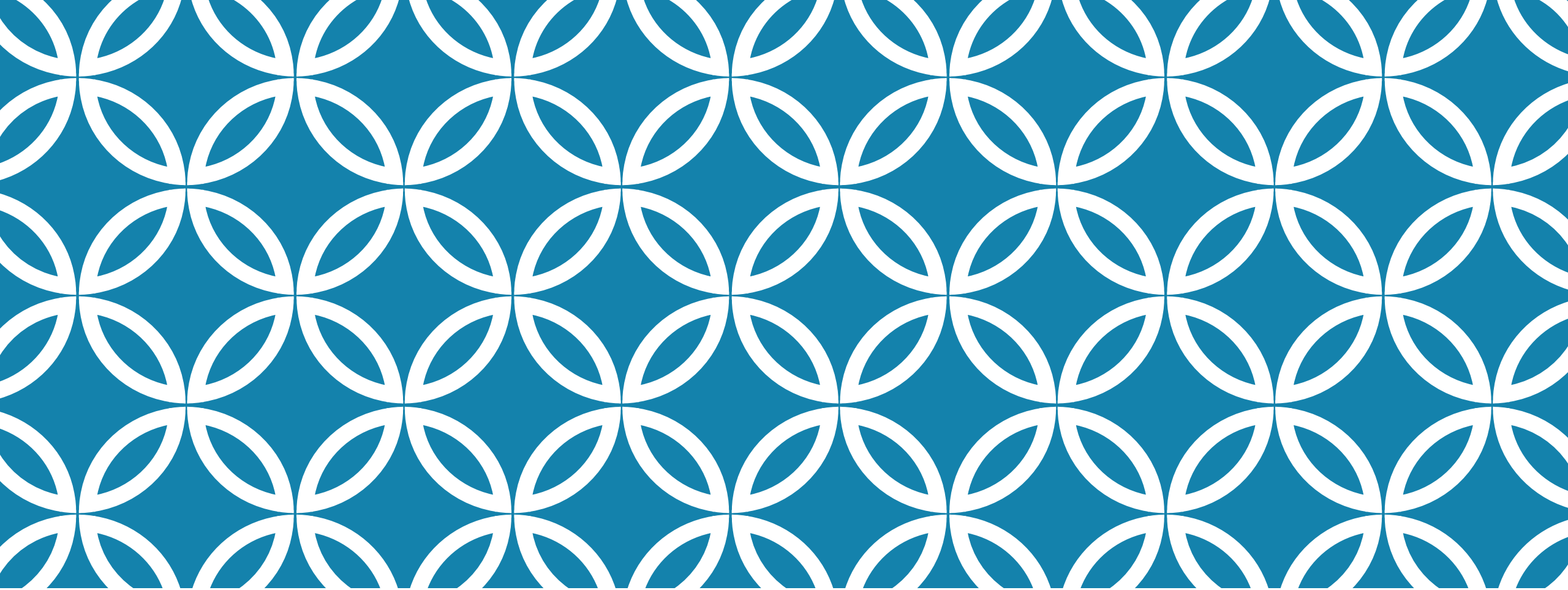


CS5412/LECTURE 7 CONSISTENT STORAGE FOR IoT

Ken Birman

CS5412 Spring 2019

CONSIDER A SMART HIGHWAY

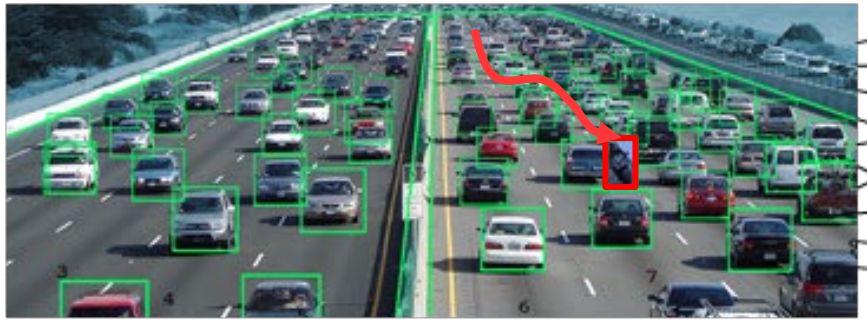
We have lots and lots of sensors deployed

Cars are getting some form of "guidance" and if they accept it (and maybe pay a fee) get to drive faster.

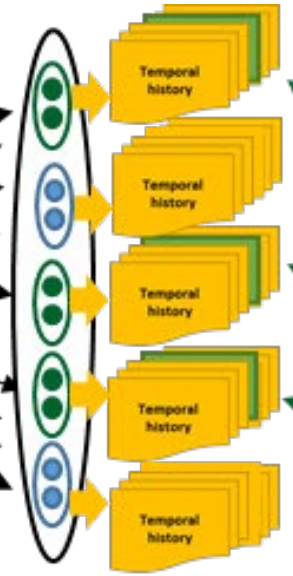
Would we run into consistency issues of the sort seen in Lecture 6?

SMART HIGHWAY

Massive inflow of real-time data



Hashing the video-id maps streams to shards.



A smart memory interprets data using machine learning and analytics, then stores findings in temporal version-vectors.

Processes communicate to compare data from distinct video streams.

Within a shard, Paxos state-machine replication guarantees consistency, durability, fault-tolerance.

Movie is generated by combining sub-results

Query: motorcycle at 10:03.22-10:03.56am?

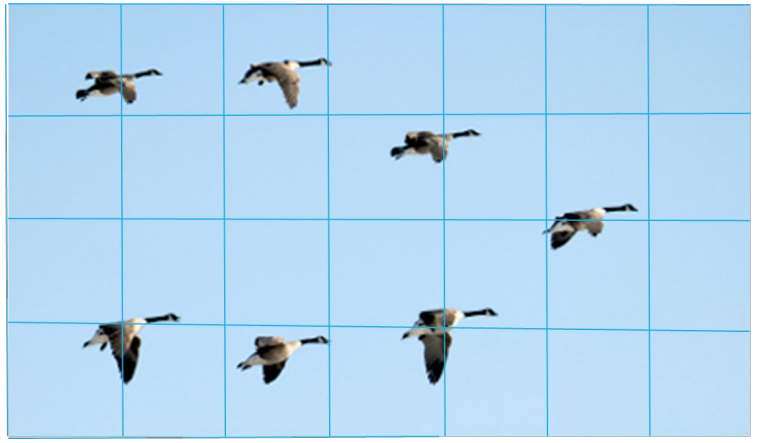
Temporal queries access versions within the histories, returning precise, causally-consistent results. This query accesses three shards (the green ones)

TRACKING TRINITY…

In this example, we are doing a few things in one picture

- Data is being captured by IoT sensors.
- We are relaying it into a key-value storage layer, and saving it in some sort of sharded, replicated form
- A "query" is pulling up images that show Trinity with the KeyMaker on her motorcycle)

REMINDER: FLOCK OF GEESE



In the last lecture we saw how the concept of a *causal snapshot* can help us create consistent views of a distributed system.

Can we use that same idea here?

Goals: We want temporally precise and causally consistent data, and then will search it for clear images of Trinity's ride.

ANIMATION: A WAVE IN AN AQUARIUM

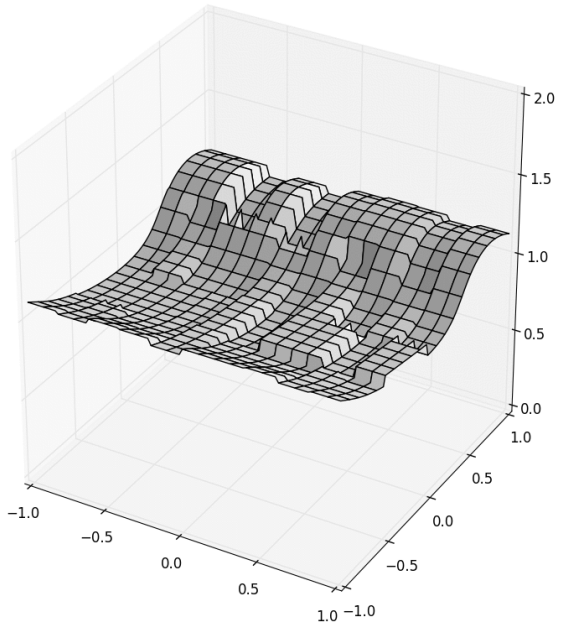
To illustrate this point visually, we made a simulation.

Rather than a flock of geese, it simulates a wave in an aquarium, as if 400 cameras were watching the water, each sending 20fps. We captured this "IoT sensor data" into files.

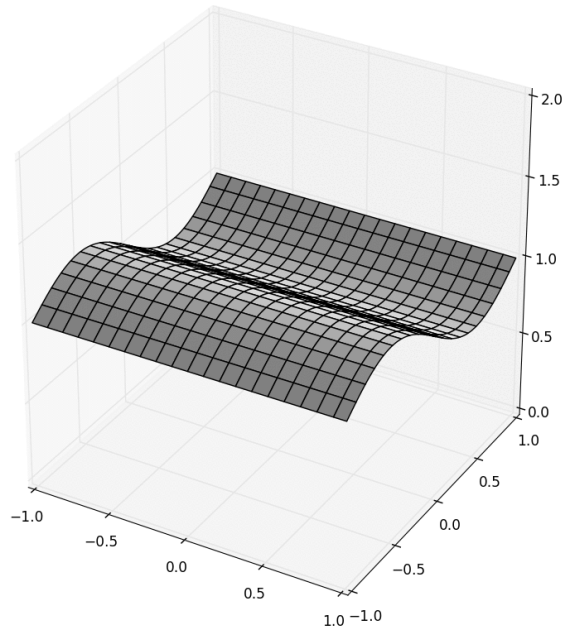
Then we took snapshots at a rate of 5fps and made a movie.

CONSISTENCY PROBLEM: HDFS DOES BADLY!

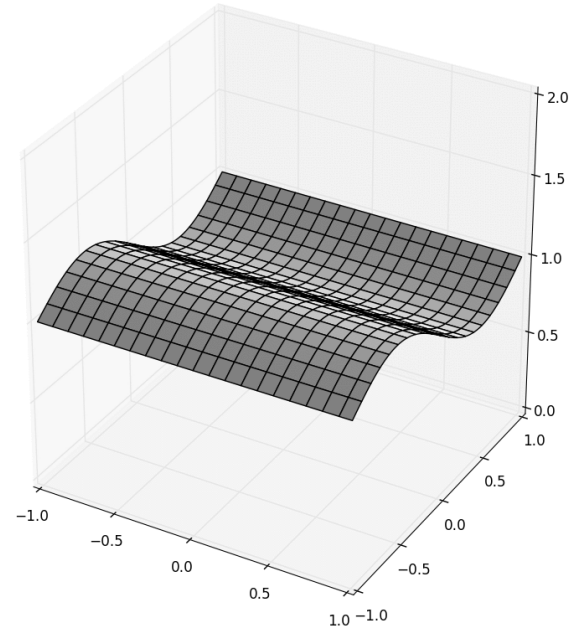
HDFS



FFFS+Server Time



FFFS+Sensor TIME



Existing file systems (like HDFS on the left) make mistakes when handling real-time data. But we can fix such problems (right).

WHY IS THE ONE ON THE RIGHT "BEST"? WELL… GARBAGE IN, GARBAGE OUT

Many machine learning systems are "tolerant" of noise, but HDFS was way worse than just noisy: it was inconsistent!

We might not trust the system when it tracks Trinity.

Inconsistent inputs can defeat any algorithm!

SMART SYSTEMS NEED CONSISTENCY!

As we saw, one dimension concerns *time*

- After an event occurs, it should be rapidly processed
- Any application using the platform should see it soon

Another centers on *coordination and causality*

- Replicate for fault-tolerance and scale
- Replicas should evolve through the same values, and data shouldn't be lost

FREEZE FRAME FILE SYSTEM ($FFFS_{V1}$)

This was created by our TA, Theo, with Weijia Song!

The idea was to bring ideas from Lamport's models into a file system so that the end-user (you) could benefit without needing to implement the mechanisms.

He took advantage of the fact that HDFS has a snapshot API, even though it didn't work. FFFS "reimplements" this API!

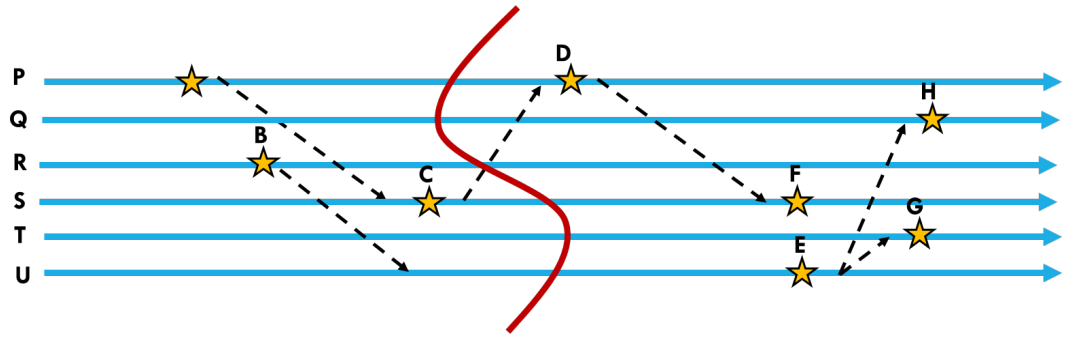
HOW DOES IT WORK?

Normal file systems only store one copy of each file.

FFFS starts by keeping every update, as a distinct record. The file system state at a particular moment is accessed by indexing into the collection of records and showing the "last bytes" as of that instant in time.

So FFFS looks just like a normal file system to its users.

HOW DOES IT WORK?

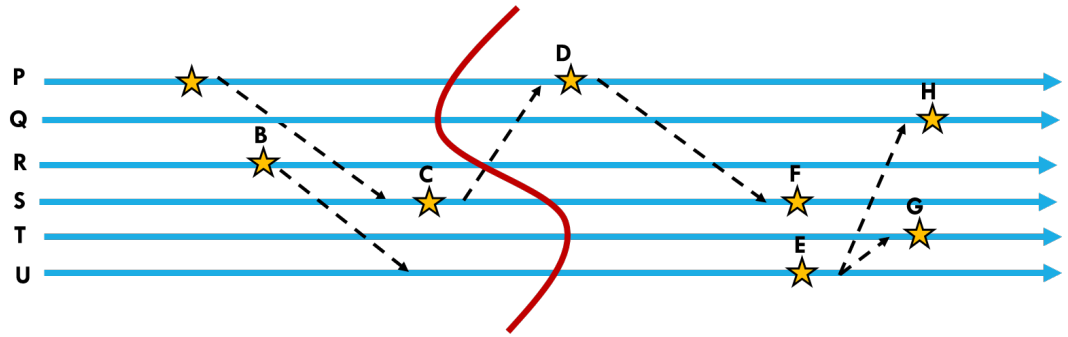


Next, just like in our space-time figures, FFFS tags every record with a special kind of timestamp.

In our examples we used logical clocks and vector clocks.

FFFS actually uses a *hybrid clock*. This includes the IoT timestamp from the sensor, the platform timestamp from a clock, and a causal timestamp from a logical clock.

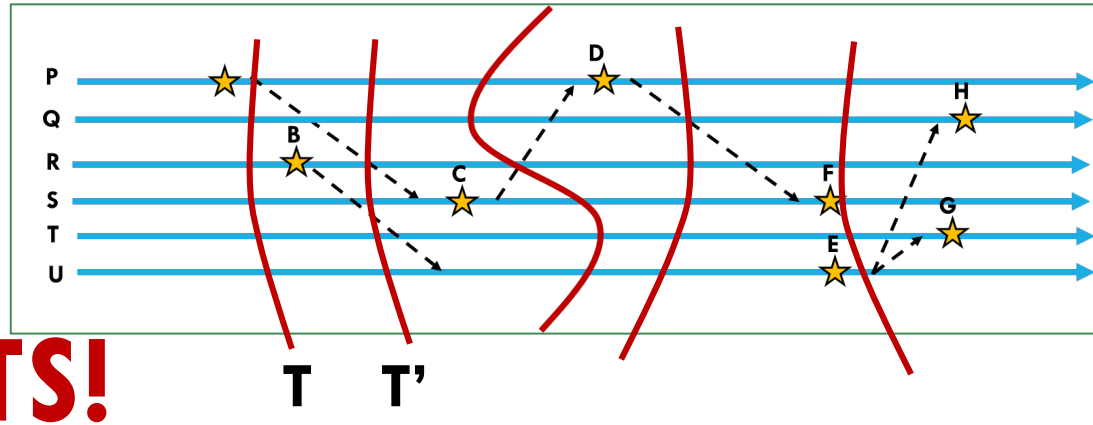
HOW DOES IT WORK?



Even though FFFS has multiple servers (in fact data spreads over them using the same key-value sharding discussed in Lecture 2), for an access at time T (you open "filename @ T"):

- It accesses data accurate for time T, despite clock skew
- It tracks causality, so that if it returns Y for some read, and update X → update Y, then it also returns X.
- In effect, FFFS does temporal reads *along a consistent cut*.

WHAT IF YOU DO MANY READS? CONSISTENT CUTS!



In effect, each time your application does a read from a set of files, that operation occurs along a consistent cut that:

- Is as accurate as $FFFS_{v1}$ can make it, given clock precision limits
- If T' $\geq$ T, the cut for T' includes everything the cut for T included
- If you read multiple files, the results are causally consistent
- Reads are deterministic (other readers see the same data)

IN OUR HIGHWAY EXAMPLE?

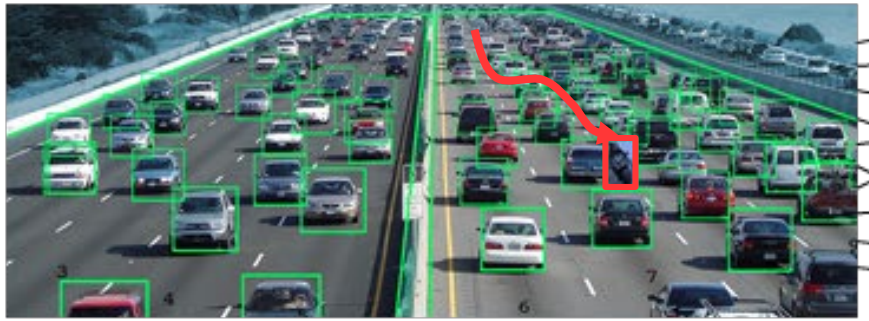
When we query, we want the machine-learning tool to see data as a series of consistent snapshots across the full data set.

Then it can select data that includes video-snippets of Trinity with exactly one snippet per unit of time, no overlaps, no "lies".

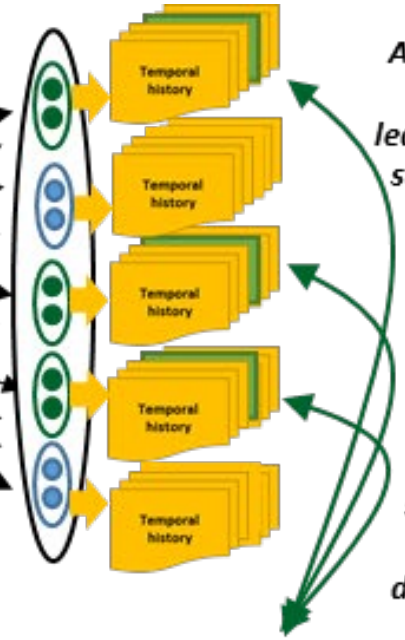
Thought question: How does the overlap issue relate to sensor overlap from the Meta system, discussed previously?

REVISIT THE SMART HIGHWAY

Massive inflow of real-time data



Hashing the video-id maps streams to shards.



A smart memory interprets data using machine learning and analytics, then stores findings in temporal version-vectors.

Processes communicate to compare data from distinct video streams.

Within a shard, Paxos state-machine replication guarantees consistency, durability, fault-tolerance.

Movie is generated by combining sub-results

Query: motorcycle at 10:03.22-10:03.56am?

Temporal queries access versions within the histories, returning precise, causally-consistent results. This query accesses three shards (the green ones)

BEYOND $FFFS_{v1}$

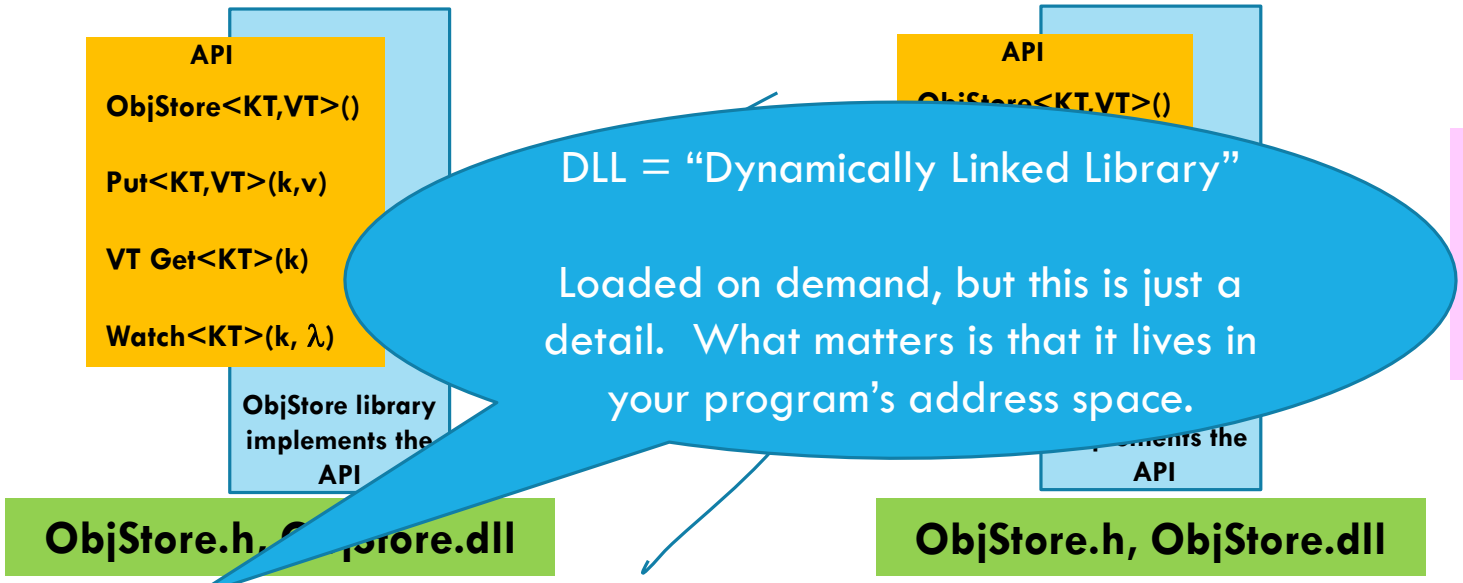
A file system is not a natural API to use if the way you think of the application is through key-value data.

So for Azure IoT, as part of a system called Derecho, also invented at Cornell, we are building $FFFS_{v2}$. It will be inside Derecho and looks like a key-value storage layer for "objects".

But in fact it can do anything $FFFS_{v1}$ could do.

FIRST, A TINY DIGRESSION

Libraries, programs that link to libraries, and μ-services.



Puzzle: All this is obvious… but what "is" a μ-service?

Tiny digression, not on exam

FIRST, A TINY DIGRESSION

A μ-service is just an (elastic, stateful) group of processes.

- All group members are instances of the identical program,
- They cooperate to accept requests from (stateless) functions.
- The (stateless) functions run in the function service tier.

RESTful RPC

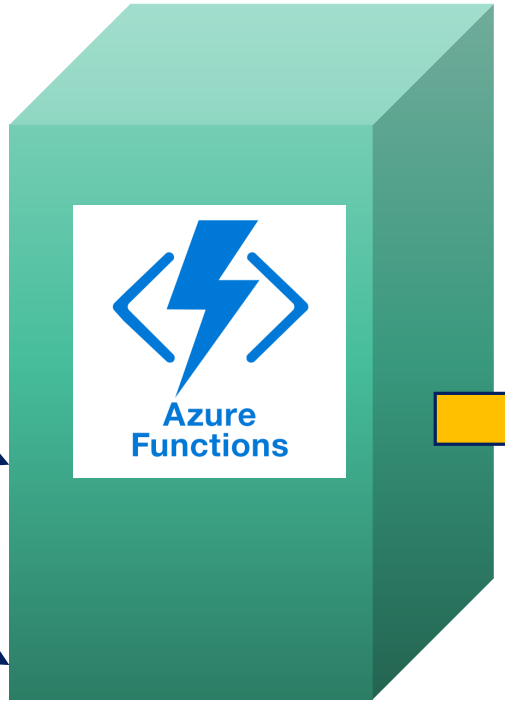
- A simple and standard way for a program (like a function) to invoke a method in some other program (like a μ-service instance)
- Based on HTTPS!

Tiny digression, not on exam

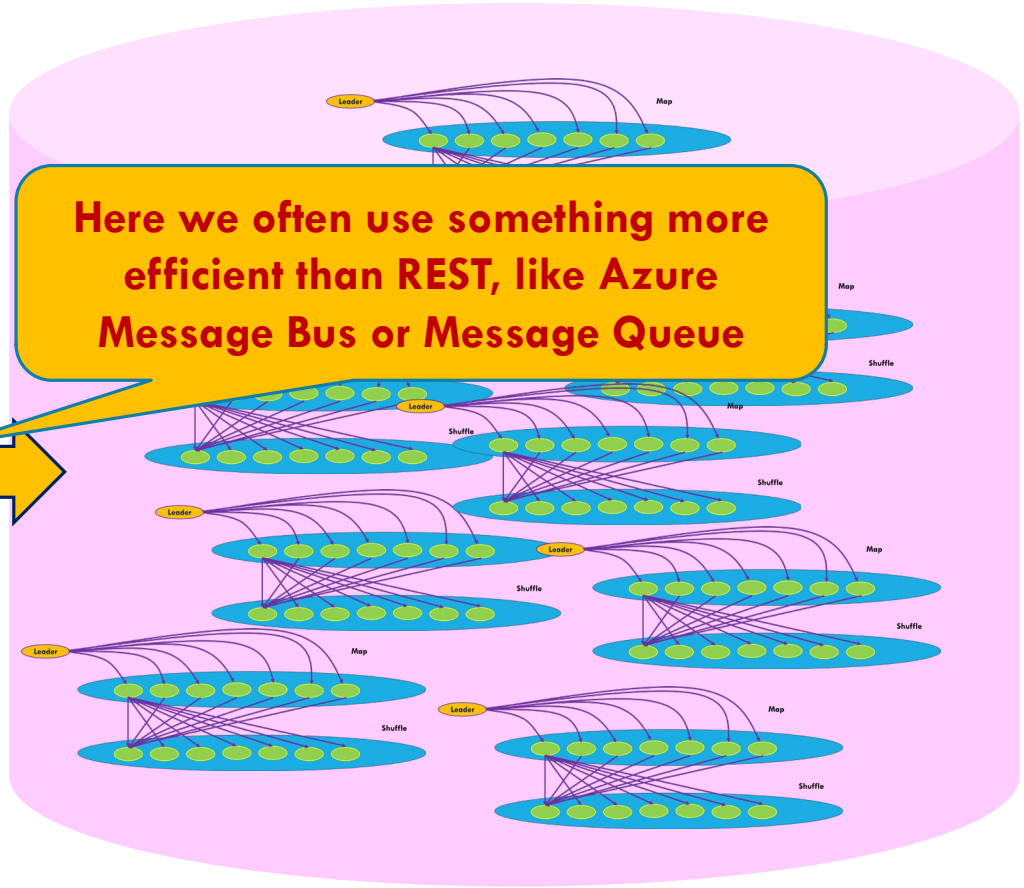
A MACHINE-LEARNING μ-SERVICE ATTACHED TO AZURE IOT, USED TO MONITOR SOME COWS

REST RPC over HTTPS (slow but universal)

Vast numbers of data sources live outside the cloud itself



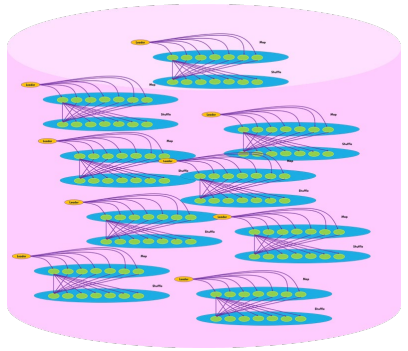
The IoT Cloud uses a tier of lightweight stateless "functions" to absorb load



This example shows a μ-service running MapReduce.

Tiny digression, not on exam

INSIDE THAT μ-SERVICE



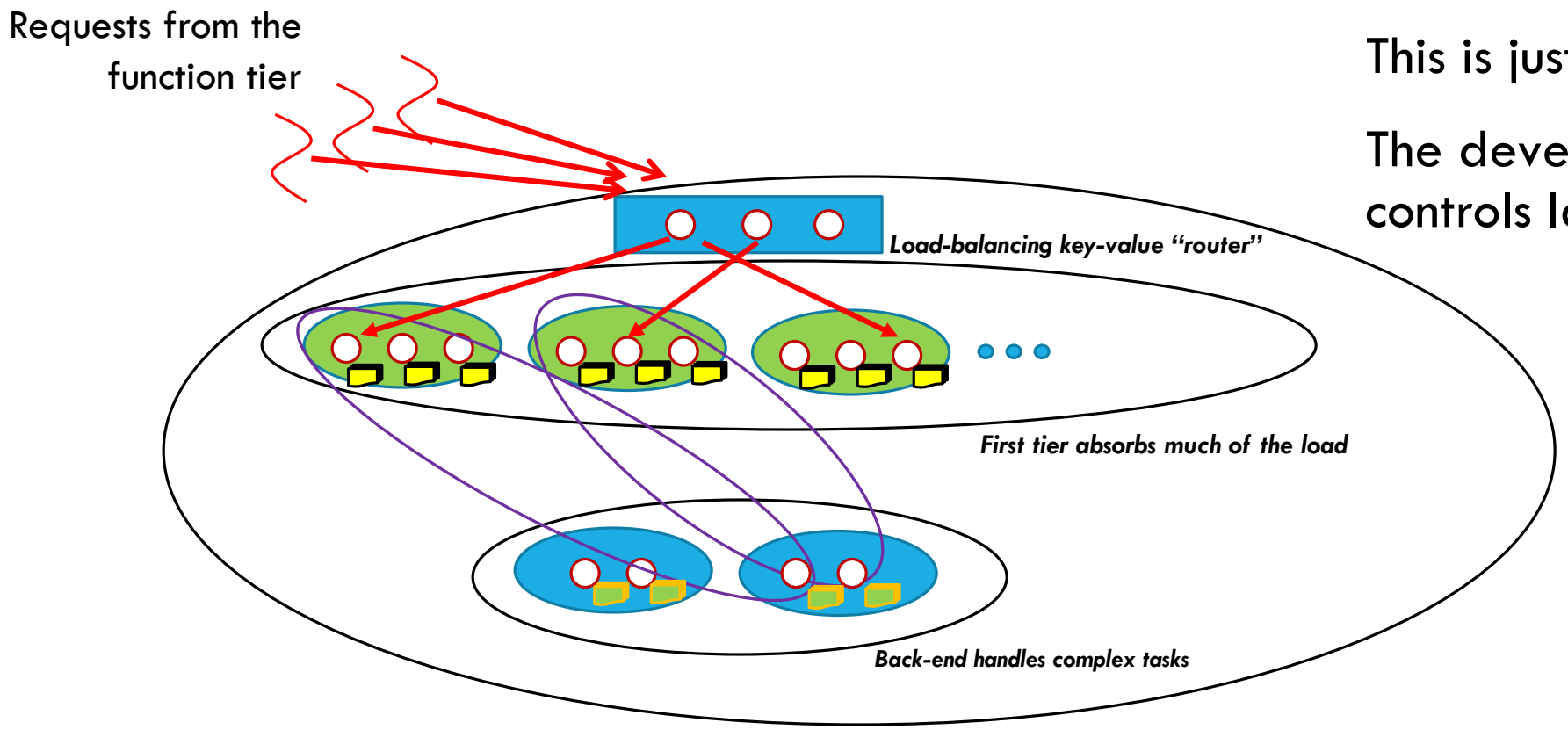
We would find a group of Linux processes.

Some (or perhaps all) would accept REST RPC's. Standard IDEs let you set this up automatically.

Then there would be processes to run the machine-learning logic, perhaps using MapReduce as shown here.

Tiny digression, not on exam

… STATE MACHINE REPLICATION IN GROUPS (ATOMIC MULTICAST OR DURABLE LOGGING)

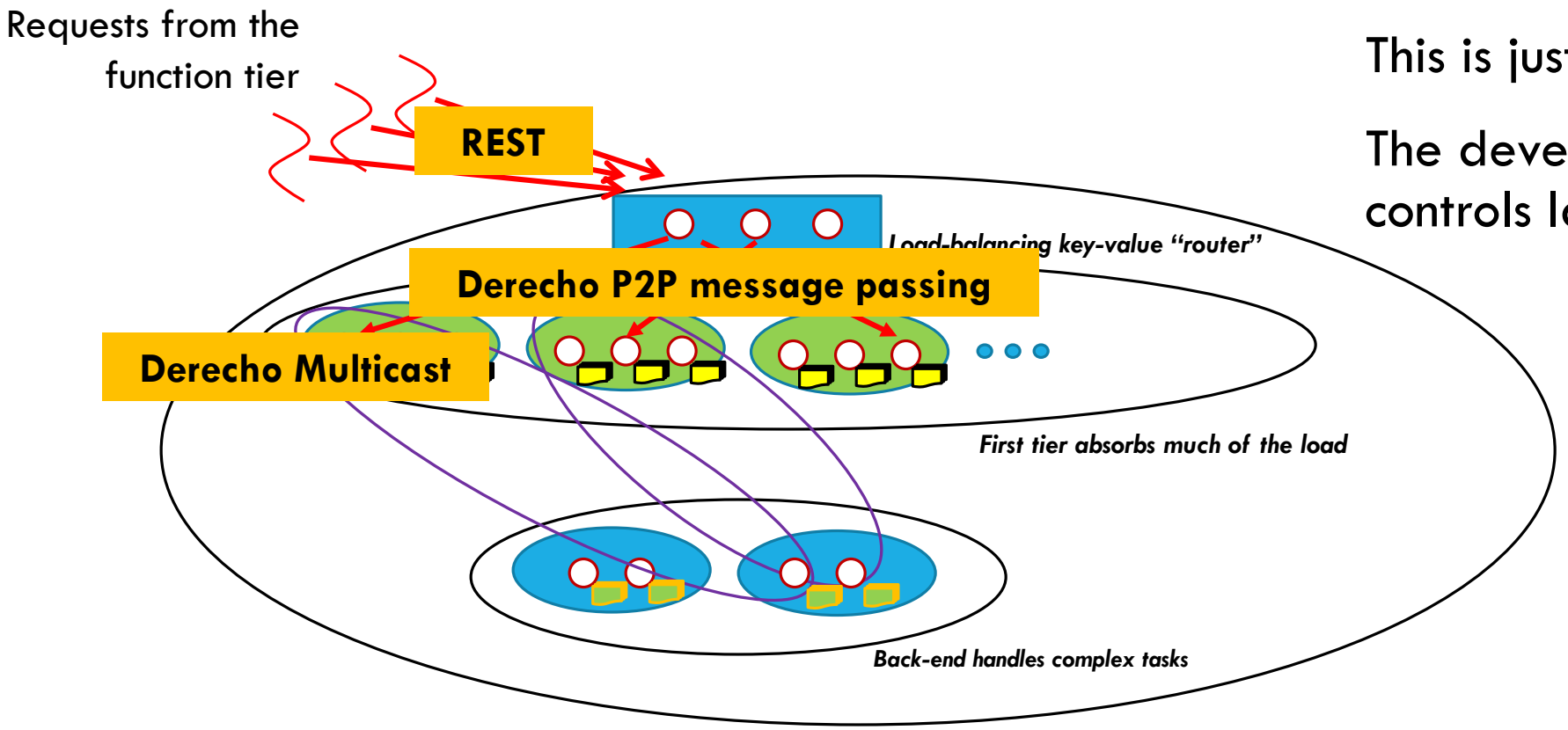


This is just an example.

The developer defines subgroups, controls layout and "shard" pattern

Tiny digression, not on exam

… STATE MACHINE REPLICATION IN GROUPS (ATOMIC MULTICAST OR DURABLE LOGGING)



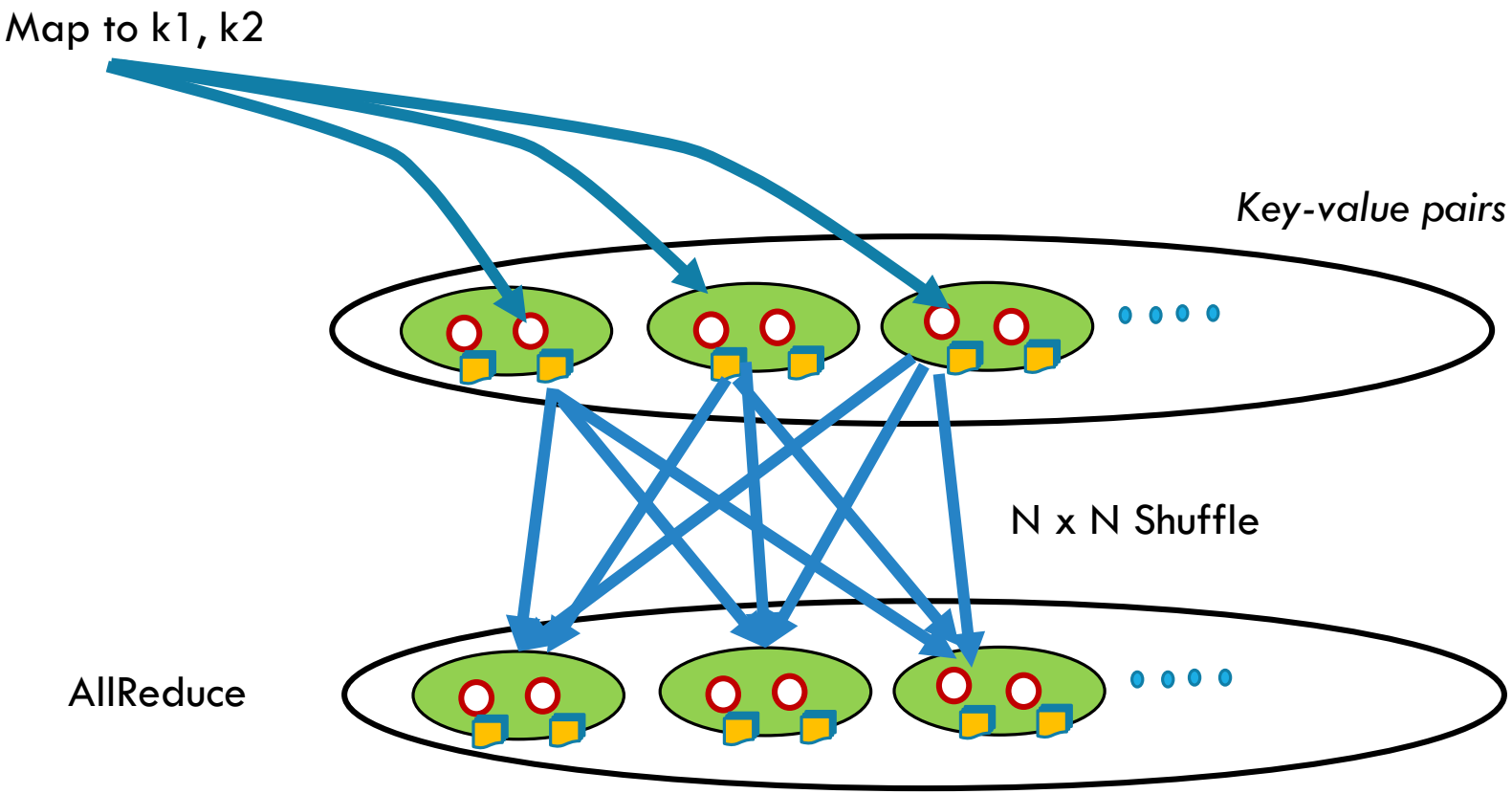
This is just an example.

The developer defines subgroups, controls layout and "shard" pattern

Inside Derecho we avoid REST and use highly efficient point-to-point and multicast primitives, for performance reasons.

Tiny digression, not on exam

MAP-REDUCE ON SUCH A GROUP



We obtain a completely atomic MapReduce primitive within Derecho!

Tiny digression, not on exam

DERECHO: BUT WHAT IS IT?

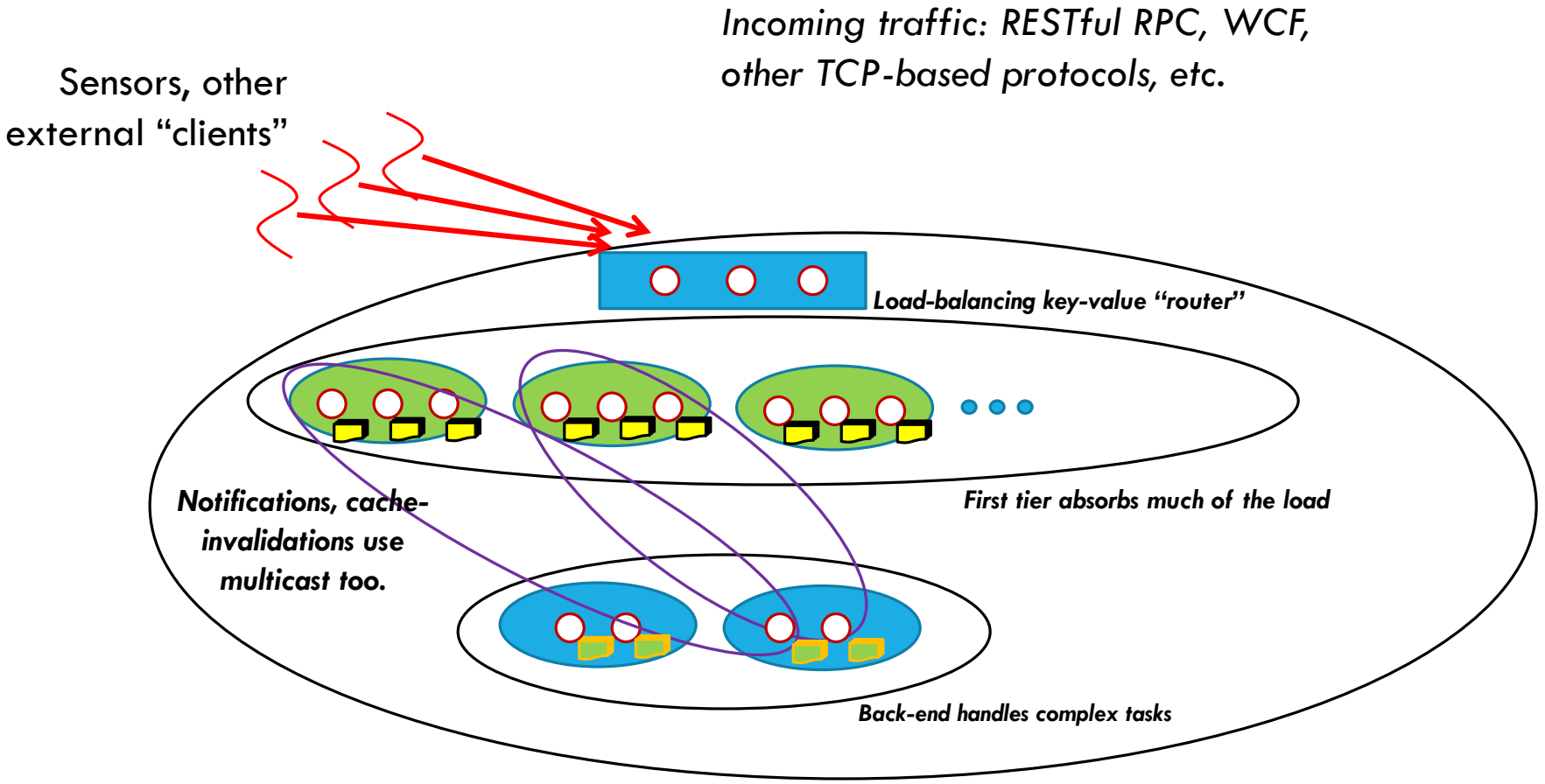
A Derecho

Derecho is an open-source tool for developers creating new cloud μ-services. Download from GitHub.com/Derecho-Project

Derecho leverages RDMA to gain exceptional speed, but can map to TCP if RDMA isn't available.

Currently targets C++ developers in Linux cloud environments like Azure IoT Edge, Azure Intelligent Edge, and Amazon AWS.

… BACK TO OUR EXAMPLE



Reminder: a μ-service can have any structure you like. You, the application developer, define the subgroups, controls the layout, tells us what pattern of sharding to use, etc.

ROLES DERECHO IS PLAYING

Derecho:

1. Automates the "mapping" from processes to these roles using layout parameters that you specify, like how many shards & how big.
2. Auto-instantiates C++ types for subgroups & shards
3. Fault-tolerant, repairs damage so data is always consistent.
4. Employs ultra-fast multicast (Paxos) for updates.
5. Offers a unique new read-only query mechanism that is consistent and can index in time, accurate to milliseconds.

DRILL DOWN ON "OBJECT STORE"

In the market, you find key-value stores like Cassandra, but with weak consistency and lacking these time-indexing capabilities.

Others, like Microsoft FaRM, are proprietary tools for specific needs (FaRM for example supports Bing's transactional queries and updates in a massive shared memory).

You also find file systems implemented over a layer like Derecho (think of Zookeeper), but they are slow and used mostly for configuration management.

Derecho's object store lives in this space, but is both *simpler* and *more powerful*.

OBJECT STORE API ($FFFS_{V2}$)

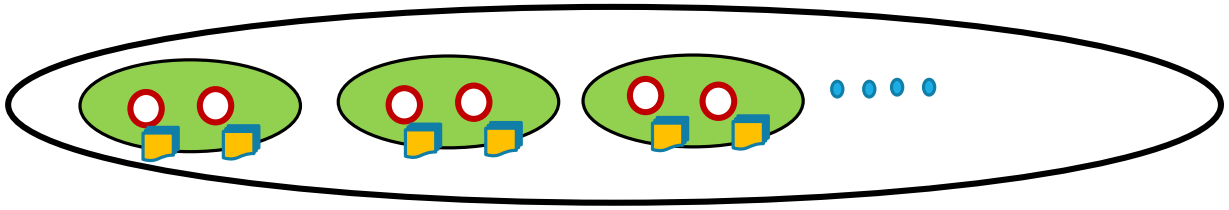
Extremely simple: Stores any kind of "binary information"

- Derecho::ObjectStore::**put**(key, value), or **cput**(key, value)
- Derecho::ObjectStore::**get**(key[, time])
- Derecho::ObjectStore::**watch**(key, Callback f)

The key could be a string, an integer, even a complex object.

The value could be a byte array, a photo, a video, and can be huge.

SIMPLEST CASE



We take a subgroup, shard it (for example, 2 replicas)

- **put** maps your key to some shard. It holds the key,value pairs
  - Replication uses an atomic multicast based on Paxos, so all copies are in a consistent state.
  - There is just one "most current" value, held by the store.
- **get** will fetch this most recently stored value.
- **watch** uses multicast to inform any watchers each time value changes.
- **cput** is like put, but only replaces the prior value if the version # matches

IS IT A LIBRARY? OR A μ-SERVICE? BOTH!

You can link your code directly to it, like any library.

We also have a "demo" that sets it up as a service.

- Warning: Our demo uses Derecho RPC, which is not available from the function service layer.
- Right now, the demo shows how to use it as a μ-service running as a subgroup inside a larger Derecho group.

But we plan to extend the demo to use REST. Then functions could talk to it.

- You could do this on your own, pretty easily

IN WHAT SENSE IS IT $FFFS_{V2}$?

First comment: You do not need to work with Derecho and its object store. Theo can help you set up $FFFS_{v1}$ as a file system for your project.

We think of the object store as a generalization of $FFFS_{v1}$.

- File names and record numbers can be used as keys
- The object store supports versioning, and indexed lookup
- In this perspective, it has all the functionality of $FFFS_{v1}$ except that you talk directly to it (which is far faster!), not through a file API

STORING THE DATA

For the simple case, a normal C++ "Map" is used at each process running the object store.

There is a configurable replication factor. The members of a shard use this to keep identical replicas of the C++ map.

The map itself is a hashed lookup structure employing an efficient in-memory data layout.

A single key can only map to a single value. If you replace it, the old value is garbage-collected.

SPEED? *BREAKS RECORDS!*

Every data path uses RDMA transfers (100Gbps bidirectional)

Derecho multicast is exceptionally fast and even with multiple copies, the entire update runs at nearly 125Gbps

Note: In today's Derecho, RDMA is offered *inside* a μ-service, but in 2019 we will also have RDMA for clients *outside* the service.

WHAT ABOUT BIG OBJECTS?

If objects are large, and watchers just want "some" objects, we recommend a simple two step approach:

- Create a uid, and **put** the (uid, obj) pair, first.
- **put** a "meta-data" record that lists the uid.
- Now, via **get** or **watch**, clients learn about the update from the meta-data, which can list various attributes.
- They call **get** a second time to fetch object, if desired.

VERSIONED OBJECTS

We configure the object store to track versions. **put** creates a new version:

- *key*: The object store *always* tracks information on a per-object basis
- *version-number*: Just an integer
- *time*: If the object itself lacks a timestamp, we just use "platform" time.

Now **get** can lookup most current version, or a specific one, even by time.

The object store is optimized to leverage non-volatile memory hardware.

SEQUENCES OF VERSIONS

With concurrent applications, you could worry that someone will do a **get**, then compute a new version, then **put**. But if some other process simultaneously does the same thing, one could overwrite the other.

In **cput** is a in the object store to address this kind of race condition. If an update races occurs, **cput** "fails" so that you can repeat the **get** and try again. You get consistency without locking.

STORING DELTAS

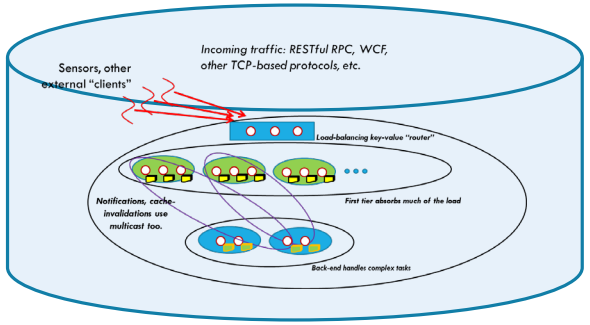
Existing DHTs lack support for versioned data.

We implemented a highly optimized versioned data structure

We implement a temporal index, and cache frequently accessed data.

- A server still manages a map (since many keys map to it), but you can think of the values for a specific key as being versioned.
- Sometimes deltas are more efficient. If you have a function to compute the delta, we won't even create a new version unless you tell us to.
- Values (or deltas) are saved on NVMe & replicated for fault-tolerance.

OBJECT STORE AS A FILE SYSTEM



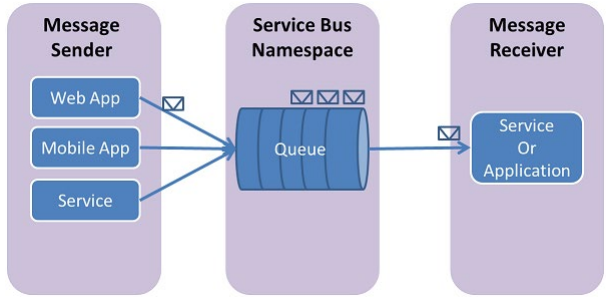
A file system is really an abstraction over a block store.

We plan to offer the Ceph object-oriented enhanced Posix API.

- Here we configure the object store to be *versioned* and *persistent*.
- Paxos for fault-tolerant updates, guaranteeing consistency.

This will offer back-compatibility, but for peak speed users should still use **put/get/watch**

OBJECT STORE AS A "BUS"



We can implement "publish" using **put.**

- Acts as a message bus in the non-versioned case
- Acts as a message queue in the versioned mode.

… and we can support "subscribe" using **watch**

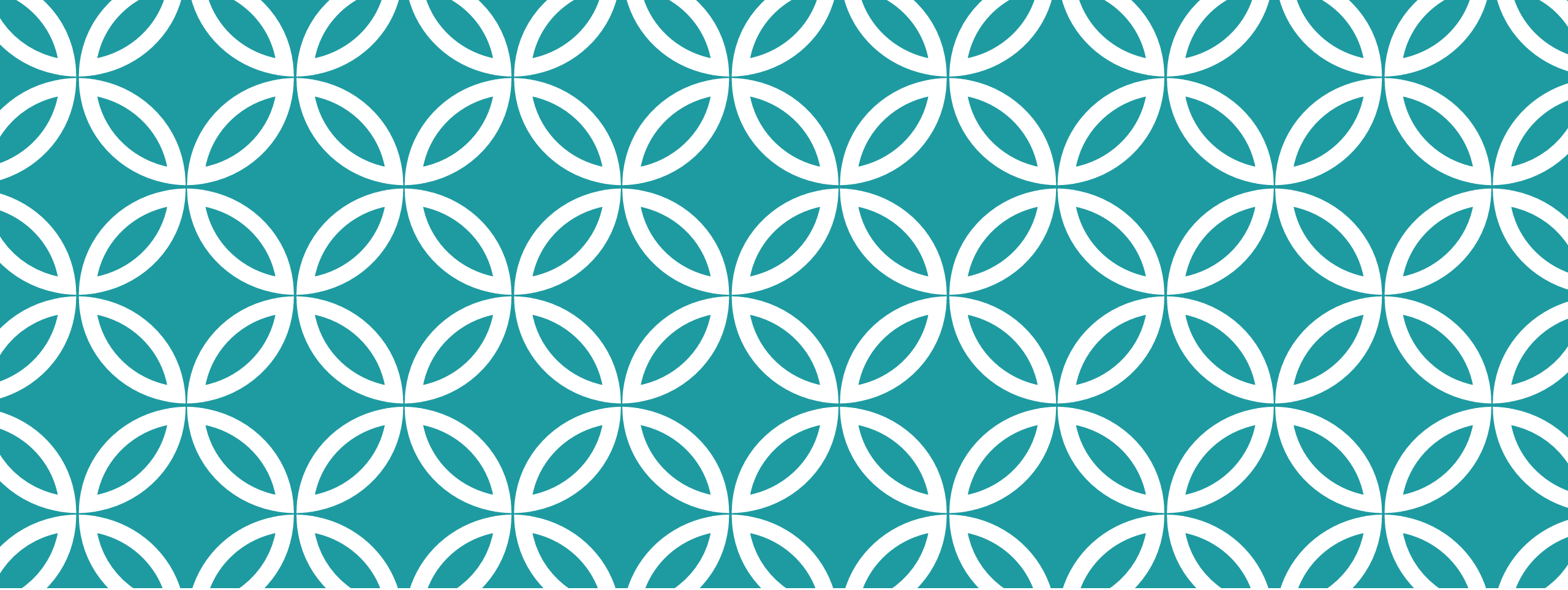
Thus the object store can support pub-sub APIs such as the OMG DDS specification, Kafka, OpenSplice, etc. We can also offer message queuing APIs such as the Azure or AWS queuing services.

STATEFUL OR STATELESS?

Configured to not store anything, we get a pure notification, sometimes called "topic-based publish-subscribe."

Configured to store the most recent value, a new subscriber can see the most recent posting, then gets notifications for updates.

Configured to track versions, we have a true "queuing" service, acting like a mailbox. A subscriber can replay old data, or we could use replay as a debugging/auditing tool. But the object store has a truncate API that can be used to force it to discard old data.



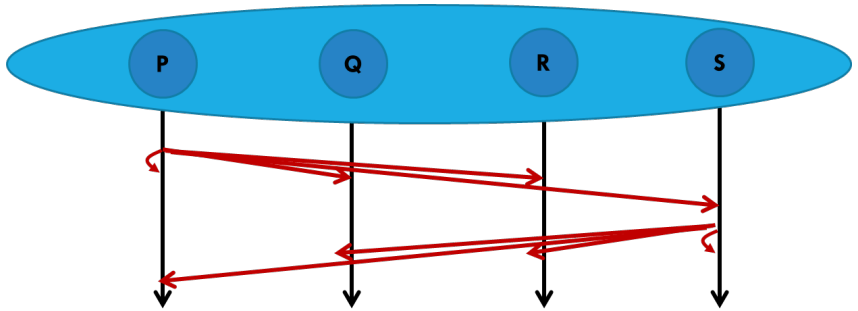
SOME PERFORMANCE GRAPHS

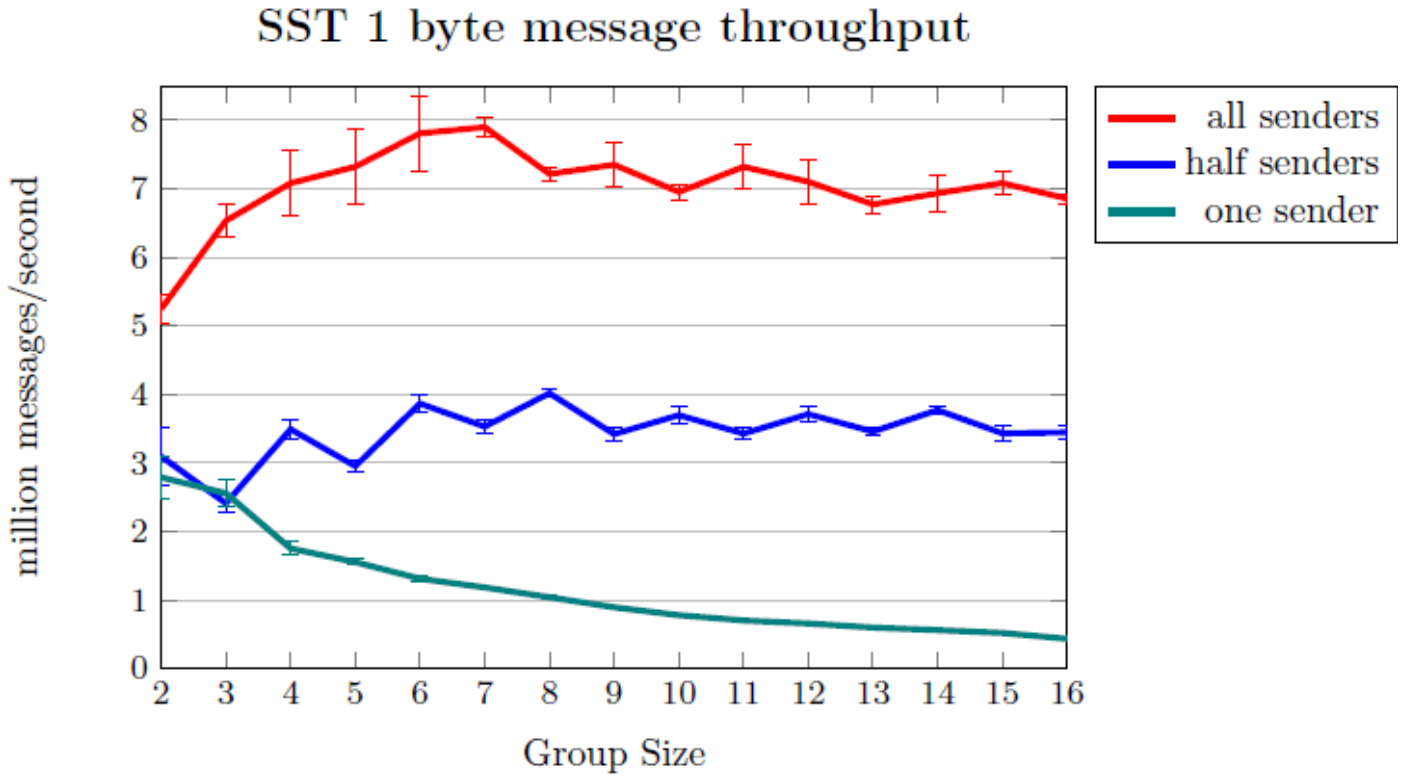
From our TOCS submission

DERECHO: SMALL MESSAGES

Mellanox 100Gbps RDMA on ROCE (fast Ethernet)

100Gb/s = 12.5GB/s





Derecho can make 16 consistent replicas at 2.5x the bandwidth of making one in-core copy

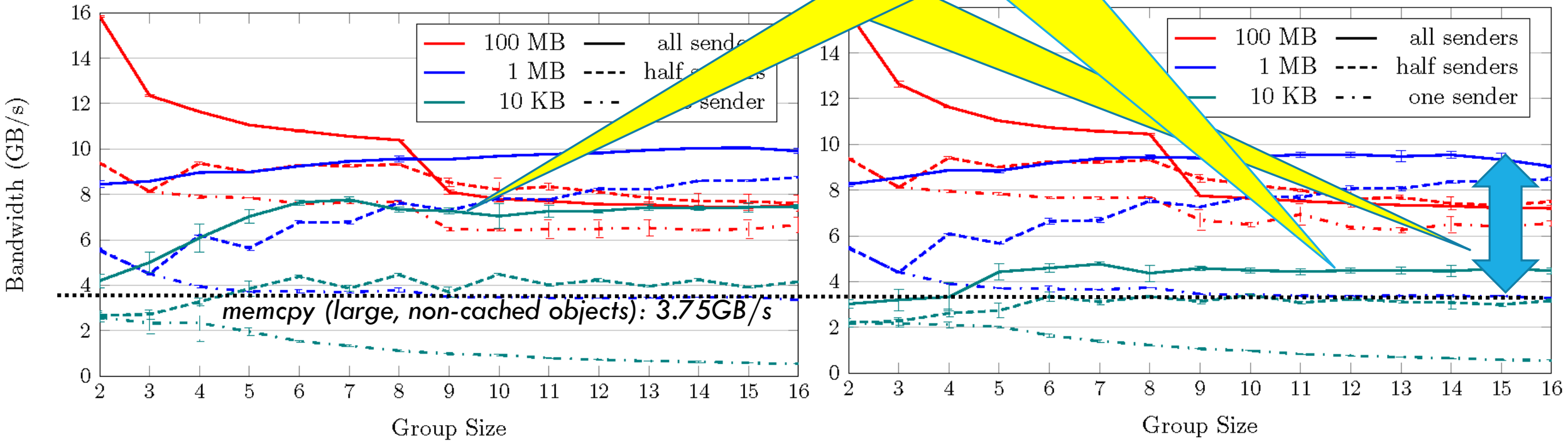
LARGE ?

Mellanox 100Gbps RDMA on ROCE (fast Ethernet)

100Gb/s = 12.5GB/s

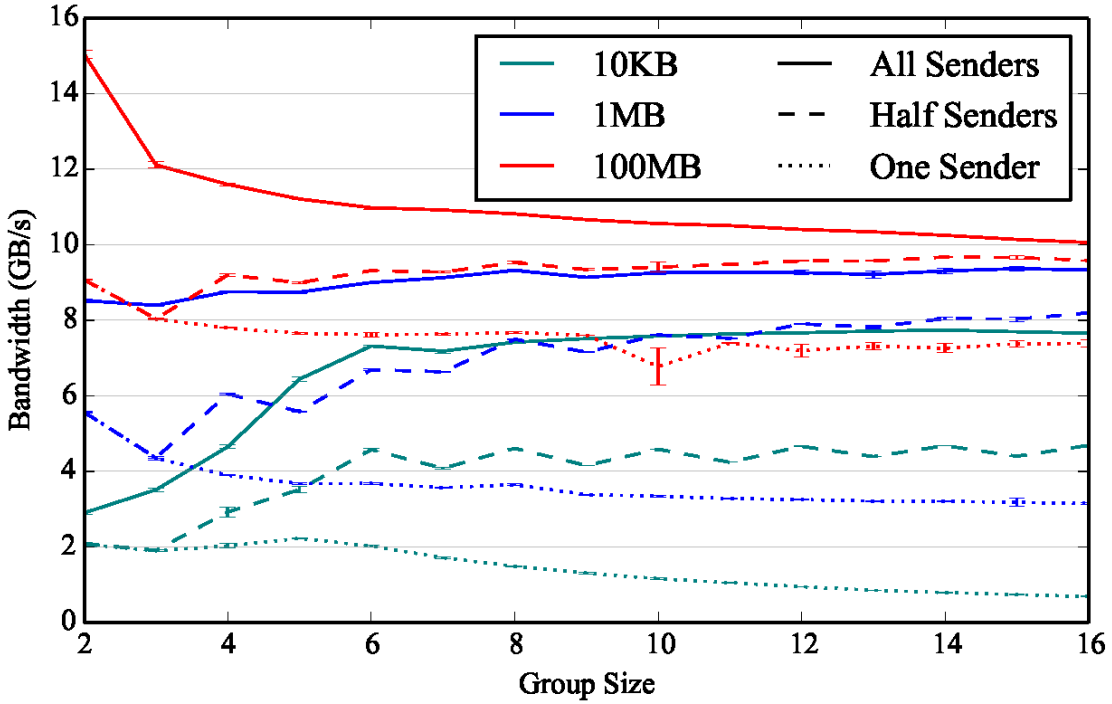
Raw RDMC is faster, but performance loss is small

RDMC: our cheapest 1:K reliable RDMA … (Vertical Paxos)

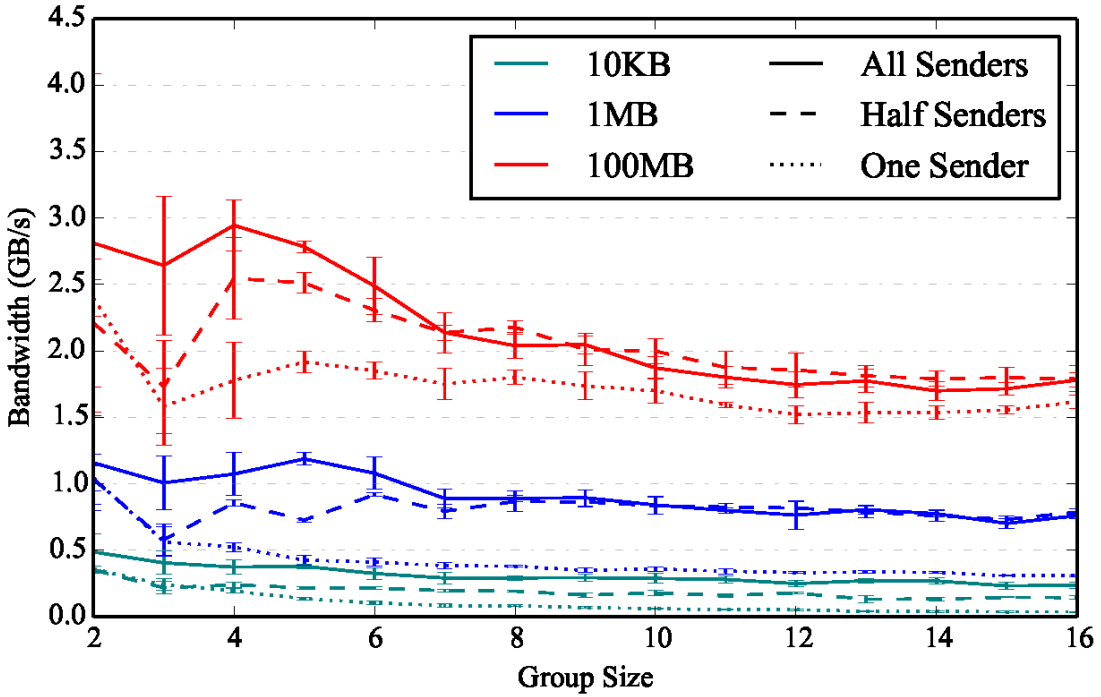


RDMA VERSUS TCP: RDMA IS 4X FASTER

Derecho Atomic Multicast: 100G RDMA

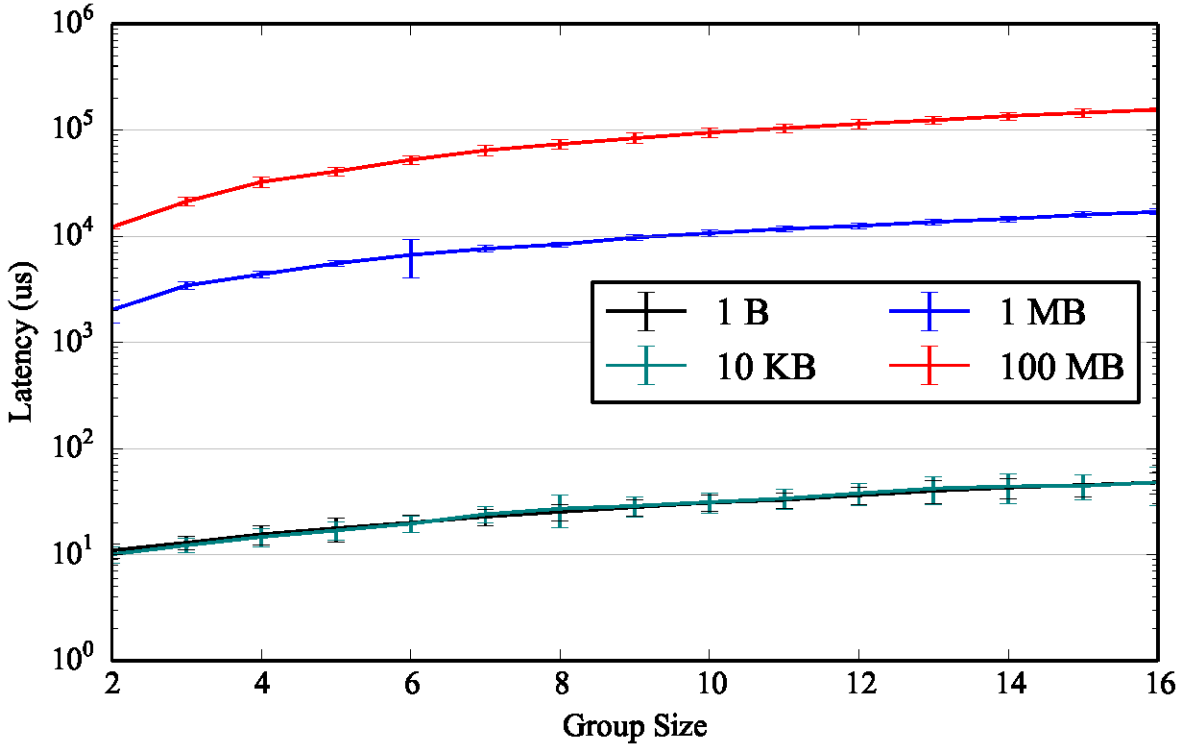


Derecho on TCP, 100G Ethernet

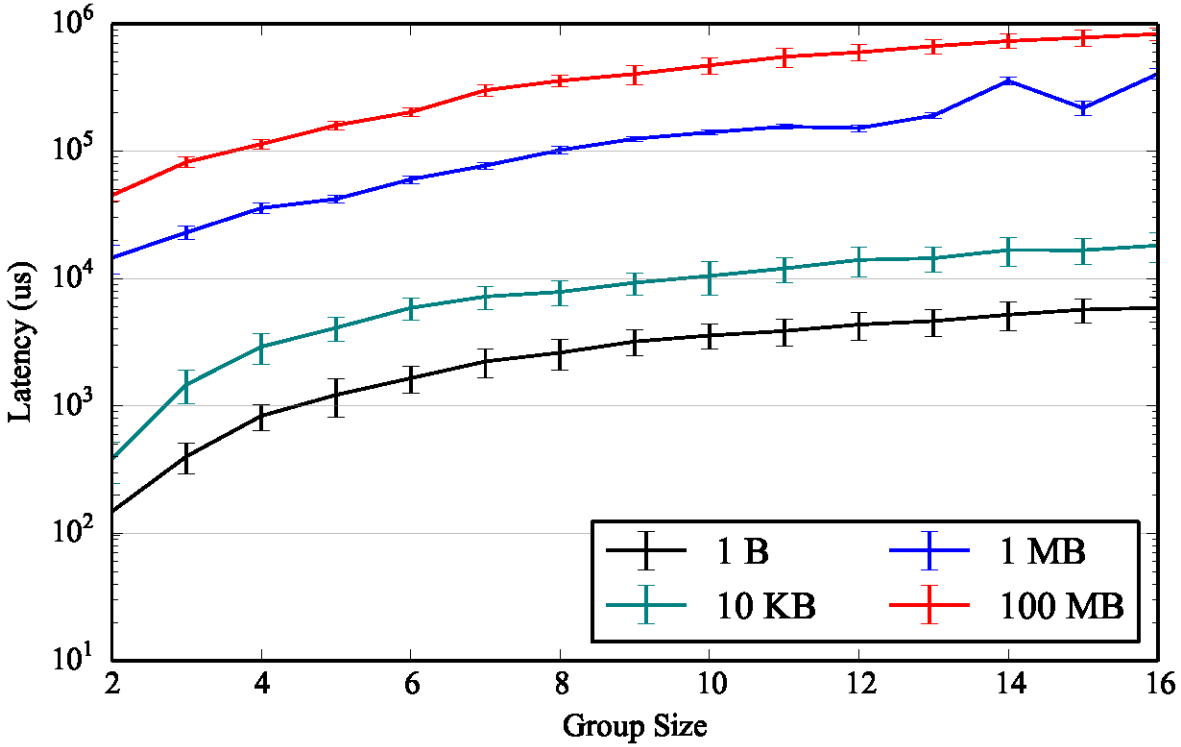


LATENCY: TCP IS ABOUT 125US SLOWER

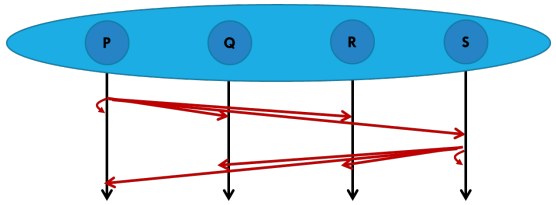
Derecho Atomic Multicast: 100G RDMA

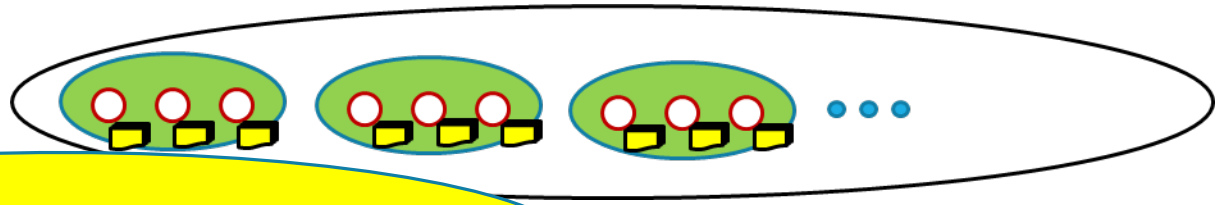


Derecho on TCP, 100G Ethernet



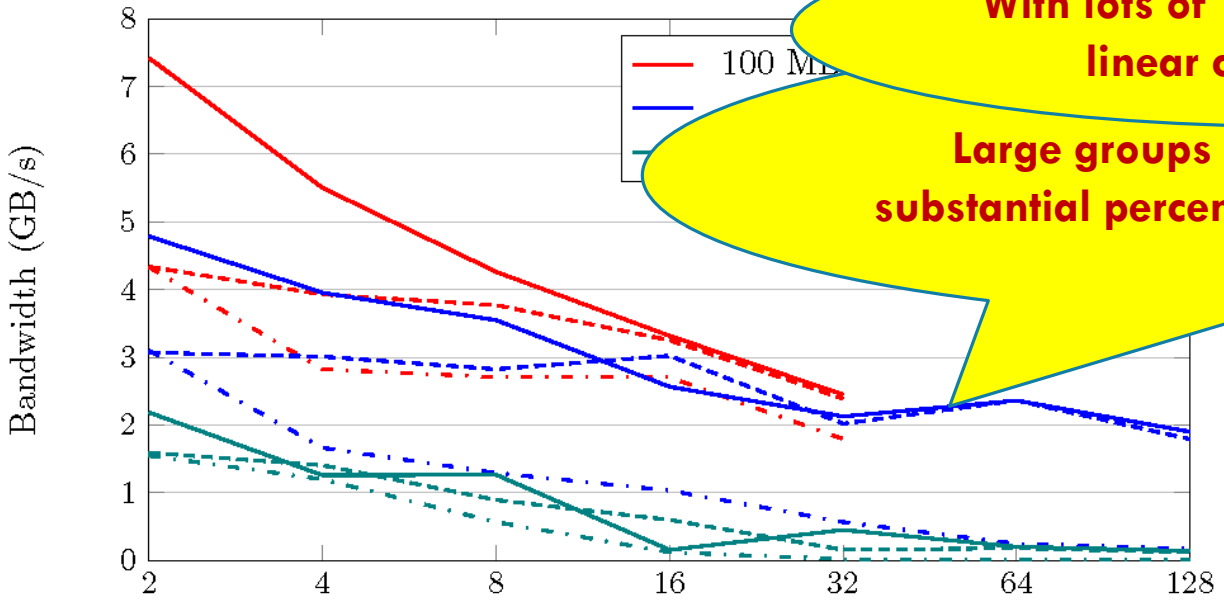
DERECHO: SCALING (56GB/S RDMA)

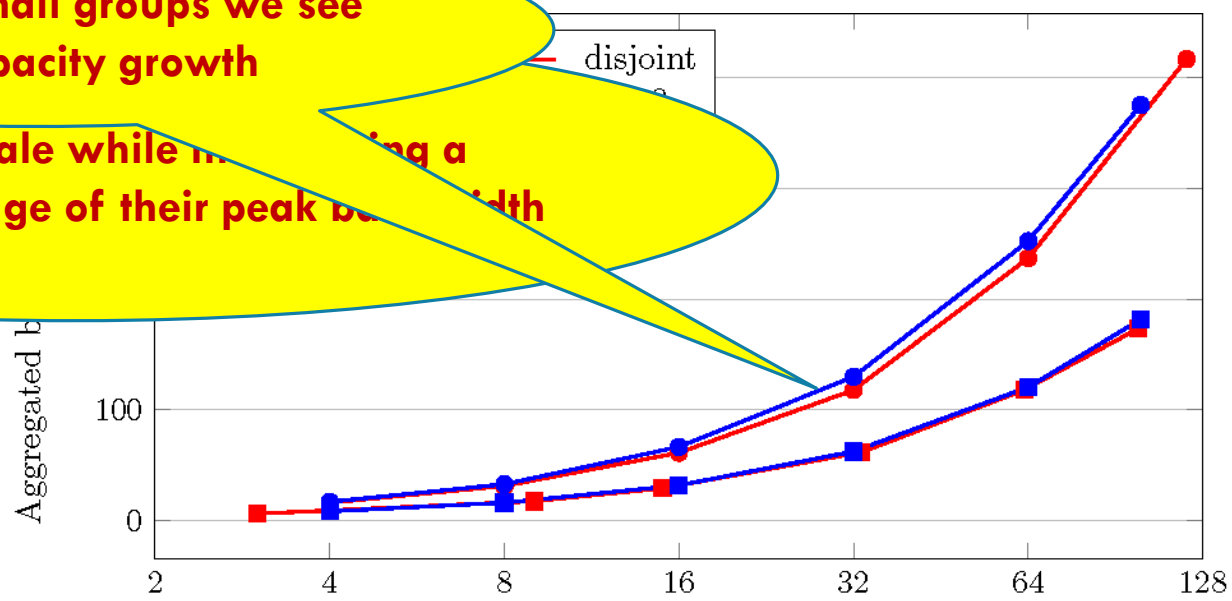




With lots of small groups we see linear capacity growth

Large groups scale while ... a substantial percentage of their peak ... dth





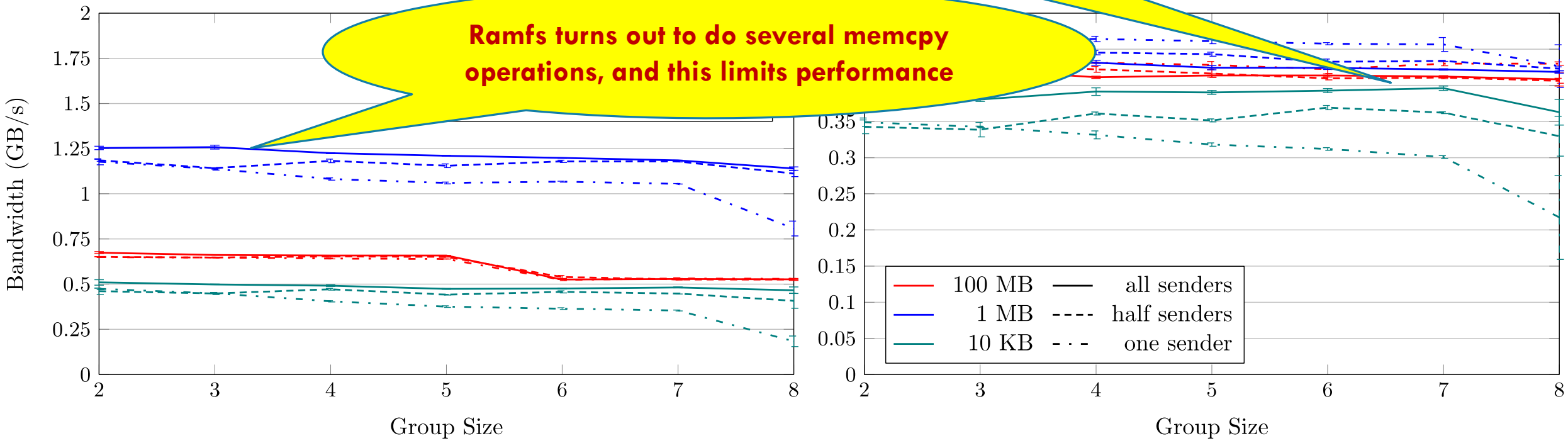
LARGE GROUP OF SIZE N (2...128)
LIMIT WAS MEMORY FOR BUFFERING

BROKEN INTO SHARDS OF SIZE 2 OR 3
LINEAR AGGREGATE THROUGHOUT

PERSISTENT<T>

Performance is limited by the peak bandwidth possible with the SSD devices on our cluster… Our (fairly old, slow) SSDs "maxed out". Derecho's protocols are not a limiting factor.

Ramfs turns out to do several memcpy operations, and this limits performance



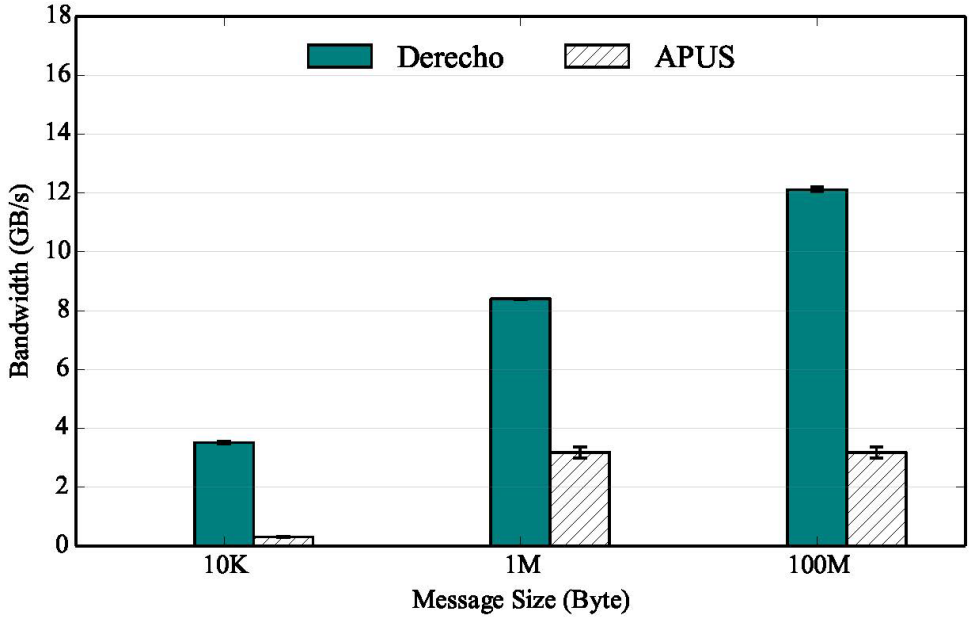
OBJECT STORE: VERSIONED TAKEAWAYS

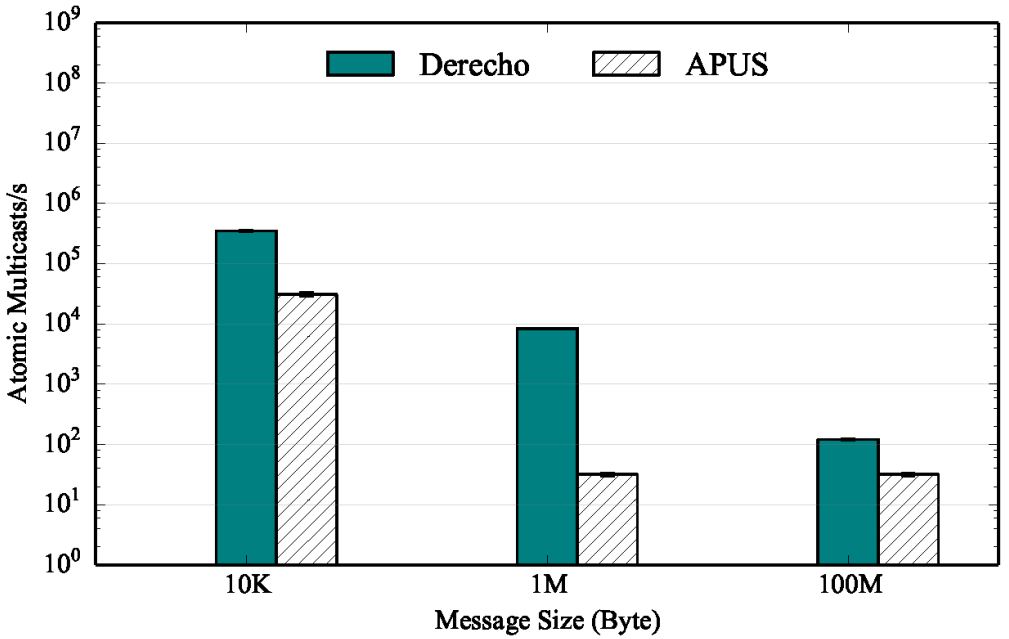
… in both cases, the storage medium was the limiting factor

Derecho can deliver bytes far faster than RamDisk or SSD can soak them up, so performance looks flat.

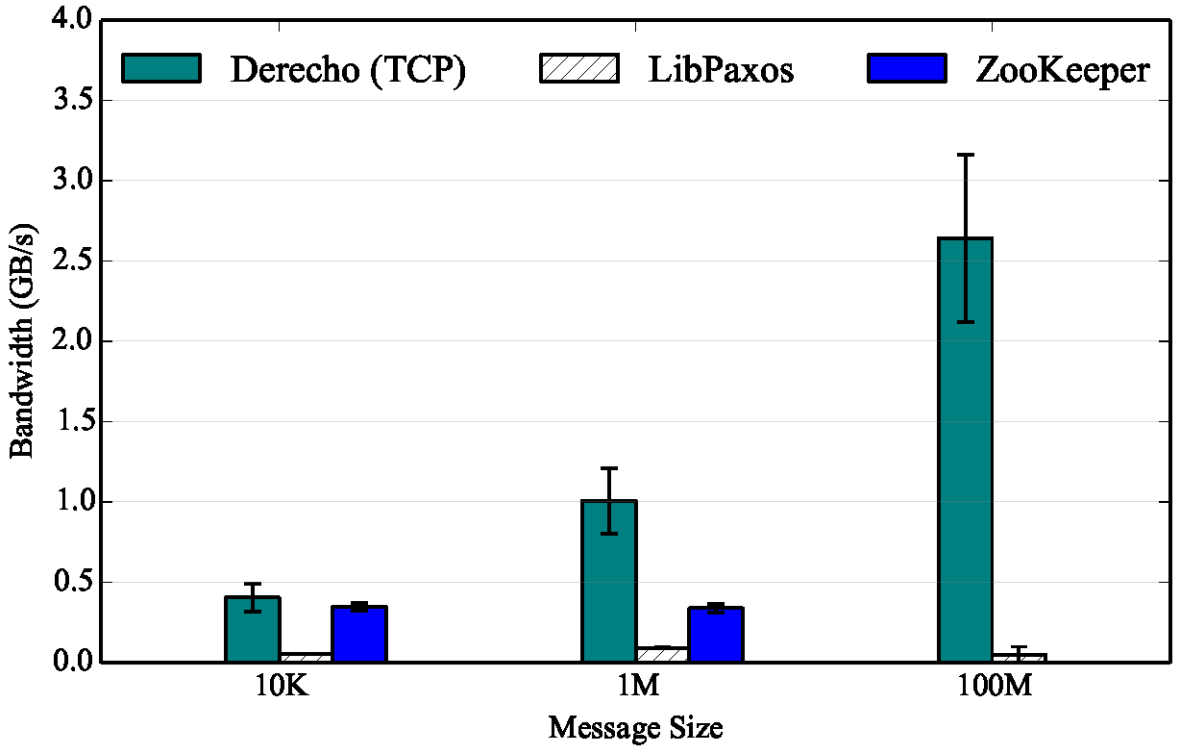
Note: In this mode, Derecho is the world's fastest durable Paxos!

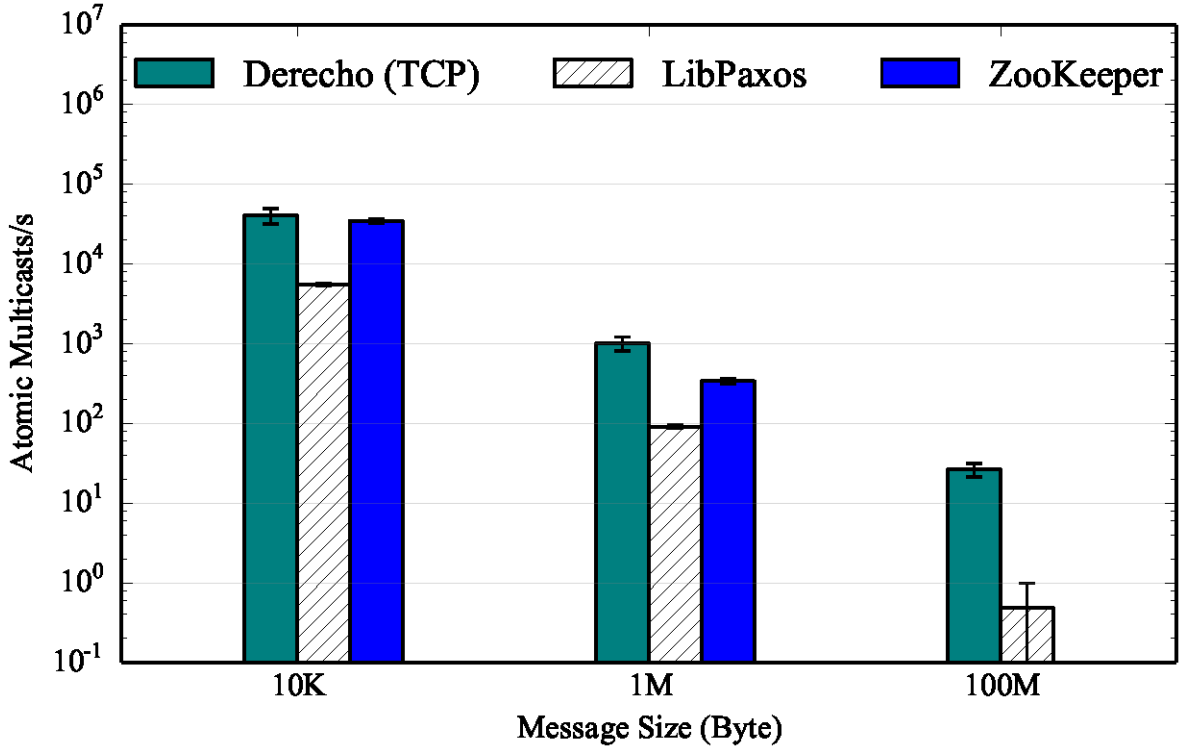
DERECHO VS APUS (RDMA PAXOS), N=3





DERECHO VS LIBPAXOS, ZOOKEEPER, N=3 (ALL THREE CONFIGURED FOR TCP ONLY)





CONCLUSIONS

Derecho is up and running solidly, and can be used on pure TCP systems as well as on RDMA-enhanced ones. Our project site and collaboration hub is **GitHub.com/Derecho-Project/.**

The new object store offers a very simple and flexible C++ API. It is gradually replacing $FFFS_{v1}$.

These are good examples of Lamport's ideas applied in practice.