Fault Tolerance

Ken Birman

Too many seminal concepts

Lorenzo Alvisi's Byzantine twin wants you to use 2f+1 replicas

- Process pairs, primary-backup
- 2PC and 3PC, Quorums
- Atomic Transactions
- State machine replication
- RAID storage solutions

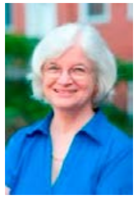



- Checkpoints, Message Logging
- Byzantine Agreement
- Gossip protocols
- Virtual synchrony model
- Paxos
- Zookeeper



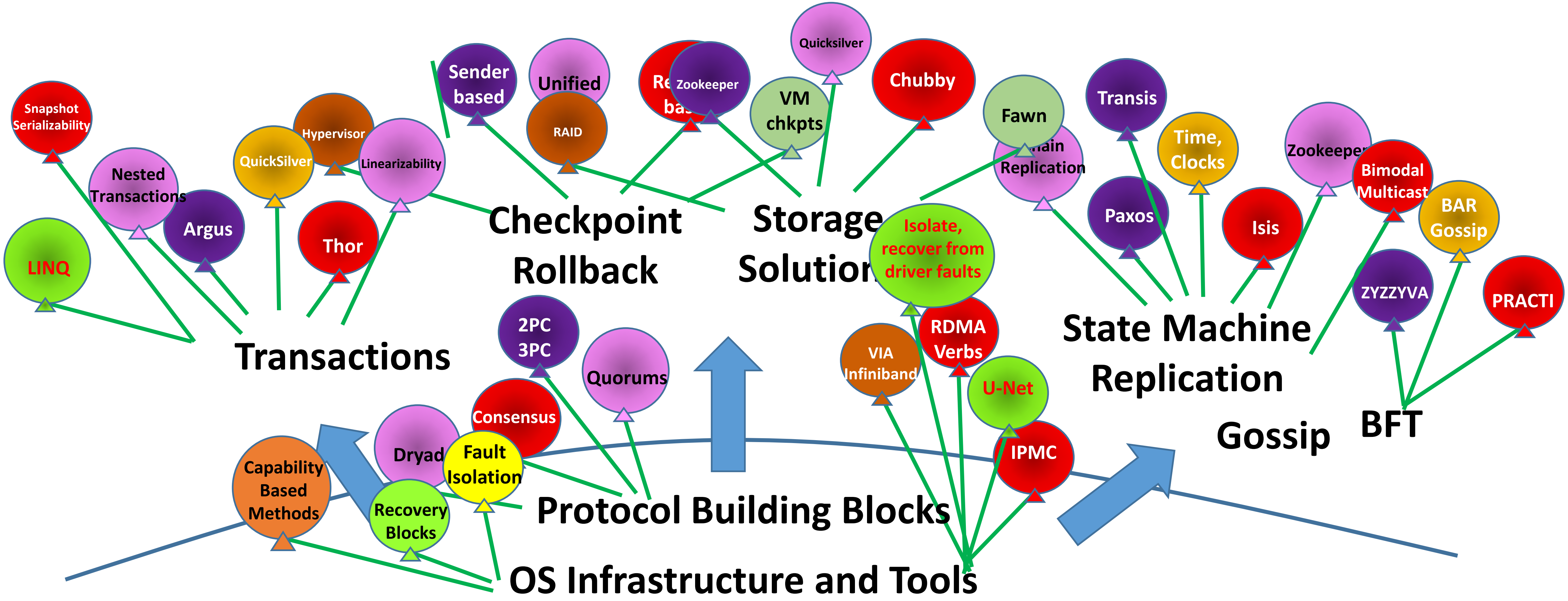
Theory

- Consensus ◊W: consensus
- FLP + oracle




… Skepticism

- CATOCS CAP

- Too much for 25 minutes…
- Focus on state machine replication with crash failures

Fault-Tolerance via Replication: Rich History

- Early debate about the question itself
  - *Some believed that the OS layer is the wrong place to offer strong properties…*
- Today that debate has reemerged:
  - *Some believe that the cloud can't afford strong properties!*

Theory

Basic questions

- What sort of system are we talking about?
- What do we mean by “failure”?
- What does “tolerating” mean?

Thinking of Fault-Tolerance in terms of Safety

- Consistent State: A system-specific invariant: Pred(S)
- S is fault-tolerant if:

S maintains/restores Pred(S) even if something fails

- Normally, we also have *timeliness* requirements.

Principles from the theory side…

- FLP: Protocols strong enough to solve asynchronous consensus cannot guarantee liveness (progress under all conditions).
- If running a highly available database with network partition, conflicting transactions induce inconsistencies (CAP theorem).
- Need 3f+1 replicas to overcome Byzantine faults

Systems

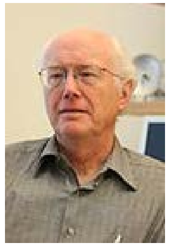
Principles from the systems side…

- Make core elements as simple as possible
  - *Pare down, optimize the critical path*
  - Captures something fundamental about systems.

Butler

- Generalized End-to-End argument:
  - Let the application layer pick its own models.
  - Limit core systems to fast, flexible building blocks.

Jerry



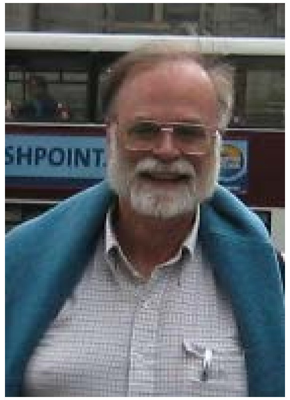
Dave

Dave

B. Lampson. Hints for computer system design. *ACM Operating Systems Rev*. 1983.

J. Saltzer/D. Reed/D. Clark. End-To-End Arguments in System Design. 1984.

Gray: How do systems really fail?



Jim Gray

- Studied Tandem's "non-stop" platforms

  Failures caused by bugs, user mistakes, poor designs.

  Few hardware failures, and nothing malicious.

- Jim's advice? Focus our efforts on the real needs

J. Gray. Why Do Computers Stop and What Can Be Done About It? SOSP, 1985.

Tensions

Why aren't <u>existing</u> OS mechanisms adequate?

Is fault-tolerance / consistency too complex or costly?

Do the needed mechanisms <u>enable</u> or <u>impose</u> models?

Do we need fault-tolerant replication?

- Not just for making systems tolerant of failures
  - Cloud computing: Provision lots of servers
  - Performance-limiting for many machine-learning systems
- So we agree, hopefully: replication is awesome!
- But is there a core OS mechanism here?

It comes down to performance and scalability

- As systems researchers, abstracted properties are…
  - Useful when designing and testing
  - Valuable tools for explaining behavior to users
  - Not obstacles: “Impossible” problems don’t scare us…

- Performance is a more fundamental challenge
  - Can fault-tolerance mechanisms be *fast*?

Existing core OS support: Inadequate

- IP multicast just doesn't work…
  - Amazon AWS disables IPMC and tunnels over TCP
- TCP is the main option, but it has some issues:
  - No support for reliable transfer to multiple receivers
  - Uncoordinated model for breaking connections on failure
  - Byte stream model is mismatched to RDMA

… Higher-level replication primitives?

- Isis: In 1985 used state machine replication on objects
  - Core innovation was its group membership model, which integrates membership dynamics with ordered multicast.
  - Durability tools: help application persist its state

- Paxos*: Implements state machine replication (1990)
  - A durable database of events (not an ordered multicast)
  - Runs in “quasi-static” groups.

*Homework: First version of Paxos protocol?

Delays on the critical path: Isis

Original Isis Tookit:
State machine replication of user-defined objects.
Durability was optional.

Refactor ('87)

- Oracle
  - Uses quorums
  - Outputs "Views"
  - Bisimulates Paxos

- Critical Path
  - Asynchronous, pipelined
  - Flush when view changes
  - Only pay for properties used

Paxos: Many optimizations, often via transformations like the Isis ones

But Paxos theory and formal methodology are very clean, elegant...

Virtual Synchrony: Model + menu of choices

[Note: CATOCS controversy arose here...]

How does one speed such systems up?

- Start with simple, easily analyzed solution... Study the code
  - The critical paths often embody inefficiencies, like requesting total order for actions already in order, or that commute.
  - Often, synchronous events can be asynchronously pipelined

- Restructure critical paths to leverage your insights
  - Hopefully, the correctness argument still holds…

Pattern shared by Isis, Paxos, Zookeeper, Chain Replication, Zyzzyva, many others…

… Real systems informed by sound theory

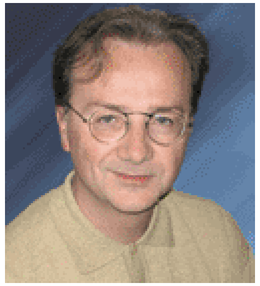
- Isis: Widely adopted during the 1995-2005 period
  - French ATC system, US Navy AEGIS, NYSE...
- Paxos: Very wide uptake 2005-now
  - Locking, file replication, HA databases…
  - Clean methodology and theory appeal to designers
  - Corfu is the purest Paxos solution: robust logging

CATOCS: A case against consistent replication

- Too complex
- Violates End-to-End by imposing model on the user
- No matter what form of update order is supported, user won't like it
- Ordering is just too slow, won't scale

Dave Cheriton

Dale Skeen



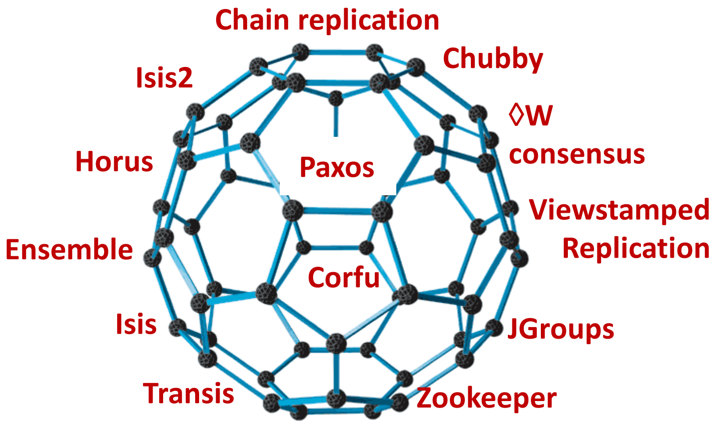
So were CATOCS claims true?

- Early replication solutions really were too slow.
  - Later ones were faster, but more complex.

- But CATOCS analysis of ordering was dubious.

- Yet… what about that missing low-level building block?
  - … a puzzle (we’ll come back to it later)

The “consensus” family…



- Can transform one to another… optimizations driven by desired properties.

- For me, durability remains puzzling
  - Is the goal durability of the application, or of its “state”?

… a few winners:

- State Machine Replication, Paxos, ACID transactions

Conceptual Tools

- Chubby, Zookeeper, Corfu

Real Systems

- Primary + Warm backup… Chain Replication

Servers: 3-5 nodes

A cloud-hosted service could run on 5,000 nodes in each of dozens of data centers

Meanwhile, along came a cloud!

… Cloud rebellion: "Just say no!"

Werner Vogels

- State Machine Replication, Paxos, ACID transactions

Conceptual Tools

- Chubby, Zookeeper, Corfu

Real Systems

- Primary + Warm backup… Chain Replication

- Dynamo: Eventual consistency (BASE), NoSQL KVS

Is consistency just too costly?

Eric Brewer

- CAP: Two of {**<u>C</u>**onsistency, **<u>A</u>**vailability, **<u>P</u>**artition-Tolerance}
  - Widely cited by systems that cache or replicate data
  - Relaxed consistency eliminates blocking on the critical path
  - CAP theorem: proved for a WAN partition of an H/A database
- BASE (eBay, Amazon)
  - Start with a transactional design, but then weaken atomicity
  - Eventually sense inconsistencies and repair them

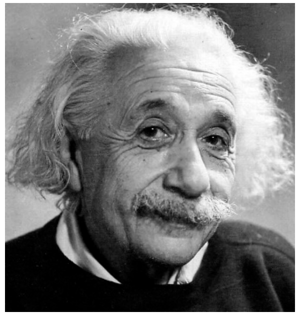
… but does CAP+BASE work?

- CAP folk theorem: “*don’t even try to achieve consistency.”*

… meaning what?

- “Anything goes”? “Bring it on?”

- Einstein: “A thing should be as simple as possible,
  but not simpler.”

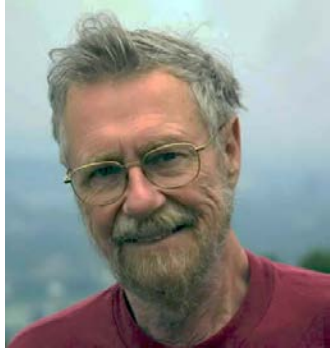


… but does CAP+BASE work?

- ~~CAP folk theorem: "*don't even try to achieve consistency*~~."

- CAP + BASE are successful *for a reason:*
  - In the applications that dominate today's cloud, stale cache reads have negative utility but don't cause safety violations.
  - In effect a *redefinition*, not a rejection, of consistency

A fascinating co-evolution



Edsger Dijkstra

- The cloud fits the need; the applications fit the cloud. At first, fault-tolerance wasn't given much thought.
  - Jim Gray : *"Why do systems fail?"*
  - Today: Why *don't* CAP+BASE systems fail?
- Could we apply Dijkstra's theory of "self-stabilization" to BASE?

Dijkstra: Self-stabilizing systems in spite of distributed control, CACM 17 (11): 1974.

Future Shock: Disruption is coming

- Life and safety-critical cloud computing…
  - Smart power grid, homes, cities
  - Self-driving cars
  - Cloud-hosted banking, medical care

- *Weakened consistency won't suffice for these uses.*

Homework (due date: SOSP 2017)

- Start with a clean slate (but do learn from the past)
- Embrace a modern architecture
  - Cloud-scale systems…
  - Multicore servers with NVRAM storage
  - RDMA (like Tesla's "insane speed" button).

- Propose a new approach to cloud-scale consistency

Future Cloud…

- The O/S has been an obstacle… even embraced inconsistency.
  - The future cloud should embrace *consistency.*
- Key: Elegance, speed, support real needs of real developers
- Need a core OS building block that works, integrated with developer tools and IDEs that are easy to use.