

Towards Robust Distributed Systems

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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









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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...



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“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)

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Three Basic Issues



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

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Where's the state?

(not all locations are equal)



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Santa Clara Cluster



- Very uniform
- No monitors
- No people
- No cables
- Working power
- Working A/C
- Working BW



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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)

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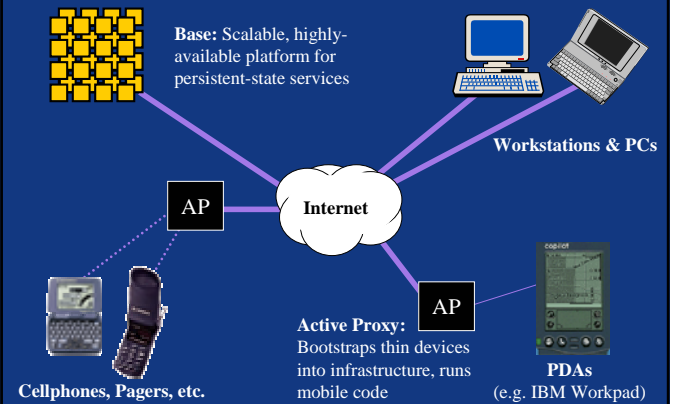
Persistent State is HARD



- ◆ 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

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Berkeley Ninja Architecture



Consistency vs. Availability (ACID vs. BASE)



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ACID vs. BASE



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

This tradeoff is fundamental.

BASE:

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

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ACID vs. BASE

ACID

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

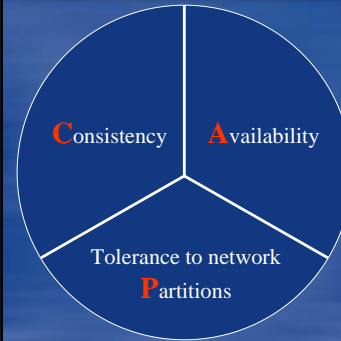
BASE

- ◆ 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 →

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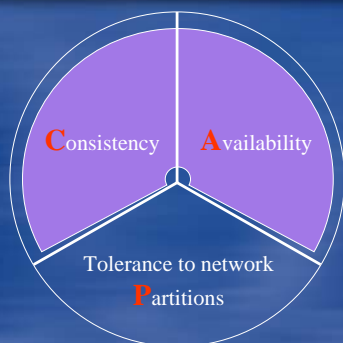
The CAP Theorem



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

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Forfeit Partitions



Examples

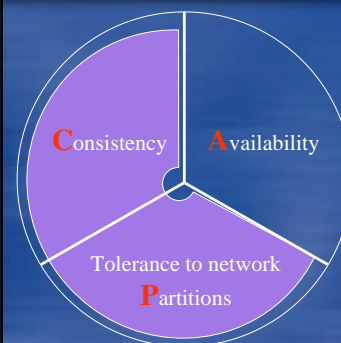
- ◆ Single-site databases
- ◆ Cluster databases
- ◆ LDAP
- ◆ xFS file system

Traits

- ◆ 2-phase commit
- ◆ cache validation protocols

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Forfeit Availability



Examples

- ◆ Distributed databases
- ◆ Distributed locking
- ◆ Majority protocols

Traits

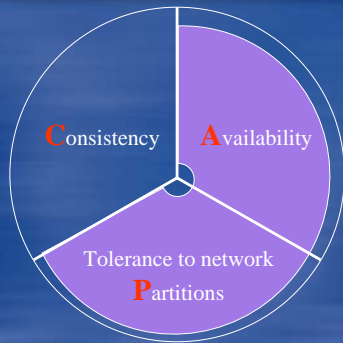
- ◆ Pessimistic locking
- ◆ Make minority partitions unavailable

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Forfeit Consistency



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Examples

- ◆ Coda
- ◆ Web caching
- ◆ DNS

Traits

- ◆ expirations/leases
- ◆ conflict resolution
- ◆ optimistic

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These Tradeoffs are Real



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- ◆ 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)

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CAP Take Homes



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- ◆ 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...

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Understanding Boundaries (the RPC hangover)



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The Boundary



- ◆ The interface between two modules
 - client/server, peers, libraries, etc...
- ◆ Basic boundary = the procedure call



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

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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

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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

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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)

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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

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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)

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Example: protocols vs. APIs



- ◆ Protocols have been more successful than 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

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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

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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

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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

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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)

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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)

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Harvest Options



1) Ignore lost nodes

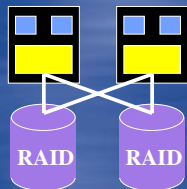
- RPC gives up
- forfeit small part of the database
- reduce D, keep Q

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...



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Replica Groups



With n members:

- ◆ Each fault reduces Q by $1/n$
- ◆ D stable until n th fault
- ◆ Added load is $1/(n-1)$ per fault
 - $n=2 \Rightarrow$ double load or 50% capacity
 - $n=4 \Rightarrow$ 133% load or 75% capacity
 - “load redirection problem”
- ◆ Disaster tolerance: better have >3 mirrors

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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 \Rightarrow redirect load, then reduce D to compensate for extra load

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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

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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...

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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”

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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

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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...

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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

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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)

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Backup slides



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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

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Parallel Disk I/O



- ◆ **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

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