Actor-Oriented Database Systems

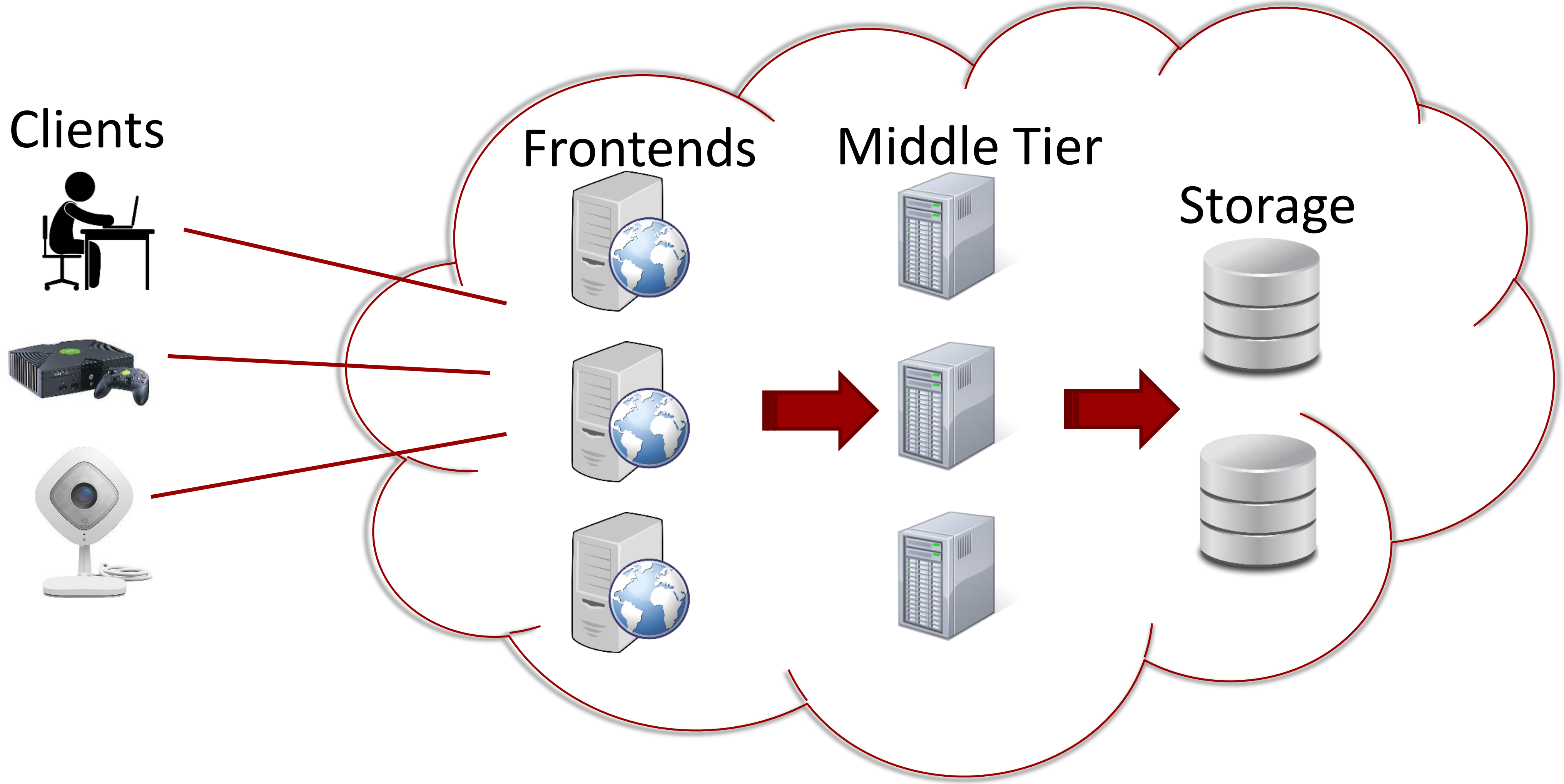
Philip Bernstein
Microsoft

ICDE 2018
April 19, 2018

Preview

- Most new services are written as stateful middle-tier applications
- These apps do a lot of data management
- But they are poorly served by data management technology
- There are technical reasons for this
- This is a research opportunity!

What's a Middle Tier?



Stateful Object-Oriented Applications

- Interactive services are built as a stateful, object-oriented middle tier
  - Multi-player games, IoT, social networking, mobile, telemetry
  - They comprise a large fraction of new app development
  - Naturally object-oriented, modeling real-world objects

- Examples of objects
  - Gaming: players, games, grid positions, lobbies, player profiles, leaderboards, in-game money, and weapon caches
  - Social: chat rooms, messages, photos, and news items
  - IoT: sensors, virtual sensors (flood, break-in), buildings, vehicles, locations

Scenario

- Player logs into game console
- Console connects to cloud service, creating Player object
- Player object connects to a Game-Lobby object
- Game-Lobby runs an algorithm to group players into a Game
  - Returns a reference to the Game object to all players

Stateful Micro-Services

- Many micro-services are stateful middle-tier apps
  - Data ingestion – event streams, real-time analytics
  - Workflow – manage long-running jobs, e.g., ETL, resource allocation
  - Smart contracts – workflows on blockchains
- Example – merge event streams from 100K servers
  - Index them, store them in batches, run standing queries
- To scale out, they're partitioned by keys or key-range
  - Stream ID, workflow ID, contract ID
- A partition is identified by a key = object

Application Properties

- Objects are **active for minutes to days**, sometimes forever
- App manages **millions of objects**, streams, images, and videos, and huge knowledge graphs.
- App does **heavy computation**: complex actions, render images, standing queries, compute over graphs, …
- App does **heavy communication**: high-bandwidth message streams

System Properties

- Service is highly available
- Scale out to large number of servers
- Compute servers must scale out independently of storage servers
- . . . and independently of communication servers
- Geo-distributed for worldwide low-latency access

Middle-tier Objects Comprise a Distributed DB

- Many (but not all) objects are persistent
  - Player is persistent, Lobby is not
- Active objects are in-memory for fast response
- Latest state is in main memory. Storage might be stale
  - Sensor object persists state periodically

Actor Systems

- Many of these apps are implemented using **actor systems**
  - Simplifies distributed programming
- Actors are objects that …
- Communicate only via asynchronous message-passing
  - Messages are queued in the recipient's mailbox
  - No shared-memory state between actors
- Process one message at a time
  - No multi-threaded execution inside an actor

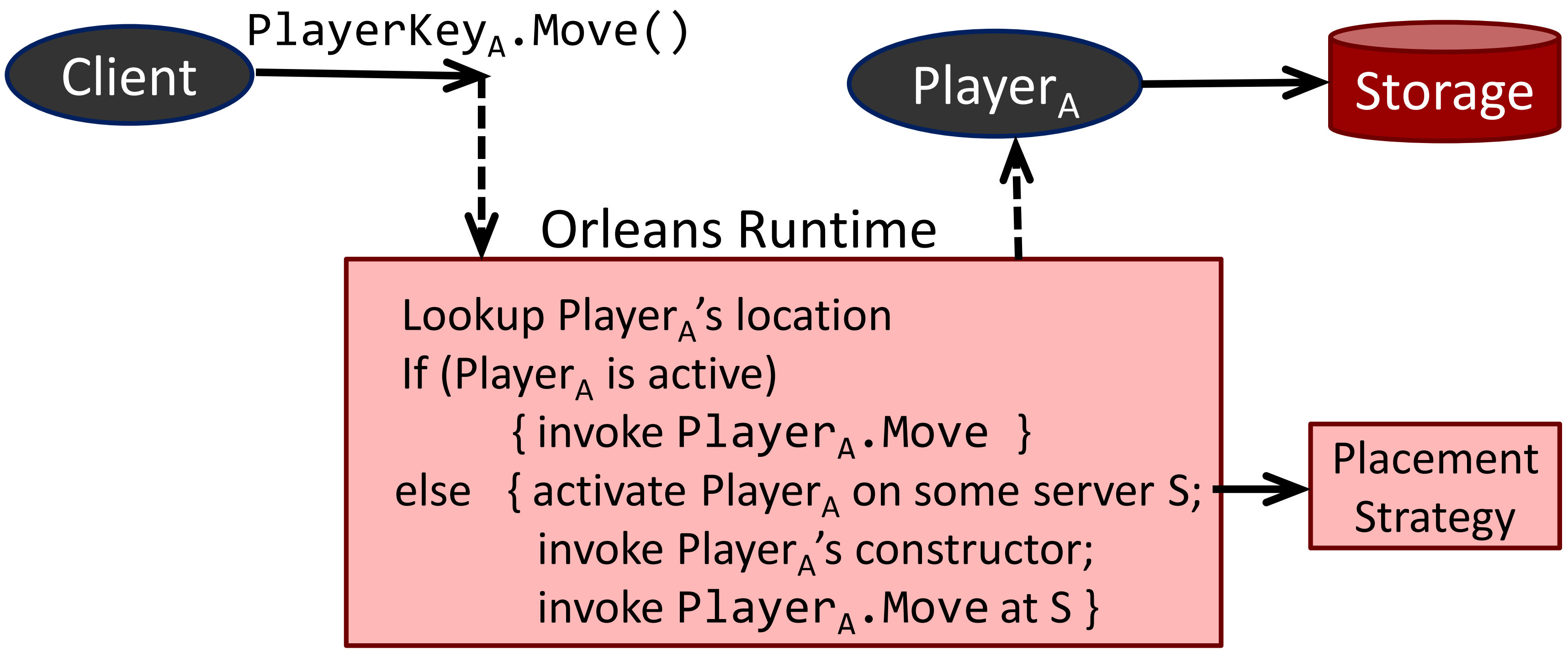
Orleans Actor Programming Framework

- Orleans is an open-source actor framework in C#
  - https://dotnet.github.io/orleans/
- Invented the Virtual Actor model
  - Like virtual memory, actors are loaded and activated on demand
  - Deactivated after an idle period
- Supports scalability by load-balancing objects across servers
- Supports fault-tolerance by automatically reactivating failed objects

Orleans Programming Model

- Actor is fully-encapsulated and single-threaded
- Each class has a key, whose values identify instances
  - Game, player, phone, device, scoreboard, input stream, workflow, etc.
- Asynchronous RPC
  - `Key.Method(params)` returns a "task" (i.e., a promise)
  - `Await Task` - blocks the caller until the task completes
  - .NET has language support for this (`Async-Await`)

Calling an Actor's Method



Fault Tolerance

- Actor can save state at any time, e.g., to storage
- Runtime automates fault-tolerance
- Orleans magic:
  A fault-tolerant DHT that maps actor-ID to server-ID

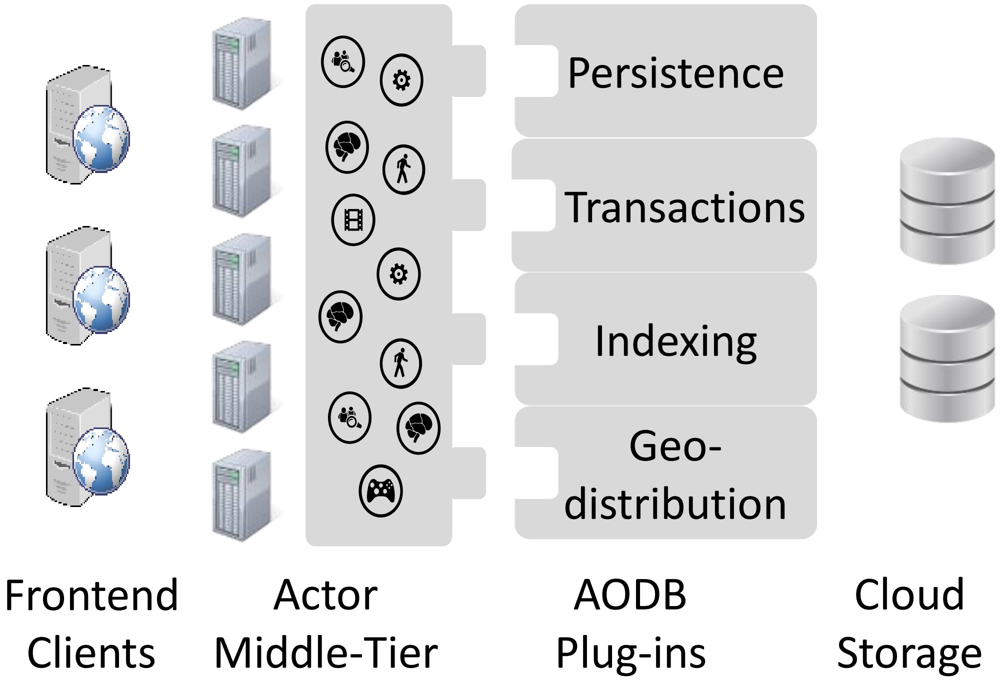
```
public class Account
{
  int balance;

  Task Withdraw(int x);
    { if (balance >= x)
         { balance = balance – x;
           Save State;
           return (1);
      else return (0);
    }
}
```

Good news / Bad news

- Good news
  - The virtual actor model automates scalability and fault tolerance
- Bad news
  - App is responsible for managing its state
- Let’s help them out!

Actor-Oriented Database System (AODB)

- Indexes
- Transactions
- Queries
- Streams
- Views
- Triggers
- Replication
- Geo-distribution



Examples

- Index – Get all players in Paris
- Transaction – Player X buys a kryptonite shield
- Query – Get all players in Paris who are playing Halo with $\geq$ 8 other players
- Stream – Watch player actions, looking for players who might be cheating
- View – the number of active instances of each game
- Trigger – notify a chess player when the other player made a move

AODB’s Distinguishing Features

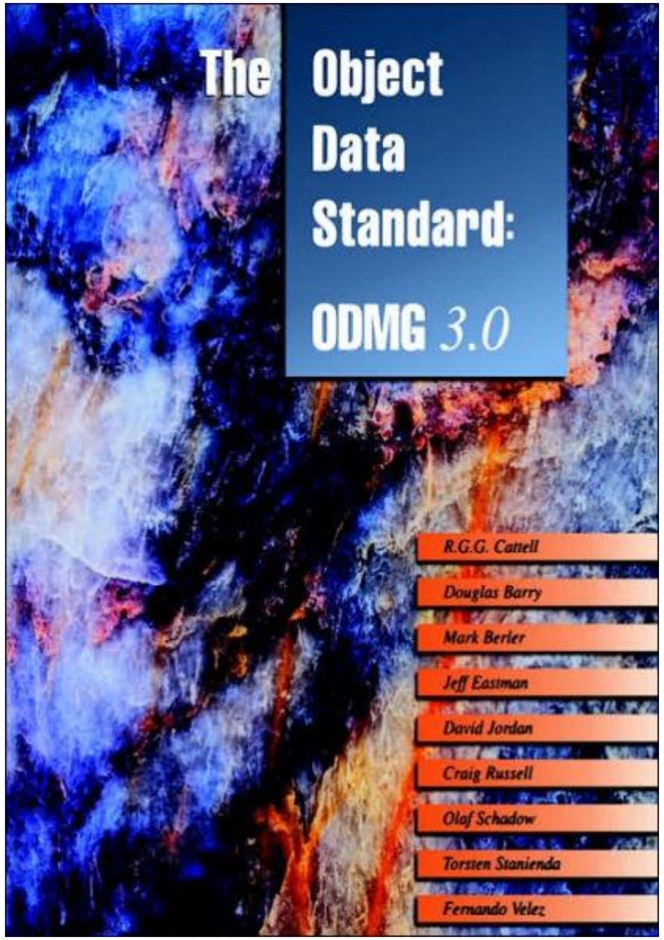
- Developer friendly - Compatible with actor framework’s programming model
- Elastically scales out to hundreds of servers
- Data is in-memory and on cloud storage
- Works with any cloud storage system
  - Files, BLOBs, KV store, document (JSON) store, SQL DBMS

Been There, Done that

- Object-oriented database
- Persistent programming language
- Object-to-relational mapper
- Application server
- Main memory database
- Graph database

Object-Oriented Database

- C++ objects are mapped to persistent storage
  - Gemstone, Vbase, ObjectStore, O_2, Objectivity, ONTOS, Versant, …
  - ODMG standard
- Target markets: CAD, telecom, scientific apps
- Like AODB, it's compatible with the OO programming language
- Unlike AODB, it's targeted at workstation apps, all shared state is in a custom storage system



Persistent Programming Language

- Annotate some program variables as persistent
- Variation: Persistence by reachability
- Very similar to OODB's, but driven from a PL viewpoint
- Typically, the app runs in one OS process
- Negligible commercial market
- Examples – PS Algol, Galileo, Argus

Object-to-Relational Mapper

- Map OO classes to relational tables
- Translate queries and updates on classes into SQL on tables
- They're popular, but only target SQL databases, no distributed transactions, …
- Examples – Hibernate, .NET Entity Framework

Application Server

- Middle-tier objects communicate with DB's
  - OLTP monitors (1970s & 80s) -> .NET transactions, J2EE (1990s)
- Each class executes as an OS process (not actor-oriented)
  - multi-threaded
  - synchronous RPC
- Static mapping of classes to servers
- Offers distributed transactions over DBMS's that support XA interface
- Offers dynamic SQL or an object-to-relational mapper

Main Memory Database

- Like AODB, state is in main memory
- Unlike AODB . . .
- Manages records, not objects
- Not integrated with OO programming language
- Doesn’t scale to large number of servers

Graph Database

- Nodes are passive data, not active objects
- Could be a storage target for actors

Why do it again?

- Different combination of requirements …
- Scalable to large number of servers
- Highly available
- Uses cloud storage
- Storage independence
- Geo-distributed for worldwide low-latency access

Scalability Implies …

- Limited ability to co-locate functionality
- Functionality must be parallelizable
- Scale-out is more important than a fast path

High Availability Implies …

- Tolerates server failures
- Fast recovery from failure
- Add or remove servers without shutting down
- Best effort to tolerate storage unavailability

Storage Independence Implies …

- Works with any cloud storage system
- Works for persisted and non-persisted objects
- Doesn’t require DB-feature-support by the storage system
- Should benefit from DB-feature-support by the storage system
- Copes with latency of cloud storage

It's a Tall Order

- Elastically scale out to hundreds of servers
- Data is in-memory and on cloud storage
- Works with any cloud storage system
- Works for persisted & non-persisted objects
- Limited ability to co-locate functionality
- Tolerates server failures
- Fast recovery from failure
- Functionality is parallelizable
- Scale-out is more important than a fast path
- Add/remove servers without shutting down
- Tolerates storage unavailability
- Doesn't need built-in storage system support
- Benefits from a storage system's built-in support
- Copes with latency of cloud storage

Let’s Explore Features

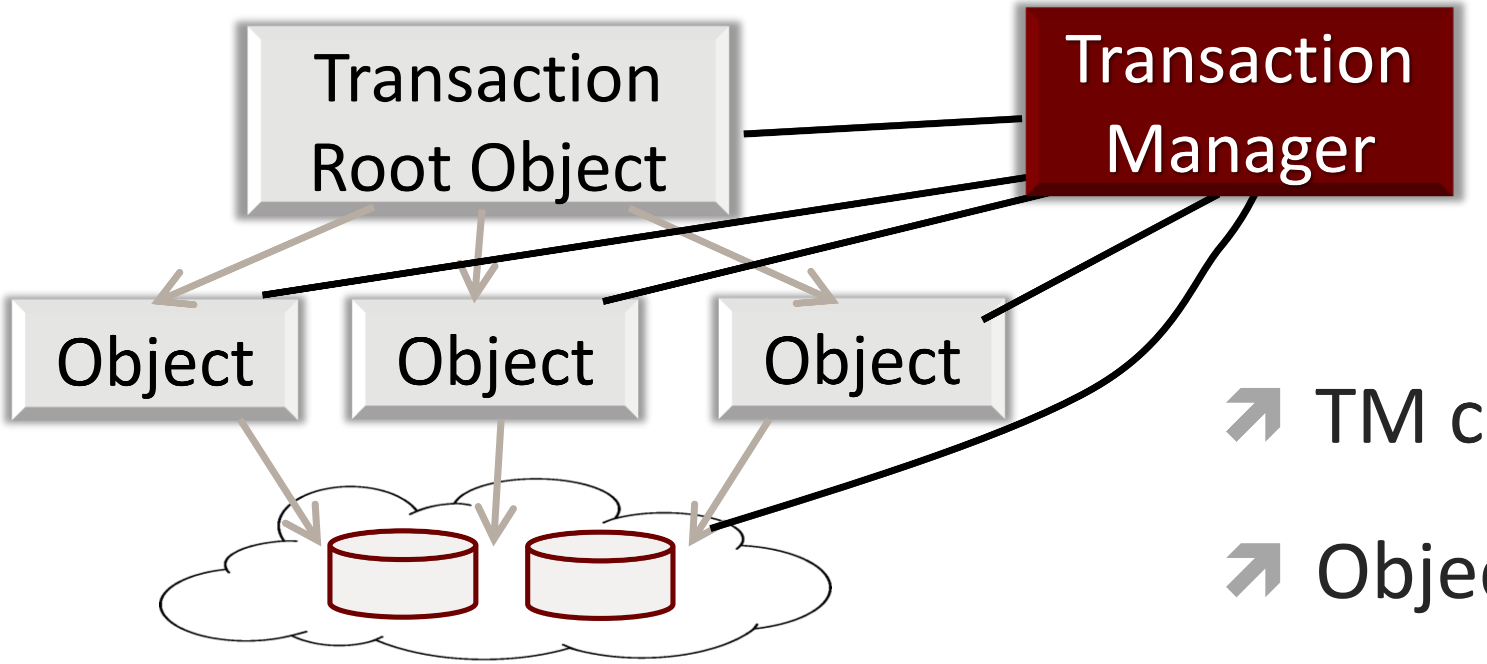
- Transactions
- Geo-distribution
- Indexing
- Queries

Transactions

- Programming model
  - App server model is fine
- Performance challenges
  - No shared log
  - Cloud storage latency
  - Object migrate between servers
  - Many/most transactions are distributed

```
public interface IAccountActor
{
    [TransactionOption.Required]
    Task Withdraw(uint amount);

    [TransactionOption.Required]
    Task Deposit(uint amount);

    [Transaction(TransactionOption.Required)]
    Task<uint> GetBalance();
}
```

Transaction Implementation



- TM coordinates 2PC
- Objects are participants

Early Lock Release

- Problem: object remains locked until it receives Commit
- When object o receives Prepare, it releases T_1's lock
- If T_2 reads/writes o, it takes a "commit dependency" on T_1
  - TM commits transactions in dependency order
- When T_2 terminates, it releases locks, allowing T_3 to read/write o. Etc.
- Cascading abort is possible only due to server failure
- When T_1 commits, [T_2, T_3, …] prepare in a batch (= group-commit).

Early Lock Release (cont'd)

- Benefits
  - Conflicting transactions execute in parallel with 2PC
  - Enables group commit without a shared log
  - Up to 20x throughput improvement
- ☹ Single-object transaction must ask TM to validate its dependency

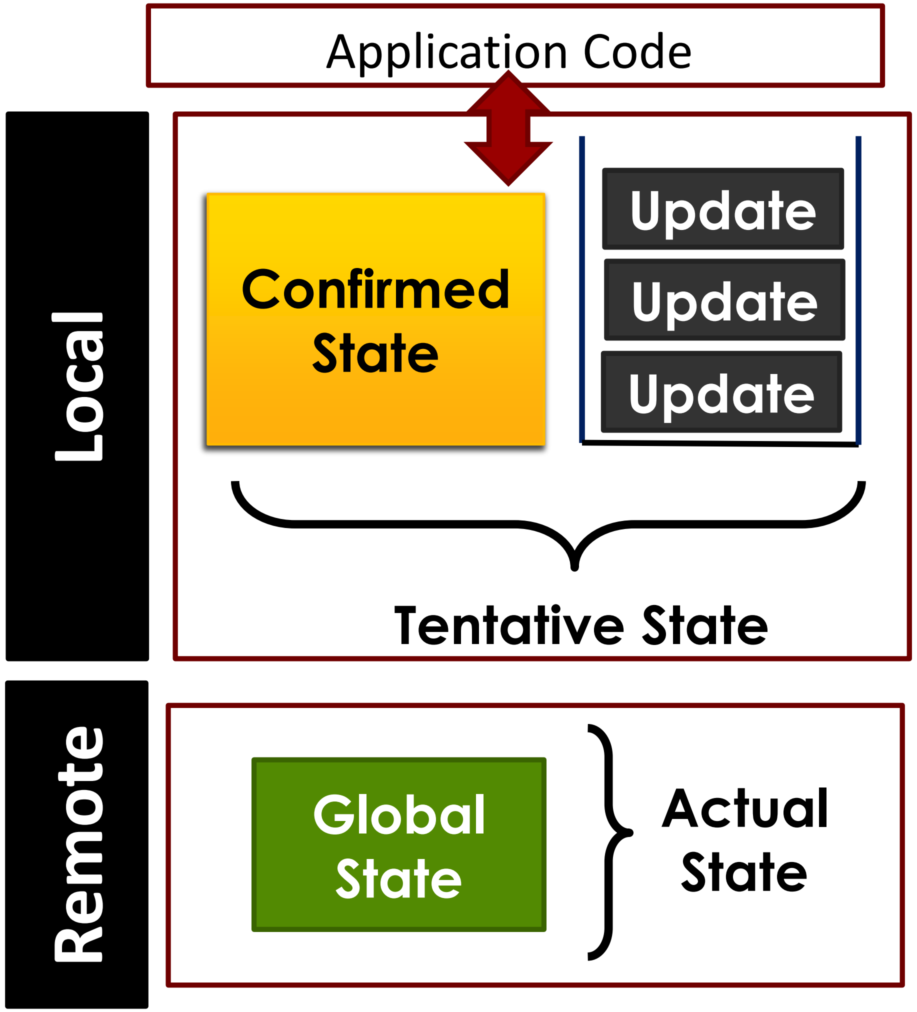
Solution: One TM per Object

- Single-object transactions resolve dependencies locally
- Other benefits
  - No central TM bottleneck or single point-of-failure
  - Less configuration complexity
  - TM’s are naturally geo-distributed, with the objects

Geo-Distribution [OOPSLA 2017]

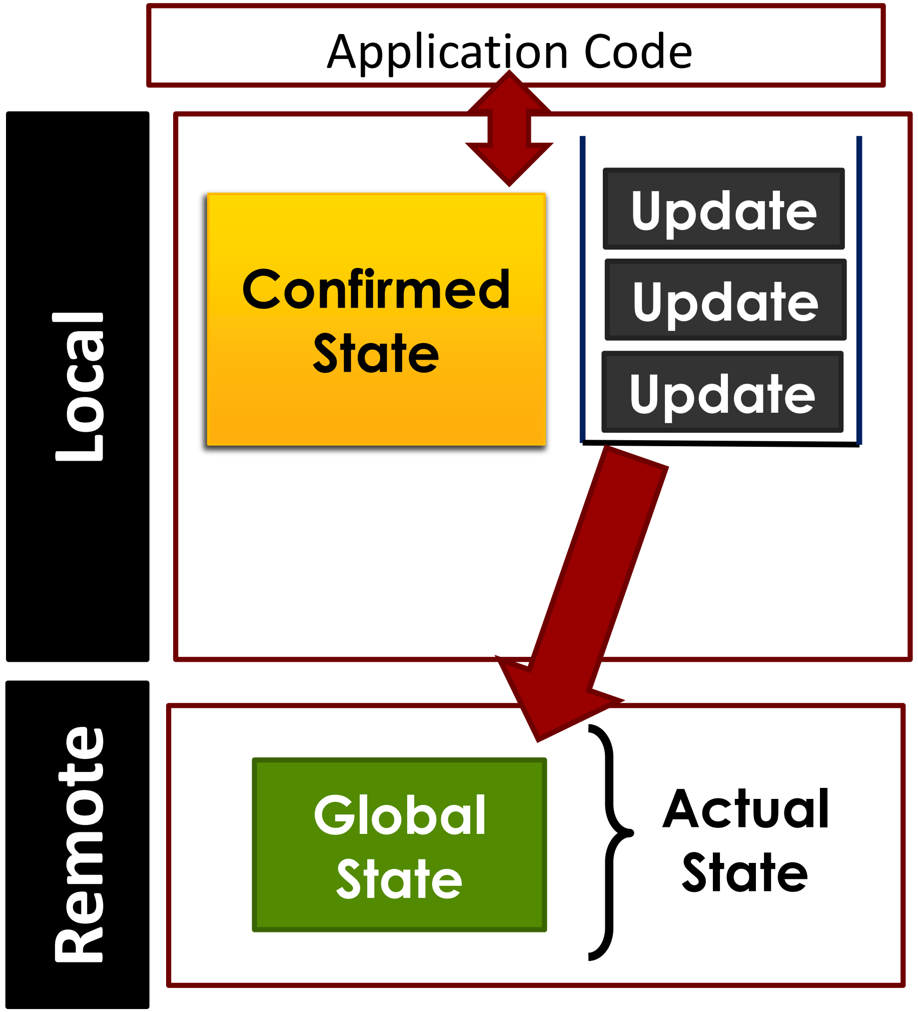
- Extend single-instance invariant world-wide
  - Requires a global mutual-exclusion protocol on actor activation
- Multi-master replication
  - Programming model – eventually linearizable

Versioned Actor



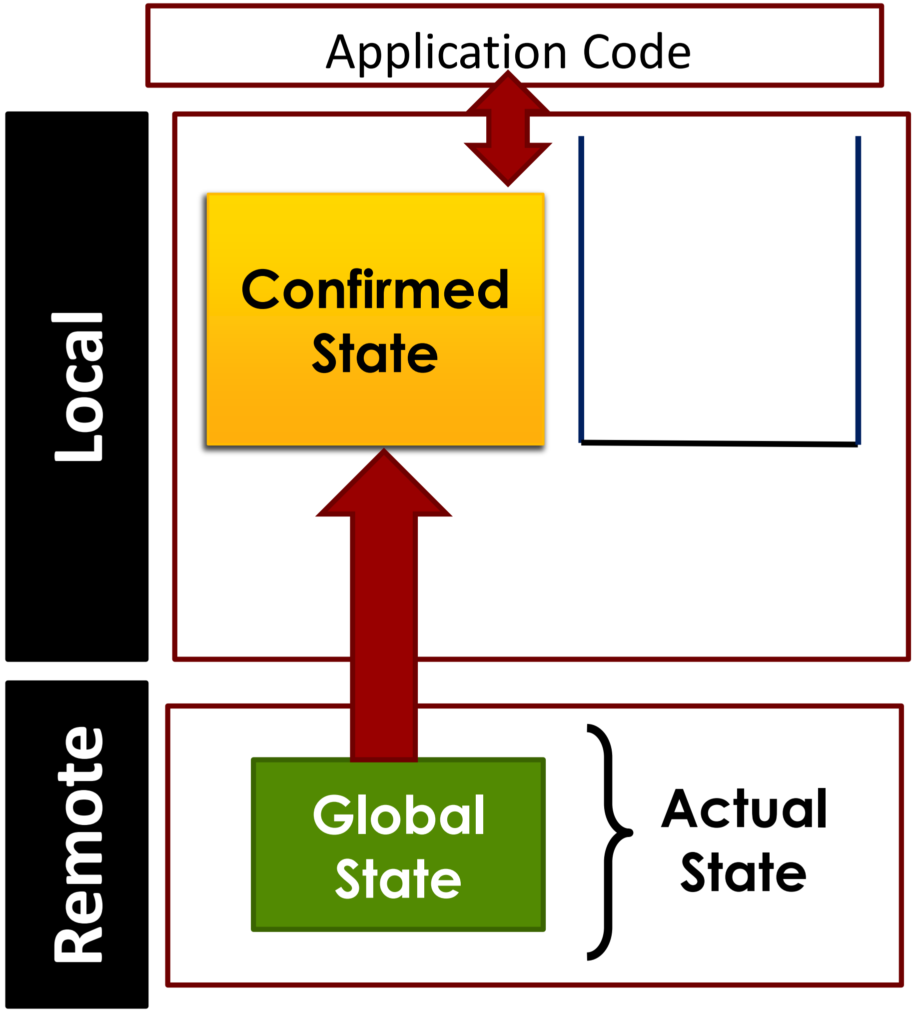
- Updates are specified as **functions** and queued locally
- App sees a **local state** and **global state** of each actor
- Can read confirmed state
  - Optionally with local updates applied
- Can read global state with local updates applied (slow)

Versioned Actor



- Updates are applied asynchronously to the global state

Versioned Actor



- All changes to global state are pushed to confirmed state
- Updates are removed from queue when confirmed

Indexing [CIDR 2017]

- Each Orleans class has a unique key
- Support indexing of other members

```
public class PlayerProperties
{
   public int Rank { get; set; }

   [Index]
   public string Location { get; set; }
}
```

```
public interface IPlayer :
       IndexableActor<PlayerProperties>
{
    Task Move(Direction d);

    Task<string> GetLocation();
}
```

Indexing Examples

- Ensure every player has a unique email address
- Offer an ad hoc tournament to all Halo players who are on-line
- Identify all players with weapons stashes in a given location
- Survey all players who logged in after 3PM today

Index Requirements

- Can index persistent and non-persistent actors
- Leverage actor storage that supports indexing
- Works if storage does not support indexing
- Can index active actors only
- Both hashed and B-tree indexes must scale out
- Plus unique indexes, transactional consistency, fault tolerance, …

Queries over Actors

- Extent – all actors of a class, all active actors, explicit collection, and index
- Split execution between active and inactive actors
- Joins and aggregates
  - Reward the player with the best score in the last 15 minutes of a Microsoft game
- Materialized views – can use mid-tier caching technology
- Streams – Dynamically reconfigure distributed operators
- Triggers – for reactive applications

Summary

- Developers of mid-tier stateful applications need our help
- Whatever database topic interests you, there's an opportunity to help

Bibliography

- P.A. Bernstein, M. Dashti, T. Kiefer, D. Maier: Indexing in an Actor-Oriented Database. CIDR 2017
- P.A. Bernstein, et al.: Geo-distribution of actor-based services. PACMPL 1 (OOPSLA 2017)
- T. Eldeeb, P. Bernstein, “Transactions for Distributed Actors in the Cloud”, MSR-TR
- P.A. Bernstein, S Bykov, A. Geller, G. Kliot, J. Thelin: Orleans: Distributed Virtual Actors for Programmability and Scalability, MSR-TR

Acknowledgments

- Sebastian Burckhardt
- Sergey Bykov
- Natacha Crooks
- Mohammad Dashti
- Tamer Eldeeb
- Jose Faleiro
- Alan Geller
- Tim Kiefer
- Alok Kumbhare
- Gabriel Kliot
- David Maier
- Christopher Meiklejohn
- Muntasir Rahman
- Vivek Shah
- Adrienne Szekeres
- Jorgen Thelin
- Alejandro Tomsic