JSimpleDB: Language Driven Persistence for Java

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Why Persistence?

- Computers are state machines and persistence allows flexibility in handling that state
- Machines crash, power cycle, reboot, ...
- Code is always evolving
- Program state may not all fit into memory
- Multiple computers accessing the same state
- Separation of concerns: code vs. data
- Persistence is part of almost all software
Programming Language Fantasyland

- Data access is atomic
- Data access is instantaneous
- Data access never fails
- Data has no encoding issues
  - Data can never be corrupted
- Data always behaves the same way
- No other computer can touch my data
The Persistence Reality

- All data must be encoded into 1’s and 0’s
- Encodings can change between code versions
- Data access can be slow
- Data access can fail randomly
- Data access is not atomic
  - Transaction semantics can be very subtle
- Other machines can touch my data
The Problem

- Persistence is basic to real-world programming
- Yet programming language designers have never addressed persistence
- Result: persistence technologies have been shoehorned into programming languages
- Examples:
  - Shoehorn #1: JDBC
  - Shoehorn #2: JPA, JDO
- The inevitable results
  - “Impedence mismatch” - in other words, BUGS!
  - Injection attacks and other security nightmares
JPA Fails (1)

• Configuration complexity
  – 108 annotation and enum classes
• A “query language” (actually more than one)
• No query performance transparency
  – Will `SELECT * FROM User ORDER BY lastName` be fast??
  – Multiple layers hide performance reality from the programmer
• Lack of data type congruence
  – `DATETIME != java.util.Date`
  – Floating point – there is no `NaN`
  – String truncation
JPA Fails (2)

- “Offline” Data – after the transaction has closed
- Imprecise control of what is kept in memory
  - JPA conflates “online cache” with “offline storage”
- After transaction closes, you can’t query
- No offline index information is kept
  - So queries would be slow even if you could do them
JPA Fails (3)

- Zero support for *schema management*:
  - Schema verification
  - Incremental schema evolution
    - `ALTER TABLE ...` is a “stop the world” operation
- Structural vs. semantic schema updates
  - Structural: should be entirely automatic
  - Semantic: should be done at the language level
- Schema update type safety
  - Example: adding, renaming `Enum` constants
JPA Fails (4)

- Validation is not transactional
  - Foreign Key constraints apply on cache flush, not on commit
- Delete cascade can’t handle cycles
- Data maintenance functions
  - At the database level instead of the language level
  - `SELECT name WHERE name.hashCode() = 17 ??`
- Inconsistent handling of unique and `NULL`
- Cross-object validation is awkward
What is a Database?

• One or both of:
  – Hash table (unsorted keys)
    • Get, Put, Delete, Iterate
  – Balanced tree (sorted keys)
    • Find key via lower/upper bound
    • Iterate keys in sorted order

• Transactions

• A bunch of other convenience stuff
  – Data types (i.e., certain predefined encodings)
  – Automatically maintained indexes
  – SQL or other access language
JSimpleDB Approach

• The database is just a transactional, sorted key/value store

• JSimpleDB handles:
  – Encoding of data values (objects and fields)
  – Collection types (Set, List, Map)
  – Referential integrity
  – Indexes
  – Querying
  – Schema management
  – Validation
JSimpleDB Layering

- Key/Value Store Layer
  - `byte[]` keys and values
  - Provides transactions (and transaction semantics)

- Core API Layer
  - Data Encoding
  - Query views
  - Indexing
  - Schema management

- Java Layer
  - Maps Java model classes onto Core API
  - Wraps object ID’s with actual Java objects
@JSimpleClass
public abstract class User implements HasAccount {

  @JField(indexed = true, unique = true)
  public abstract String getUsername();
  public abstract void setUsername(String username);

  public abstract String getEmail();
  public abstract void setEmail(String email);

  public abstract float getRanking();
  public abstract void setRanking(float ranking);

  public abstract Set<User> getFriends();
}

public interface HasAccount {
  Account getAccount();
  void setAccount(Account account);
}
Fields and Encoding

- Self-delimited encoding of all atomic values
  - For integers, optimized for small values (1 byte)
- Unique “storage ID” identifies types and fields
- Objects have unique 64 bit “object ID”
- Object ID’s assigned randomly, not sequentially
  - Avoids single point of contention
Key/Value Store Mapping

- ObjectID ➔ Object meta-data
  - E.g., schema version
- ObjectID + FieldID ➔ Field Value
  - No need to store default values
- ObjectID + FieldID + Index ➔ List Element
- ObjectID + FieldID + Set Element ➔ empty
- ObjectID + FieldID + Map Key ➔ Map Value
Key/Value Store Mapping - Indexes

- Create index by inverting field and value:
  - FieldID + Field Value + ObjectID ➔ empty
  - FieldID + List Item + ObjectID + Index ➔ empty
  - FieldID + Set Element + ObjectID ➔ empty
  - FieldID + Map Key + ObjectID ➔ empty
  - FieldID + Map Value + ObjectID + Map Key ➔ empty
Reference Fields

- Always Indexed
  - Just like foreign keys in SQL
- Forward and Reverse delete cascades
  - Cycles are handled correctly
  - Possible to “ON DELETE REMOVE” from List
- Support for inverting reference paths
  - Inverting children.element.friend starting from X finds the parents of all for whom X is friend
  - This mechanism is used to implement @OnChange
Queries

- There are (only) three ways to start a query:
  - Find object by object ID  \( \Rightarrow T \)
  - Find objects by Java type  \( \Rightarrow \text{Set}\langle T\rangle \)
  - Query an index  \( \Rightarrow \text{Map}\langle V, \text{Set}\langle T\rangle\rangle \)

- What is an index on a field? A Map where:
  - Key = Field value
  - Value = Set of objects having that value in the field

- E.g. last name: \( \text{Map}\langle \text{String}, \text{Set}\langle \text{Person}\rangle\rangle \)

- Actually, NavigableSet and NavigableMap
  - Sorted, reversible, searchable
What about Joins?

- SQL joins are rooted in set theory
- Inner join = intersection
- Outer join = union
- Use regular Java collections
- Can iterate an intersection efficiently in $O(n \times m)$ time when the sets are sorted consistently, where $n = \# \text{ of sets}$ and $m = \text{size of the smallest set}$. Provided by `NavigableSets.intersection()`. 
Querying: The Price You Pay

- Programmer must now create a “query plan”
- In return: query performance transparency

```java
// Get this user’s registration timestamp
public abstract Date getRegistrationDate();
public abstract void setRegistrationDate(Date date);

// Get users registered in the past day, sorted
// in reverse order of their registration time
public static Stream<User> getRegisteredToday() {

    // Get a view of the User.regDate index
    NavigableMap<Date, NavigableSet<User>> byRegDate = JTransaction.getCurrent()
        .queryIndex(User.class, "registrationDate", Date.class)
        .asMap();

    // Get all users registered in the past 24 hrs
    Date cutoff = new Date(
        System.currentTimeMillis() - 86400000);
    return byRegDate
        .tailMap(cutoff)
        .descendingMap()
        .stream()
        .flatMap(NavigableSet::stream);
}
Schema Management

- 100% schema verification
  - Active schema versions are recorded in the database
  - Incompatibilities are detected when transaction is opened

- Incremental schema evolution
  - Schema version is tracked on a per-object basis
  - “Rolling” application upgrades are possible

- Structural schema changes are fully automated

- Language-level semantic schema changes
  - @OnVersionChange methods handle any “fixups”
  - Previous version’s fields are made available

- JSimpleDB always guarantees type safety
Transactional Validation

- JSimpleDB maintains list of the object ID’s of any objects having pending validation
- Auto-detection of JSR 303 constraints
- You can manually add objects to the list as well
- `@OnValidate` for custom validation logic
- Actual validation is performed at commit time
  - Or any other time you want
  - Or never
Change Detection

- `@OnChange` methods invoked after any change in the specified object field(s)
- Fields may exist in objects reached through an arbitrary path of references
- Facilitates custom “indexes” (i.e., derived data)
public abstract Set<Integer> getScores();

public double getAverageScore() {
    return (double) this.getSum().get() / this.getCount().get();
}

// Private fields
protected abstract Counter getSum();
protected abstract Counter getCount();

@OnChange("scores.element")
private void scoreAdded(SetFieldAdd<User, Integer> change) {
    this.getSum().increment(change.getElement());
    this.getCount().increment(1);
}

@OnChange("scores.element")
private void scoreRemoved(SetFieldRemove<User, Integer> change) {
    this.getSum().increment(-change.getElement());
    this.getCount().increment(-1);
}

@OnChange("scores.element")
private void scoresCleared(SetFieldClear<User> change) {
    this.getSum().set(0);
    this.getCount().set(0);
}
@OnChange Validation Example

// My salary
public abstract int getSalary();
public abstract void setSalary(int salary);

// My direct reports
public abstract Set<Employee> getReports();

// Invoked on my or any report's salary change
@OnChange({ "salary", "reports.element.salary" })
private void onReportSalaryChange() {
    this.revalidate(); // enqueue for validation
}

// Validate my salary vs. my direct reports.
// Invoked at end of transaction if my salary,
// or any of my reports' salaries, has changed
@OnValidate
private void checkSalaryInvariant() {
    int avgReportSalary = this.getReports().stream()
        .mapToLong(Employee::getSalary)
        .average()
        .orElse(0);
    if (avgReportSalary > this.getSalary())
        throw new ValidationException("need a raise!");
}
Snapshot Transactions

- Offline data is stored in snapshot transactions
- A snapshot transaction is a regular transaction backed by an in-memory key/value store
- You explicitly specify what offline data to keep
- Indexes and querying function the same way
- Methods are provided to copy objects (in general, between any two transactions)
  - Data is copied efficiently at the key/value layer
  - Reference graph cycles are properly handled
- Snapshot transactions are handy for RPC as well
  - Same issues arise: encoding, schemas, indexes, querying
Command Line Interface

- Java 8 expression parser (method refs, etc.)
- Embeddable into application
- Pluggable CLI commands
- XML import/export
  - Key/value layer
  - Core API layer
Key/Value Implementations

- Third Party
  - Any SQL database (MySQL, Cockroach DB, ...)
  - Berkeley DB Java Edition
  - FoundationDB
  - LevelDB, RocksDB

- JSimpleDB provided (serializable semantics)
  - Simple/flat file (uses read/read-write locking)
  - Read-optimized, memory mapped “array” k/v store
  - RaftKVDDatabase distributed (Raft algorithm)
Links

- http://jsimpledb.org/  ...which redirects to...
- https://github.com/archiecobbs/jsimpledb
- Raft Consensus Algorithm: https://raft.github.io/