Dependability Lessons from Internet Systems: An Overview

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Consistency/Availability Tradeoff: CAP

CAP principle (this formulation due to Brewer):
- In a networked/distributed storage system, you can have any 2 of consistency, high availability, partition resilience.
  - Internet systems favor A and P over C
  - Databases favor C and A over P
  - Surely other examples
- Generalization: can you trade some of one for more of another? (hint: yes)

Consistency/Availability: Harvest/Yield

- **Yield**: probability of completing a query
- **Harvest**: (application-specific) fidelity of the answer
  - Fraction of data represented?
  - Precision?
  - Semantic proximity?
- Harvest/yield questions:
  - When can we trade harvest for yield to improve availability?
  - How to measure harvest “threshold” below which response is not useful?
  - Application decomposition to improve “degradation tolerance” (and therefore availability)

Concepts Overview

- Trading consistency for availability: Harvest, yield, and the DQ principle; TACT
- Runtime fault containment: virtualization and its uses
- Orthogonal mechanisms: timeouts, end-to-end checks, statistical detection of performance failures
- State management, hard and soft state
- Revealed truths: end-to-end argument (Saltzer), software pitfalls (Leveson), and their application to dependability
- Many, many supplementary readings about these topics
Generalization: TACT (Yu & Vahdat)

- Model: distributed database using anti-entropy to approach consistency
- “Conit” captures app-specific consistency unit (think: ADU of consistency)
  - Airline reservation: all seats on 1 flight
  - Newsgroup: all articles in 1 group
- Bounds on 3 kinds of inconsistency
  - Numerical error (value is inaccurate)
  - Order error (write(s) may be missing, or arrive out-of-order)
  - Staleness (value may be out-of-date)
- “Consistency cost” of operations can be characterized in terms of conits, and bounds on inconsistency enforced

TACT-like example: TranSend

- Early stab at lossy on-the-fly Web image compression, extensively parameterized (per user, device, etc.)
- Harvest: “semantic fidelity” of what you get
  - Worst case: the original image
  - Intermediate case: “close” image that has been previously computed and cached
- Trade harvest for yield/throughput
- TACT-like, though TACT didn’t exist then

Another special case: DQ Principle

- Model: read-mostly database striped across many machines
- Idea: Data/Query x Queries/Sec = Data/Sec
- Goal: design system so that D/Q or Q/S are tunable
  - Then you can decide how partial failure affects users
  - In practice, Internet systems constraint is offered load of Q/S, so failures affect D/Q for each user
  - Can use some replication of most common data to mitigate effects of reducing D/Q

Fault Containment

- Uses of software based fault isolation and VM technology
  - Protecting the “real” hardware (now will also be used for ASP’s)
  - Hypervisor-based F/T
- Orthogonal mechanisms for fault containment
- …and enforcing your assumptions
**Orthogonal Mechanisms**
- Bunker mentality: *Design with unexpected failure in mind*
  - Minimize assumptions made of rest of system
  - Keep your own house in order, but be prepared to be shot if outside monitoring sees something wrong
  - Design systems to allow independent failure
- In real life (hardware)
  - Mechanical interlock systems
  - Microprocessor hardware timeouts
- In real life (software)
  - Security and safety
  - Deadlock detection and shutdown

**Examples of Orthogonality**
- examples of orthogonality
  - Software fault isolation/virtualization
  - IP firewalls
  - Deadlock *detection & recovery* in databases - Note: not deadlock *avoidance!*
  - Hardware orthogonal security - Fuses and hardware interlocks; recall the Therac-25
  - Theme: you don’t know *why* something went wrong, only *that* something went wrong; and you can usually do fault containment
- What’s appealing about orthogonal mechanisms?
  - Small state space - Behavior simple to predict (usually)
  - Allows us to enforce at least some simple invariants - and invariants are your friends
- Important concept: critical events occur at points of possible nondeterminism in instruction stream

**Example: What Really Happened on Mars**
- Dramatis personae
  - Low-priority thread A: infrequent, short-running meteorological data collection, using bus mutex
  - High-priority thread B: bus manager, using bus mutex
  - Medium-priority thread C: long-running communications task (that *doesn’t* need the mutex)
- Priority inversion scenario
  - A is scheduled, and grabs bus mutex
  - B is scheduled, and blocks waiting for A to release mutex
  - C is scheduled while B is waiting for mutex
  - C has higher priority than A, so it prevents A from running (and therefore B as well)
  - Watchdog timer notices B hasn’t run, concludes something is wrong, reboots

**Extension: Hypervisor-Based Fault Tolerance**
- Basic ideas (Bressoud et al, SOSP-15)
  - Use VM’s to implement a *hypervisor* that coordinates between a primary process and its backup
  - Instruction *epochs are separated by periodic S/W interrupts*
  - Hypervisor arranges to deliver interrupts only on epoch boundaries
  - Primary and backup can also communicate during “environmental” instructions (so they see same result of I/O, eg)
  - Backup is one epoch “behind” primary, can take over right away
  - Recently applied to JVM by Lorenzo Alvisi et al. at UT Austin
  - Again, successful virtualization requires some lower-level guarantees
- Important concept: critical events occur at points of possible nondeterminism in instruction stream
On Enforcing Your Assumptions

- Orthogonal mechanisms can be used to enforce assumptions about system behavior
  - Infer failure of a peer -> shoot it
  - Assume peers will respond within a specific time -> use timeout to force
- Why is this important?
  - Response to a detected condition may be inappropriate if assumptions are incorrect

Enforcing Invariants Made Easier

- Some other possible replies to fopen():
  - "Maybe later" (NFS soft mount failed this time)
  - "How about a stale copy" (AFS server down, cached copy available, freshness questionable)
  - "Took too long, you consumed too many resources, try again later" (like "HTTP server too busy")
- Essence of the "MIT approach" vs "New Jersey approach"
  - Weaken the guarantee/illusion offered by subsystem
  - Force higher-level app to deal with being told "no"
  - Perhaps wrappers or other mechanisms will be developed to simplify this
  - Makes system more robust: simpler --> easier to understand, plus instills "bunker mentality" in (good) programmers

Soft State

- Soft state and announce/listen
- Soft state and its relation to robustness
- An example of using soft state for managing partial failures

Loose coupling with soft state

- Announce/listen + soft state, vs. hard state
  - "sender" continually sends state messages to "receiver", who may or may not reply/ack
  - If receiver "forgets" state, just wait for next message
  - Example: setting a variable on the server
- Assumptions & challenges
  - Assumption: messages may get lost, receiver may be down, etc.
  - Messages must be idempotent (this is a big one)
  - May not work for real-time-constrained activities
  - Or may require hysteresis to avoid oscillation
Uses of Soft State

- Wide-area Internet protocols, esp. multicast routing
- Scalable Reliable Multicast (SRM)
  - Members of a group session each have soft copies of group state
  - State “repairs” are multicast
  - New members can ask for “fast replay” to catch up
- Related concept: expiration-based schemes
  - Web caching: expiration bounds staleness
  - Leases: expiration bounds unavailability of a locked resource due to node failure

Soft State Pros and Cons

+ No special recovery code
  - Recovery == restart
  - “Recovery” paths exercised during normal operation
+ Leaving the group (or dying) doesn’t require special code
  - Timeouts/expirations mean no garbage collection
  - “Passive” entities will not consume system resources
- Staleness or other imprecision in answer
- Possible lack of atomicity/ordering of state updates

Next: Exploiting soft state/approximate values for failure masking...

Software Pitfalls (Leveson, Ch. 2)

- Unlike hardware, software is purely abstract design
  - Unlike hardware, software doesn’t “fail”
  - Design unconstrained by physical laws
  - Cost of modifying design hidden by lack of physical constraints
  - Real state space includes what the hardware and other software are doing, and includes states that don’t correspond to states in the abstract model
- Software as a discrete (vs. analog) state system
  - Effect of small perturbation on an analog system vs. on a software discrete system
  - Software can “fail” in a way that is completely unrelated to how the environment/inputs were perturbed

Software Pitfalls, cont’d.

- Exploding some common myths
  - “Reuse of software increases safety” - or, it perpetuates the same (hidden) bugs (e.g. Therac-25)
  - “Formal verification can remove all software-related errors” - unless software/system fails in a way that is outside its design point (e.g. overload/thrashing)
  - “GP computers + software are more cost effective [compared to a dedicated purpose-designed system]” - Space Shuttle software costs ~$100M/year to maintain
** Revealed Truth: End-to-End Argument **

- Don’t put functionality in a lower layer if you’ll just have to repeat it in a higher layer anyway.
  - If you do put it in a lower layer, make sure it's only a performance optimization.

- Jim Gray: “you can’t trust anything”
  - Silent HW failures/incorrectness not that uncommon
  - Examples: ECC memory, disk controllers, OS VM system, etc.
  - Still need end-to-end app-level checks (e.g. Exchange Server)
  - ...Is this ominous news for the VM approach?

- To what extent do various fault-masking mechanisms violate (or reinforce) the end-to-end argument?
  - e.g. “transparent” checkpointing and restarting

** E2E and Dependability: Some Thoughts **

- Use both end-to-end and component-level checks
  - e.g. cross-check answer to a simple query

- Use cross-checks to validate/enforce assumptions about e2e or component-level checks
  - observation: TImeout occurred communicating with component X
  - -> hypothesis: component X is wedged and must be restarted
  - cross-check: look for other signs consistent with X being wedged (ps, rusage, etc)
  - enforcement: shoot X, then verify it’s gone from process table

- Challenge: requires knowledge of end-to-end semantics
  - Most “classical F/T” approaches don’t take this tack.

** Other readings (will be on Web) **

- Virtualization and sandboxing: other readings
  - Hypervisor-Based Fault Tolerance (Bressoud et al., SOSP-15)
  - Disco: Running Commodity OS’s on Scalable Multiprocessors (Bugnion et al., ACM TOCS 15(4) and SOSP-16)
  - Recursive Virtual Machines in Fluke (Ford et al., OSDI 96)
  - Efficient Software-Based Fault Isolation (Lucco & Wahbe, 1993)
  - JANUS: an environment for running untrusted helper apps (Goldberg et al., USENIX 1996 Security Conference)

- Harvest, yield, consistency, availability
  - Harvest, Yield, and Scalable Tolerant Systems (Fox & Brewer, HotOS-VII)
  - TACT (Yu & Vahdat, SOSP-18 and others)

** Other readings **

- Reliability in cluster based servers
  - Lessons From Giant-Scale Services (Brewer, IEEE Internet Computing; draft on Web)
  - Cluster-based Scalable Network Services (Fox, Brewer et al, SOSP-16)
Putting It All Together

Berkeley SNS/TACC: an application-level example of several of these techniques in action:

- Supervisor-based redundancy for both availability and performance
- Loose coupling and announce/listen to circumvent SPF for supervisor
- Orthogonal mechanisms to account for legacy code vagaries
- Normal-operation and failure-recovery code paths are the same

TACC/SNS

- Specialized cluster runtime to host Web-like workloads
  - TACC: transformation, aggregation, caching and customization--elements of an Internet service
  - Build apps from composable modules, Unix-pipeline-style
- Goal: complete separation of *ility concerns from application logic
  - Legacy code encapsulation, multiple language support
  - Insulate programmers from nasty engineering

“Starfish” Availability: LB Death

- FE detects via broken pipe/timeout, restarts LB

New LB announces itself (multicast), contacted by workers, gradually rebuilds load tables

If partition heals, extra LB’s commit suicide
FE’s operate using cached LB info during failure
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SNS Availability Mechanisms

- Soft state everywhere
  - Multicast based announce/listen to refresh the state
  - Idea stolen from multicast routing in the Internet!

- Process peers watch each other
  - Because of no hard state, "recovery" == "restart"
  - Because of multicast level of indirection, don't need a location directory for resources
  - Timeouts and restarts everywhere

- Load balancing, hot updates, migration are "easy"
  - Shoot down a worker, and it will recover
  - Upgrade == install new software, shoot down old
  - Mostly graceful degradation