Ads Click Counter and Aggregator Backend

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- Consistency vs Availability
- Real-time vs Batch Processing
- Storage Cost vs Query Performance

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Requirements Gathering

Functional Requirements

Core Click Recording Functionality: - Capture and log advertisement click events in real-time - Record comprehensive metadata including user demographics, ad placement, and context - Support deduplication of duplicate clicks using unique identifiers - Enable complex analytical queries for marketing insights - Provide aggregated metrics across multiple dimensions (time, geography, demographics)

Analytics and Reporting: - Generate real-time dashboards for click performance - Support historical trend analysis and reporting - Enable segmentation by user demographics, ad campaigns, and time periods - Provide conversion funnel analysis capabilities - Support A/B testing metrics and campaign performance comparisons

Data Management: - Handle high-volume click streams with minimal latency - Support long-term data retention (10+ years) with cost optimization - Enable data export capabilities for external analytics tools - Provide data lineage tracking for audit purposes

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Non-Functional Requirements

Performance Requirements: - Handle 1 billion clicks per day (peak load: 50,000 clicks/second) - Click logging latency: < 100ms (p99) - Analytics query response time: < 2 seconds for standard reports - Support 99.9% availability with graceful degradation

Scalability Requirements: - Horizontally scalable to handle traffic spikes - Support global deployment across multiple data centers - Auto-scaling capabilities based on traffic patterns - Linear performance scaling with resource addition

Consistency and Durability: - Eventual consistency acceptable for analytics (few minutes delay) - Strong consistency for revenue-critical metrics - Zero data loss for click events (financial impact) - Support for replay capabilities in case of system failures

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Traffic Estimation & Capacity Planning

Click Volume Analysis

Daily Traffic Patterns: - 1 billion clicks per day baseline - Peak hours: 3x average traffic (evening hours across time zones) - Average: 11,574 clicks/second - Peak: 50,000 clicks/second during major events or campaigns

Geographic Distribution: - North America: 40% of traffic - Europe: 30% of traffic - Asia-Pacific: 25% of traffic - Other regions: 5% of traffic

Seasonal Variations: - Holiday seasons: 5x normal traffic - Black Friday/Cyber Monday: 10x normal traffic - Regular seasonal fluctuations: ±50% variance

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Storage Calculations

Per-Click Data Size: - Basic click metadata: 0.1 KB per click - Extended user demographics: Additional 0.05 KB - Total per click: ~0.15 KB

Daily Storage Requirements: - Raw clicks: 1B × 0.15 KB = 150 GB/day - Aggregated data: ~10 GB/day (compressed) - Total daily: 160 GB/day

Long-term Storage Projections: - Annual raw data: 160 GB × 365 = ~58 TB/year - 10-year retention: ~580 TB - With compression and archival: ~200 TB effective storage

Query Performance Storage: - Hot data (last 30 days): SSD storage for fast queries - Warm data (3-12 months): Standard storage with caching - Cold data (1+ years): Archival storage (S3 Glacier)

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Throughput Requirements

Write Throughput: - Peak write: 50,000 writes/second - Average write: 11,574 writes/second - Batch write optimization: 1,000 records per batch

Read Throughput: - Analytics queries: 1,000 concurrent queries - Dashboard updates: 100 real-time connections - Report generation: 50 concurrent heavy queries

Network Bandwidth: - Ingress: 50,000 × 0.15 KB = 7.5 MB/second peak - Egress: Query results + dashboard data ~10 MB/second - Internal replication: 2x ingress for redundancy

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Database Schema Design

Click Events Schema

Primary Click Events Table: - Click ID (UUID): Unique identifier for deduplication - Ad ID (UUID): Reference to advertisement - User ID (hashed): Privacy-compliant user identifier - Timestamp: Precise click time with timezone - IP Address (hashed): Geographic analysis while preserving privacy - User Agent: Browser and device information - Referrer URL: Source of the click - Click coordinates: X/Y position for heat map analysis

Partitioning Strategy: - Primary partition: Date (daily partitions) - Secondary partition: Geographic region - Enables efficient time-based and geographic queries

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Aggregation Tables Schema

Time-based Aggregations: - Minute-level aggregations: Real-time dashboards - Hour-level aggregations: Standard reporting - Daily aggregations: Historical analysis - Monthly aggregations: Long-term trends

Dimensional Aggregations: - By ad campaign: Campaign performance metrics - By geography: Regional performance analysis - By demographics: Audience segment analysis - By device type: Cross-platform performance

Pre-computed Metrics: - Click-through rates (CTR) - Conversion rates - Revenue per click (RPC) - Cost per acquisition (CPA)

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User Demographics Schema

User Profile Aggregation: - Age groups: Demographic targeting analysis - Geographic regions: Location-based insights - Device categories: Platform performance - Behavioral segments: Interest-based groupings

Privacy-Compliant Design: - Hashed identifiers only - Aggregated data with k-anonymity - No direct PII storage - GDPR/CCPA compliance built-in

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System API Design

Click Ingestion APIs

Bulk Click Ingestion: - High-throughput batch ingestion endpoint - Support for compressed payloads - Idempotent operations with duplicate detection - Asynchronous pro-

cessing with acknowledgment

Real-time Click Capture: - Low-latency single click endpoint - Optimized for CDN edge caching - Minimal payload validation for speed - Fire-and-forget semantics with reliability

Click Validation Service: - Fraud detection integration - Bot traffic filtering - Geographic validation - Rate limiting per user/IP

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Analytics Query APIs

Dashboard Data APIs: - Real-time metrics endpoint - Cached aggregation serving - WebSocket for live updates - Optimized for visualization libraries

Reporting APIs: - Complex query execution engine - Support for custom date ranges - Multi-dimensional filtering - Export capabilities (CSV, JSON)

Trend Analysis APIs: - Time-series data serving - Comparative analysis support - Statistical computation endpoints - Predictive analytics integration

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Aggregation Management APIs

Background Processing Control: - Aggregation job scheduling - Processing status monitoring - Error handling and retry logic - Resource utilization tracking

Data Lifecycle Management: - Archive policy configuration - Data retention rule enforcement - Storage tier management - Compliance and audit support

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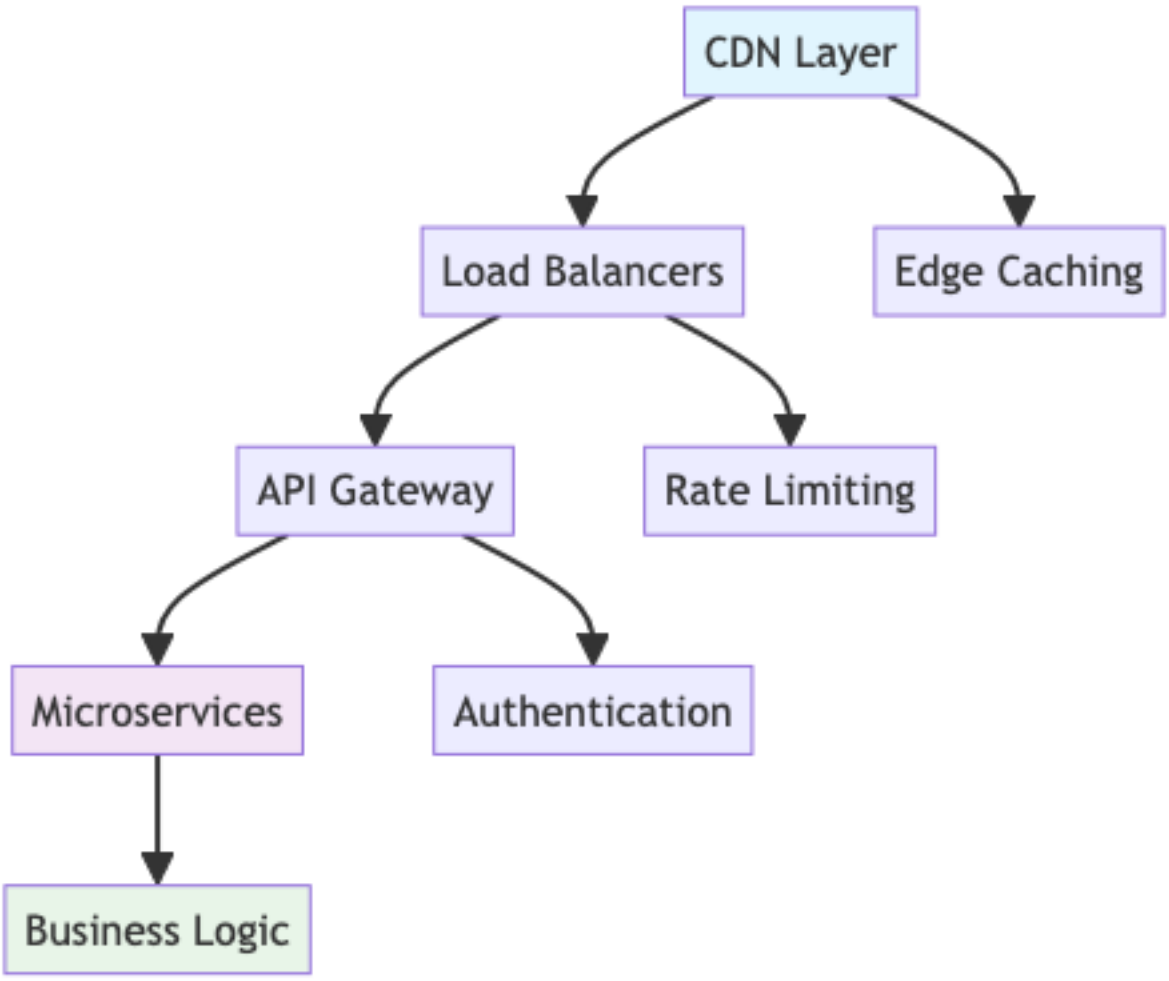
High-Level Design (HLD)

System Architecture Overview

Multi-tier Architecture:



Core Components: - **Click Capture Service**: High-throughput event ingestion - **Stream Processing Engine**: Real-time data transformation - **Aggregation Service**: Batch and real-time metric computation - **Query Engine**: Optimized analytics query processing - **Storage Layer**: Multi-tier data storage with lifecycle management

Geographic Distribution: - Global CDN for click capture with edge processing - Regional data centers for reduced latency - Cross-region replication for disaster recovery - Geo-sharded databases for regulatory compliance

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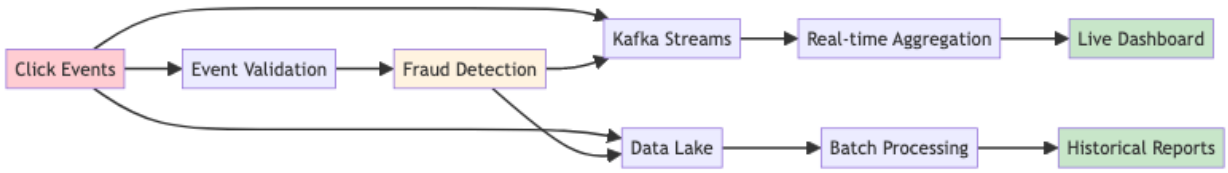
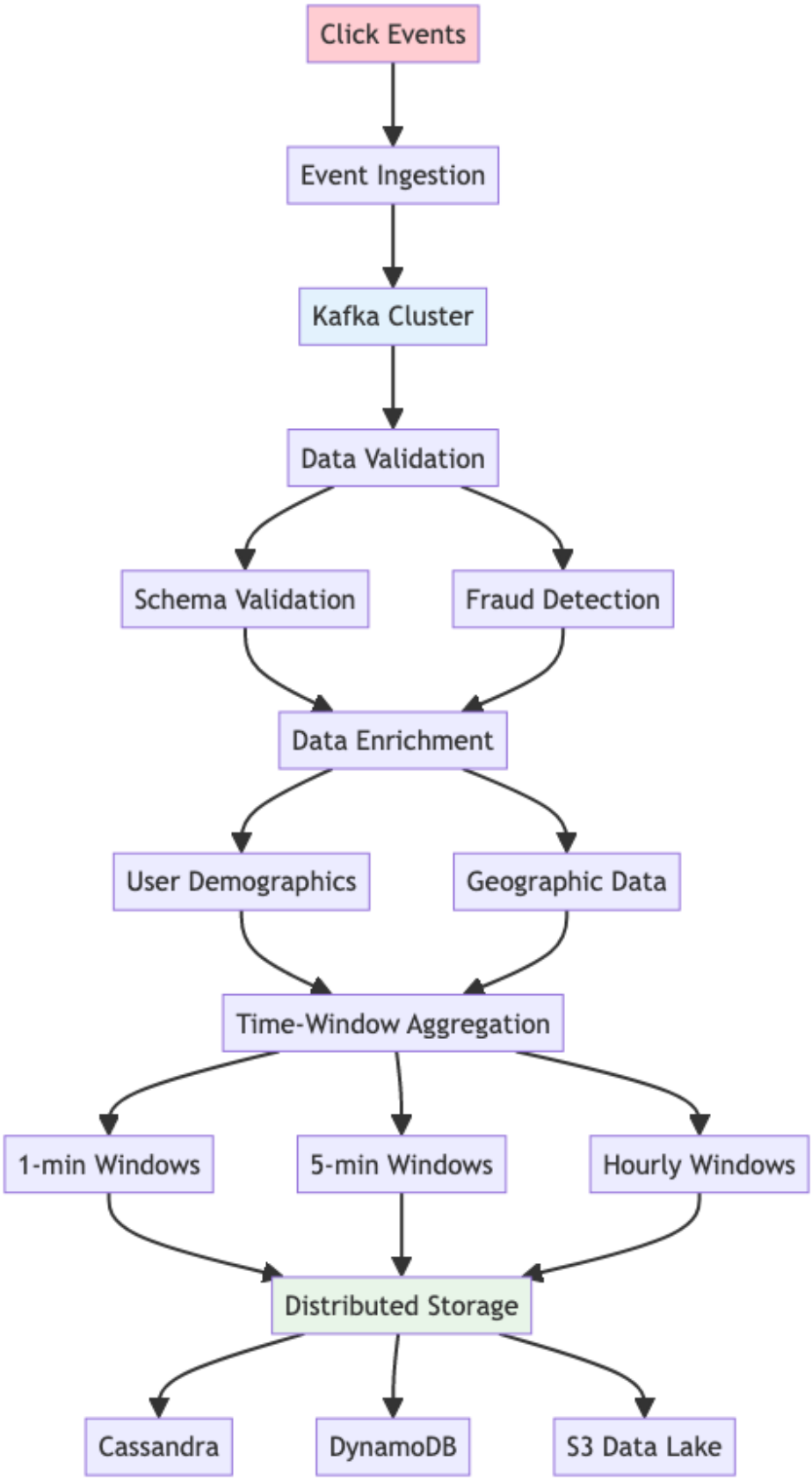
Data Flow Architecture

Lambda Architecture Data Flow:



Stream Processing Pipeline:


Click Events
Event Ingestion
Kafka Cluster
Data Validation
Schema Validation
Fraud Detection
Data Enrichment
User Demographics
Geographic Data
Time-Window Aggregation
1-min Windows
5-min Windows
Hourly Windows
Distributed Storage
Cassandra
DynamoDB
S3 Data Lake

Data Lake Architecture: - Raw events stored in object storage (S3/GCS) - Partitioned by date and region for efficient querying - Multiple data formats: Parquet for analytics, JSON for flexibility - Data catalog for schema evolution and discovery

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CDN Integration

Edge Processing Capabilities: - Click capture at CDN edge nodes - Basic validation and filtering - Geographic tagging and routing - Reduced latency to sub-50ms globally

Cache Strategy: - Static assets (tracking pixels, JavaScript) cached at edge - Dynamic aggregation results cached with TTL - Geographic distribution based on traffic patterns - Intelligent cache warming for popular queries

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Low-Level Design (LLD)

Click Capture Service

High-Throughput Ingestion Design: - Async event processing with message queuing - Connection pooling for database writes - Batch processing for improved throughput - Circuit breaker pattern for fault tolerance

Deduplication Strategy: - Time-window based duplicate detection - Bloom filters for memory-efficient checking - UUID-based unique identification - Configurable deduplication windows

Load Balancing: - Consistent hashing for even distribution - Health check integration - Auto-scaling based on queue depth - Geographic routing for latency optimization

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Stream Processing Pipeline

Kafka Configuration: - Topic partitioning by ad campaign and geography - Replication factor of 3 for durability - Configurable retention policies - Producer acknowledgment settings for reliability

Processing Topology: - Parallel processing streams for scalability - Stateful processing for aggregations - Windowing functions for time-based analysis - Error handling with dead letter queues

State Management: - Distributed state stores for stream processing - Checkpoint and recovery mechanisms - State compaction for efficiency - Hot-standby replicas for fast failover

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Aggregation Engine

Multi-level Aggregation: - Real-time: Sliding window aggregations (1-minute, 5-minute) - Near real-time: Tumbling window aggregations (hourly) - Batch: Daily, weekly, monthly aggregations - On-demand: Custom query aggregations

Distributed Computing: - Map-Reduce paradigm for large-scale processing - Spark/Flink for complex analytical computations - Distributed storage for intermediate results - Resource isolation for different workload types

Optimization Techniques: - Pre-aggregation at ingestion time - Materialized views for common queries - Incremental aggregation updates - Parallel processing across multiple dimensions

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Core Algorithms

1. Click Deduplication Algorithm

Time-Window Deduplication: - Maintain sliding window of recent clicks (configurable duration) - Use composite key: User ID + Ad ID + Timestamp window - Implement probabilistic data structures (Bloom filters) for memory efficiency - Handle edge cases: clock skew, network delays, retries

UUID-based Approach: - Generate unique identifiers for each ad placement - Client-side UUID generation with server-side validation - Handle UUID collisions with timestamp tiebreakers - Persist deduplication state with configurable TTL

Distributed Deduplication: - Consistent hashing for deduplication service distribution - Shared state across service instances - Eventual consistency model for deduplication decisions - Conflict resolution for concurrent duplicate detection

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2. Real-time Aggregation Algorithm

Sliding Window Aggregation: - Maintain multiple overlapping time windows - Incremental updates as new events arrive - Efficient memory management with window expiration - Support for various aggregation functions (sum, count, average, percentiles)

Hierarchical Aggregation: - Bottom-up aggregation: minute □ hour □ day □ month - Incremental computation to avoid reprocessing - Rollup strategies for different granularities - Error propagation and correction mechanisms

Approximate Algorithms: - HyperLogLog for distinct count estimation - Count-Min Sketch for frequency estimation - Reservoir sampling for representative samples - Trade accuracy for performance in high-volume scenarios

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3. Hot Partition Mitigation Algorithm

Dynamic Partitioning: - Monitor partition load in real-time - Automatic partition splitting when load exceeds threshold - Consistent hashing with virtual nodes - Load balancing across available partitions

Traffic Shaping: - Rate limiting for individual ad campaigns - Priority queuing for different traffic types - Backpressure handling with queue management - Graceful degradation under extreme load

Consistent Hashing Strategy: - Virtual node mapping for even distribution - Partition rebalancing without service interruption - Replica placement optimization - Hot spot detection and mitigation

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4. Data Retention and Archival Algorithm

Lifecycle Management: - Automated data classification by age and access patterns - Tiered storage migration (hot warm cold) - Compression algorithms for long-term storage - Metadata preservation during archival process

Cost Optimization: - Storage cost analysis and optimization - Intelligent compression based on data characteristics - Deduplication at the storage level - Archive retrieval optimization for occasional access

Compliance and Audit: - Retention policy enforcement - Audit trail for data lifecycle events - Legal hold capabilities for compliance requirements - Secure deletion with verification

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5. Fraud Detection Algorithm

Pattern Recognition: - Machine learning models for bot detection - Behavioral analysis for suspicious patterns - Geographic anomaly detection - Time-based pattern analysis

Real-time Scoring: - Risk score calculation for each click - Threshold-based filtering - Adaptive scoring based on historical data - Integration with external fraud detection services

Feedback Loop: - Continuous model training with new data - Human verification integration - False positive reduction strategies - Performance metric tracking and optimization

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Performance Optimizations

Partition Strategy

Geographic Partitioning: - Partition data by geographic regions - Optimize for local query patterns - Reduce cross-partition queries - Enable regulatory compliance (data residency)

Time-based Partitioning: - Daily/weekly partitions for time-series data - Partition pruning for historical queries - Parallel processing across time ranges - Efficient archival of old partitions

Hybrid Partitioning: - Multi-dimensional partitioning strategy - Composite partitioning keys - Query pattern optimization - Dynamic repartitioning based on data distribution

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Caching Strategy

Multi-level Caching: - L1: Application-level caching for frequently accessed data - L2: Distributed cache (Redis/Memcached) for shared data - L3: CDN caching for static and semi-static content - Cache coherency strategies across levels

Intelligent Cache Warming: - Predictive cache warming based on usage patterns - Priority-based cache population - Cache hit ratio optimization - Memory usage optimization

Cache Invalidation: - Event-driven cache invalidation - TTL-based expiration strategies - Write-through and write-behind patterns - Consistency guarantees across cache layers

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Batch Processing Optimization

Parallel Processing: - Data parallelism across processing nodes - Task parallelism for different aggregation types - Resource isolation for batch vs. real-time workloads - Dynamic resource allocation based on workload

I/O Optimization: - Columnar storage formats (Parquet, ORC) - Compression optimization for storage and transfer - Batch size optimization for throughput - Memory mapping for large dataset processing

Processing Pipeline: - ETL pipeline optimization - Incremental processing for efficiency - Error handling and retry mechanisms - Monitoring and alerting for batch jobs

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Security Considerations

Click Fraud Prevention

Multi-layered Detection: - Rate limiting per IP address and user - Pattern analysis for automated traffic - Device fingerprinting for bot detection - Geographic and temporal anomaly detection

Machine Learning Integration: - Real-time fraud scoring models - Behavioral analysis algorithms - Adaptive threshold adjustment - Continuous model retraining

Third-party Integration: - External fraud detection services - IP reputation databases - Device intelligence platforms - Threat intelligence feeds

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Data Privacy

Privacy by Design: - Data minimization principles - Purpose limitation enforcement - Anonymization and pseudonymization - Consent management integration

Compliance Framework: - GDPR compliance for European users - CCPA compliance for California residents - Data subject rights implementation - Privacy impact assessments

Encryption and Security: - End-to-end encryption for sensitive data - Encryption at rest and in transit - Key management and rotation - Access control and audit logging

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Testing Strategy

Load Testing

Performance Testing: - Gradual load increase testing - Peak load simulation - Sustained load testing - Breaking point identification

Stress Testing: - System behavior under extreme conditions - Resource exhaustion scenarios - Recovery testing after failures - Cascading failure prevention

Scalability Testing: - Horizontal scaling validation - Auto-scaling behavior verification - Resource utilization optimization - Performance regression testing

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Data Consistency Testing

Eventual Consistency Validation: - Cross-replica consistency checking - Convergence time measurement - Conflict resolution validation - Data integrity verification

Aggregation Accuracy: - End-to-end data flow validation - Aggregation result verification - Temporal consistency checking - Cross-dimensional consistency

Disaster Recovery Testing: - Data loss prevention validation - Recovery time objective (RTO) testing - Recovery point objective (RPO) validation - Failover and failback procedures

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Trade-offs and Considerations

Consistency vs Availability

CAP Theorem Application: - Prioritize availability for click ingestion - Accept eventual consistency for analytics - Strong consistency for revenue-critical operations - Partition tolerance through replication

Consistency Models: - Strong consistency for financial transactions - Eventual consistency for analytics aggregations - Session consistency for user-facing operations - Monotonic consistency for time-series data

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Real-time vs Batch Processing

Lambda Architecture Benefits: - Real-time insights for immediate decision making - Batch processing for complex analytics - Cost optimization through appropriate processing choice - Flexibility in handling different data access patterns

Processing Trade-offs: - Real-time: Higher cost, lower latency, approximate results - Batch: Lower cost, higher latency, exact results - Hybrid approach for optimal cost-performance balance

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Storage Cost vs Query Performance

Storage Optimization: - Hot data on fast storage for quick access - Cold data on cheap storage with slower access - Compression for long-term storage cost reduction - Intelligent data lifecycle management

Query Performance: - Indexing strategies for common query patterns - Materialized views for complex aggregations - Caching for frequently accessed data - Query optimization through data modeling

Cost Management: - Storage tier optimization based on access patterns - Compute resource optimization for batch processing - Network cost reduction through geographic distribution - Monitoring and alerting for cost anomalies

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