CS5412: VIRTUAL SYNCHRONY

Lecture XIV

Ken Birman

Group Communication idea

- System supports a new abstraction (like an object)
  - A “group” consisting of a set of processes (“members”) that join, leave and cooperate to replicate data or do parallel processing tasks
  - A group has a name (like a filename)
  - … and a state (the data that its members are maintaining)
    - The state will often be *replicated* so each member has a copy
    - Note that this is in contrast to Paxos where each member has a partial copy and we need to use a “learner algorithm” to extract the actual current state
    - Think of state much as you think of the value of a variable, except that a group could track many variables at once

Group communication Idea

- The members can send each other
  - Point-to-point messages
  - Multicasts that go from someone to *all* the members
- They can also do RPC style queries
  - Query a single member
  - Query the whole group, with all of them replying

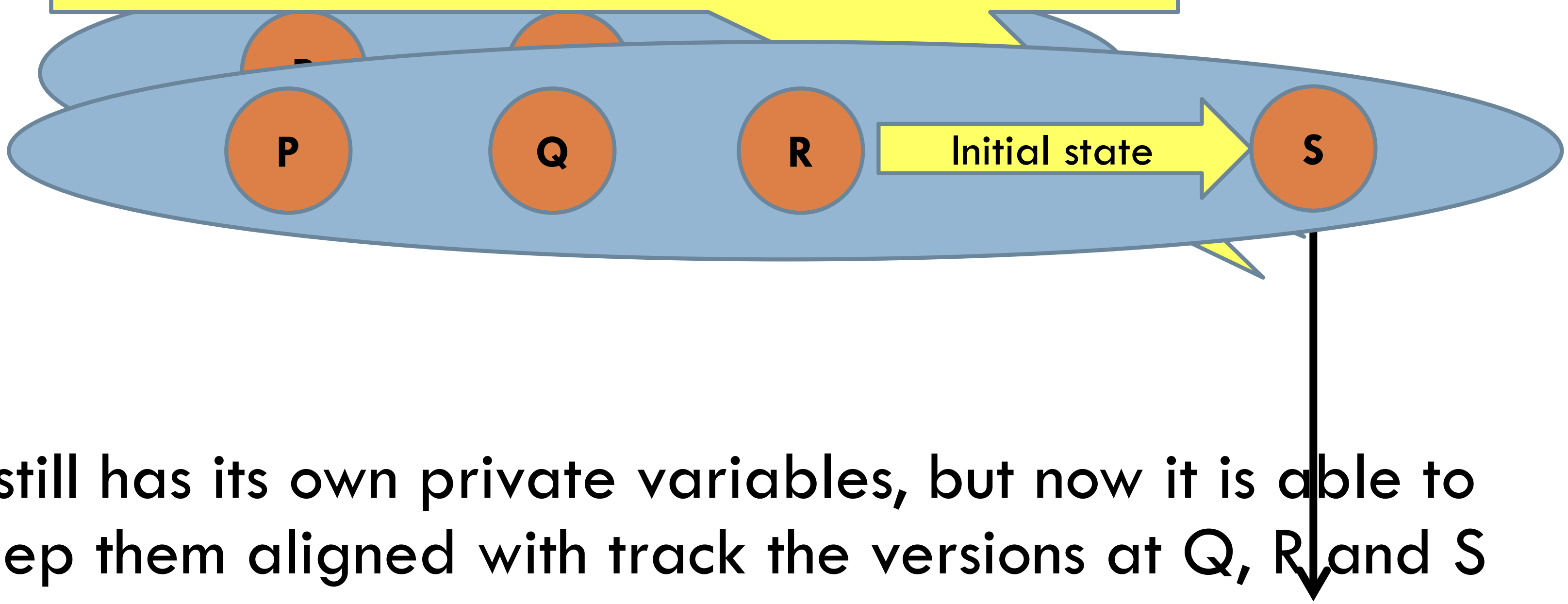
- Example: The Isis^2 system (but there are many such systems)

Animation: A process joins a group

- ... purely local

S starts by creating an endpoint object, attaching upcall
han...

Once the group endpoint is properly configured, S issues a "join" request. Isis[2] checks to see if the group already exists. If not, p can create a new instance, but in this case, the group is already active.



- P still has its own private variables, but now it is able to keep them aligned with track the versions at Q, R and S

P's endpoint

- Just an object that is P's "portal" for operations involving the group

- The endpoint lets P see events occurring in the group such as members joining, failing (detected slowly via timeout) or leaving (very fast notification), multicasts reporting updates or other events, queries, etc

- *But no data is automatically replicated.* P provides logic to maintain the data it associates with the group.

Isis^2 is a *library* for group communication

It Uses a Formal model

- Formal model permits us to achieve correctness
- Isis^2 is too complex to use formal methods as a development tool, but does facilitate debugging (model checking)
- Think of Isis^2 as a collection of modules, each with rigorously stated properties

It Reflects Sound Engineering

- Isis^2 implementation needs to be fast, lean, easy to use
- Developer must see it as easier to use Isis^2 than to build from scratch
- Seek great performance under "cloudy conditions"
- Forced to anticipate many styles of use

Isis^2 makes developer's life easier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Group g = new Group("myGroup");
Dictionary <string,double> Values = new Dictionary<string,double>();
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g.Handlers[UPDATE] += delegate(string s, double v) {
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g.Join();

g.OrderedSend(UPDATE, "Harry", 20.75);

List<double> resultlist = new List<double>();
nr = g.Query(ALL, LOOKUP, "Harry", EOL, resultlist);
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- First sets up group
- Join makes this entity a member. State transfer isn't shown
- Then can multicast, query. Runtime callbacks to the "delegates" as events arrive
- Easy to request security (g.SetSecure), persistence
- "Consistency" model dictates the ordering seen for event upcalls and the assumptions user can make. User can tell Isis2 how strong ordering needs to be.

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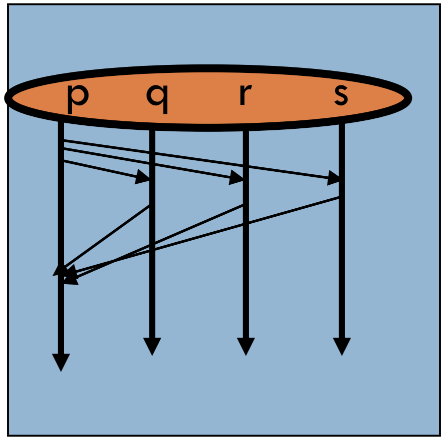
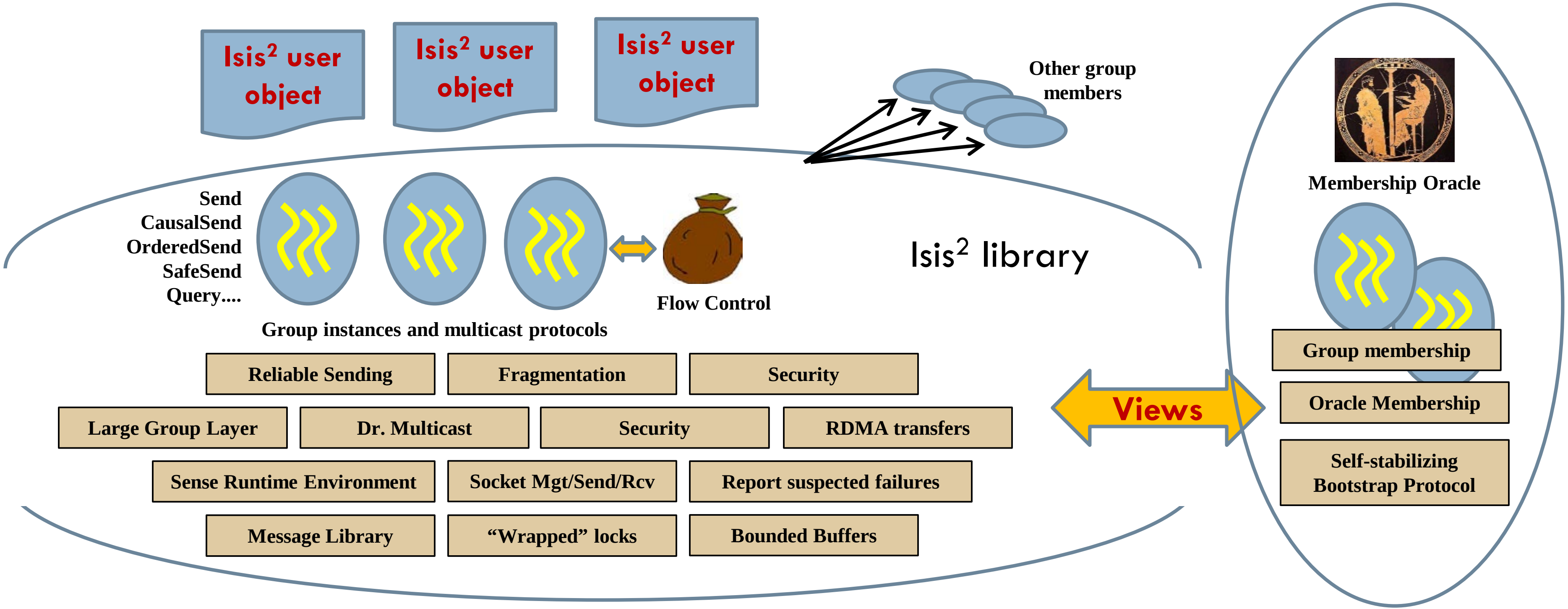
Concept: Query as a "multi-RPC"

- One member asks multiple group members to perform some action
- It could be doing this on behalf of an external client, and it might participate too
- Often group members subdivide the task (but there could be a fault-tolerance benefit to asking 2 or more to do the same work)

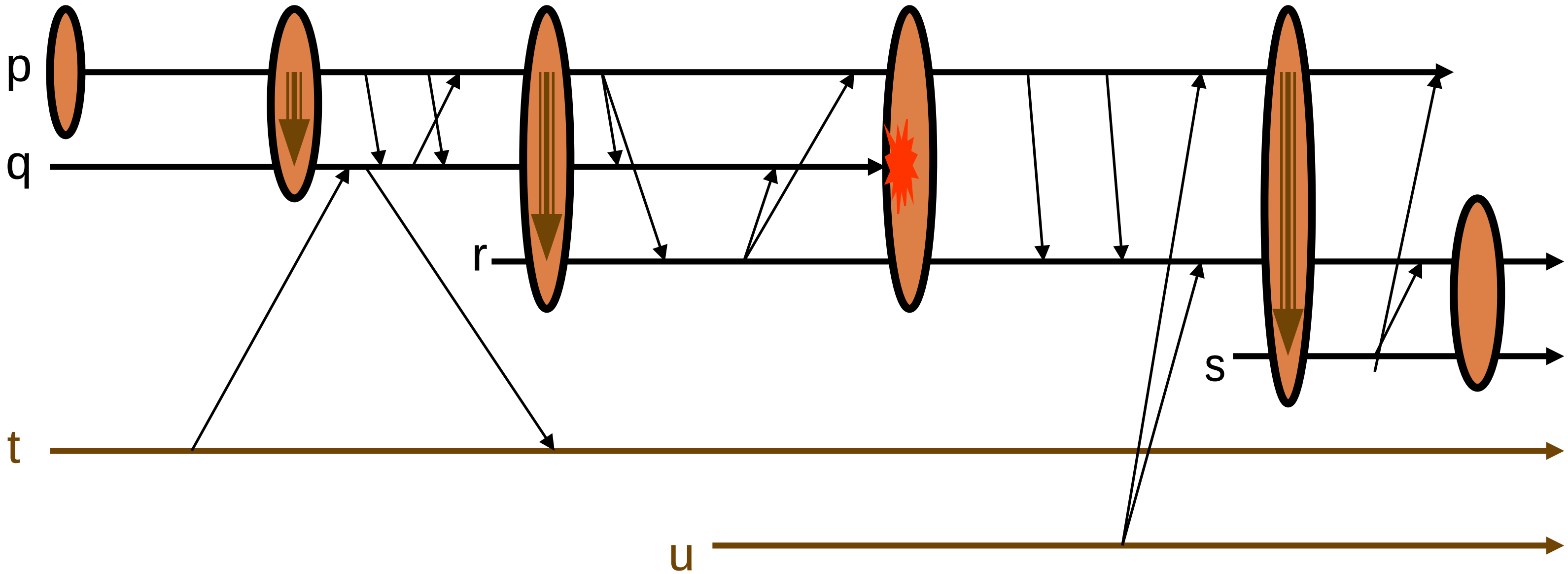


It takes a "community"

- A lot of complexity lurks behind those simple APIs
- Building one of your own would be hard
- Isis² took Ken >3 years to implement & debug



What goes on down there?



- Terminology: group create, view, join with state transfer, multicast, client-to-group communication
- This is the “dynamic” membership model: processes come & go

Clients of a group

- Applications linked to $Isis^2$ can access a group by joining it as a member, but can also issue requests as a "client" in RPC style
- One can also build a group that uses a web service standard (SOAP, WCF, REST) to accept requests from web clients that don't use $Isis^2$ at all. Many cloud services can automatically load balance such requests over the set of group members.
- The representative acts as a "proxy" for the client and can issue multicasts or queries on its behalf

Concepts

- You build your program and link with Isis[2]
- It starts the library (the new guy tracks down any active existing members)
- Then you can create and join groups, receive a "state transfer" to catch up, cooperate with others
- All kinds of events are reported via upcalls
  - New view: View object tells members what happened
  - Incoming message: data fields extracted and passed as values to your handler method

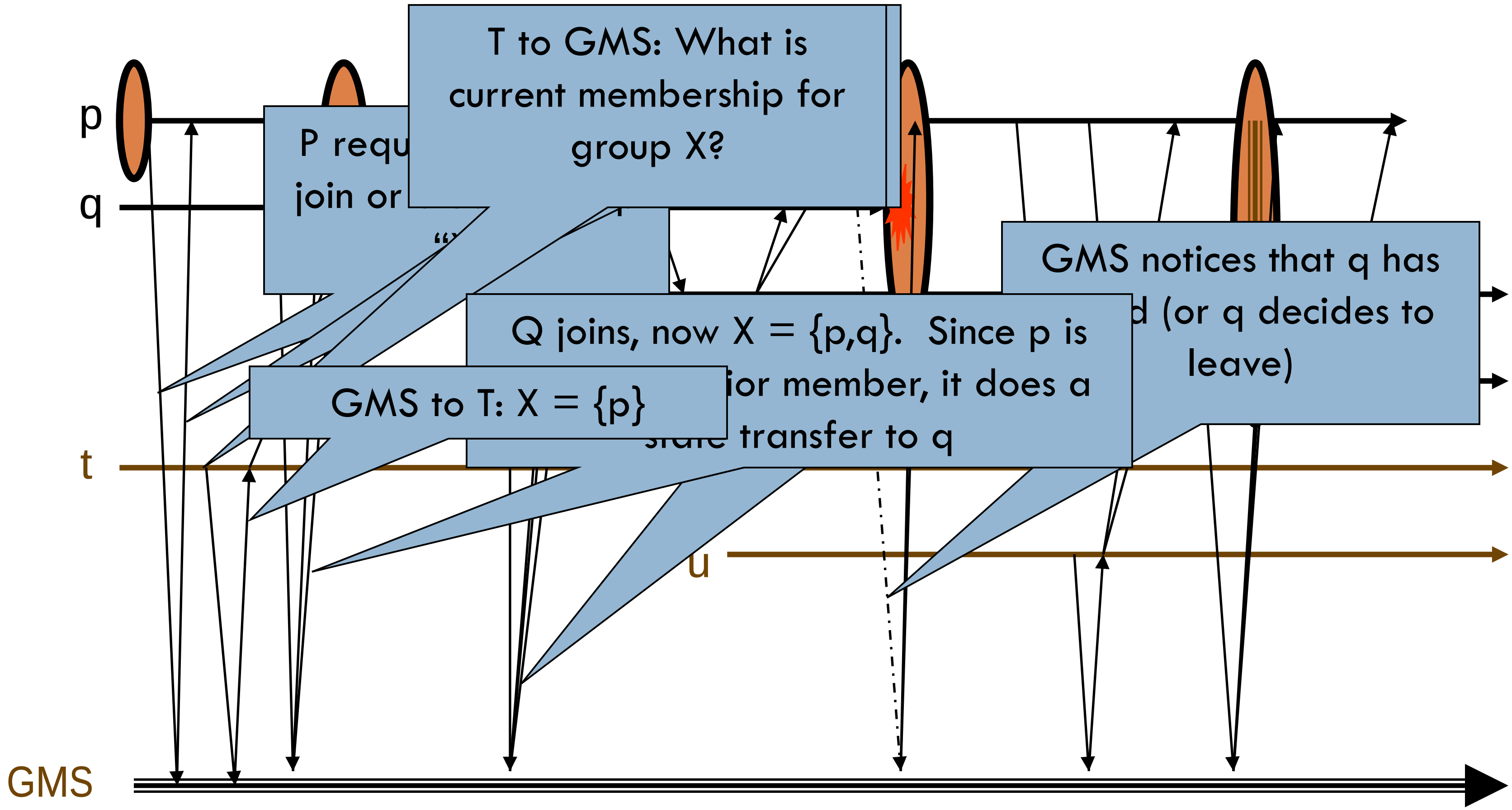
Recipe for a group communication system

- Bake one pie shell
  - *Build a service that can track group membership and report "view changes"*
- Prepare 2 cups of basic pie filling
  - *Develop a simple fault-tolerant multicast protocol*
- Add flavoring of your choice
  - *Extend the multicast protocol to provide desired delivery ordering guarantees*
- Fill pie shell, chill, and serve
  - *Design an end-user "API" or "toolkit". Clients will "serve themselves", with various goals…*

Role of GMS

- We'll add a new system service to our distributed system, like the Internet DNS but with a new role
  - Its job is to track membership of groups
  - To join a group a process will ask the GMS
  - The GMS will also monitor members and can use this to drop them from a group
  - And it will report membership changes

Group picture… with GMS



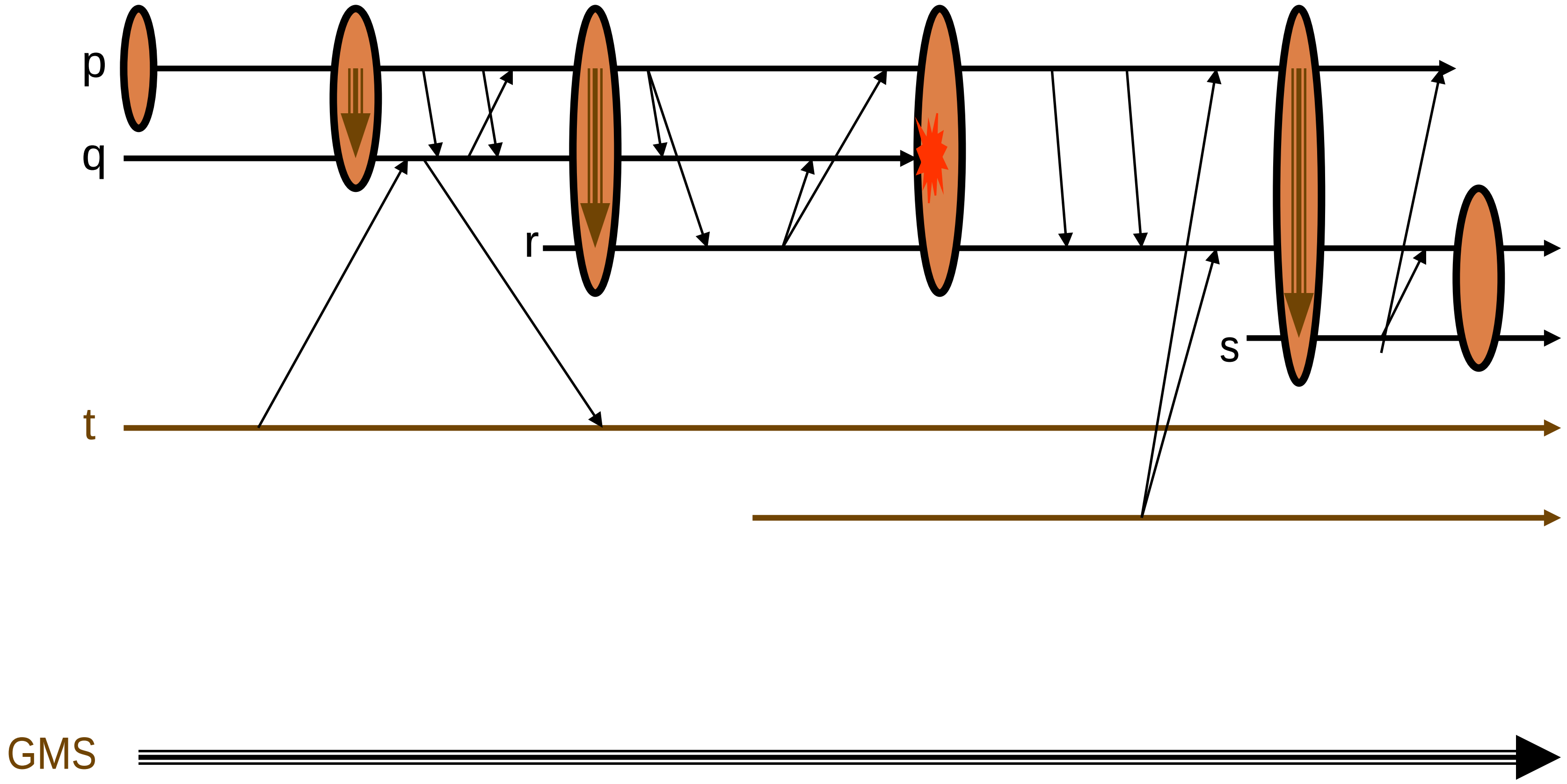
Group membership service

- Runs on some sensible place, like the first few machines that start up when you launch Isis[2]
- Takes as input:
  - Process "join" events
  - Process "leave" events
  - Apparent failures
- Output:
  - Membership views for group(s) to which those processes belong
  - Seen by the protocol "library" that the group members are using for communication support

Issues?

- The service *itself* needs to be fault-tolerant
  - Otherwise our entire system could be crippled by a single failure!
- So we'll run two or three copies of it
  - Hence Group Membership Service (GMS) must run some form of protocol (GMP)

Group picture… with GMS



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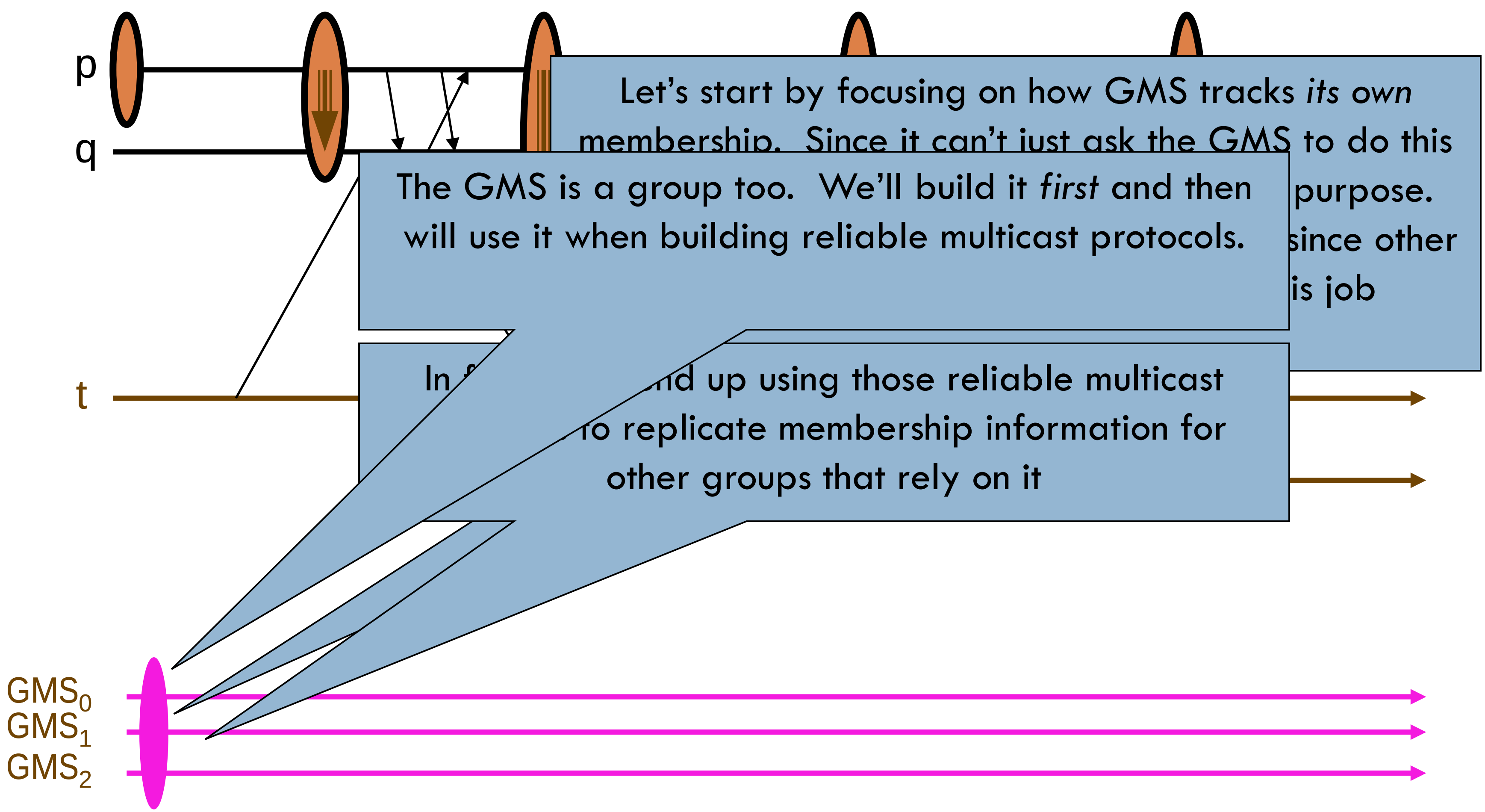
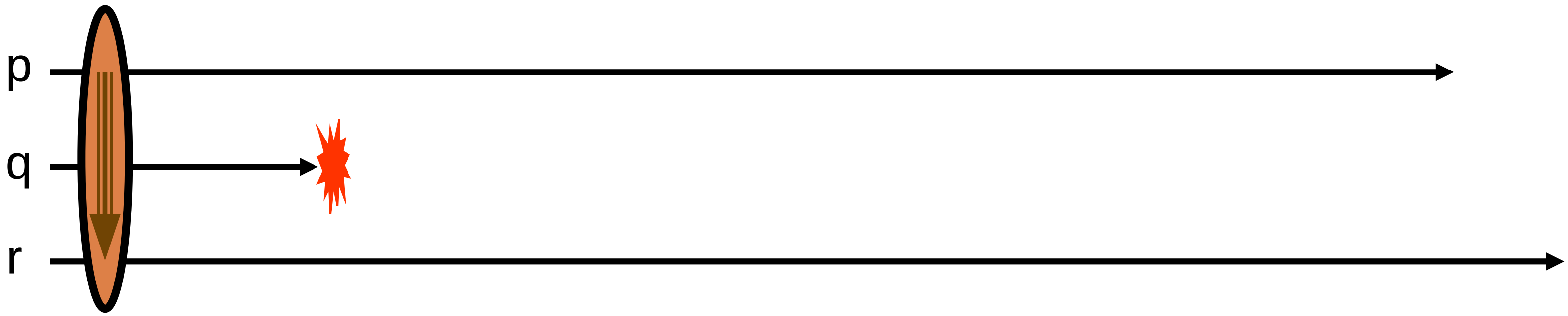


Approach

- Assume that GMS has members {p,q,r} at time t
- Designate the "oldest" of these as the protocol "leader"
  - To initiate a change in GMS membership, leader will run the GMS
  - Others can't run the GMS; they report events to the leader

GMS example

The GMS group



- Example:
  - Initially, GMS consists of {p,q,r}
  - Then q is believed to have crashed

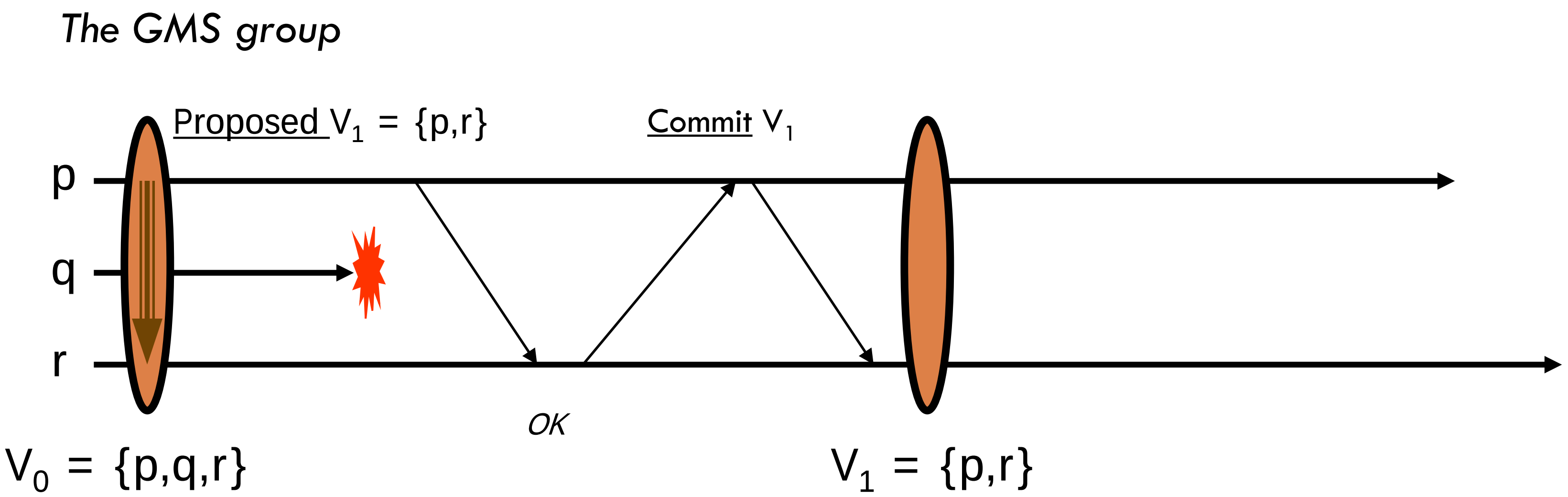
Failure detection: may make mistakes

- Recall that failures are hard to distinguish from network delay
  - So we accept risk of mistake
  - If p is running a protocol to exclude q because "q has failed", all processes that hear from p will cut channels to q
    - Avoids "messages from the dead"
  - q must rejoin to participate in GMS again

Basic GMS

- Someone reports that "q has failed"
- Leader (process p) runs a 2-phase commit protocol
  - Announces a "proposed new GMS view"
    - Excludes q, or might add some members who are joining, or could do both at once
  - Waits until a <u>majority</u> of members of current view have voted "ok"
  - Then commits the change

GMS example



- Proposes new view: {p,r} [-q]: "*p and r; q has left*"
- Needs majority consent: p itself, plus one more ("current" view had 3 members)
- Can add members at the same time

Special concerns?

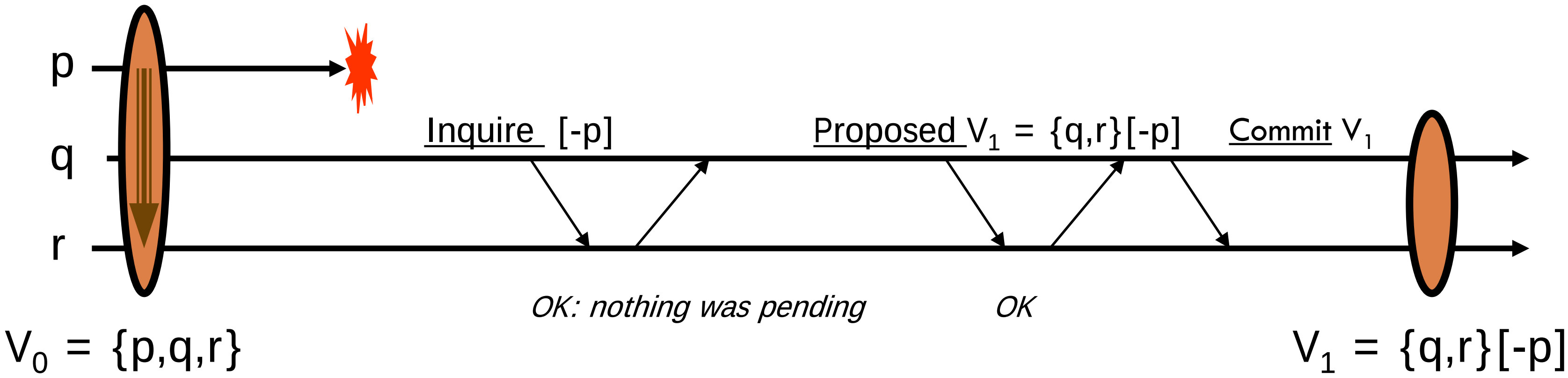
- What if someone doesn't respond?
  - P can tolerate failures of a minority of members of the current view
    - New first-round "overlaps" its commit:
      - "Commit that q has left. Propose add s and drop r"
  - P must wait if it can't contact a majority
    - Avoids risk of partitioning

What if leader fails?

- Here we do a 3-phase protocol
  - New leader identifies itself based on age ranking (oldest surviving process)
  - It runs an inquiry phase
    - "The adored leader has died. Did he say anything to you before passing away?"
    - Note that this causes participants to cut connections to the adored previous leader
  - Then run normal 2-phase protocol but "terminate" any interrupted view changes leader had initiated

GMS example

The GMS group



- New leader first sends an inquiry
- Then proposes new view: {q,r} [-p]
- Needs majority consent: q itself, plus one more ("current" view had 3 members)
- Again, can add members at the same time

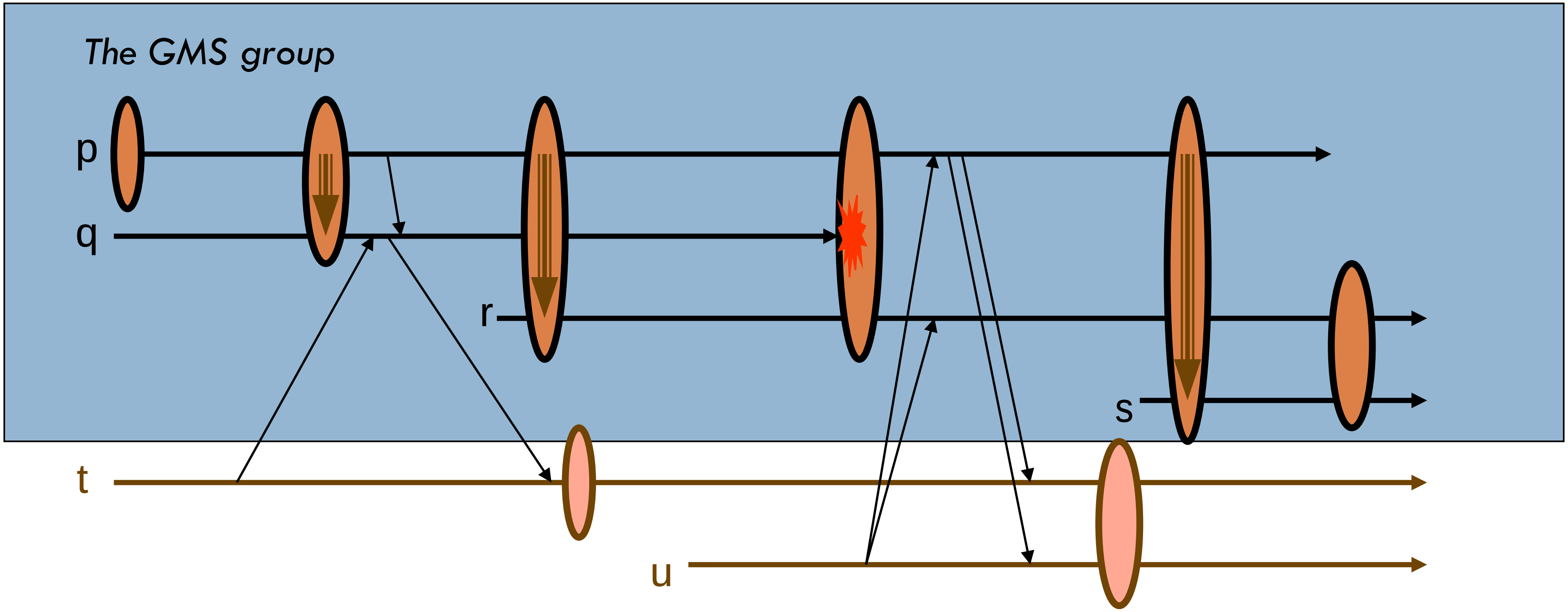
Properties of GMS

- We end up with a single service shared by the entire system
  - In fact every process can participate
  - But more often we just designate a few processes and they run the GMS
- Typically the GMS runs the GMP and also uses replicated data to track membership of *other* groups

Use of GMS

- A process t, not in the GMS, wants to join group "Upson309_status"
  - It sends a request to the GMS
  - GMS updates the "membership of group Upson309_status" to add t
  - Reports the new view to the current members of the group, and to t
  - Begins to monitor t's health

Processes t and u "using" a GMS



- The GMS contains p, q, r (and later, s)
- Processes t and u want to form some other group, but use the GMS to manage membership on their behalf

Relate to Paxos

- In fact we're doing something *very* similar to Paxos
  - The "slot number" is the "view number"
  - And the "ballot" is the current proposal for what the next view should be
  - With Paxos proposers can actually talk about multiple future slots/commands (concurrency parameter α)
  - With GMS, we do that too!
    - A single proposal can actually propose multiple changes
    - First [add X], then [drop Y and Z], then [add A, B and C]…
    - In order… eventually 2PC succeeds and they all commit

How does this differ from Paxos?

- Details are clearly not identical, and GMS state isn't durable
- Runs with a well-defined leader; Paxos didn't need one (in Paxos we often prefer to have a single leader but correctness is ensured with multiple coordinators)
- Very similar guarantees of ordering and if we added logging, durability too. (Isis^2 SafeSend adds this logging)
- Isis GMS protocol predates Paxos. It "bisimulates" Paxos, meaning that each can simulate the other.

We have our pie shell

- Now we've got a group membership service that reports identical views to all members, tracks health
- Can we build a reliable multicast?

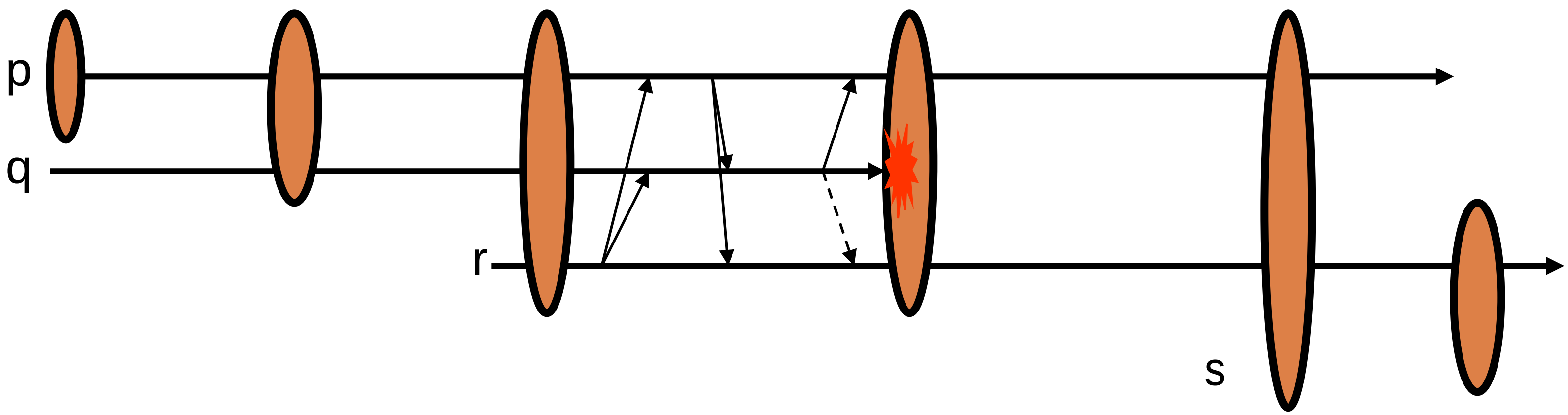
Unreliable multicast

- Suppose that to send a multicast, a process just uses an unreliable protocol
  - Perhaps IP multicast
  - Perhaps UDP point-to-point
  - Perhaps TCP
- … some messages might get dropped. If so it eventually finds out and resends them (various options for how to do it)

Concerns if sender crashes

- Perhaps it sent some message and only one process has seen it
- We would prefer to ensure that
  - All receivers, in "current view"
  - Receive any messages that <u>any</u> receiver receives (unless the sender and all receivers crash, erasing evidence…)

An interrupted multicast



- A message from q to r was “dropped”
- Since q has crashed, it won’t be resent

Terminating an interrupted multicast

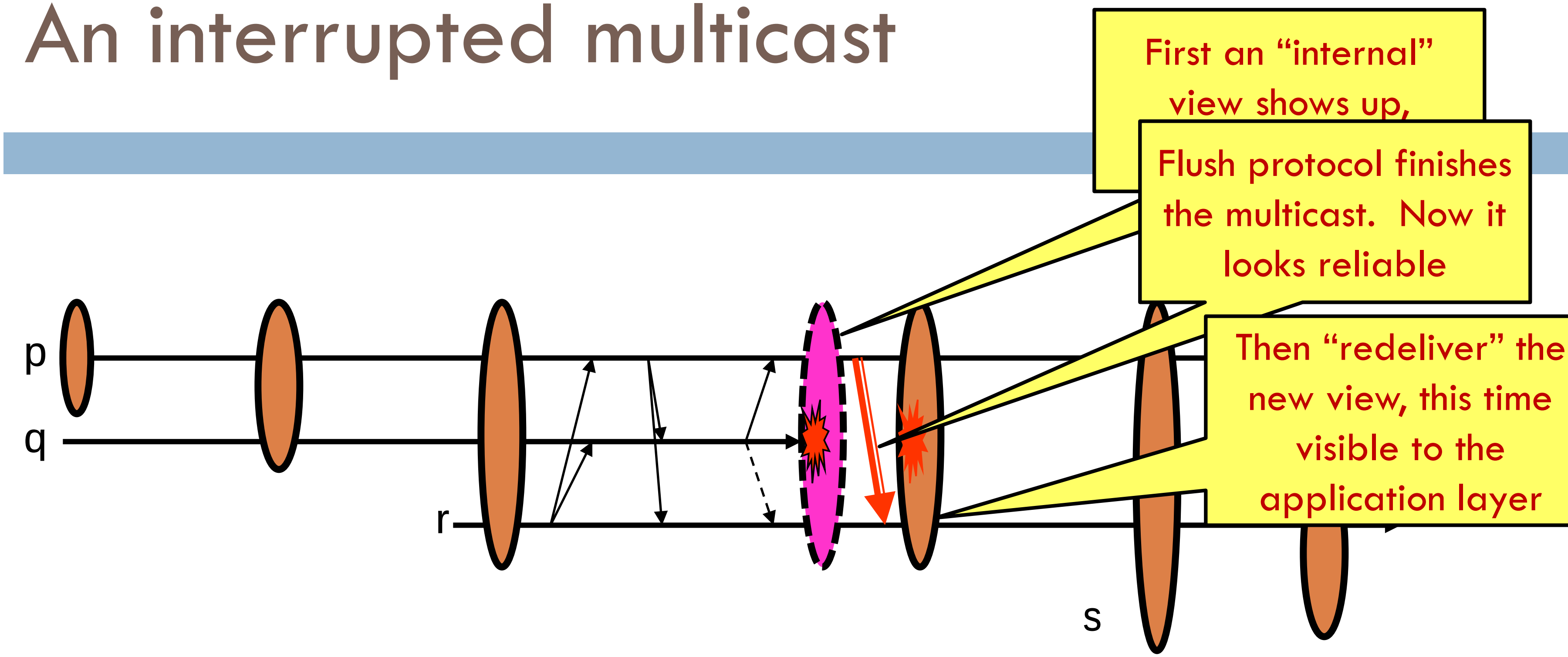
- We say that a message is *unstable* if some receiver has it but (perhaps) others don't
  - For example, q's message is unstable at process r
- If q fails we want to terminate unstable messages
  - Finish delivering them (without duplicate deliveries)
  - Masks the fact that the multicast wasn't reliable and that the leader crashed before finishing up

How to do this?

- Easy solution: all-to-all echo
  - When a new view is reported
  - All processes echo any unstable messages on all channels on which they haven't received a copy of those messages
- A flurry of $O(n^2)$ messages

- *Note: must do this for <u>all</u> messages, not just those from the failed process. This is because more failures could happen in future*

An interrupted multicast



- p had an unstable message, so it echoed it when it saw the new view

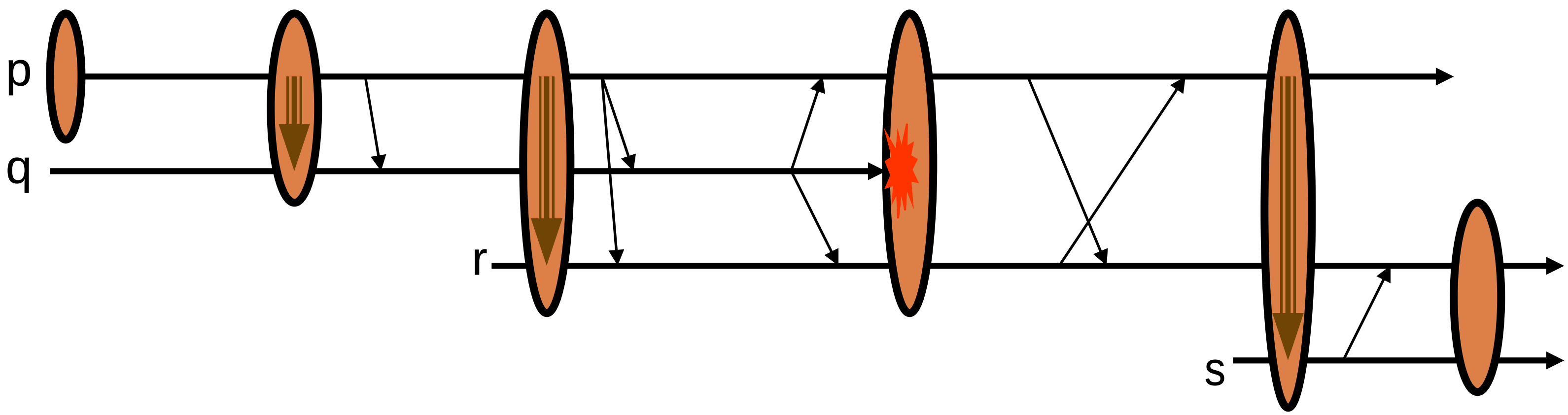
Event ordering

- We should *first* deliver the multicasts to the application layer and *then* report the new view
- This way all replicas see the same messages delivered "in" the same view
  - Some call this "view synchrony"

State transfer

- At the instant the new view is reported, a process already in the group makes a checkpoint
- Sends point-to-point to new member(s)
- It (they) initialize from the checkpoint

State transfer and reliable multicast



- After re-ordering, it looks like each multicast is reliably delivered in the same view at each receiver
- Note: if sender *and all receivers* fails, unstable message can be "erased" even after delivery to an application
  - This is a price we pay to gain higher speed

What about ordering?

- It is trivial to make our protocol FIFO wrt other messages from same sender
  - If we just number messages from each sender, they will "stay" in order
- Concurrent messages are unordered
  - If sent by different senders, messages can be delivered in different orders at different receivers
- This is the protocol called "Send"

When is Send used?

- The protocol is very fast
  - Useful if ordering really doesn't matter
  - Or if all the updates to some object are sent by the same process. In this case FIFO is what we need

- Send is not the right choice if multiple members send concurrent, conflicting updates
  - In that case use g.OrderedSend()

Other options?

- OrderedSend: used if there might be concurrent sends

- SafeSend: Most conservative but also quite costly. A version of Paxos (topic of next lecture)

What does this give us?

- A second way to implement state machine replication in which each member has a complete and correct state
  - Notice contrast with Paxos where to learn the state you need to run a decision process that reads Q_R copies
  - Isis^2 replica is just a local object and you use it like any other object (with locking to prevent concurrent update)
  - Paxos has replicated state but you need to read multiple process states to figure out the value
- This makes Isis^2 faster and cheaper

Isis^2 versus Paxos

- Isis^2 offers control over message ordering and durability. Paxos has just one option.
- By default, Isis^2 is a multicast layer that just delivers messages and doesn't log them
- But you can log group states in various ways, including exactly what Paxos does.

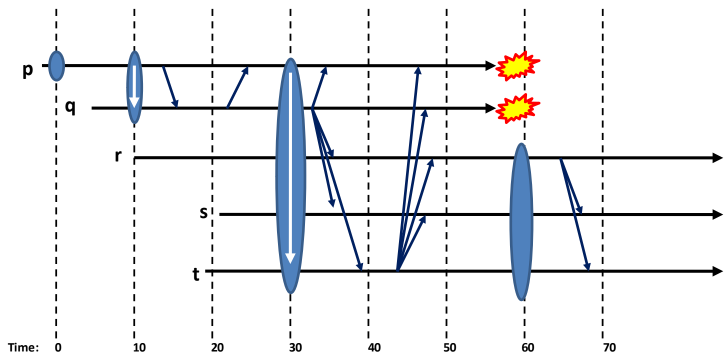
How can $Isis^2$ offer Paxos?

- Via the SafeSend API mentioned last time
  - SafeSend is a genuine Paxos implementation
  - But it does have some optimizations
  - And it has an unlogged mode. For Paxos durability you need to enable the logged feature.

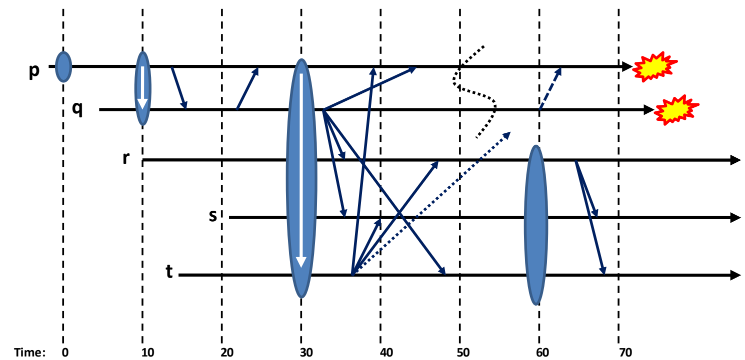
- In normal Paxos we don't have a GMS
  - With a GMS the protocol simplifies slightly and we can relax the quorum rules
  - SafeSend includes these performance enhancements but they don't impact the correctness or properties of sol'n

Consistency model: Virtual synchrony meets Paxos (and they live happily ever after…)

Non-replicated reference execution



Synchronous execution



Virtually synchronous execution

- **Virtual synchrony is a "consistency" model:**
  - *Synchronous runs: indistinguishable from non-replicated object that saw the same updates (like Paxos)*
  - *Virtually synchronous runs are indistinguishable from synchronous runs*

Is Isis^2 hard to use? Paxos was hard…

- We mentioned that just sticking Paxos in front of a set of file or database replicas is tempting, but a mistake
  - The protocol might "decide" something but this doesn't mean the database has the updates
  - Surprisingly tricky to ensure that we apply them all
- Isis^2: apply update when multicast delivered
  - This is safe and correct: all replicas do same thing
  - But it does require a state transfer to add members: we need to make a new DB copy for each new member
  - Can we do better?

Durability options

- Normal configuration of Isis^2 is optimized for "in-memory" applications.
  - State transfer: make a checkpoint, load it into a joining process, to initialize a joining group member
  - Checkpoint/reload can be used to make an entire group remember its state across shutdowns
- SafeSend, the Isis^2 version of Paxos, can be asked to log messages. This gives a stronger durability guarantee than with checkpoint/restart.

State transfer worry

- If my database is just a few Mbytes… just send it
- But in the cloud we often see databases with tens of Gbytes of content!
- Copying them will be a very costly undertaking

Out-of-Band (OOB) technology

- Allows copying big state by replication of memory-mapped files, very efficient
- There is a clever way to integrate OOB transfers with state transfer
- Effect is that with a bit more effort, Isis^2 won't need to send big objects through its multicast layer

Isis^2 DHT

- The system also has a fancy key-value store
  - Runs in a group and shards the data
  - One-hop get and put: no indirect routing needed!
  - Can even put or get multiple key-value pairs at a time, and there is a way to request totally ordered, consistent get and put: gives a form of atomicity

- Then you can do "aggregated query" operations to leverage the resulting parallel computing opportunity

GridCloud: Example Isis^2 application

GridCloud Cloud-hosted high-assurance system to monitor the electric power grid

sponsored by the Department of Energy ARPA-E program

Goal

Demonstrate a cloud-scale monitoring infrastructure able to host "smart grid" applications: the code that will make the power grid "smart"

Use cases

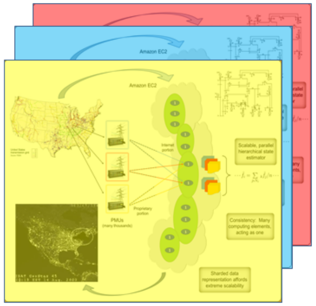
- Routine balancing of loads and generation
- Grid protection
- Analysis and adaptation after topology changes
- Integration of renewable energy

Challenges

Cloud lacks consistency, assurance, and timing guarantees. Industry demands very strong control over data flow with provable security.

Status

We're using Isis^2 to manage a structure in which replicated data permits high assurance reactive smart-grid monitoring and control. GridCloud features state estimation and GridStat software from Washington State University.

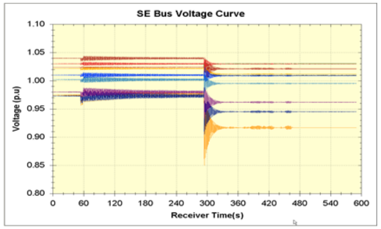


GridCloud enables

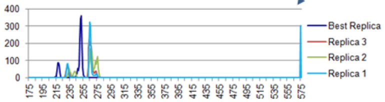
Large-scale, distributed power system applications in the cloud

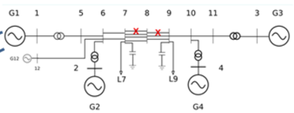
Low-latency and high-reliability using replicated data streams and application processes

- Key GridCloud technologies
  - ISIS and Dmake to manage a large number of processes running in the cloud
  - GridStat to provide multi-cast and rate filtering
  - Hierarchical Linear State Estimator (HLSE) as example application

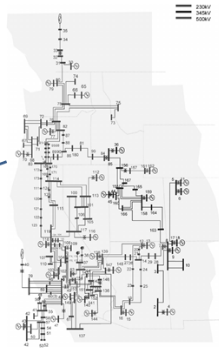


The HLSE uses EC2 Cloud resources to quickly and reliably do full-system SE 5 times per second with thousands of PMU data streams as input





	Aggregate Data Rate (Mb/s)	Total Connections	Substation SEs
Mar '13 12-bus (1 replica)	2.92	98	12
12-bus (3 replicas)	**8.75**	**294**	**36**
Oct '13 179-bus (1 replica)	46.93	1,577	127
179-bus (3 replicas)	**140.79**	**4,731**	**381**
Spring '14 6K-bus (3 replicas)	~570	~18,000	~3,000



- 2014 goal: Demonstrate GridCloud in a real-world setting, such as the regional transmission network for the North East USA

Definitions

PMU

A sensor (synchrophasor) used to measure voltage and phase angle of a power bus

Linear State Estimator (LSE)

Code that computes the state of a power grid using PMU data as input

Cornell University


Ken Birman


Robbert van Renesse


Zhiyuan Teo

Washington State University


Dave Bakken


Anjan Bose


Carl Hauser

www.cs.cornell.edu/Projects/Gridcontrol/

Cornell University

Washington State University
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Summary

- Group communication offers a nice way to replicate an application
  - Replicated data (without the cost of quorums)
  - Coordinated and replicated processing of requests
  - Automatic leader election, member ranking
  - Automated failure handling, help getting external database caught up after a crash
  - Tools for security and other aspects that can be pretty hard to implement by hand