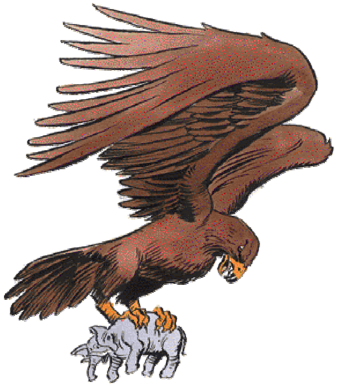

Embracing Failure: Availability via Recovery-Oriented Computing (ROC)

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Outline

- Motivation for ROC
- Principles of ROC design
- Initial ROC implementation target
- Evaluating ROC: availability benchmarks
- Summary

Motivation for a new philosophy

- **Internet service availability is a big concern**
  - outages are frequent
    - » 65% of IT managers report that their websites were unavailable to customers over a 6-month period
      - 25%: 3 or more outages
  - outages costs are high
    - » NYC stockbroker: $6,500,000/hr
    - » EBay: $ 225,000/hr
    - » Amazon.com: $ 180,000/hr
    - » social effects: negative press, loss of customers who "click over" to competitor
  - but, despite marketing, progress seems slow. . .
- **Why?**

Source: InternetWeek 4/3/2000

Traditional HA vs. Internet reality

- **Traditional HA env't**
  - stable
    - » functionality
    - » software
    - » workload and scale
  - high-quality infrastructure designed for high availability
    - » robust hardware: fail-fast, duplication, error checking
    - » custom, well-tested, single-app software
    - » single-vendor systems
  - certified maintenance
    - » phone-home reporting
    - » trained vendor technicians

- **Internet service env't**
  - dynamic and evolving
    - » weekly functionality changes
    - » rapid software development
    - » unpredictable workload and fast growth
  - commodity infrastructure coerced into high availability
    - » cheap hardware lacking extensive error-checking
    - » poorly-tested software cobbled together from off-the-shelf and custom code
    - » multi-vendor systems
  - ad-hoc maintenance
    - » by local or co-lo. techs

Facts of life

- **Realities of Internet service environment:**
  - hardware and software failures are inevitable
    - » hardware reliability still imperfect
    - » software reliability thwarted by rapid evolution
    - » Internet system scale exposes second-order failure modes
  - unanticipated failures are inevitable
    - » commodity components do not fail cleanly
    - » black-box system design thwarts models
    - » seemingly-obscure failure modes are normal
  - human operators are imperfect
    - » human error accounts for ~50% of all system failures
    - » human error probability is 10%-100% under stress
- **Traditional HA doesn't address these realities!**

Sources: Gray86, Hamilton99, Kuhn97, Menn99, Murphy95, Perrow99, Pope86

Recovery-Oriented Computing (ROC)

"If a problem has no solution, it may not be a problem, but a fact, not to be solved, but to be coped with over time"

— Shimon Peres

- **Failures are a fact, and recovery/repair is how we cope with them**
- **Hypothesis: improving recovery will improve availability**
  - availability = $\dfrac{\text{MTTF}}{(\text{MTTF} + \text{MTTR})}$

ROC systems

- **A recovery-oriented system**
  - uses recovery and repair to tolerate failures of hardware, software, and humans
  - provides **rapid** recovery
    - » efficiently detects and diagnoses failures
  - provides **effective** recovery
    - » proactively verifies efficacy and speed of repair procedures
  - provides **robust** recovery
    - » tolerates errors during repair and maintenance

Context: ROC design

- **Vs. traditional fault-tolerance approaches**
  - different philosophy
    - » traditional: focus on HW; assume good software, operators
      - build good SW by controlling development, modeling
    - » repair-centric: assume that any HW, SW, operator can fail
      - assume environment too dynamic to control or model
  - some shared techniques
    - » testing, checkpoints, fault-injection, diagnosis
    - » but applied differently: online, system-wide, without models
- **Other existing recovery-oriented approaches**
  - restartable systems
    - » Recursive Restartability, soft-state worker frameworks
  - application-level checkpoint recovery

Sources: Candea01, Fox97, Lowell98, Lowell00, Ninja01

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Approaching ROC design

- **Tentative principles of ROC design**
  1) isolation and redundancy: fault containment
     » prevent failure propagation and enable proactive testing
  2) online verification: fully-integrated online testing
     » detect failures quickly to expedite repair
     » provide trust in repair mechanisms and human operators
  3) undo: the ultimate repair mechanism?
     » tolerate human error and repair unanticipated failures
  4) diagnosis: dependency and fault tracking
     » assist operator in pinpointing failures to expedite repair

(1) Isolation and redundancy

- **System is redundant**
  - sufficient HW redundancy/data replication => part of system down but satisfactory service still available
  - enough to survive 2nd failure or more during recovery
- **System is partitionable**
  - to isolate faults
  - to enable online repair/recovery
  - to enable online HW growth/SW upgrade
  - to enable operator training/expand experience on portions of real system

Approaches to isolation

- **Shared-nothing cluster design**
  - no shared storage between nodes
  - total physical partitioning of nodes possible via network disconnection
  - system versions can coexist: easy expansion, upgrades
- **HW support to limit scope of faults**
  - separate address spaces whenever possible
  - queue-based communication between processes
  - read/write protection of memory pages
  - physical (electrical) network partitioning
- **Geographic replication for last-resort isolation**

(2) Online verification

- **System enables input insertion, output check of all modules (including fault insertion)**
  - to check module operation to find failures faster
    - » correctness and performance
  - to test correctness of recovery mechanisms
    - » insert faults and known-incorrect inputs
    - » also enables availability benchmarks
  - to discover if warning systems are broken
  - to expose and remove latent errors from each system
  - to train/expand experience of operator

More online verification

- **Modules (HW and SW) perform redundant calculation to help discover errors**
  - program checking analogy: if computation is $O(n^x)$, $(x > 1)$ and if check is $O(n)$, little cost to check
  - extension of assertion checking, checksums, ECC-like approaches to all software and hardware
- **System proactively discovers its configuration**
  - including interconnect and power supply topology, etc.
  - verifies available redundancy, thwarts human mistakes
- **System continuously verifies global invariants**
  - use "conservation law analysis" as in industrial plants to prevent loss, misdirection of data

Online verification of operators

- **To expand operator experience beyond normal events, regular fault insertion on live system**
  - provide training for new operators
  - familiarize operators with failure modes, repair tasks
    - » reduce human error potential
  - test operator performance during repair
    - » results reflected back to management to discover in advance if there is a people problem
  - use partitioning and isolation mechanisms to protect production data during testing/training

(3) Undo

- **ROC system should offer Undo**
  - to recover from operator errors
    - » undo is ubiquitous in productivity apps
    - » should have "undo for maintenance"
  - to recover from inevitable SW errors
    - » restore entire system state to pre-error version
  - to recover from operator training via fault-insertion
  - to replace traditional backup and restore?
- **Implement using checkpoint and logging technology**
  - restrict semantics and granularity for simpler implementation, lower overhead

(4) Diagnosis

- **System assists human in diagnosing problems**
  - root-cause analysis to suggest possible failure points
    - » track resource dependencies of all requests
    - » correlate symptomatic requests with component dependency model to isolate culprit components
  - "health" reporting to detect failed/failing components
    - » failure information, self-test results propagated upwards
  - unified status console to highlight improper behavior, predict failure, and suggest corrective action
- **Log faults, errors, failures and recovery**
  - to create a library of failures
    - » for future diagnoses, training, fault-injection, and research

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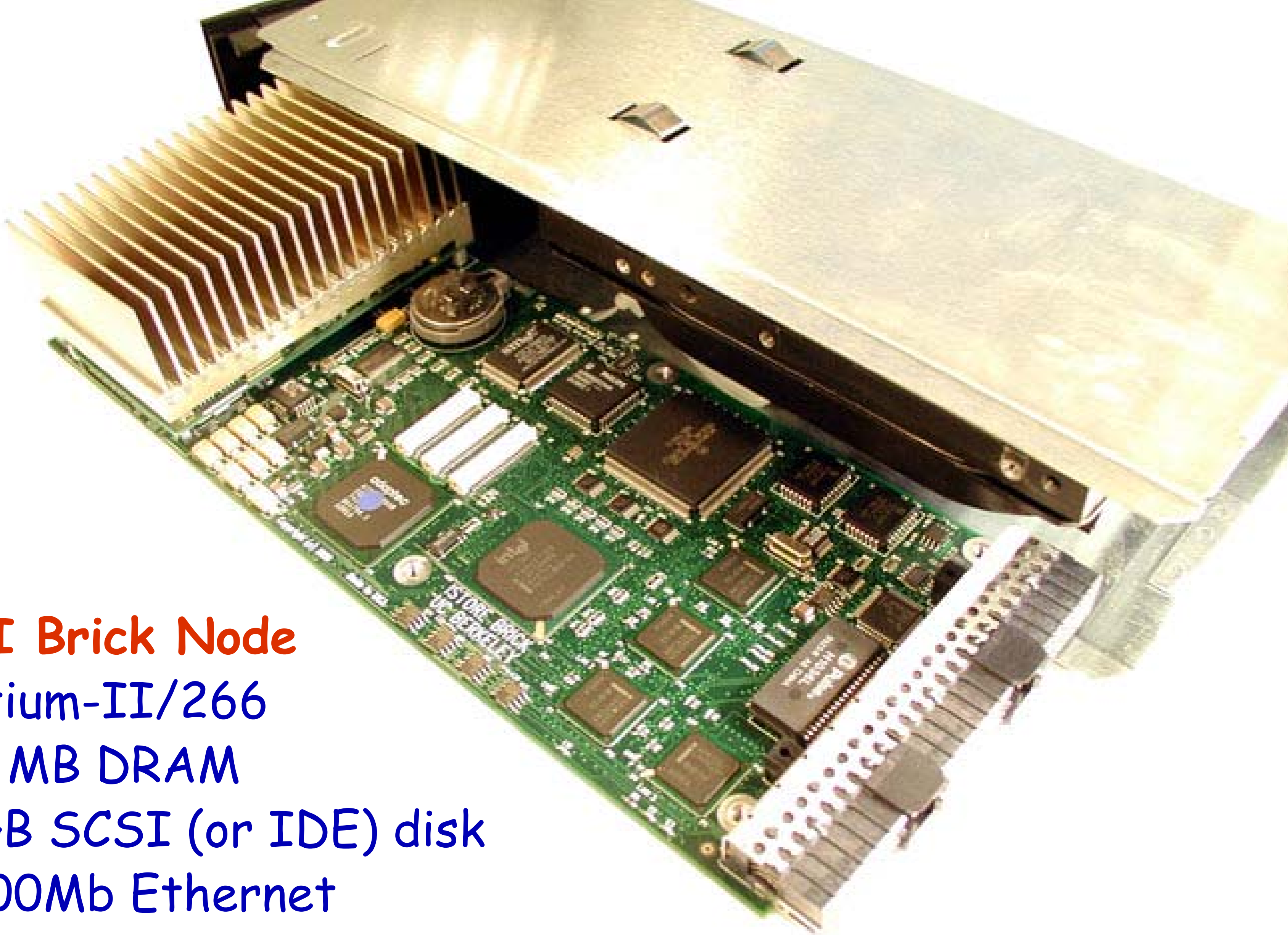
First ROC implementation target

- **Hardware: ROC-I cluster**
  - 64-node PC cluster with integrated storage
  - special features for ROC-based high availability
    - » support for hardware fault-injection
    - » support for partitioning at the electrical level
    - » support for topology discovery of network and power
    - » highly instrumented hardware enables online HW verification
    - » integrated diagnostic system: per-node diagnostic processors and independent diagnostic network
  - modular, cable-less "brick" design enables easy maintenance, reduces human-induced HW failures



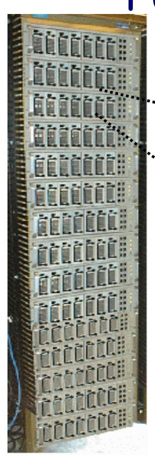
ROC-I Brick Node

- Pentium-II/266
- 256 MB DRAM
- 18 GB SCSI (or IDE) disk
- 4x100Mb Ethernet
- m68k diagnostic processor & CAN diagnostic network
- Packaged in standard half-height RAID array canister

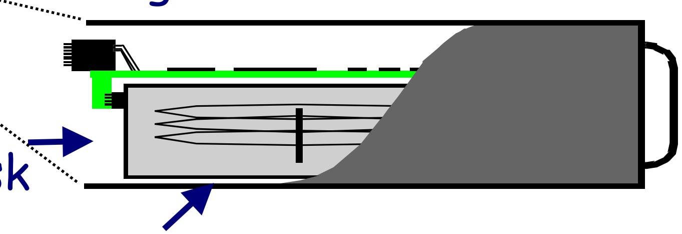
ROC-I system

- **64-node cluster of nodes, 1.1TB storage**
  - cluster nodes are plug-and-play, intelligent, network-attached storage "bricks"
    - » a single field-replaceable unit to simplify maintenance
  - more CPU per disk than NAS or cluster architectures

ROC-I Chassis
64 nodes, 8 per tray
2 levels of switches
•20 100 Mb/s
•2 1 Gb/s
Environment Monitoring:
UPS, redundant PS,
fans, heat and vibration
sensors...



Storage-Oriented Node "Brick"
Portable PC CPU: Pentium II/266 + DRAM
Redundant NICs (4 100 Mb/s links)
Diagnostic Processor

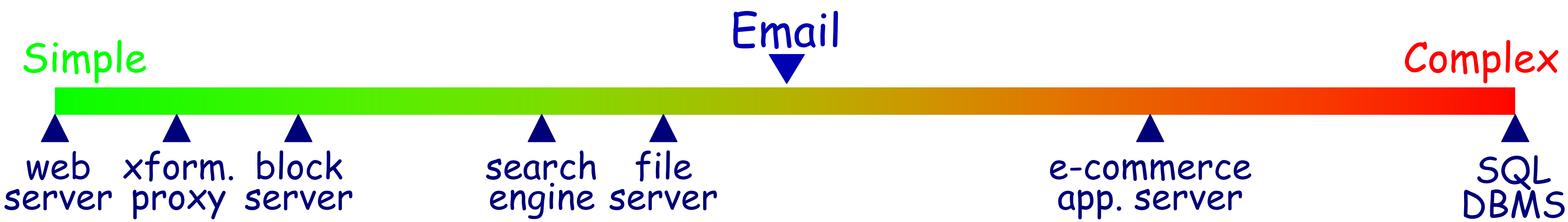


Disk

Half-height canister

First ROC implementation target

- **Software application: Internet email service**
  - simple, but enough complexity to be interesting
    - » hard state, rich data, relaxed consistency requirements



  - techniques for email should generalize
    - » but stronger consistency may add complexity
  - proposed base email implementation: NinjaMail
    - » research implementation from UCB Ninja group
    - » provides needed infrastructure for investigating ROC

Outline

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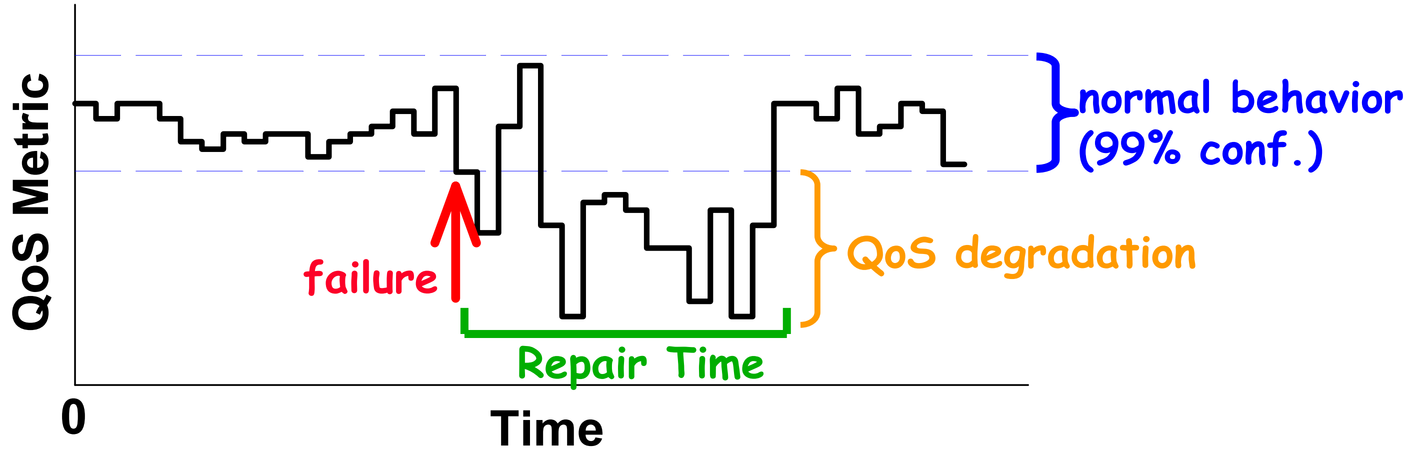
Evaluating ROC systems

- **Traditional benchmarks focus on performance**
  - ignore availability
  - assume perfect hardware, software, human operators

- **Evaluating ROC requires evaluating availability gains from repair-oriented design techniques**
  - requires *availability benchmarking*
    - » a technique we developed in earlier work

Availability benchmarking 101

- **Availability benchmarks quantify system behavior under failures and maintenance**



- **They require**
  - a realistic workload for the system
  - quality of service metrics and tools to measure them
  - fault-injection to simulate failures
  - human operators to perform repairs

Example: email application

- **Workload**
  - SPECmail2001 industry-standard email benchmark
- **Quality of service metrics**
  - performance (SPECmail messages per minute)
  - error rate (lost or corrupted messages and mailboxes)
  - consistency (fraction of inconsistent mailboxes)
  - human maintenance time and error rate

Fault injection

- **Fault workload**
  - must accurately reflect failure modes of real-world Internet service environments
    - » plus random tests to increase coverage, simulate Heisenbugs
  - but, no existing public failure dataset
    - » we have to collect this data
    - » a challenge due to proprietary nature of data
    - » interest expressed by Microsoft, IBM, and Hotmail
  - major contribution will be to collect, anonymize, and publish a modern set of failure data
- **Fault injection harness**
  - build into system: needed anyway for online verification

Evaluating ROC: human aspects

- **Must include humans in availability benchmarks**
  - to verify effectiveness of undo, training, diagnostics
  - humans act as system administrators
- **Subjects should be admin-savvy**
  - system administrators
  - CS graduate students
- **Challenge will be compressing timescale**
  - i.e., for evaluating training
- **We have some experience with these trials**
  - earlier work in maintainability benchmarks used 5-person pilot study

Summary

- **ROC: Recovery-Oriented Computing**
  - a new approach to increasing availability by focusing on recovery and repair
  - based on realities of today's Internet service env't
  - tackles the universally-ignored problem of human error
- ***A departure from traditional HA philosophy***
  - embracing failure, not attempting perfection
  - model of proactive testing/verification, on live systems
- **ROC offers the potential for unprecedented advances in availability**

Acknowledgements

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- **Industry supporters**
  - Bill Tetzlaff, Brendan Murphy, Gautam Kar
- **Questions or comments?**
  - email: abrown@cs.berkeley.edu
  - www: http://istore.cs.berkeley.edu/

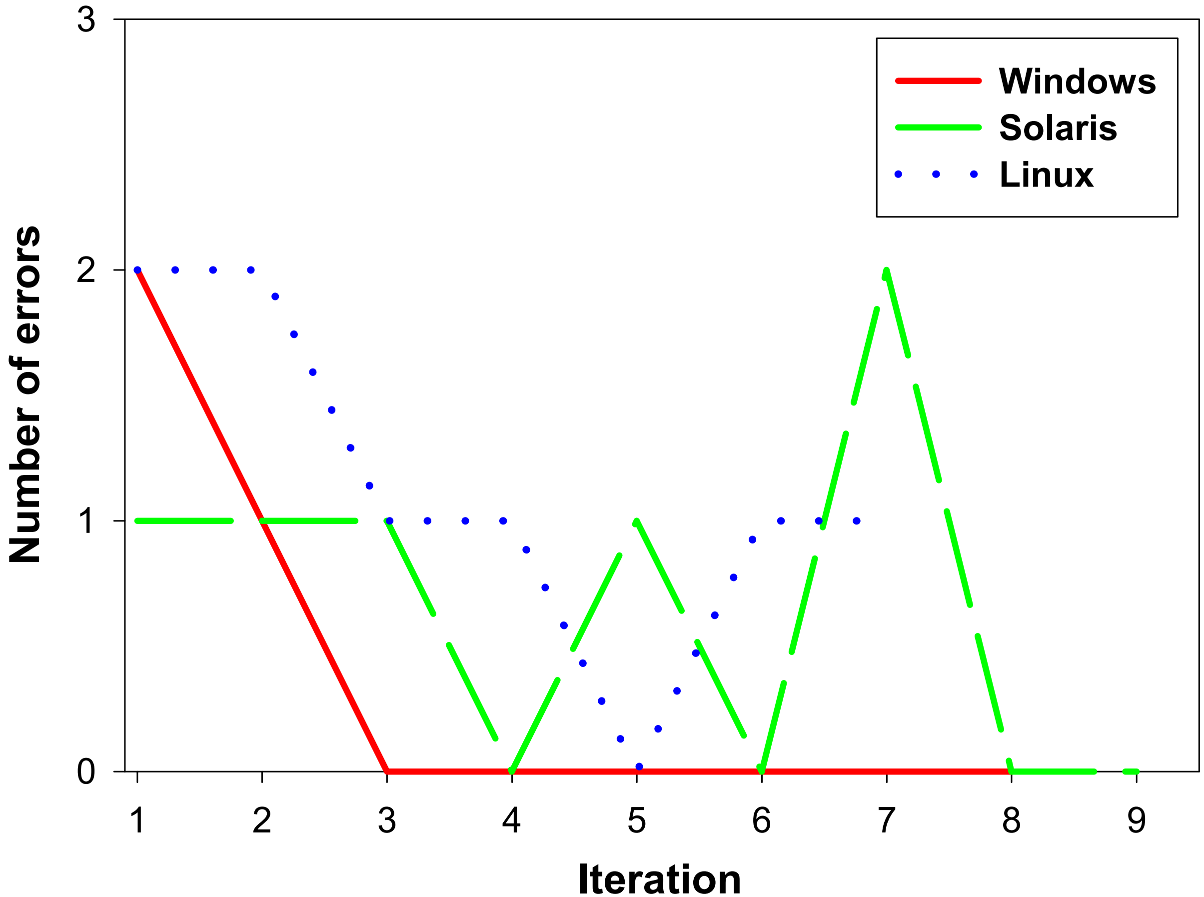
End

Contributions

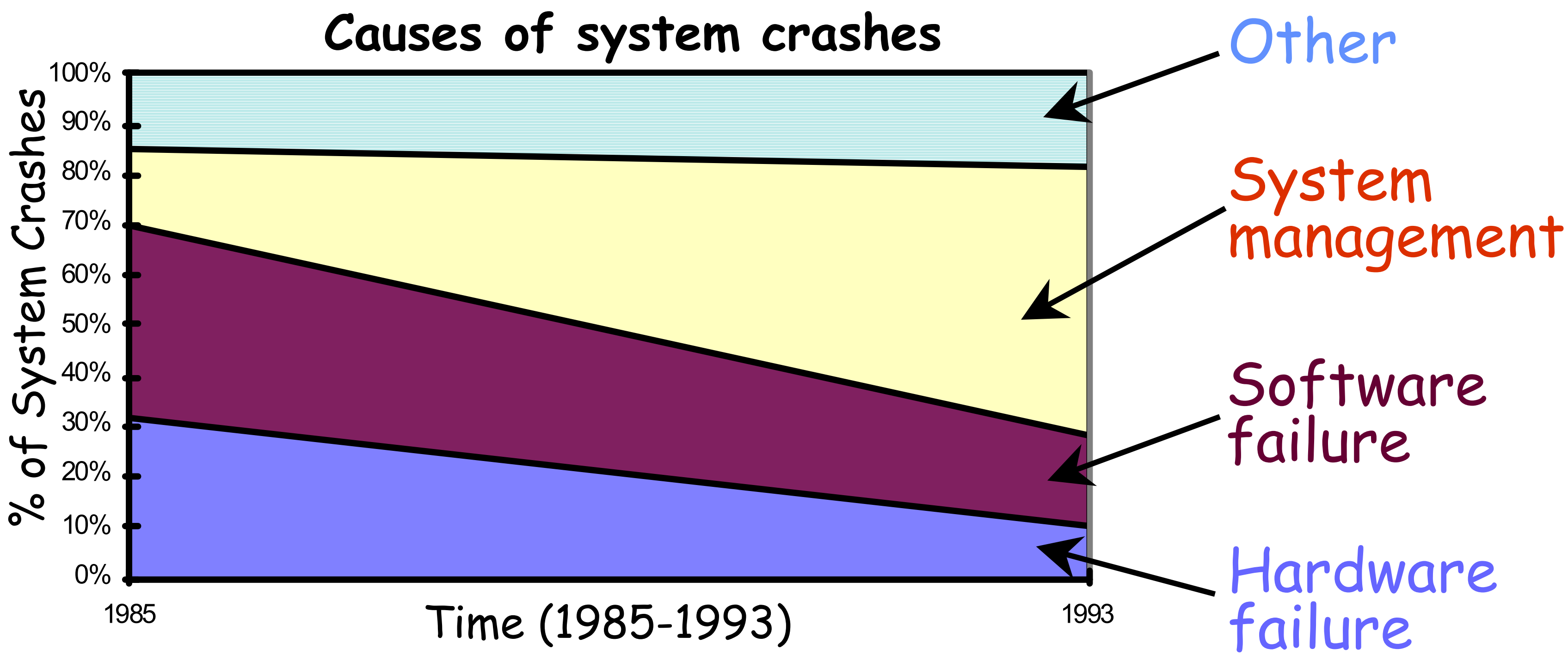
- **New philosophy for high-availability design**
- **Definition of repair-centric design techniques**
  - addressing hardware, software, and human failures
- **Prototype repair-centric system implementation**
- **Quantitative, human-aware availability evaluation methodology**
  - including collection and characterization of data on real-world system failure modes and maintenance tasks

Human error rate experiments

- **Human error rates during simple RAID repair**
  - 5 trained subjects repeatedly repairing disk failures
  - aggregate error rate across subjects plotted over time



What causes un-availability?



- **Many different factors are involved**
  - human behavior during maintenance dominates

Source: Murphy95

How does ROC differ from Fault Tolerant Computing?

- **Systems like Tandem, IBM mainframes concentrate on Hardware Failures**
  - Mirrored disks, Redundant cross-checked CPUs, …
  - Designed to handle 1 failure until repaired
- **Also some work on Software failures: Tandem's process pairs, transactions, …**
  - Rather than embracing failure, goal is SW perfection
- **No attention to human failures**
- **FTC works on improving reliability vs. recovery/repair**
- **Generally ROC is synergistic with FTC**

Traditional HA vs. repair-centric

- **Traditional HA system**
  - hardware-centric focus
  - assumes robust software
    - » by controlling entire stack
  - assumes robust operator
    - » by controlling maintenance
  - may not tolerate errors during repair/maintenance
- **Repair-centric system**
  - tolerates hardware, software, human errors
  - assumes black-box software stack
  - tolerates operator error
  - tolerates errors during maintenance/repair

Assumptions

- **Cluster-like environment**
  - replicated data and services
  - partitionable hardware
- **Single-application system**
- **Modular HW/SW design**
- **Availability trumps performance**
  - willing to sacrifice performance to increase availability
- **Extra resources are available**
  - willing to overprovision resources to improve availability
    - » especially inexpensive disks and disk bandwidth

Undo

- **Undo definition**
  - undo restores modified system state to a previous snapshot while preserving externally-initiated updates
    - » i.e., for email, it restores state while preserving mail delivery and user mailbox modifications
- **Undo is the most fundamental repair-centric design mechanism**
  - provides a way to tolerate human errors
    - » undo is ubiquitous in productivity apps
    - » should have "undo for maintenance"
  - allows recovery from inevitable HW/SW errors
    - » restore entire system state to pre-error version
  - subsumes traditional backup and restore

Undo examples

- **Tolerating human maintenance errors**
  - operator disconnects wrong component during repair
    - » undo: replace component, system continues normally
  - operator installs software upgrade that corrupts data or performs poorly (E*Trade, EBay)
    - » undo: roll-back upgrade, restore uncorrupted data, replay interim requests
  - operator overwrites data store or critical config file
    - » undo: restore data store, config state; replay lost requests
- **Tolerating failures**
  - hardware or software failure corrupts data
    - » undo: restore snapshot and replay interim requests
  - system destabilizes when new hardware is added
    - » undo: revert system configuration state to disable hardware

Undo context

- **Similar to existing checkpoint techniques...**
  - file system snapshots (e.g., NetApp)
  - DBMS log-based recovery
  - application checkpointing for failure recovery
- **...but with some new twists**
  - use for tolerating human mistakes
  - use at system level as well as application level
    - » mandatory for tolerating errors during repair/maintenance
  - preservation of externally-initiated updates
    - » logging/replay at external interfaces and full state restoration avoid inherent save-work/lose-work conflict

Sources: Hitz95, Lowell98, Lowell00, Mohan92

Undo implementation

- **As a repair mechanism, undo must be simple**
  – no complex fine-grained distributed checkpoints, etc.
- **Two types of simple undo**
  1) allow replacement of incorrectly-removed components
     » enforce queuing in front of all removable resources
     » spill queues to disk to allow reasonable replacement window
     » Ninja's queue-based communication model should match well
  2) coarse-grained maintenance-undo of system state
     » provide cluster-wide hard state rollback mechanism with preservation of external updates (like mail delivery)
     » leverage properties of email service to simplify implementation

Undo implementation (2)

- **Coarse-grained maintenance undo**
  - use standard snapshot and logging techniques
  - restrict semantics to simplify implementation
    - » coarse-grained in space: undo affects entire cluster partition
    - » coarse-grained in time: undo rolls back to a previous snapshot
    - » undo restores only system hard-state
      - software, config. files, mail store contents
      - updates preserved by logging and replaying at external interfaces
      - enabled by Ninja design of stateless workers
  - these semantics are sufficient
    - » coarse granularity is appropriate for a repair mechanism
    - » email can tolerate inconsistencies during undo/rollback

Undo issues

- **Open issues in implementing undo**
  - defining undo points
    - » simplest: a special “undo mode” for tolerating human error
    - » but periodic snapshots are needed for repairing unanticipated failures
  - snapshot and logging mechanisms
    - » overhead affects granularity of undo points
    - » with cheap disks and disk bandwidth, are simple but high-overhead schemes acceptable?
  - protecting undo from failures
    - » snapshots, external request logs must be independent
    - » undo should be tested like any repair mechanism: stage 3

Stage 2: Online verification

- **Goal: expedite repair**
  - expose latent problems for repair
  - reduce failure propagation with faster detection
- **Techniques**
  - continuously verify HW & SW component operation
    - » check correctness to detect bugs and hard failures
    - » check performance to detect bottlenecks and soft failures
    - » use real test inputs, not heartbeats
  - add verification at all component interfaces
    - » check received data against specifications, checksums
  - check global system properties
    - » use "conservation law analysis" as in industrial plants [Lind81] to prevent loss, misdirection of data

Issues in online verification

- **Standard testing issues**
  - input selection, result verification, coverage analysis
- **Online testing challenges**
  - ensuring non-destructive operation
    - » perform testing on an isolated partition of the cluster
    - » use hardware isolation and existing Ninja partitioning and node-reincorporation mechanisms
  - detecting dynamic performance problems
    - » check all tests against running statistical estimates of range of normal performance
- **Developing global conservation laws for email**
  - example: rate of incoming messages must equal sum of rates of additions to user mailboxes

Stage 3: Exercising repair

- **Repair mechanisms are often untrustworthy**
  - buggy automatic recovery code
  - humans unfamiliar with system repair procedures
- **Goal: proactively verify repair mechanisms by exercising them in realistic environment**
  - detect broken recovery code so it isn't relied on
  - provide framework for testing recovery code
  - familiarize operators with failure modes and repair procedures, and test them
- **Basic technique: fault-injection**
  - *performed in online, production system!*

Exercising repair: approach

- **Inject realistic faults to simulate failures**
  - targeted faults simulate most likely failure modes
  - random faults capture tail of the failure distribution
- **Allow automatic recovery attempt**
  - if recovery fails or is not available, log fault and use in human exercises
    - » approach is self-tuning for level of automatic recovery
- **Perform human training/testing**
  - using fault set that failed automatic recovery
- **Do testing on isolated subset of system**
  - to avoid damage to production system

Issues in exercising repair

- **Fault injection**
  - need realistic fault set and injection harness
  - also needed for evaluation -> discussed later
- **Verification**
  - straightforward for targeted faults
    - » effects are known
  - a challenge for random faults
    - » use stage 2 testing and verification infrastructure
- **Protection**
  - use partition-isolation mechanisms from stage 2

Stage 4: Diagnosis aids

- **Goal: assist human diagnosis, not subsume it**
  - reduce space of possible root causes of failure
  - provide detailed "health status" of all components
- **Technique #1: dependency analysis**
  - model dependencies of requests on system resources
    - » use model to identify potential resource failures when a request fails
    - » correlate dependencies across symptomatic requests to reduce failure set
  - generate model dynamically
    - » stamp requests with ID of each resource/queue they touch
  - issues
    - » tracking dependencies across decoupling points
    - » accounting for failures in background non-request processing

Diagnosis aids

- **Technique #2: propagating fault information**
  - explicitly propagate component failure and recovery information upward
    - » provide "health status" of all components
    - » can attempt to mask symptoms, but still inform upper layers
    - » rely on online verification infrastructure for detection
  - issues
    - » devising a general representation for health information
    - » using health information to let application participate in repair

Details: application spectrum

Application	Hard state	Consistency requirement	Interface complexity	Internal knowledge of data semantics	Query complexity	Total
SQL database	3	3	3	3	3	15
E-commerce app. server	0	3	3	3	3	12
Email	3	1	1	2	2	9
File server	3	2	1	1	1	8
Search engine	1	1	0	3	2	7
Block server	3	2	0	0	0	5
Transforming proxy	0	0	0	3	1	4
Web server	1	1	0	1	0	3

Context: undo

- **Undo is common for application recovery**
  - database transaction rollback
  - checkpoint/restore of long-running scientific codes
  - app. checkpointing may help tolerate Heisenbugs
- **But is rare at the system level**
  - only common example is snapshotting file systems
    » Network Appliance, new BSD FFS, Elephant, etc.
  - system-level undo needed to handle maintenance errors
- **Implementing undo requires implementing standard recovery techniques at system level**
  - checkpointing, logging, snapshots, . . .

Sources: Hitz95, Lowell98, Lowell00, Mohan92

Context: exercising repair

- **Similar to traditional "fire-drill" testing**
  - but automated, so it really gets done
  - unique to perform testing in context of live system using fault-injection
- **Training aspect is similar to offline training**
  - Tandem's "uptime champion" uses pilot-system-trained operators to increase availability
  - aircraft industry has long-standing tradition of simulator-based training to reduce human error
  - our approach provides same, but on live system
- **Built-in fault injection similar to mainframes**
  - IBM 3090, ES/9000 used built-in fault injection, but only during test-floor burn-in

Sources: Bartlett01, Merenda92, Nawrocki81

Context: online verification

- **Most existing approaches are in hardware**
  - lockstep hardware in mainframe and FT systems
  - ECC and other hardware verification schemes
  - hardware Built-In-Self-Test (BIST), online & offline
- **Online software techniques are usually ad-hoc**
  - assertion checking
  - heartbeats
  - checksums
- **We systematically extend hardware techniques to software and system level**

Sources: Gray86, Spainhower92, Spainhower98, Steininger99

Context: diagnosis

- **One-off system-specific diagnosis aids**
  - NetApp network diagnoser: cross-layer correlation and expert-system approaches
- ***General diagnostic methods***
  - expert systems and fault-tree approaches
    - » all require good understanding/model of failure modes, and thus conflict with real-world observations
  - dependency-based root-cause analysis
    - » requires system model, but only at level of resource dependencies
    - » our request-tracing approach dynamically discovers resource dependency model

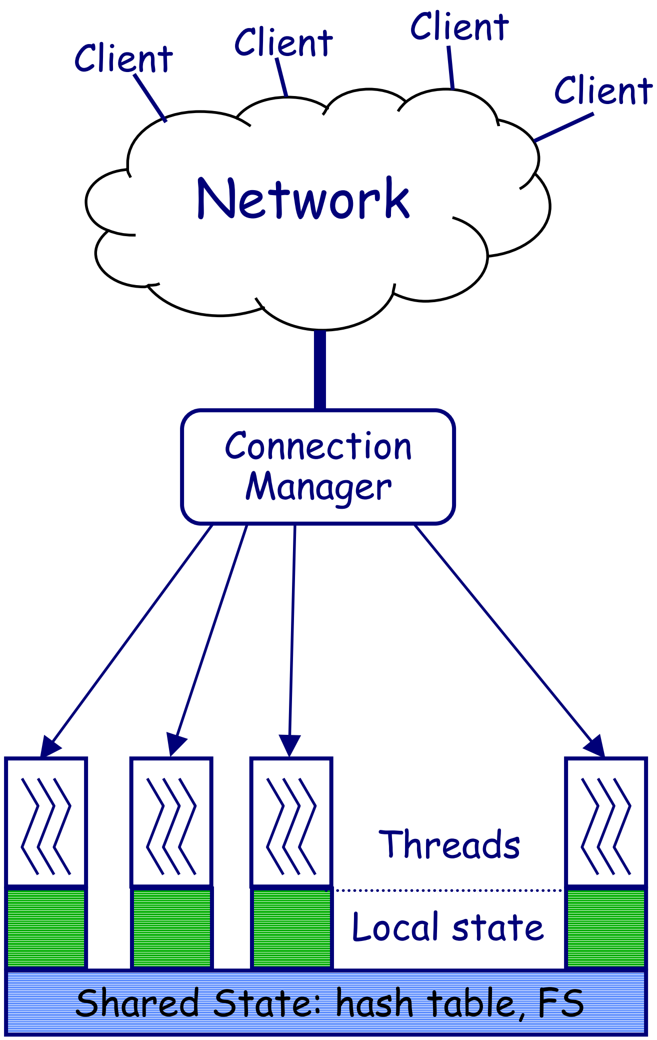
Sources: Banga00, Brown01, Kar00, Orge92

What we're NOT trying to do

- **Invent new recovery mechanisms for NinjaMail**
  - orthogonal
- **Remove the human operator from the loop**
  - unrealistic. But we can maybe simplify their job.
- **Eliminate human errors completely**
  - impossible
- **Guarantee fault detection, fail-stop behavior**
  - orthogonal: byzantine fault-tolerance
- **Precisely auto-diagnose failure root causes**
- **Build the world's fastest email service**
  - willing to sacrifice performance for effective repair

Ninja details

- **Framework for cluster-based Internet services**
  - SPMC programming model
  - built-in mechanisms
    - » clone groups (virtual nodes)
    - » partitions
    - » FE connection manager
    - » asynchronous comm. layer
  - built-in services
    - » distributed hash table
    - » streaming, txnal file system
  - size: ~20,000 lines of code
    - » NinjaMail: ~3,000
    - » file system: ~5,000
    - » hash table: ~12,000

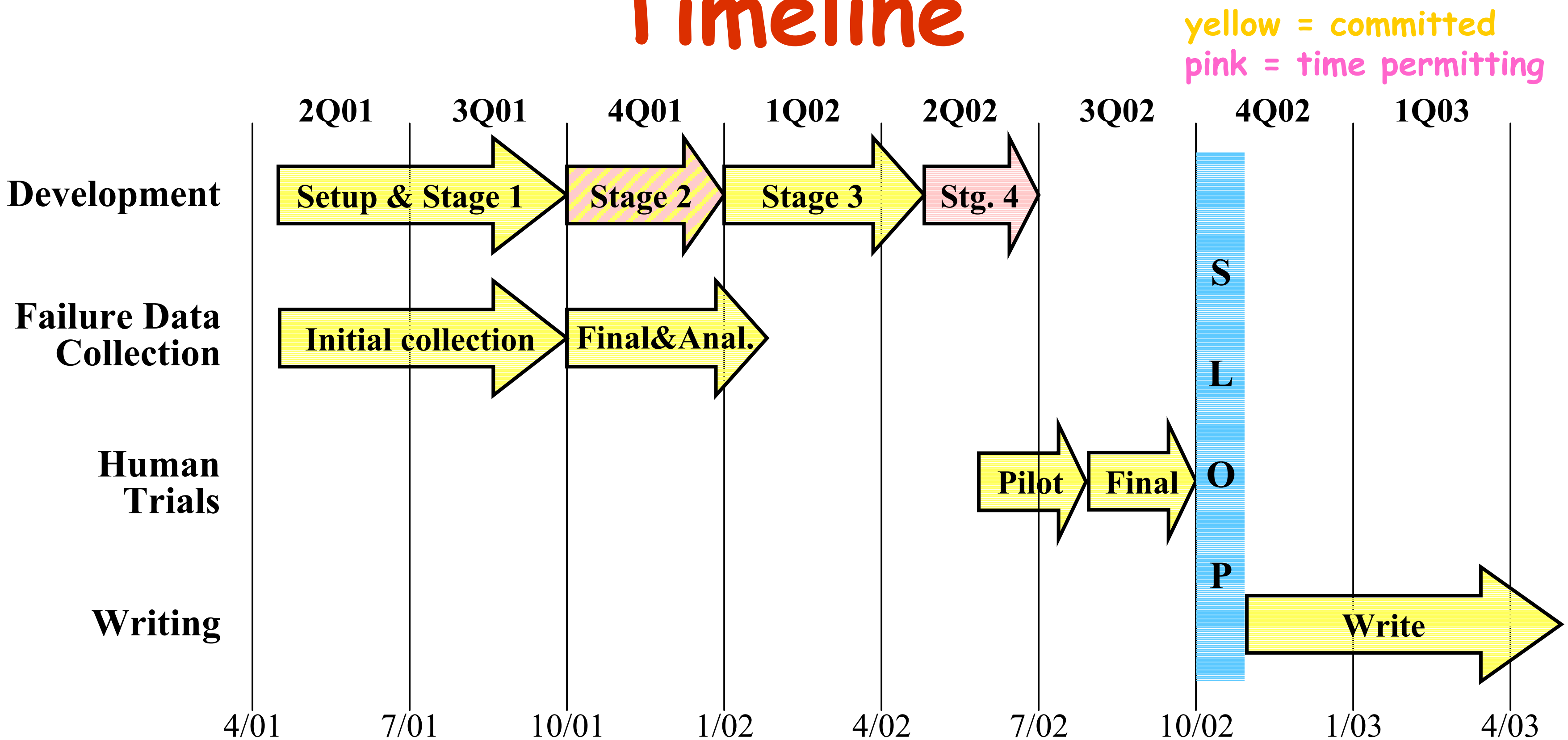


Context: repair-centric design

- **The philosophy of repair-centric design is rarely seen**
  - mostly found in “restartable systems”
    - » Recursive Restartability repairs Heisenbugs via reboot
    - » soft-state designs (TACC, Ninja, some production services) tolerate coding errors by restarting errant workers
  - our approach is much broader and adds human focus
    - » almost no work in systems and fault-tolerance community on tolerating human error
    - » UI work minimizes human errors, but cannot prevent entirely
- **Some repair-centric mechanisms more common**
  - but not in service to repair-centric philosophy
  - unique: maintenance undo, proactive verification via online fault-injection

Sources: Candea01, Fox97, Ninja01

Timeline



- At minimum, committed to:
  - stage 1 (undo) and stage 3 (exercising repair)
  - a partial implementation of stage 2 (online verification)
  - failure data collection
  - availability benchmarking using human trials

Research Plan

- **Evaluate the repair-centric hypothesis by**
  - identifying repair-centric design techniques
  - implementing the design techniques in a prototype
  - assessing the resulting availability improvements using availability benchmarks
- **Target application: Internet email service**
- **Staged research plan**
  - addresses practical concerns of scope, new grads
  - provides coherent fallback positions

Context: implementation platform

- **Base implementation: NinjaMail**
  - research implementation from UCB Ninja group
  - already implements non-repair-centric HA techniques
    - » clustered, replicated, load-balanced, modular, restartable
  - written in Java in the Ninja environment
    - » low-level Ninja mechanisms useful for repair-centric design
  - using existing system increases relevance, saves work

Staged research plan

- **Techniques for ROC**
  - 1) fault isolation
  - 1) undo: the ultimate repair mechanism
    - » tolerate human error and repair unanticipated failures
  - 2) online verification: fully-integrated online testing
    - » detect failures quickly to expedite repair
  - 3) exercising repair: online fault-injection
    - » provide trust in repair mechanisms and train operators
  - 4) diagnosis: dependency and fault tracking
    - » assist operator in pinpointing failures to expedite repair
- **Evaluation can be done after any stage**