Wrong Answer**: Output doesn't match expected result - **Presentation Error**: Correct answer with formatting issues - **Time Limit Exceeded**: Execution time beyond allowed limit - **Memory Limit Exceeded**: Memory usage beyond allowed limit - **Runtime Error**: Program crash or abnormal termination

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4. Load Balancing Algorithm

Intelligent Work Distribution: - Monitor worker pool capacity and current load distribution - Assign submissions based on estimated execution time and complexity - Balance load across geographic regions for global contests - Implement circuit breakers for overloaded or failing workers - Provide graceful degradation during peak load periods

Adaptive Scheduling: - **Shortest Queue**: Route to worker with minimum pending submissions - **Weighted Round Robin**: Distribute based on worker capacity - **Least Connection**: Route to worker with fewest active executions - **Performance-based**: Consider historical execution times - **Geographic Affinity**: Prefer local workers for latency optimization

Auto-scaling Logic: - **Queue Depth Monitoring**: Scale based on pending submission count - **Response Time Tracking**: Scale when evaluation times increase - **Resource Utilization**: Monitor CPU and memory usage patterns - **Predictive Scaling**: Use historical data to anticipate load - **Cost Optimization**: Balance performance with infrastructure costs

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5. Contest Scheduling Algorithm

Contest Lifecycle Management: - Schedule contests with global timezone considerations - Handle contest start/end times with atomic state transitions - Manage registration periods and participant eligibility - Coordinate distributed contest state across multiple regions - Provide contest replay and virtual contest capabilities

Timing Synchronization: - **Global Clock**: Synchronized time across all system components - **Atomic Transitions**: Ensure consistent contest state changes - **Grace Periods**: Handle clock skew and network delays - **Replay Capability**: Allow virtual participation in past contests - **Time Zone Handling**: Present local times while maintaining UTC internally

State Management: - **Registration Phase**: Open registration with eligibility checks - **Contest Phase**: Active submission and evaluation period - **Frozen Phase**: Hide leaderboard before contest end - **Post-contest**: Final standings and editorial publication - **Archive Phase**: Read-only access to contest data

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Performance Optimizations

Execution Environment Optimization

Container Performance: - **Pre-warmed Containers**: Maintain pool of ready-to-use execution environments - **Base Image Optimization**: Minimal container images with necessary tools only - **Layer Caching**: Efficient Docker layer management for fast startup - **Resource Pooling**: Reuse containers for multiple submissions when safe

Compilation Optimization: - **Compiler Caching**: Cache compiled binaries for identical source code - **Incremental Compilation**: Support for languages with incremental builds - **Parallel Compilation**: Multi-threaded compilation for large programs - **Template Precompilation**: Pre-compile common competitive programming templates

Execution Efficiency: - **Memory Management**: Efficient allocation and deallocation strategies - **I/O Optimization**: Buffered I/O for large input/output operations - **CPU Affinity**: Bind execution to specific CPU cores for consistency - **NUMA Awareness**: Optimize memory access patterns on multi-socket systems

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Caching and Pre-computation

Multi-level Caching Strategy: - **L1 Cache**: Application-level caching for hot data and frequent queries - **L2 Cache**: Redis cluster for shared data across multiple service instances - **L3 Cache**: Database query result caching for expensive operations - **CDN Caching**: Global caching for static contest content and problem statements

Pre-computation Strategies: - **Leaderboard Pre-computation**: Background calculation of ranking data - **Problem Statistics**: Pre-computed solve rates and difficulty metrics - **User Profiles**: Cached user performance and rating information - **Contest Analytics**: Pre-computed statistics and historical data

Cache Invalidation: - **Event-driven Invalidation**: Invalidate based on submission result changes - **TTL-based Expiration**: Time-based cache expiration for non-critical data - **Version-based Invalidation**: Cache versioning for contest data updates - **Selective Invalidation**: Granular cache invalidation for affected data only

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Database Query Optimization

Indexing Strategy: - **Composite Indexes**: Multi-column indexes for complex query patterns - **Partial Indexes**: Indexes on filtered data subsets for efficiency - **Covering Indexes**: Include all query columns to avoid table lookups - **Time-based Partitioning**: Partition large tables by contest date

Query Optimization: - **Query Plan Analysis**: Regular analysis of slow queries and optimization - **Materialized Views**: Pre-computed aggregations for leaderboard queries - **Read Replicas**: Distribute read traffic across multiple database instances - **Connection Pooling**: Efficient database connection management

Data Architecture: - **Horizontal Sharding**: Distribute data across multiple database instances - **Cassandra Integration**: Use Cassandra for high-volume submission data - **Time Series Optimization**: Specialized storage for ranking and performance data - **Archive Strategy**: Move old contest data to cheaper storage tiers

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Security Considerations

Code Execution Security

Sandbox Isolation: - **Container Security**: Hardened Docker containers with minimal attack surface - **Resource Limits**: Strict CPU, memory, and disk usage enforcement - **System Call Filtering**: Whitelist allowed system calls using seccomp - **Network Isolation**: No external network access during code execution - **File System Protection**: Read-only root filesystem with limited writable areas

Malicious Code Prevention: - **Static Analysis**: Pre-execution scanning for dangerous patterns - **Runtime Monitoring**: Real-time detection of suspicious behavior - **Resource Abuse Detection**: Identify and terminate resource-intensive attacks - **Code Injection Prevention**: Sanitize all user inputs and prevent shell access - **Privilege Escalation Protection**: Run all code with minimal privileges

Infrastructure Security: - **Regular Security Updates**: Automated patching of execution environments - **Vulnerability Scanning**: Regular security assessments of the platform - **Access Control**: Strict access controls for administrative functions - **Audit Logging**: Comprehensive logging of all security-relevant events

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Contest Integrity

Cheating Prevention: - **Plagiarism Detection**: Advanced similarity detection algorithms - **Behavioral Analysis**: Monitor submission patterns for suspicious activity - **IP Tracking**: Detect multiple accounts from same location - **Time Analysis**: Identify unrealistic solving speeds and patterns - **Code Fingerprinting**: Detect slight modifications of copied solutions

Data Protection: - **Test Case Security**: Protect test cases from unauthorized access - **Contest Data Encryption**: Encrypt sensitive contest information - **Secure Communication**: TLS encryption for all client-server communication - **Database Security**: Encrypted storage and secure database access - **Backup Security**: Encrypted backups with secure key management

Fair Competition: - **Equal Environment**: Consistent execution environment for all participants - **Time Synchronization**: Accurate timing for contest start/end - **Server Stability**: Maintain stable performance during contests - **Emergency Procedures**: Protocols for handling technical issues during contests

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Testing Strategy

Evaluation System Testing

Correctness Testing: - **Judge Verification**: Validate judge correctness against known solutions - **Test Case Coverage**: Ensure comprehensive test case coverage for problems - **Language Consistency**: Verify consistent behavior across programming languages - **Edge Case Testing**: Test boundary conditions and corner cases - **Regression Testing**: Ensure system updates don't break existing functionality

Performance Testing: - **Execution Time Accuracy**: Verify accurate timing measurement - **Memory Usage Tracking**: Test memory limit enforcement - **Resource Isolation**:

Ensure submissions don't interfere with each other - **Compilation Testing**: Test compiler behavior and error handling - **Timeout Handling**: Verify proper handling of time limit exceeded cases

Security Testing: - **Sandbox Escape Testing**: Attempt to break out of execution sandbox - **Resource Abuse Testing**: Test system behavior under resource attacks - **Malicious Code Testing**: Test with various attack vectors and malicious code - **Data Exfiltration Testing**: Ensure no unauthorized data access - **Privilege Escalation Testing**: Test for unauthorized privilege gains

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Load and Performance Testing

Scalability Testing: - **Concurrent User Testing**: Test with thousands of simultaneous users - **Submission Volume Testing**: Test with high submission rates - **Contest Load Testing**: Simulate major contest conditions - **Database Performance**: Test database under heavy load conditions - **Cache Performance**: Verify cache effectiveness under load

Stress Testing: - **Resource Exhaustion**: Test system behavior when resources are depleted - **Cascade Failure**: Test resilience against component failures - **Recovery Testing**: Test system recovery after failures - **Data Consistency**: Ensure data consistency under stress conditions

Performance Benchmarking: - **Response Time Measurement**: Track API response times under various loads - **Throughput Analysis**: Measure system throughput for different operations - **Resource Utilization**: Monitor CPU, memory, and network usage - **Bottleneck Identification**: Identify and address performance bottlenecks

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Trade-offs and Considerations

Real-time vs Batch Evaluation

Real-time Benefits: - Immediate feedback for participants during contests - Better user experience with instant submission results - Real-time leaderboard updates for competitive engagement - Quick identification and resolution of technical issues

Batch Processing Advantages: - Higher throughput for large submission volumes - More efficient resource utilization through batching - Easier implementation of complex evaluation pipelines - Better cost optimization through resource sharing

Hybrid Approach: - Real-time evaluation for contest submissions - Batch processing for practice submissions and analysis - Priority queues for different submission types - Dynamic switching based on system load

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Accuracy vs Speed

Accuracy Requirements: - Precise timing measurement for competitive programming - Comprehensive test case coverage for correctness - Detailed error reporting for educational value - Consistent evaluation across all submissions

Speed Optimization: - Fast feedback for better user experience - High throughput to handle submission spikes - Minimal latency for contest operations - Efficient resource utilization

Balance Strategies: - Parallel test case execution when possible - Progressive feedback (quick basic tests, then comprehensive) - Cached results for identical submissions - Approximate timing for non-critical operations

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Cost vs Performance

Performance Investment: - High-performance compute instances for code execution - Premium storage for fast data access - Global CDN for low-latency content delivery - Redundant infrastructure for high availability

Cost Optimization: - Auto-scaling to match demand - Spot instances for non-critical workloads - Efficient resource scheduling and sharing - Data archival strategies for old contest data

Technology Selection: - **Compute**: EC2 M5.2xlarge instances for balanced performance - **Storage**: S3 for submissions with intelligent tiering - **Database**: Cassandra for high-volume data, PostgreSQL for transactional - **Cache**: Redis cluster for distributed caching - **Queue**: SQS for reliable message processing with Kafka for high-throughput

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