DISTRIBUTED SYSTEMS: GROUP COMMUNICATION

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Slides borrowed liberally from past presentations from Julia Proft, Utkarsh Mall, Scott Phung, and Jared Cantwell
The Process Group Approach to Reliable Distributed Computing

Communications of the ACM, Dec. 1993

Ken Birman, Cornell University

Reviews a decade of research on the Isis system.

By naming our system ‘The Isis Toolkit’ we wanted to evoke this very old image of something that picks up the pieces and restores a computing system to life.
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1978</td>
<td>Time, Clocks, and the Ordering of Events in a Distributed System</td>
<td>Lamport</td>
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<td>1982</td>
<td>Byzantine Generals Problem</td>
<td>Lamport, Shostak, and Pease</td>
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<td>1983</td>
<td>Impossibility of Distributed Fault Tolerant Consen</td>
<td>Fischer, Lynch, and Patterson</td>
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<td>1983</td>
<td>Virtual Synchrony and the Isis Toolkit</td>
<td>Birman et al.</td>
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<td>1984</td>
<td>State Machine Replication</td>
<td>Lamport, Schneider</td>
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<td>1985</td>
<td>Distributed Process Groups (V System)</td>
<td>Cheriton, Deering, and Zwaenepoel</td>
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<td>1987-</td>
<td>Bulk of development on the Isis Toolkit</td>
<td>Birman et al.</td>
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Problem: the construction of **reliable distributed software**.

- Issues of reliability have been left to the application programmers, who are “largely unable to respond to the challenge”; solutions to the problems are “probably beyond the ability of a typical distributed applications programmer.”

Solution: programming with **distributed groups of cooperating programs**, implemented in the computing environment itself or the operating system.

- “The only practical approach”!
**Anonymous groups**
- Application *publishes* data to a *topic*
- Other processes *subscribe* to this topic
- Properties needed for automatic, reliable operation:
  - Ability to address group
  - Atomic message delivery
  - Ordered message delivery
  - Access to history of group

**Explicit groups**
- Direct cooperation between members
- Share responsibility for responding to requests
- Membership changes published to the group
Example: the Robot Operating System (ROS)

- ROS Master
  - Register
  - Image Processing Node (Subscribe)
  - /image_data topic (Publish)
  - Camera Node (Publish)
    - Input
  - /gestures topic (Publish)
Advantages

- **Fault tolerance**
  - Transparent adaptation to failure and recovery
  - State machine replication

- **Consistency**
  - Ordered and atomic message delivery
  - Consistent view of group membership

- **Ease of development**
  - Need not worry about communication protocol
  - Leave fault tolerance and consistency to the OS
Problems

- Unreliable communication
- Membership changes
- Delivery ordering
- State transfer
- Failure atomicity
Unreliable communication

- UDP: packets lost, duplicated, delivered out of order
- RPC: sender cannot distinguish reason for failure
- TCP: broken channels result in inconsistent behavior
- How to recover consistently from message loss?
Group membership changes do not happen instantaneously

How to make sure messages reach the latest group members?
Delivery ordering

- Messages need to be ordered by causality
- How to deliver in causal ordering?
State transfer

- Processes joining group must get latest state
- How to handle inconsistencies from concurrent messages?
Failure atomicity

- Need to achieve all-or-nothing message delivery
- How to handle mid-transmission failures?
Close Synchrony

A **synchronous** execution model.

- *Multicasts* to a process group are delivered to all members
- Send and delivery events occur as a single, instantaneous event
Execution runs in genuine lockstep.
Close Synchrony

- **Unreliable Communication**
  - Multicast is always reliable

- **Membership changes**
  - Consistent membership at any logical instant

- **Delivery Ordering**
  - Concurrent multicasts are distinct events

- **State Transfer**
  - Happens instantaneously

- **Failure Atomicity**
  - Multicast is a single logical event
Problems with Close Synchrony

- In the real world, events are not instantaneous!
- Expensive: execution runs in genuine lockstep!
- Impossible to achieve in presence of failures (why?)

What do we do?
Virtual Synchrony

- **Asynchronous Close Synchrony**
- Synchronization needed only for events sensitive to ordering
Virtual Synchrony

- **Group Membership Service**
  - Replicated service within the process group itself
  - Membership change needs to be done synchronously

- **Group Communication Service**
  - Uses Lamport’s happened before relationship
  - CBcast (Causal Broadcast) or ABcast (Atomic Broadcast)
  - Multicasts are going to be a total event ordering equivalent to some close synchrony execution
Vector Clocks

- Array of clocks, indexed by processes in the process group

- Protocol:
  - $VT(p_i)$ = clock maintained by process $p_i$
  - $VT(p_i)$ initialized to zero
  - For each send($m$) at $p_i$, $VT(p_i)[i] += 1$ and $VT(m) = VT(p_i)$
  - If $p_j$ delivers a message, received from $p_i$:
    - For $k$ in 1..n: $VT(p_j)[k] = \max(VT(m)[k], VT(p_i)[k])$

- Ordering
  - $VT_1 \leq VT_2$ iff $\forall i$, $VT_1[i] \leq VT_2[i]$
  - $VT_1 < VT_2$ iff $VT_1 \leq VT_2$ and $\exists i$, $VT_1[i] < VT_2[i]$
CBcast

- Uses vector clocks to detect causality
- Delivery of received messages delayed until “happened before” messages are delivered
- Protocol:
  - \( p_j \) on receiving message \( m \) from \( p_i \), delays delivery until
    - \( \text{VT}(m)[k] = \text{VT}(p_i)[k] + 1 \) if \( k = i \)
    - \( \text{VT}(m)[k] \leq \text{VT}(p_i)[k] \) otherwise
  - When \( m \) is delivered follow vector clock protocol
- Delayed messages stored in CBcast delay queue
- Concurrent messages delivered out of order
- Fast because asynchronous
ABcast

- Stronger ordering guarantee than CBcast
- Total message ordering within a group
- Messages can only be delivered if, no prior ABcast is undelivered
- Slow

Protocol:
- A process $p_i$ holding token CBcasts message
- If $p_i$ is not holding the token
  - CBcast but mark undeliverable
  - Token holder delivers and CBcasts a set-order
  - Other follow the set-order
Virtual Synchrony

- Unreliable Communication
  - Group communication service

- Membership changes
  - Group membership service

- Delivery Ordering
  - ABcast, CBcast

- State Transfer
  - Group membership service

- Failure Atomicity
  - Group communication service, group membership service
Isis

An implementation of virtual synchrony

- Used by
  - New York/Swiss stock exchange
  - French air traffic control system (PHIDIAS)

- Also provides
  - monitoring facilities: site failures, triggers
  - Automated recovery
  - Styles of group
Discussion Questions

- How is virtual synchrony with ABcast different from close synchrony?
Takeaways

Close synchrony with process groups provides:
- Ease of development
- Consistency
- Fault tolerance

Virtual synchrony:
- Faster asynchronous system
Bimodal Multicast (1999)

**Ken Birman**  
PhD Berkeley '81  
→ Cornell University

**Mark Hayden**  
PhD Cornell '98  
→ Compaq Research  
→ North Fork Networks  
→ Lefthand Networks  
→ Ventura Networks

**Öznur Özkasap**  
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**Zhen Xiao**  
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→ IBM Research  
→ Peking University

**Mihai Budiu**  
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→ Microsoft Research  
→ Barefoot Networks  
→ VMware Research  
Spent a year at Cornell

**Yaron Minsky**  
PhD Cornell '02  
→ Jane Street  
Fun fact: introduced Jane Street to OCaml
Motivation

- **Virtual synchrony**
  - Costly protocol
  - Unstable under stress
  - Not scalable

- **Best effort reliability protocols**
  - Scalable
  - Starts re-multicasting under low levels of noise
  - No membership check
  - No end-to-end guarantee

- **Multicast with stable throughput**
  - e.g. Streaming Media, teleconferencing
Two step protocol

1. Optimistic Dissemination Protocol
   - Unreliable Multicast like IP multicast
2. Two-Phase Anti-Entropy Protocol
   - Random gossip
   - Unicast lost messages
   - Cheaper than re-multicasting
Advantages

- PBcast (Probabilistic Broadcast)
  - Atomicity (Almost all or almost none)
  - Scalability
  - Throughput Stability

![Pbcast bimodal delivery distribution](image)
Performance

Low bandwidth comparison of pbcast performance at faulty and correct hosts

- traditional w/1 perturbed
- pbcast w/1 perturbed
- throughput for traditional, measured at perturbed host
- throughput for pbcast measured at perturbed host
Takeaways

Bimodal Multicast

- Stable throughput
- Scalability at cost of “weaker” reliability
- Predictable reliability
- Predictable load
CAP Conjecture

- Consistency
  - Client receives the latest version of state

- Availability
  - Client request always gets a response

- Partition Tolerance
  - Can tolerate network partition

- In presence of partition, choose a trade-off between Consistency and Availability.
Acknowledgments

Many slides/diagrams borrowed from Julia Proft and Utkarsh Mall, CS 6410 Fall 2017, Scott Phug, CS 6410 Fall 2011, Ken Birman, CS 614 Fall 2006

Vector Clock, CBcast and ABcast borrowed from Birman, Schiper, Stephenson, *Lightweight causal and atomic group multicast*, 1991