

Test creaeting pdf from markdown

Generating single mermaid chart 🎨 Rendered Mermaid diagram 1 Generating single mermaid chart 🎨 Rendered Mermaid diagram 2 Generating single mermaid chart 🎨 Rendered Mermaid diagram 3 Generating single mermaid chart 🎨 Rendered Mermaid diagram 4 Generating single mermaid chart 🎨 Rendered Mermaid diagram 5 Generating single mermaid chart 🎨 Rendered Mermaid diagram 6 Generating single mermaid chart 🎨 Rendered Mermaid diagram 7 Generating single mermaid chart 🎨 Rendered Mermaid diagram 8 Generating single mermaid chart 🎨 Rendered Mermaid diagram 9

Caching - 1 Hour Session

Duration: 60 minutes **Level:** Intermediate



Session Agenda

- ▢ Introduction to Caching (10 min)
- ▢ Cache Types & Layers (10 min)
- ▢ Caching Strategies & Patterns (15 min)
- ▢ Cache Eviction Policies (10 min)
- ▢ Implementation & Best Practices (15 min)



Learning Objectives

By the end of this session, you will understand: - What caching is and when to use it - Different types and layers of caching - Common caching patterns and strategies - Cache eviction policies and their trade-offs - How to implement and manage caching effectively - Common pitfalls and how to avoid them

1. Introduction to Caching (10 min)

What is Caching?

Caching is the process of storing copies of data in a temporary storage location (cache) for faster access.

 **Quote** “There are only two hard things in Computer Science: cache invalidation and naming things.” - Phil Karlton

Why Cache?

Performance Improvements: -  **Speed:** RAM access ~100ns vs Database ~10ms (100,000x faster) -  **Cost:** Reduce database load and infrastructure costs -  **Scalability:** Handle more requests with same resources -  **User Experience:** Faster response times = happier users

The Cache Hit/Miss Concept

Request Flow:

1. Check Cache
 - |— HIT: Return cached data (fast!) ✓
 - |— MISS:
 - |— Query database/API (slow)
 - |— Store in cache
 - |— Return data

Cache Hit Ratio = (Cache Hits / Total Requests) × 100%

Target: 80–95% for most applications

Key Metrics

| Metric | Description | Good Target |
|--------------|--|---------------------|
| Hit Ratio | Percentage of requests served from cache | > 80% |
| Latency | Time to retrieve from cache | < 10ms |
| TTL | Time data stays in cache | Depends on use case |
| Memory Usage | Cache size vs available memory | < 80% of allocated |

2. Cache Types & Layers (10 min)

Caching Layers (Closest to Farthest from User)

1. Client-Side Cache (Browser) -- Fastest 2. CDN Cache (Edge Locations) 3. Application Cache (In-Memory) 4. Distributed Cache (Redis/Memcached) 5. Database Cache (Query Cache) 6. Disk Cache -- Slowest

Diagram

1. Client-Side Cache

Browser Cache: - Stores static assets (images, CSS, JS) - Controlled via HTTP headers

HTTP Headers:

```
Cache-Control: max-age=3600, public
ETag: "33a64df551425fcc55e4d42a148795d9f25f89d4"
Last-Modified: Wed, 21 Oct 2023 07:28:00 GMT
Expires: Thu, 01 Dec 2024 16:00:00 GMT
```

LocalStorage/SessionStorage: - JavaScript-accessible storage - 5-10MB limit per domain

```
// LocalStorage example
localStorage.setItem('user_preferences', JSON.stringify(data));
const prefs = JSON.parse(localStorage.getItem('user_preferences'));
```

2. CDN Cache

Content Delivery Network caches at edge locations worldwide.

```
User in Tokyo → Tokyo Edge Server (cached) ✓ (50ms)
vs
User in Tokyo → US Origin Server (not cached) ✗ (250ms)
```

Use Cases: - Static assets (images, videos, CSS, JS) - API responses (with proper headers) - Entire pages (for static sites)

3. Application-Level Cache

In-Process Cache: - Stored in application memory - Fastest but not shared across instances

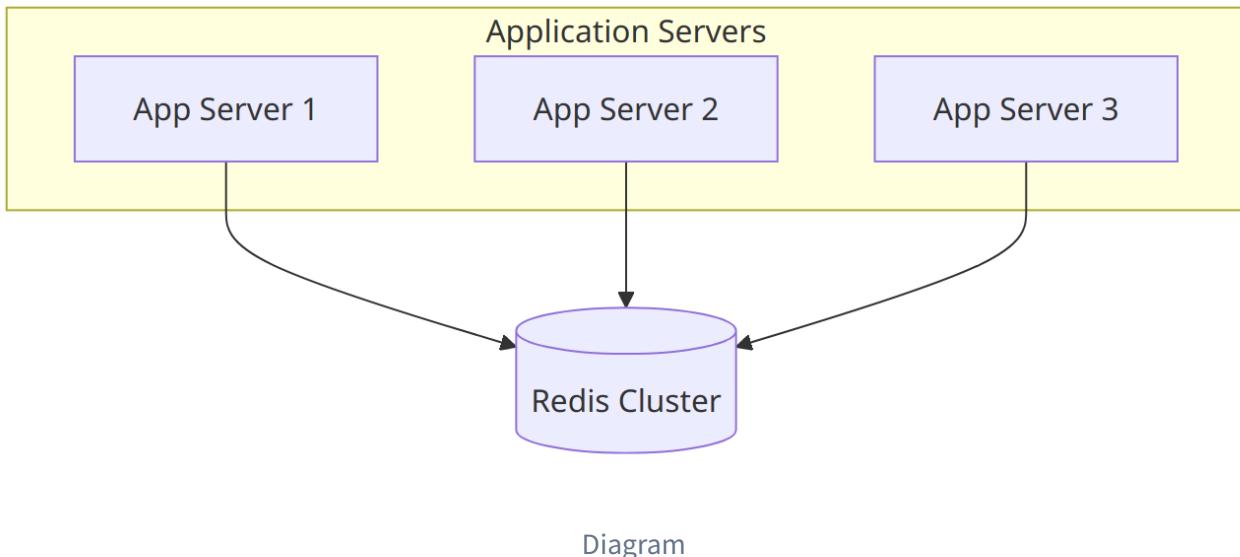
```
# Python simple in-memory cache
from functools import lru_cache

@lru_cache(maxsize=1000)
def get_user(user_id):
    # This result will be cached
    return database.query(f"SELECT * FROM users WHERE id={user_id}")
```

4. Distributed Cache

Shared cache across multiple application instances.

Popular Solutions: - **Redis** - Feature-rich, supports data structures - **Memcached** - Simple, fast, key-value only - **Hazelcast** - Distributed in-memory data grid



Diagram

5. Database Cache

Query Result Cache: - MySQL Query Cache (deprecated in 8.0) - PostgreSQL shared buffers - MongoDB WiredTiger cache

ORM-Level Cache: - Hibernate second-level cache - Django cache framework - Entity Framework caching

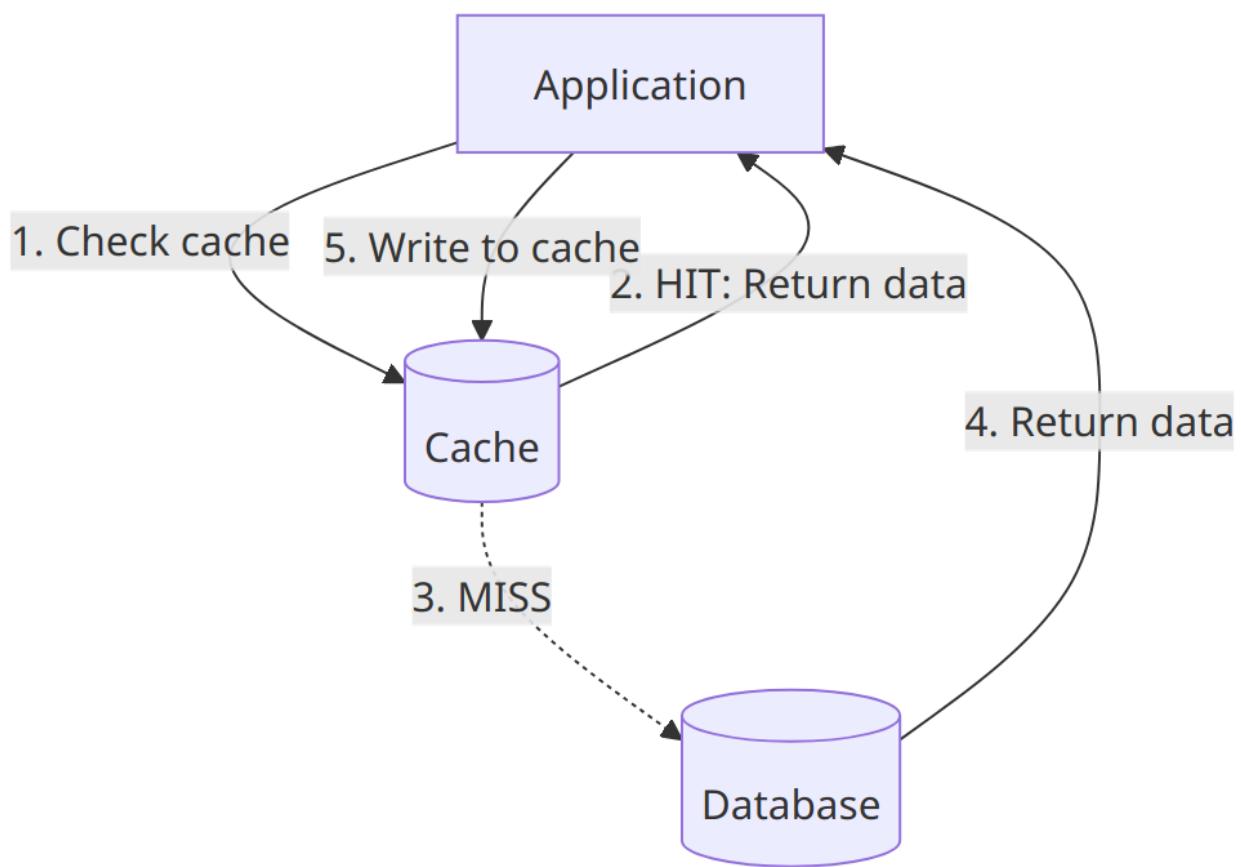
Cache Type Comparison

| Type | Speed | Shared | Complexity | Persistence |
|-----------|-----------|--------|------------|---------------|
| Browser | Fastest | No | Low | Session-based |
| CDN | Very Fast | Yes | Medium | Configurable |
| In-Memory | Fast | No | Low | No |
| Redis | Fast | Yes | Medium | Optional |
| Database | Medium | Yes | Low | Yes |

3. Caching Strategies & Patterns (15 min)

1. Cache-Aside (Lazy Loading)

Most common pattern. Application manages cache explicitly.



Diagram

Implementation:

```

def get_user(user_id):
    # 1. Try cache first
    cache_key = f"user:{user_id}"
    user = cache.get(cache_key)

    if user is not None:
        return user # Cache HIT

    # 2. Cache MISS - query database
    user = database.query(f"SELECT * FROM users WHERE id={user_id}")

    # 3. Store in cache
    cache.set(cache_key, user, ttl=3600) # 1 hour

    return user

```

Pros: - Only requested data is cached - Cache failure doesn't break the app

Cons: - Cache miss penalty (extra latency) - Data can become stale

2. Read-Through Cache

Cache sits between app and database. Cache manages data loading.

Application → Cache → Database
 (auto-loads on miss)

```

# Pseudo-code (handled by cache library)
user = cache.get(user_id) # Cache automatically queries DB on miss

```

Pros: - Simplified application code - Consistent pattern

Cons: - Tight coupling to cache - First request still slow

3. Write-Through Cache

Write to cache and database simultaneously.

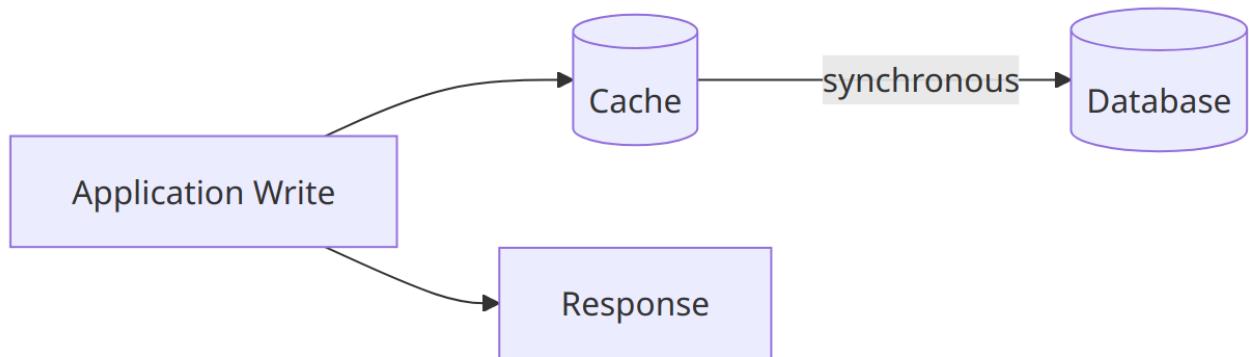
```

def update_user(user_id, data):
    # 1. Update database
    database.update(user_id, data)

    # 2. Update cache
    cache_key = f"user:{user_id}"
    cache.set(cache_key, data, ttl=3600)

    return data

```



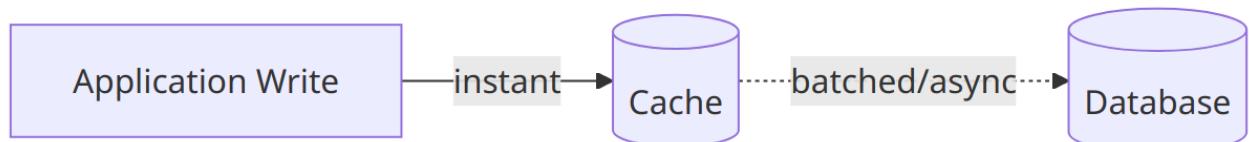
Diagram

Pros: - Cache always consistent with DB - No stale data

Cons: - Write latency (two operations) - Wasted writes for unread data

4. Write-Behind (Write-Back) Cache

Write to cache immediately, database asynchronously.



Diagram

```

def update_user(user_id, data):
    # 1. Update cache immediately
    cache_key = f"user:{user_id}"
    cache.set(cache_key, data, ttl=3600)

    # 2. Queue database update (async)
    queue.enqueue('db_update', user_id, data)

return data # Fast response!

```

Pros: - Very fast writes - Can batch database operations

Cons: - Risk of data loss if cache fails - Complex to implement correctly

5. Refresh-Ahead

Proactively refresh cache before expiration.

```

import time
from threading import Thread

def get_user_with_refresh(user_id):
    cache_key = f"user:{user_id}"
    user, expiry = cache.get_with_expiry(cache_key)

    if user is None:
        # Cache miss - load from DB
        user = database.query(user_id)
        cache.set(cache_key, user, ttl=3600)
    elif time.time() > (expiry - 300): # 5 min before expiry
        # Refresh in background
        Thread(target=refresh_cache, args=(user_id,)).start()

    return user

def refresh_cache(user_id):
    user = database.query(user_id)
    cache.set(f"user:{user_id}", user, ttl=3600)

```

Pros: - Reduced latency (no cache miss delays) - Predictable performance

Cons: - Additional complexity - May refresh unused data

Strategy Comparison

| PATTERN | READ PERF | WRITE PERF | COMPLEXITY | DATA FRESHNESS |
|---------------|-----------|------------|------------|-----------------------|
| Cache-Aside | Good | Good | Low | Can be stale |
| Read-Through | Good | Good | Medium | Can be stale |
| Write-Through | Good | Slower | Medium | Always fresh |
| Write-Behind | Good | Fastest | High | Eventually consistent |
| Refresh-Ahead | Best | Good | High | Very fresh |

4. Cache Eviction Policies (10 min)

Why Eviction?

⚠ Warning Caches have finite memory. When full, old data must be removed to make room for new data.

Common Eviction Algorithms

1. LRU (Least Recently Used)

Removes the least recently accessed item.

```
Cache: [A, B, C, D] (max size: 4)
```

```
Access B → [A, C, D, B]
```

```
Access C → [A, D, B, C]
```

```
Add E → [D, B, C, E] (A evicted - oldest access)
```

Best for: General purpose, temporal locality

```
from collections import OrderedDict

class LRUCache:
    def __init__(self, capacity):
        self.cache = OrderedDict()
        self.capacity = capacity

    def get(self, key):
        if key not in self.cache:
            return None
        # Move to end (most recently used)
        self.cache.move_to_end(key)
        return self.cache[key]

    def put(self, key, value):
        if key in self.cache:
            self.cache.move_to_end(key)
        self.cache[key] = value
        if len(self.cache) > self.capacity:
            # Remove first item (least recently used)
            self.cache.popitem(last=False)
```

2. LFU (Least Frequently Used)

Removes the least frequently accessed item.

```
Item A: accessed 10 times
Item B: accessed 5 times
Item C: accessed 2 times  ← Evicted first
Item D: accessed 8 times
```

Best for: Items with consistent popularity

3. FIFO (First In, First Out)

Removes oldest item regardless of access.

Cache: [A(1st), B(2nd), C(3rd), D(4th)]

Add E → [B(2nd), C(3rd), D(4th), E(5th)] (A evicted)

Best for: Simple use cases, streaming data

4. TTL (Time To Live)

Items expire after a set time.

```
import time

cache = {}

def set_with_ttl(key, value, ttl_seconds):
    expiry = time.time() + ttl_seconds
    cache[key] = {'value': value, 'expiry': expiry}

def get_with_ttl(key):
    if key not in cache:
        return None

    item = cache[key]
    if time.time() > item['expiry']:
        del cache[key] # Expired
        return None

    return item['value']
```

Best for: Time-sensitive data (sessions, tokens)

5. Random Replacement

Randomly selects item to evict.

Best for: When access patterns are unpredictable

Eviction Policy Comparison

| POLICY | COMPLEXITY | HIT RATIO | USE CASE |
|--------|------------|-----------|----------------------------------|
| LRU | Medium | High | General purpose, recency matters |
| LFU | High | High | Popularity-based content |
| FIFO | Low | Low | Simple queues |
| TTL | Low | Medium | Time-sensitive data |
| Random | Low | Low | Unpredictable patterns |

Redis Eviction Policies

Redis supports multiple policies:

```
# redis.conf
maxmemory 2gb
maxmemory-policy allkeys-lru

# Options:
# noevasion      - Return errors when memory limit reached
# allkeys-lru    - Remove any key, LRU algorithm
# volatile-lru   - Remove keys with TTL, LRU
# allkeys-lfu    - Remove any key, LFU algorithm
# volatile-lfu   - Remove keys with TTL, LFU
# allkeys-random - Remove random key
# volatile-random - Remove random key with TTL
# volatile-ttl   - Remove key with nearest expiration
```

5. Implementation & Best Practices (15 min)

Redis Implementation Examples

Basic Operations

```
import redis
import json

# Connect to Redis
r = redis.Redis(host='localhost', port=6379, db=0, decode_responses=True)

# SET with TTL
def cache_user(user_id, user_data):
    key = f"user:{user_id}"
    r.setex(key, 3600, json.dumps(user_data)) # 1 hour TTL

# GET
def get_cached_user(user_id):
    key = f"user:{user_id}"
    data = r.get(key)
    return json.loads(data) if data else None

# DELETE
def invalidate_user_cache(user_id):
    key = f"user:{user_id}"
    r.delete(key)

# CHECK EXISTS
def is_cached(user_id):
    key = f"user:{user_id}"
    return r.exists(key) > 0
```

Advanced Patterns

1. Cache Warming:

```

def warm_cache():
    """Pre-load frequently accessed data"""
    popular_users = database.query("SELECT * FROM users ORDER BY views DESC
LIMIT 100")

    pipeline = r.pipeline()
    for user in popular_users:
        key = f"user:{user['id']}"
        pipeline.setex(key, 3600, json.dumps(user))

    pipeline.execute() # Batch operation

```

2. Cache Stampede Prevention:

```

import time
import random

def get_with_stampede_protection(key, fetch_func, ttl=3600):
    """Prevent multiple threads from fetching same data simultaneously"""

    data = r.get(key)
    if data:
        return json.loads(data)

    # Try to acquire lock
    lock_key = f"lock:{key}"
    lock_acquired = r.set(lock_key, "1", nx=True, ex=10) # 10 sec lock

    if lock_acquired:
        try:
            # Fetch data
            data = fetch_func()
            r.setex(key, ttl, json.dumps(data))
        return data
    finally:
        r.delete(lock_key)
    else:
        # Wait and retry
        time.sleep(random.uniform(0.1, 0.5))
    return get_with_stampede_protection(key, fetch_func, ttl)

```

3. Multi-Level Cache:

```
class MultiLevelCache:
    def __init__(self):
        self.l1_cache = {} # In-memory (fast)
        self.l2_cache = redis.Redis() # Redis (shared)

    def get(self, key):
        # Try L1 first
        if key in self.l1_cache:
            return self.l1_cache[key]

        # Try L2
        data = self.l2_cache.get(key)
        if data:
            # Promote to L1
            self.l1_cache[key] = data
            return data

    return None

def set(self, key, value, ttl=3600):
    # Write to both levels
    self.l1_cache[key] = value
    self.l2_cache.setex(key, ttl, value)
```

Memcached Implementation

```
import memcache

mc = memcache.Client(['127.0.0.1:11211'], debug=0)

# SET
mc.set("user:123", user_data, time=3600)

# GET
user = mc.get("user:123")

# DELETE
mc.delete("user:123")

# GET MULTIPLE
users = mc.get_multi(["user:123", "user:456", "user:789"])
```

Application-Level Caching (Node.js)

```
const NodeCache = require('node-cache');
const cache = new NodeCache({ stdTTL: 3600 });

// Middleware for Express
function cacheMiddleware(duration) {
    return (req, res, next) => {
        const key = req.originalUrl;
        const cachedResponse = cache.get(key);

        if (cachedResponse) {
            return res.send(cachedResponse);
        }

        // Override res.send to cache response
        const originalSend = res.send;
        res.send = function(data) {
            cache.set(key, data, duration);
            originalSend.call(this, data);
        };

        next();
    };
}

// Usage
app.get('/api/users', cacheMiddleware(300), (req, res) => {
    // This response will be cached for 5 minutes
    const users = database.getUsers();
    res.json(users);
});
```

Best Practices

1. Cache Key Naming Convention

Pattern: {resource}:{identifier}:{attribute}

Examples:

| | |
|--------------------------|---------------------|
| user:123 | - User object |
| user:123:profile | - User profile |
| user:123:posts | - User's posts |
| session:abc123 | - Session data |
| product:456:inventory | - Product inventory |
| api:v1:users:list:page:1 | - API response |

2. TTL Strategy

```
# Different TTL for different data types
CACHE_TTL = {
    'static_content': 86400,      # 24 hours
    'user_profile': 3600,        # 1 hour
    'user_session': 1800,        # 30 minutes
    'api_response': 300,         # 5 minutes
    'real_time_data': 60,        # 1 minute
}
```

3. Cache Invalidation Strategies

Time-based (TTL): ~python cache.setex('user:123', 3600, user_data) # Auto-expires~

Event-based: ~python def update_user(user_id, new_data): database.update(user_id, new_data) cache.delete(f'user:{user_id}') # Invalidate on update~

Tag-based: ~python # Invalidate all user-related caches tags = cache.smembers(f'tags:user:{user_id}') for tag in tags: cache.delete(tag)~

4. Monitoring & Alerting

```
# Track cache metrics
def cache_get_with_metrics(key):
    start_time = time.time()
    data = cache.get(key)
    latency = time.time() - start_time

    # Log metrics
    if data:
        metrics.increment('cache.hit')
    else:
        metrics.increment('cache.miss')

    metrics.histogram('cache.latency', latency)

    return data
```

Key Metrics to Monitor: - Hit/Miss ratio - Cache memory usage - Eviction rate - Average latency - Connection pool usage

5. Cache Size Calculation

```
import sys

def calculate_cache_size(data_size_bytes, num_items, overhead=1.2):
    """
    data_size_bytes: Average size of each cached item
    num_items: Number of items to cache
    overhead: Redis overhead factor (keys, metadata)
    """
    total_size = data_size_bytes * num_items * overhead

    # Convert to GB
    size_gb = total_size / (1024 ** 3)

    return size_gb

# Example: Cache 1M user profiles, avg 2KB each
cache_size = calculate_cache_size(2048, 1_000_000)
print(f"Required cache size: {cache_size:.2f} GB")
```

💡 Common Pitfalls & Solutions

1. Cache Stampede

Problem: Multiple requests for expired key hit database simultaneously.

Cache expires → 1000 concurrent requests → 1000 DB queries! 💥

Solution: Use locks or probabilistic early expiration

```

def get_with_early_expiration(key, ttl=3600, beta=1.0):
    data, expiry, delta = cache.get_with_metadata(key)

    if data is None:
        # Cache miss - fetch and store
        data = fetch_from_db(key)
        cache.set(key, data, ttl)
        return data

    # Probabilistic early refresh
    time_to_expiry = expiry - time.time()
    if time_to_expiry < 0:
        return data

    # XFetch algorithm
    if time.time() - delta * beta * math.log(random.random()) ≥ expiry:
        # Refresh in background
        refresh_async(key)

    return data

```

2. Stale Data

Problem: Cache returns outdated information.

Solutions: - Shorter TTL for frequently changing data - Event-driven invalidation - Write-through caching - Cache versioning

```

# Cache versioning
CACHE_VERSION = "v2"

def versioned_key(key):
    return f"{CACHE_VERSION}:{key}"

# When data structure changes, increment version
# Old cached data automatically becomes inaccessible

```

3. Cache Penetration

Problem: Requests for non-existent keys always hit database.

```
Request for user:99999 (doesn't exist)
→ Cache miss
→ Database query (returns null)
→ No caching (null not cached)
→ Repeat 1000 times 💥
```

Solution: Cache null results with short TTL

```
def get_user(user_id):
    key = f"user:{user_id}"
    user = cache.get(key)

    if user == "NULL": # Cached null result
        return None

    if user:
        return user

    user = database.query(user_id)

    if user is None:
        cache.setex(key, 60, "NULL") # Cache null for 1 min
    else:
        cache.setex(key, 3600, user)

    return user
```

4. Memory Overflow

Problem: Cache grows too large, OOM errors.

Solutions: - Set maxmemory limit - Configure eviction policy - Monitor memory usage - Use TTL aggressively

```
# redis.conf
maxmemory 2gb
maxmemory-policy allkeys-lru
```

5. Cache Inconsistency

Problem: Cache and database out of sync.

Solutions:

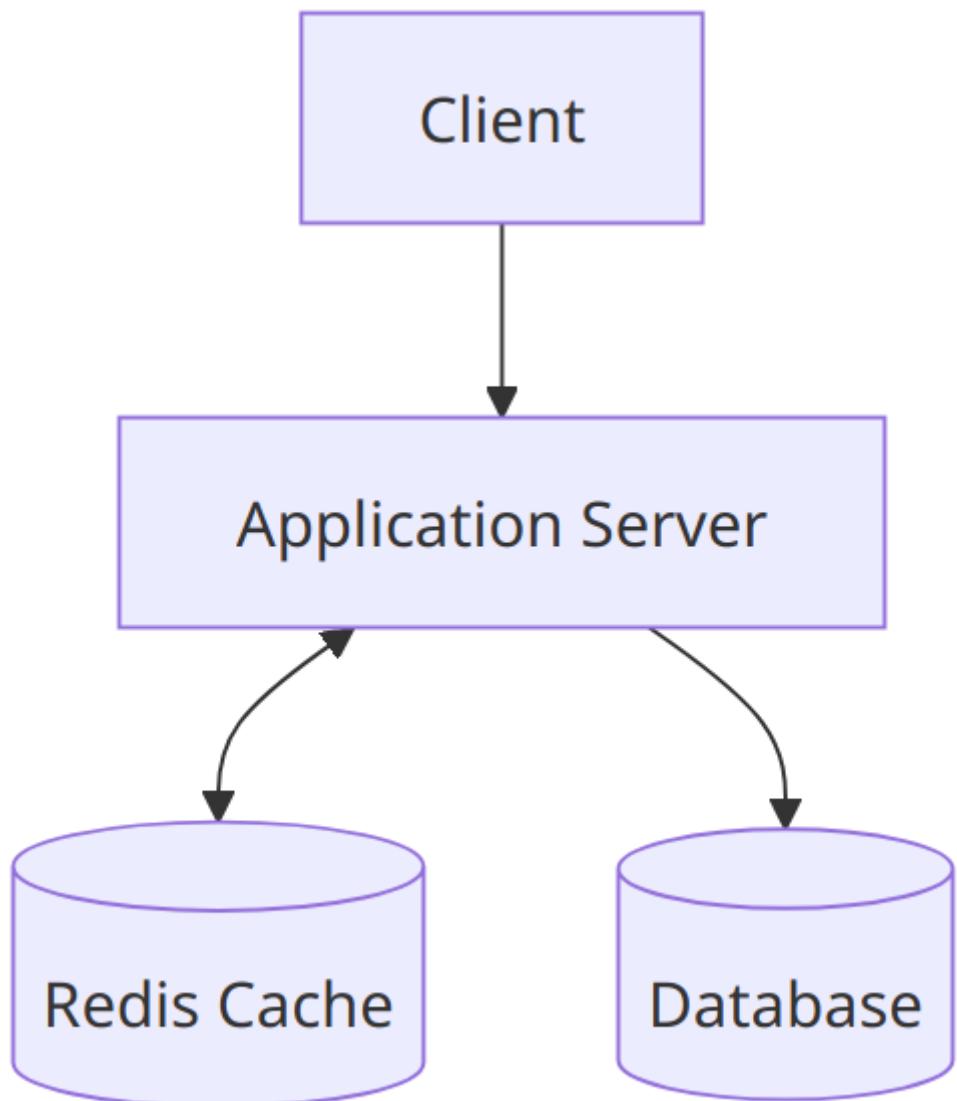
```
# Use database transactions with cache updates
def update_user_transactional(user_id, data):
    try:
        # Start transaction
        db.begin()
        db.update('users', user_id, data)
        db.commit()

        # Only update cache after successful DB update
        cache.set(f'user:{user_id}', data, ttl=3600)

    except Exception as e:
        db.rollback()
        # Don't update cache if DB update failed
        raise e
```

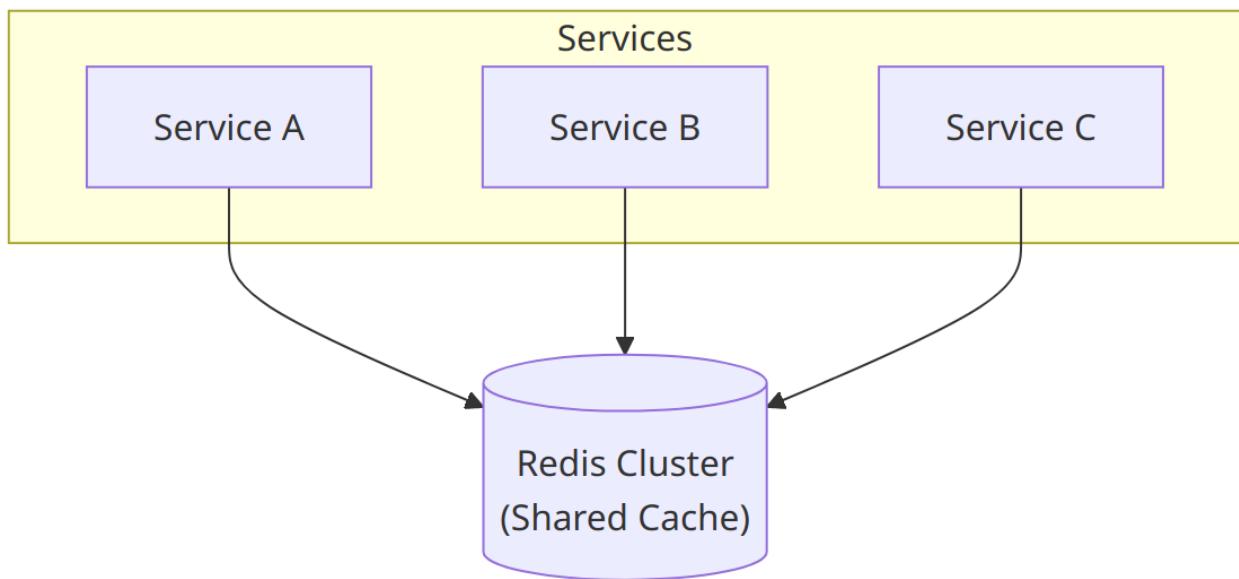


Pattern 1: Simple Web Application



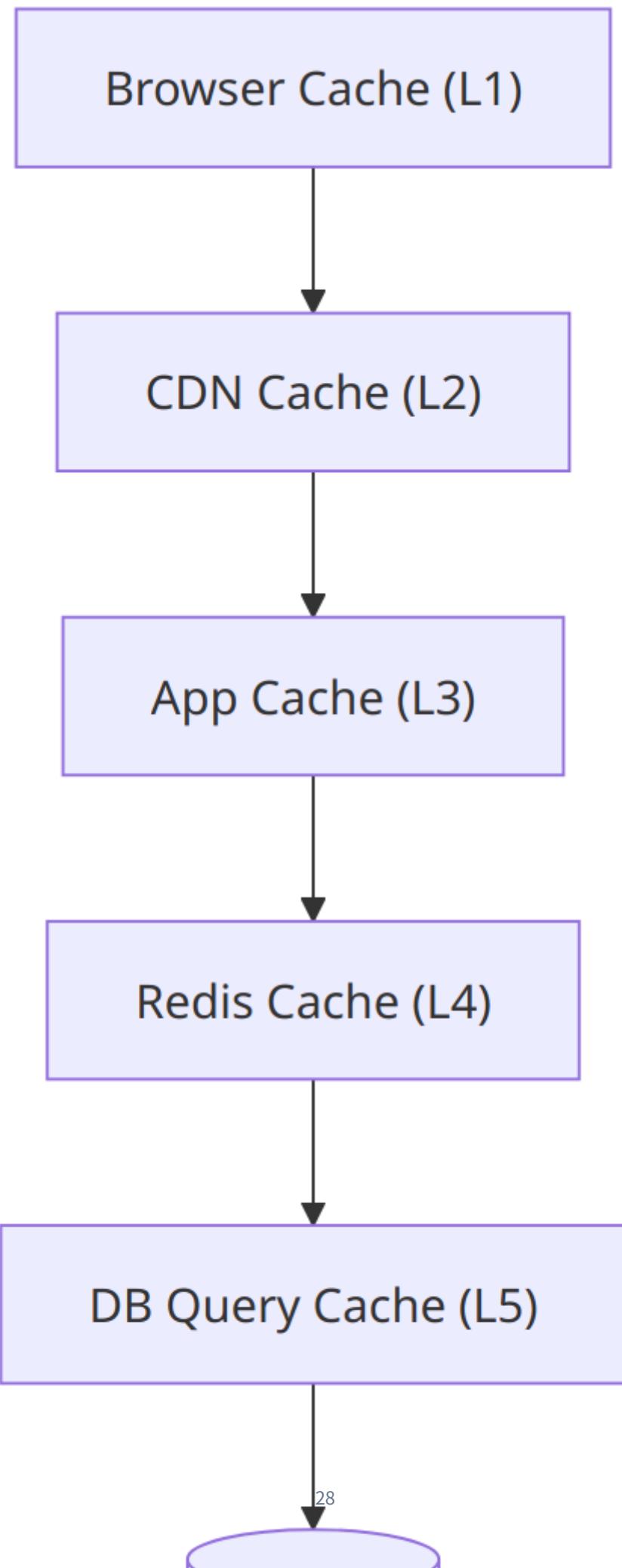
Diagram

Pattern 2: Microservices with Shared Cache



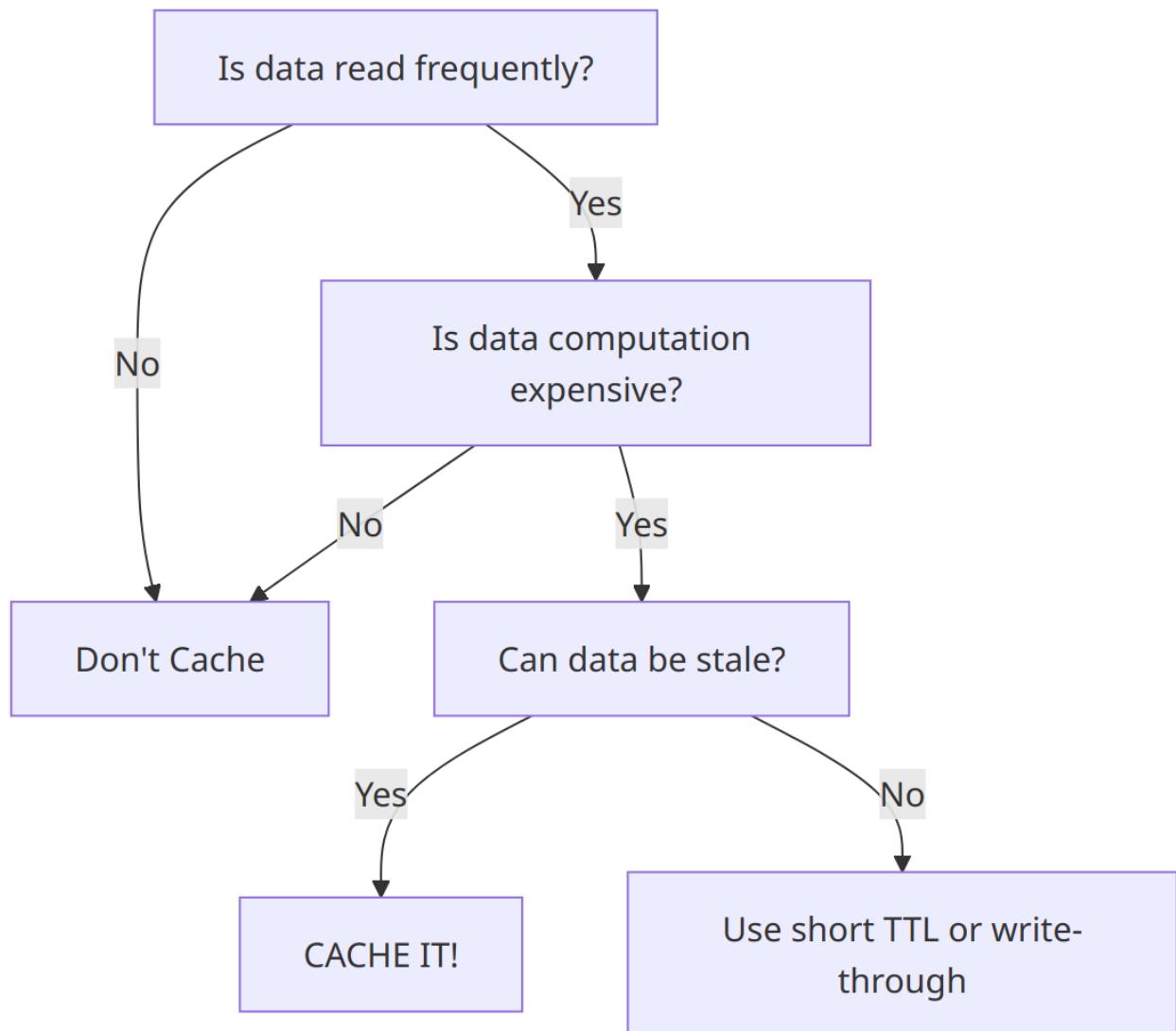
Diagram

Pattern 3: Multi-Tier Caching



🔍 Decision Framework

When to Cache?



Cache if: - ✓ Read frequency >> Write frequency - ✓ Expensive to compute/fetch - ✓ Can tolerate some staleness - ✓ Limited data size

Don't cache if: - ✗ Write-heavy workload - ✗ Must be real-time accurate - ✗ Data is already fast to fetch - ✗ Unlimited data size

Choosing Cache Type

| REQUIREMENT | RECOMMENDED SOLUTION |
|------------------------|-------------------------------|
| Static assets | CDN (CloudFront, Cloudflare) |
| Session data | Redis with TTL |
| Database query results | Application cache + Redis |
| API responses | CDN + Redis |
| Computed values | Redis with refresh-ahead |
| User preferences | Browser localStorage + Redis |
| Real-time data | Redis with short TTL (30-60s) |

Key Takeaways

1. **Caching dramatically improves performance** but adds complexity
2. **Choose the right cache layer** based on data access patterns
3. **Cache invalidation is hard** - use TTL, event-based, or hybrid approaches
4. **Monitor your cache** - hit ratio, memory, latency
5. **Handle edge cases** - stampede, penetration, inconsistency
6. **Different data needs different strategies** - one size doesn't fit all
7. **Start simple** - add complexity only when needed



Practical Exercise

Scenario: You're building a social media feed application.

Requirements: - User posts (10k posts/day) - User profiles (1M users) - Feed generation (complex algorithm, 2s to compute) - Real-time likes/comments

Questions: 1. What should you cache? 2. What TTL for each cache? 3. Which caching strategy for each? 4. How to handle real-time updates?

Suggested Solution:

Cache Strategy:

User Profiles:

- Strategy: Cache-Aside
- TTL: 1 hour
- Invalidation: On profile update

Feed (Personalized):

- Strategy: Cache-Aside with refresh-ahead
- TTL: 5 minutes
- Invalidation: Time-based + new post event

Feed (Public):

- Strategy: Write-through
- TTL: 1 minute
- Invalidation: On new post

Posts:

- Strategy: Write-through
- TTL: 1 hour
- Invalidation: On edit/delete

Likes/Comments Count:

- Strategy: Write-behind (async update)
- TTL: 30 seconds
- Invalidation: Eventual consistency OK



Redis Commands Cheatsheet

```
# String operations
SET key value EX 3600          # Set with TTL
GET key                         # Get value
DEL key                          # Delete
EXISTS key                       # Check exists
TTL key                          # Check remaining TTL
EXPIRE key 3600                 # Set TTL on existing key

# Hash operations (for objects)
HSET user:123 name "John"
HGET user:123 name
HGETALL user:123
HDEL user:123 name

# List operations
LPUSH list value                # Add to front
RPUSH list value                # Add to end
LRANGE list 0 10                 # Get range

# Set operations
SADD tags "redis" "cache"
SMEMBERS tags
SISMEMBER tags "redis"

# Sorted Set (for leaderboards)
ZADD leaderboard 100 "user1"
ZRANGE leaderboard 0 10 WITHSCORES

# Cache patterns
SETEX key 3600 value            # Set with expiry
SETNX key value                 # Set if not exists (lock)
GETEX key EX 3600                # Get and refresh TTL
```

Q&A Session

Time remaining for questions and discussion

Common Questions:

1. Redis vs Memcached?

- Redis: Feature-rich, persistent, data structures
- Memcached: Simpler, pure cache, slightly faster

2. How to size cache?

- Calculate: items × size × overhead
- Start with 20% of hot data
- Monitor and adjust

3. Cache in serverless (AWS Lambda)?

- Use external cache (ElastiCache)
- Or global variables (limited)
- Or DAX for DynamoDB

4. Handling cache cluster failures?

- Graceful degradation (fall back to DB)
- Cache replication
- Circuit breaker pattern

Session End - Thank You! 🎉

#caching #performance #redis #architecture #session-notes