Towards Robust Distributed Systems

Dr. Eric A. Brewer
Professor, UC Berkeley
Co-Founder & Chief Scientist, Inktomi

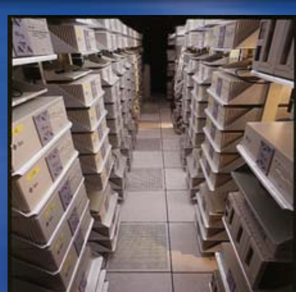
Inktomi at a Glance

Company Overview
- "INKT" on NASDAQ
- Founded 1996 out of UC Berkeley
- ~700 Employees

Applications
- Search Technology
- Network Products
- Online Shopping
- Wireless Systems

Our Perspective

- **Inktomi builds two distributed systems:**
  - Global Search Engines
  - Distributed Web Caches
- **Based on scalable cluster & parallel computing technology**
- **But very little use of classic DS research...**



"Distributed Systems" don't work...

- **There exist working DS:**
  - Simple protocols: DNS, WWW
  - Inktomi search, Content Delivery Networks
  - Napster, Verisign, AOL
- **But these are not classic DS:**
  - Not distributed objects
  - No RPC
  - No modularity
  - Complex ones are single owner (except phones)

Three Basic Issues

- Where is the state?
- Consistency vs. Availability
- Understanding Boundaries

Where's the state?

(not all locations are equal)

Santa Clara Cluster

- Very uniform
- No monitors
- No people
- No cables

- Working power
- Working A/C
- Working BW

Delivering High Availability

We kept up the service through:

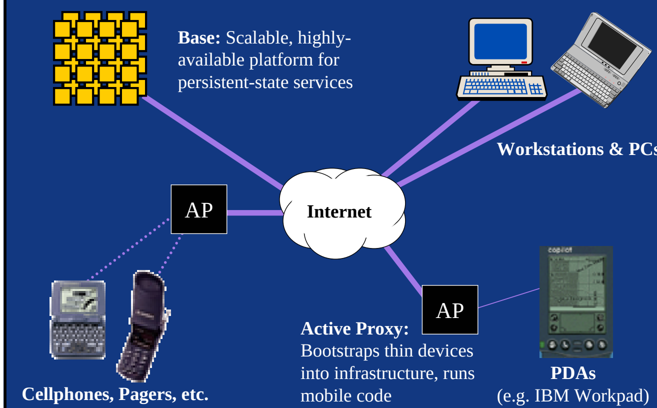
- Crashes & disk failures (weekly)
- Database upgrades (daily)
- Software upgrades (weekly to monthly)
- OS upgrades (twice)
- Power outage (several)
- Network outages (now have 11 connections)
- Physical move of all equipment **(twice)**

Persistent State is HARD

- Classic DS focus on the computation, not the data
  - this is WRONG, computation is the easy part
- Data centers exist for a reason
  - can't have consistency or availability without them
- Other locations are for caching only:
  - proxies, basestations, set-top boxes, desktops
  - phones, PDAs, …
- Distributed systems can't ignore location distinctions

PODC Keynote, July 19, 2000

Berkeley Ninja Architecture



Consistency vs. Availability

(ACID vs. BASE)

PODC Keynote, July 19, 2000

ACID vs. BASE

- DBMS research is about ACID (mostly)
- But we forfeit "C" and "I" for availability, graceful degradation, and performance

This tradeoff is fundamental.

BASE:

- **B**asically **A**vailable
- **S**oft-state
- **E**ventual consistency

PODC Keynote, July 19, 2000

ACID vs. BASE

ACID

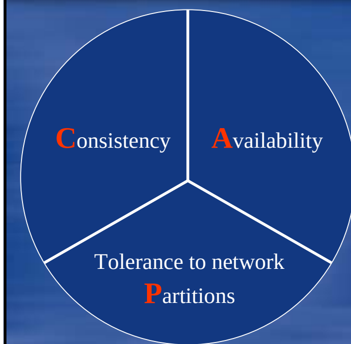
- Strong consistency
- Isolation
- Focus on “commit”
- Nested transactions
- Availability?
- Conservative (pessimistic)
- Difficult evolution (e.g. schema)

BASE

- Weak consistency
  - stale data OK
- Availability first
- Best effort
- Approximate answers OK
- Aggressive (optimistic)
- Simpler!
- Faster
- Easier evolution

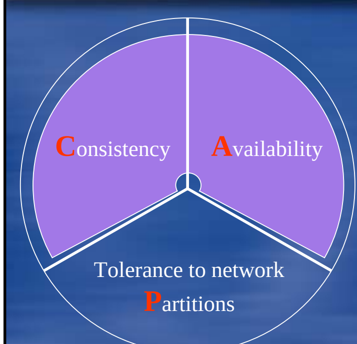
← But I *think* it’s a *spectrum* →

The CAP Theorem



Theorem: You can have **at most two** of these properties for any shared-data system

Forfeit Partitions



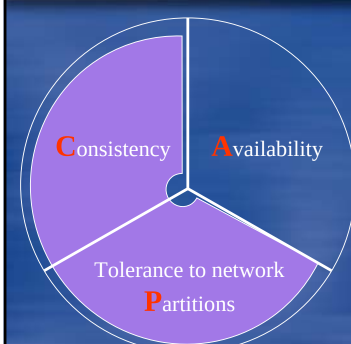
Examples

- Single-site databases
- Cluster databases
- LDAP
- xFS file system

Traits

- 2-phase commit
- cache validation protocols

Forfeit Availability



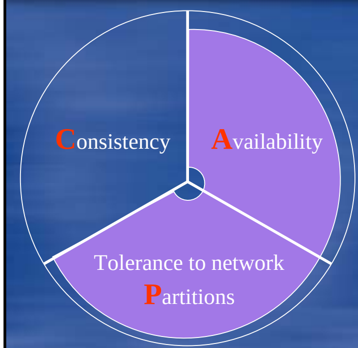
Examples

- Distributed databases
- Distributed locking
- Majority protocols

Traits

- Pessimistic locking
- Make minority partitions unavailable

Forfeit Consistency



Examples

- Coda
- Web caching
- DNS

Traits

- expirations/leases
- conflict resolution
- optimistic

These Tradeoffs are Real

- The *whole* space is useful
- Real internet systems are a careful *mixture* of ACID and BASE subsystems
  - We use ACID for user profiles and logging (for revenue)
- But there is almost no work in this area
- Symptom of a deeper problem: systems and database communities are separate but overlapping (with distinct vocabulary)

CAP Take Homes

- Can have consistency & availability within a cluster (foundation of Ninja), but it is still hard in practice
- OS/Networking good at BASE/Availability, but terrible at consistency
- Databases better at C than Availability
- Wide-area databases can't have both
- Disconnected clients can't have both
- All systems are probabilistic…

Understanding Boundaries

(the RPC hangover)

The Boundary

- **The interface between two modules**
  - client/server, peers, libaries, etc…
- **Basic boundary = the procedure call**

  - thread traverses the boundary
  - two sides are in the same address space

PODC Keynote, July 19, 2000

Different Address Spaces

- **What if the two sides are NOT in the same address space?**
  - IPC or LRPC
- **Can't do pass-by-reference (pointers)**
  - Most IPC screws this up: pass by value-result
  - There are TWO copies of args not one
- **What if they share some memory?**
  - Can pass pointers, but…
  - Need synchronization between client/server
  - Not all pointers can be passed

PODC Keynote, July 19, 2000

Trust the other side?

- **What if we don't trust the other side?**
- **Have to check args, no pointer passing**
- **Kernels get this right:**
  - copy/check args
  - use opaque references (e.g. File Descriptors)
- **Most systems do not:**
  - TCP
  - Napster
  - web browsers

PODC Keynote, July 19, 2000

Partial Failure

- **Can the two sides fail independently?**
  - RPC, IPC, LRPC
- **Can't be transparent (like RPC) !!**
- **New exceptions (other side gone)**
- **Reclaim local resources**
  - e.g. kernels leak sockets over time => reboot
- **Can use leases?**
  - Different new exceptions: lease expired
- **RPC tries to hide these issues (but fails)**

PODC Keynote, July 19, 2000

Multiplexing clients?

- Does the server have to:
  - deal with high concurrency?
  - Say “no” sometimes (graceful degradation)
  - Treat clients equally (fairness)
  - Bill for resources (and have audit trail)
  - Isolate clients performance, data, ….
- These all affect the boundary definition

Boundary evolution?

- Can the two sides be updated independently? (NO)
- The DLL problem...
- Boundaries need versions
- Negotiation protocol for upgrade?
- Promises of backward compatibility?
- Affects naming too (version number)

Example: protocols vs. APIs

- Protocols have been more successful the APIs
- Some reasons:
  - protocols are pass by value
  - protocols designed for partial failure
  - not trying to look like local procedure calls
  - explicit state machine, rather than call/return (this exposes exceptions well)
- Protocols still not good at trust, billing, evolution

Example: XML

- XML doesn’t solve any of these issues
- It is RPC with an extensible type system
- It makes evolution better?
  - two sides need to agree on schema
  - can ignore stuff you don’t understand
- Can mislead us to ignore the real issues

Boundary Summary

- We have been very sloppy about boundaries
- Leads to fragile systems
- Root cause is false transparency: trying to look like local procedure calls
- Relatively little work in evolution, federation, client-based resource allocation, failure recovery

PODC Keynote, July 19, 2000

Conclusions

- Classic Distributed Systems are fragile
- Some of the causes:
  - focus on computation, not data
  - ignoring location distinctions
  - poor definitions of consistency/availability goals
  - poor understanding of boundaries (RPC in particular)
- These are all fixable, but need to be far more common

PODC Keynote, July 19, 2000

The DQ Principle

Data/query * Queries/sec = constant = DQ
- for a given node
- for a given app/OS release

- A fault can reduce the capacity (Q), completeness (D) or both
- Faults reduce this constant linearly (at best)

PODC Keynote, July 19, 2000

Harvest & Yield

- Yield: Fraction of Answered Queries
  - Related to uptime but measured by queries, not by time
  - Drop 1 out of 10 connections => 90% yield
  - At full utilization: yield ~ capacity ~ Q
- Harvest: Fraction of the Complete Result
  - Reflects that some of the data may be missing due to faults
  - Replication: maintain D under faults
- DQ corollary: harvest * yield ~ constant
  - ACID => choose 100% harvest (reduce Q but 100% D)
  - Internet => choose 100% yield (available but reduced D)

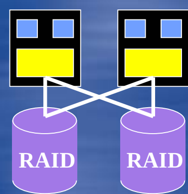
PODC Keynote, July 19, 2000

Harvest Options

1) **Ignore lost nodes**
   – RPC gives up
   – forfeit small part of the database
   – reduce D, keep Q

2) **Pair up nodes**
   – RPC tries alternate
   – survives one fault per pair
   – reduce Q, keep D

3) **n-member replica groups**



Decide *when* you care...

PODC Keynote, July 19, 2000

Replica Groups

With *n* members:

- **Each fault reduces Q by 1/*n***
- **D stable until *nth* fault**
- **Added load is 1/(*n*-1) per fault**
  – *n*=2 => double load or 50% capacity
  – *n*=4 => 133% load or 75% capacity
  – "load redirection problem"
- **Disaster tolerance: better have >3 mirrors**

PODC Keynote, July 19, 2000

Graceful Degradation

- **Goal: smooth decrease in harvest/yield proportional to faults**
  – we know DQ drops linearly
- **Saturation will occur**
  – high peak/average ratios...
  – must reduce harvest or yield (or both)
  – must do admission control!!!
- **One answer: reduce D dynamically**
  – disaster => redirect load, then reduce D to compensate for extra load

PODC Keynote, July 19, 2000

Thinking Probabilistically

- **Maximize symmetry**
  – SPMD + simple replication schemes
- **Make faults independent**
  – requires thought
  – avoid cascading errors/faults
  – understand redirected load
  – KISS
- **Use randomness**
  – makes worst-case and average case the same
  – ex: Inktomi spreads data & queries randomly
  – Node loss implies a random 1% harvest reduction

PODC Keynote, July 19, 2000

Server Pollution

- Can’t fix all memory leaks
- Third-party software leaks memory and sockets
  - so does the OS sometimes
- Some failures tie up local resources

Solution: planned periodic “bounce”

- Not worth the stress to do any better
- Bounce time is less than 10 seconds
- Nice to remove load first…

Evolution

Three Approaches:

- **Flash Upgrade**
  - Fast reboot into new version
  - Focus on MTTR (< 10 sec)
  - Reduces yield (and uptime)
- **Rolling Upgrade**
  - Upgrade nodes one at time in a “wave”
  - Temporary 1/n harvest reduction, 100% yield
  - Requires co-existing versions
- **“Big Flip”**

The Big Flip

- **Steps:**
  1) take down 1/2 the nodes
  2) upgrade that half
  3) flip the “active half” (site upgraded)
  4) upgrade second half
  5) return to 100%
- **50% Harvest, 100% Yield**
  - or inverse?
- **No mixed versions**
  - can replace schema, protocols, ...
- **Twice used to change physical location**

Key New Problems

- **Unknown but large growth**
  - Incremental & Absolute scalability
  - 1000’s of components
- **Must be truly highly available**
  - Hot swap everything (no recovery time allowed)
  - No “night”
  - Graceful degradation under faults & saturation
- **Constant evolution (internet time)**
  - Software will be buggy
  - Hardware will fail
  - These can’t be emergencies...

Conclusions

- **Parallel Programming is very relevant, except…**
  - historically avoids availability
  - no notion of online evolution
  - limited notions of graceful degradation (checkpointing)
  - best for CPU-bound tasks
- **Must think probabilistically about everything**
  - no such thing as a 100% working system
  - no such thing as 100% fault tolerance
  - partial results are often OK (and better than none)
  - Capacity * Completeness == Constant

Conclusions

- **Winning solution is message-passing clusters**
  - fine-grain communication =>
    fine-grain exception handling
  - don't want every load/store to deal with partial failure
- **Key open problems:**
  - libraries & data structures for HA shared state
  - support for replication and partial failure
  - better understanding of probabilistic systems
  - cleaner support for exceptions (graceful degradation)
  - support for split-phase I/O and many concurrent threads
  - support for 10,000 threads/node (to avoid FSMs)

Backup slides

New Hard Problems...

- **Really need to manage disks well**
  - problems are I/O bound, not CPU bound
- **Lots of simultaneous connections**
  - 50Kb/s => at least 2000 connections/node
- **HAS to be highly available**
  - no maintenance window, even for upgrades
- **Continuous evolution**
  - constant site changes, always small bugs...
  - large but unpredictable traffic growth
- **Graceful degradation under saturation**

Parallel Disk I/O

Inktomi

- **Want 50+ outstanding reads/disk**
  - Provides disk-head scheduler with many choices
  - Trades response time for throughput
- **Pushes towards a split-phase approach to disks**
- **General trend: each query is a finite-state machine**
  - split-phase disk/network operations are state transitions
  - multiplex many FSMs over small number of threads
  - FSM handles state rather than thread stack